# WINDSOR 2020

# RESILIENT COMFORT

## PROCEEDINGS

EDITED BY
SUSAN ROAF,
FERGUS NICOL
& WILLIAM FINLAYSON

# WINDSOR 2020

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# 11th Windsor Conference: Resilient Comfort

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# Proceedings

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Edited by
Susan Roaf, Fergus Nicol
& William Finlayson
Graphics by Rhiannon Hunt

WINDSOR 2020

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# INTRODUCTION

In the last ever Windsor Conference on Thermal Comfort we set out to confront head on some of the critical comfort challenges of our generation. Papers were invited for the conference from members of the worldwide 'Windsor Family' of researchers, as well as from groups in research, industry and government who are exploring Big Ideas around the role, and future, of comfort in the 21st Century. How can we keep our populations thermally safe in a heating world? What are the limits to human adaptation in extreme conditions? How do we protect the vulnerable from thermal stress? How do we frame comfort policy to reduce energy use and ghg emissions while keeping people comfortable and productive? How might technological innovations and approaches adapt to do just that? All such issues are included under our 'umbrella' title of Resilient Comfort.

A brief history of the Windsor Conferences is outlined in the last paper in this proceedings. It highlights the path travelled in comfort thinking since the early 1990s when the field of comfort research was largely dominated by laboratory based studies, dealing with variables within the steady state calculations methods used by heating and ventilating engineers to set the temperatures of thermostats in different buildings types, in different seasons. Work was also being done then on comfort in vehicles and aeroplanes, and on localised discomfort and productivity.

The 1st Windsor conference held in 1994 rather blew open the doors of thinking on the subject by triggering a fresh influx of field-based studies showing how very different the experience of comfort was in different countries, cultures and climates. The Windsor Conferences since have attempted to address the rapidly evolving context of building priorities over the last two and a half decades. Starting with the need to mitigate against climate change, and latterly moving on to deal with the burgeoning challenges thrown at our societies by economic upheavals, ever more extreme weather events and trends and in 2020 by a global Pandemic. We are extremely proud that the Windsor family of scholars and collaborators demonstrate in these Proceedings, how far, and how fast, we have travelled as a subject area. Many of the papers are clearly relevant to issues in the world we live in today, aimed at enhancing the well-being of our global societies and particularly the vulnerable, building new thinking on population level resilience and underpinning emerging discussions on building preparedness for a different future.

The first three papers look at New Comfort Approaches. Fergus Nicol uses the novel analysis tool of 'comfort clouds' to explore the importance of looking at the full range of data collected in field studies to understand what thermal environments are occupied by, and acceptable to, different populations over a year. Bjarne Olesen et al. propose another new way of evaluating thermal comfort over a year using international standards EN16798-1 and TR16798-2. Marcel Schweiker also proposes new definitions of resilience and comfort that may help us better reduce the impacts and consequences for design, operation, and energy use in buildings. All new thinking indeed.

Then we start to hit the nitty gritty of comfort challenges in our Heating World, with six very different studies on overheating in cities, buildings and bedrooms, and its impacts. Then moving on to looking at issues related to the most vulnerable in our societies. Comfort research in relation to the elderly and the young is outlined in twelve excellent papers in which authors report on field work in care homes and classrooms. The appropriateness of our current methods of measuring and managing comfort, are questioned for these important groups. We cannot just apply the same standards and guidelines to the young, and old, as we do for the heathy mainstream populations. Here a range of nuanced discussions are developed on how best to help provide safe and healthy environments for people with different needs.

It is clear that ideas of comfort discussed at Windsor have now become a much broader church than when we first met in 1994. Seven papers deal with the experience of, and interactions between, people and their environments from the viewpoint of psychology, linguistics, behavioural science and climate science. Technology now enables us to collect huge amounts of data at a range of scales, from the buildings to the person level, illuminating new ways of understanding how people sense and interpret temperature.

Another whole branch of study we have been fortunate enough to attract into the Windsor fold is that of the physiology of comfort, so that building level and personal experiences can now be explained and translated in to positive actions, notably at the thermal extremes and for vulnerable populations. Four papers here contribute considerably to our understanding. What we will miss by having had to cancel the physical conference due to the Pandemic, are the discussions at the interfaces between the different fields of expertise on particular topics, discussions that in past conferences have shed light on the dynamic and multiply complex phenomenon of thermally acceptable environments.

We are even moving away now from a core focus on discussion of what constitutes 'comfort', to looking at those temperatures people find acceptable for themselves to occupy, and what are the thermal conditions that are safe and healthy. The physics of the accoutrements of comfort also prove fascinating. What conditions are optimal for us asleep in bed? How can we develop clothes and furniture that will mean we can turn off the energy hungry heating and cooling systems while still remaining in thermal balance. Four papers interestingly explore these topics.

Twenty-four papers expand the subject out into the hugely important reaches of how do we use our knowledge of what constitutes comfort to design better, safer, buildings and cities in a warming world. A whole panoply of opportunities to defend ourselves from discomfort in homes and offices are offered here, from the use of adaptive features like blinds and shades, to looking at the roles of office workers stress levels and gender on the perception of thermal environments. From the role of air-conditioning in buildings, to experiences from Africa, China, Brazil and even nomadic tents in Siberia; the reach of these papers is large and their findings illuminating.

Then follow three sections that contribute studies undertaken on indoor environmental quality, energy saving approaches, light and view, ventilation considerations and the evidence underpinning the growing re-thinking in, and application of, radiant comfort systems to improve comfort and reduce energy costs of buildings. Mixed in here are discussions on the pros and cons of different methodological strategies and tools in determining the outcomes of studies.

The magnitude of the achievements and challenges of comfort research are emphasised in the last four papers in the Proceedings, two of which cover the development of meta-data sets on thermal comfort in Brazil and globally. In the last 26 years we have moved from largely being a theory and laboratory research dominated field towards being an evidence based endeavour focussed on understanding what conditions people normally occupy in their homes and workplaces, so that as change happens, as it does now, we know enough about to how the complex feedback systems involved in keeping people comfortable work, to help us all adapt to the different thermal futures ahead. The penultimate paper is also key. How do we educate people in a heating world on how to be, and stay comfortable, cool and accountable?

Since 1994 Michael Humphreys, Fergus Nicol and Sue Roaf as Conference Chairs, have witnessed a huge evolution in thinking around the field of comfort studies, hot-housed over eleven Conferences and outlined in the final paper. They offer their heartfelt thanks to everyone who has ever attended the Windsor Conferences, and helped shape that change. Particular thanks go to the 2020 delegates, authors, and the sponsor VELUX, for their support and tolerance over the process of the cancelling of the 11th Windsor Conference. We all regret not having been able to meet again for a final, unforgettable, happy, time in the beautiful English countryside around Windsor Castle. Special thanks go to all at Cumberland Lodge who kindly waived their charges for the conference in time for us to refund delegates. We are particularly grateful to the hard working

Windsor team, Will Finlayson for his work on the papers and proceedings, Anne Ormston for organising registrations and Rhiannon Hunt for this Proceeding's graphics. Many of us have the fondest memories of past times spent together at the first ten Windsor conferences, of its amazing location, hospitality, cuisine and the friendships, discussions and fun shared there.

Importantly, it was the intellectual excitement there that many will miss, on hearing of new developments in our field, of new thinking, and bold steps taken in new places and climates. How rewarding it was to have had the chance to share in the impacts arising from our research, working together to reach well-discussed and understood steps forward, to see the stones of our ideas being thrown into the water and watch their ripples spread out to influence the spheres of policy, standards, research, education and industry. We worked hard there, together, to ensure our research was truly Fit for Purpose in a rapidly changing world. These Proceedings bears testament to the success of those consensus building, and focus sharpening ambitions

## Windsor 2020 conference Chairs

Sue Roaf

Fergus Nicol

## Delegates at the 10th Windsor Conference

# CONTENTS

# The shapes of comfort

Fergus Nicol [1, 2, 3]

[1]London Metropolitan University, [2]Oxford Brookes University [3]University College London, UK

**Abstract:** The method of the field survey can involve the collection of large amounts of physical and subjective data much of which is not used or is found to be unnecessary when the results are analysed. A large body of information can be collected and end up with the results reduced to a simple regression analysis. Wide-ranging data are destined to result in a simplified result which can diminish the apparent usefulness, or significance, of the actions of the occupants and the design of their buildings and their understanding of comfort, and technical and policy responses to it. This paper shows how the approach of developing visual data clouds encompassing all data points avoids the jettisoning of much of the information which has been collected, and can give a richer understanding of survey results, and their implications in the real world.

Keywords: Thermal comfort, data clouds, Pakistan, Europe, field surveys

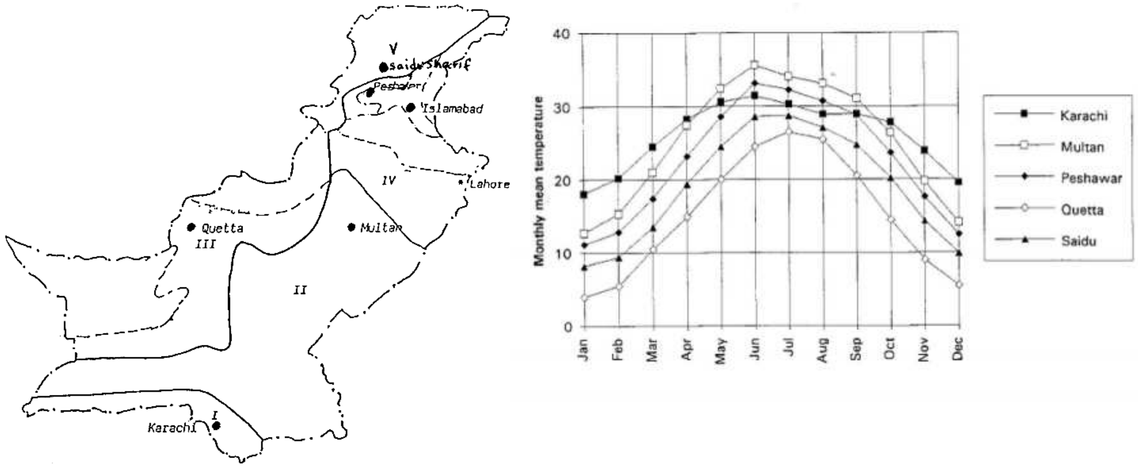
## Introduction

When researchers consider a field survey of thermal comfort (i.e. one based on information from subjects who are in their usual surroundings, rather than a laboratory or climate chamber), they will need a set of measuring instruments with which monitor, or take spot measurements of, the environment. They will also need to consider what questions to ask about subjects' subjective responses, and about the physical characteristics of the buildings or surroundings the subjects inhabit. The answers to these questions can be extensive particularly when, before the survey, it may not be clear which environmental measurements will be interesting, which will be unnecessary, and which will be best used to inform the experimental architecture of the survey. The information used to explore the issue of what results one wants, and can elicit from, such surveys in this paper comes from two surveys led by the author, one in Pakistan (Nicol et al. (1999)) and one in Europe (McCartney and Nicol (2002)). See Annexe A at the end of this paper for more detail on these surveys.

The analysis of the results from a survey will use statistics which may be extensive, and will be generally aimed at answering specific questions such as at what temperature the largest proportion of subjects will be comfortable at, how does this depend on the characteristics of the occupied building , and how do the survey subjects interact with the building, and so on. This paper introduces a new way of considering the results of such a survey, looking at the whole of the body of the data which has been collected, without the problems attendant on the jettisoning of information in the process. For each occasion on which a set of data is collected a point is entered into the 'data cloud', on a two-dimensional space bounded by the indoor and the outdoor temperatures measured during the survey. Such a two-dimensional space is shown in Figure 2.

## 1. Survey in Pakistan

Pakistan is situated in South Asia between Afghanistan and India. To the North it includes the foothills of the Himalayas and the Hindu Kush, and to the south the Indian Ocean. At the time of this survey the population was about 120 million which has expanded in the intervening twenty years to some 220 million! The country includes areas of warm humid (I), hot dry (II), cool dry (III), composite (IV) and mountain (V) climates as shown in Figure 1.




a) b)

Figure 1, a) a map of Pakistan showing the climatic zones and cities in which the surveys took place and b) a Graph showing the historical mean temperature for each month in each of the cities. The different climatic areas are marked. (Nicol et al. 1999)

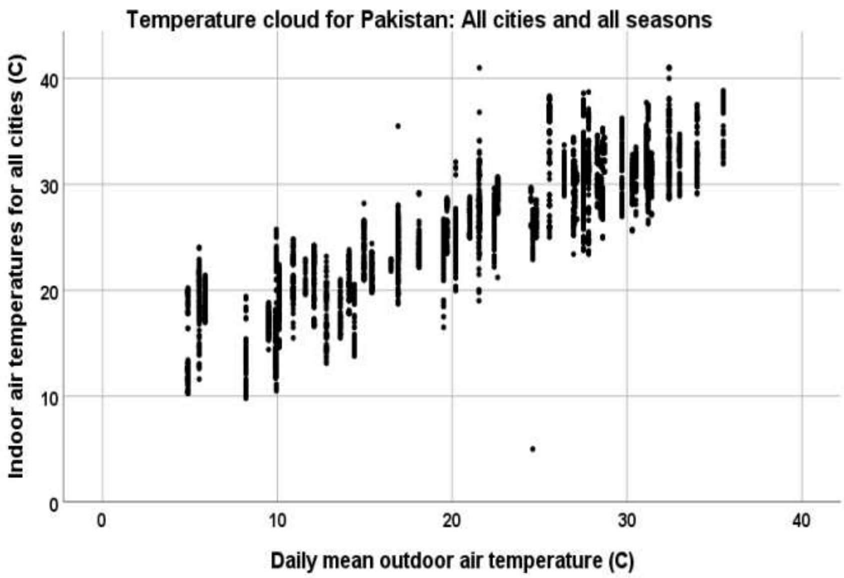



Figure 2 the two-dimensional indoor-outdoor temperature cloud for Pakistan. Each point represents the indoor and the daily mean outdoor temperatures at the time of the survey.

The outdoor temperatures were not measured at the time of the surveys but were derived from an average for each day from local meteorological records. This accounts for the striped appearance of the outdoor temperature in the graph – only one outdoor temperature was found for each day of the survey, not for each set of measurements, as was the case for the indoor temperature. Each dot on the space represents a survey site at which not just the temperature but also the air movement and the humidity were measured as well as the use of windows, fans etc. were also noted.

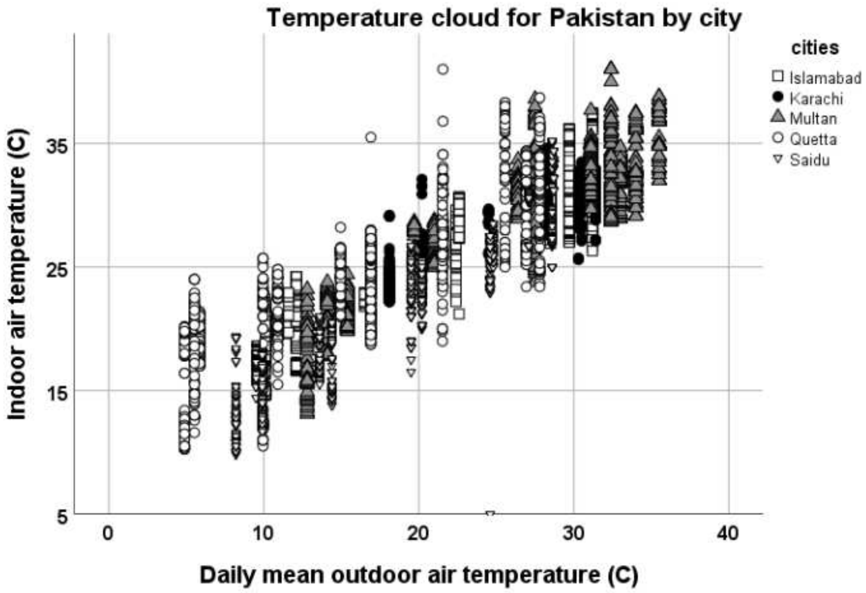


Figure 3. Indicating the city at which each survey was made. Each city effectively has its own temperature cloud

The buildings in which the surveys were made were offices or other places where the occupants are relatively static (e.g. shops). Almost all buildings were essentially free running and temperature cloud is characteristic of free running buildings. In these the indoor temperature is in effect shadowing the outdoor temperature through the form and materials of the building with no, or only minimal, use of energy.

Of the 65 buildings included in the survey only one building was fully air-conditioned and nine others were mixed mode, having cooler units - either chillers or evaporators which were used at the hottest time of the year. All buildings had ceiling fans in every room. The temperature cloud for each city can be traced. With the exception of Karachi, where the proximity of the Indian Ocean tends to damp the annual temperature swing. The shape of the clouds and the slope which characterises free running temperature clouds can be seen, but the limits of the clouds change with the climatic limits of the city. The highest outdoor temperatures can be found in the Cloud for Multan and the lowest in Quetta.

The use of air conditioning was unusual in Pakistan at the time of these surveys. In winter, the indoor temperature is usually higher than the outdoor temperature, especially in Quetta where heating was often used, and in Saidu as well. Heaters were hardly used in Karachi and Multan, and even in Saidu some buildings did not have them.

### 1.1 Comfort and discomfort

The scale used for the comfort vote was the 7- point Bedford scale which is similar to the ASHRAE scale but contains a clear division between comfort and discomfort. [1]

Notice that in the descriptors of Bedford scale comfort votes of 1, 2, 6 and 7 are clearly identified as uncomfortable. In figure 4 the uncomfortable points are shown by filled markers and the acceptable ones are open. An indoor temperature above 30-33°C seems to be found uncomfortable (warm) by a growing number of subjects, those from the hot desert climate of Multan having less sensitivity to heat (see figure 3-6). A temperature below 15-20°C is found to be too cool. The fact that both limits are variable may be a result of using

1 Descriptors for the Bedford scale are: 1 much too cool, 2 too cool, 3 comfortably cool, 4 comfortable neither warm nor cool, 5 comfortably warm, 6 too warm, 7 much too warm

data from a large range of climates. Temperatures which are too hot for a subject in a cool climate (such as Quetta) may be perfectly acceptable to a subject in Multan.

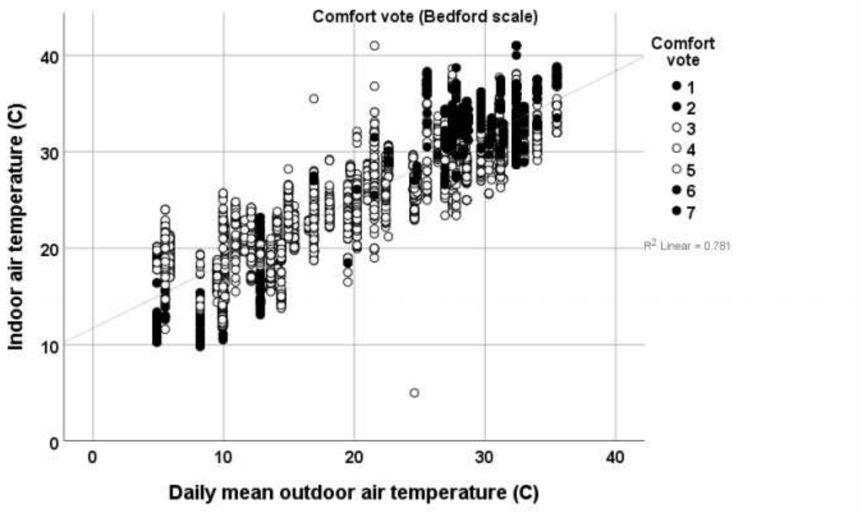
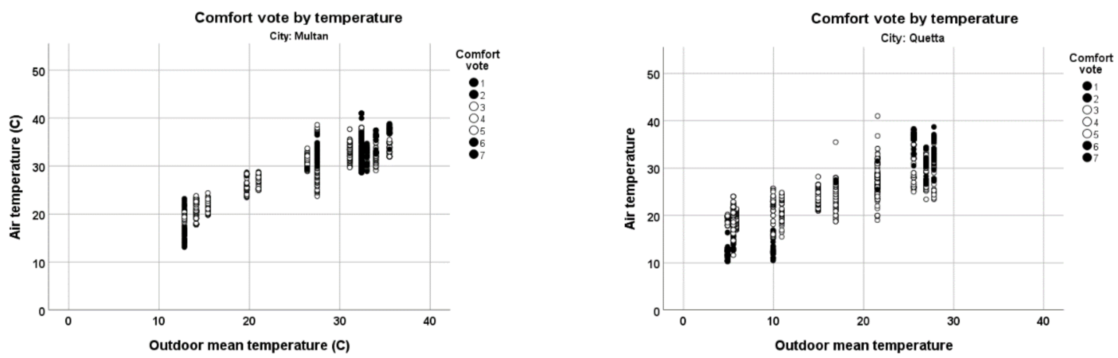



Figure 4. the comfort vote has been used to identify the areas in the temperature cloud where discomfort was identified (the filled dots).

The clouds for Multan and Quetta are shown in figure 5. Notice that the outdoor temperatures are generally higher in Multan, but the indoor temperatures have a similar range. Acceptable winter indoor temperatures centre at about 20ºC and summer at 32-35ºC. Many of the Quetta buildings are heated in winter and it may be that some in Multan have some form of coolers in the summer. Both clouds show the familiar shape for free running buildings. This suggests that the subjects in the Quetta are less liable to discomfort in the cold and those in Multan to the heat.




a) b)

Figure 5. clouds for a) Multan and B) Quetta showing point by point acceptability and discomfort as in Figure 4

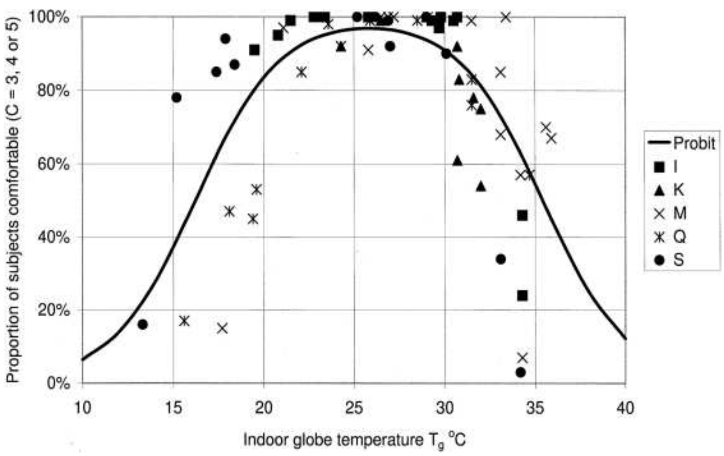



Figure 6. Proportion of subjects comfortable. Indoor temperature points are means from the monthly surveys; the line shows the proportion predicted to be comfortable using probit regression. (Nicol et al 1999).

The graph in Figure 6, using data from the field survey, gives a similar story but in a different form. The proportion of subjects who were comfortable in surveys at different outdoor temperatures is shown, and the survey site is signified by the shapes of the points. Some of the insights which can be drawn from the temperature clouds are not possible with this type of analysis.

Although the comfort lessons from the data are often the most central interest in field surveys of the kind described, there are often other areas of interest that have been under-explored to date, and in particular about the usefulness of the adaptive opportunities to hand such as the use of fans, or windows. Ceiling fans were then found universally in offices, and used to provide air movement in the hottest time of day. Windows are another adaptive opportunity which also can allow a change in air movement and temperature and may also be used to improve air quality. The difference between the indoor and outdoor temperatures recorded is a concern, and in the high outdoor temperatures frequently found outdoors in Pakistan. Opening windows may be counterproductive if the outdoor air is much hotter than that indoors. The temperature clouds for fans and windows are shown in Figure 7. Note that the fan use is concentrated during the hotter parts of the cloud – generally when the indoor temperature exceeds about 28-30°C. Windows can be opened at any temperature, but generally more in the hotter times of day. The windows are often left closed when the outdoor temperature is high and the indoor temperature relatively low.

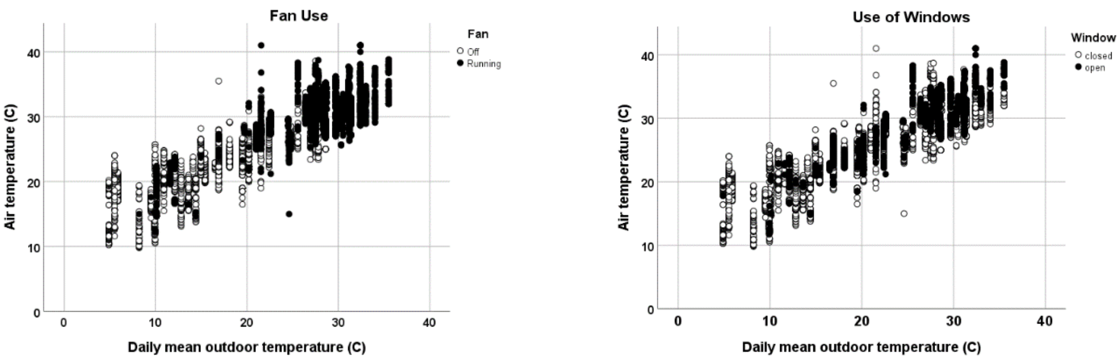



Figure 7. Clouds showing the use of adaptive opportunities a) fans and b) windows in Pakistani offices

Perhaps the biggest potential 'adaptive opportunity' is clothing. In almost any situation an appropriate change of clothing can help restore comfort. Figure 8 shows the changes in clothing with temperature, clothing is characterised in two ways: a) as the number of garments the subjects wear and b) as their combined thermal insulation. There are problems with merely counting the garments without assessing their individual or combined clothing insulation which slows the loss of heat from the body of the subject, each approach will have its advantages but it is as well to remember that clothing plays a social as well as a thermal function, the subjects are responding to this social function of garments as well as to their physical definition.

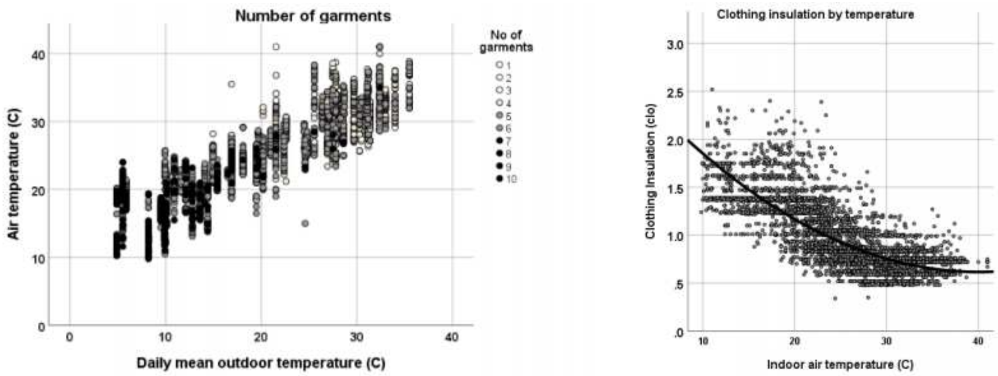



Figure 8. Changes of clothing expressed in two ways: a) the number of garments worn as it changes with the changes of indoor and outdoor temperature b) the clothing insulation changes with indoor air temperature.

So far, we have referred to the clouds as Temperature clouds because we have been considering the two-dimensional clouds between indoor and outdoor temperature. There are of course other two-dimensional spaces we could consider. One is for instance is shown in Figure 9 – the space between water vapour pressure, and the indoor air temperature, and how the subjective measure 'skin moisture'[2] changes in different parts of the water vapour – air temperature space.

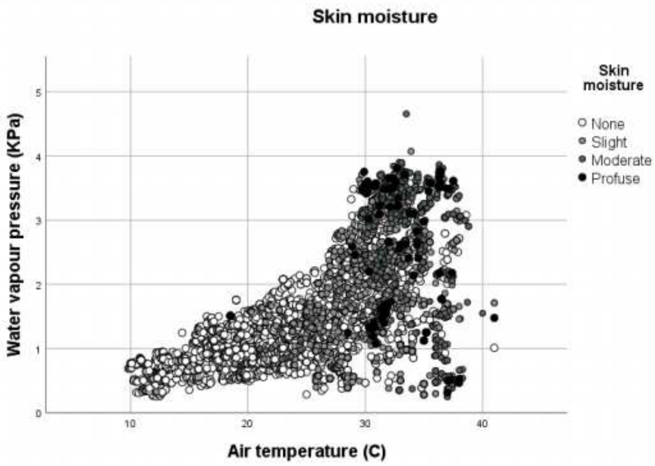



Figure 9. The two-dimensional cloud between water vapour pressure and air temperature. This figure shows the combined effect on skin moisture of these two dimensions.

## 2. Surveys in Europe

The experimental method for the comfort surveys conducted in Europe is given in Annexe A at the end of this paper. The overall cloud for the whole of Europe is shown (with its Loess regression line) in figure 10. Note the upward trend for outdoor temperatures above 12°C.

2 'Skin moisture' is a subjective scale used by Charles Webb (1964) and others particularly when conducting surveys in hot humid climates. The scale is 1 = none, 2 = slight, 3 = moderate, 4 = Profuse

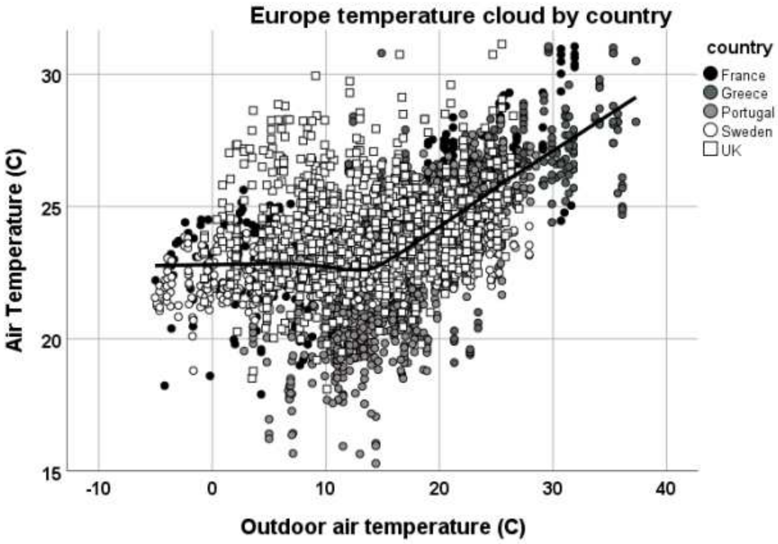



Figure 10 the collected data from the individual clouds (including available Greek data).

The data from the SCATs European survey (see appendix A) has been used to produce the clouds shown in Figure 11 (Note that the data for Greece did not include winter readings and so have been excluded).

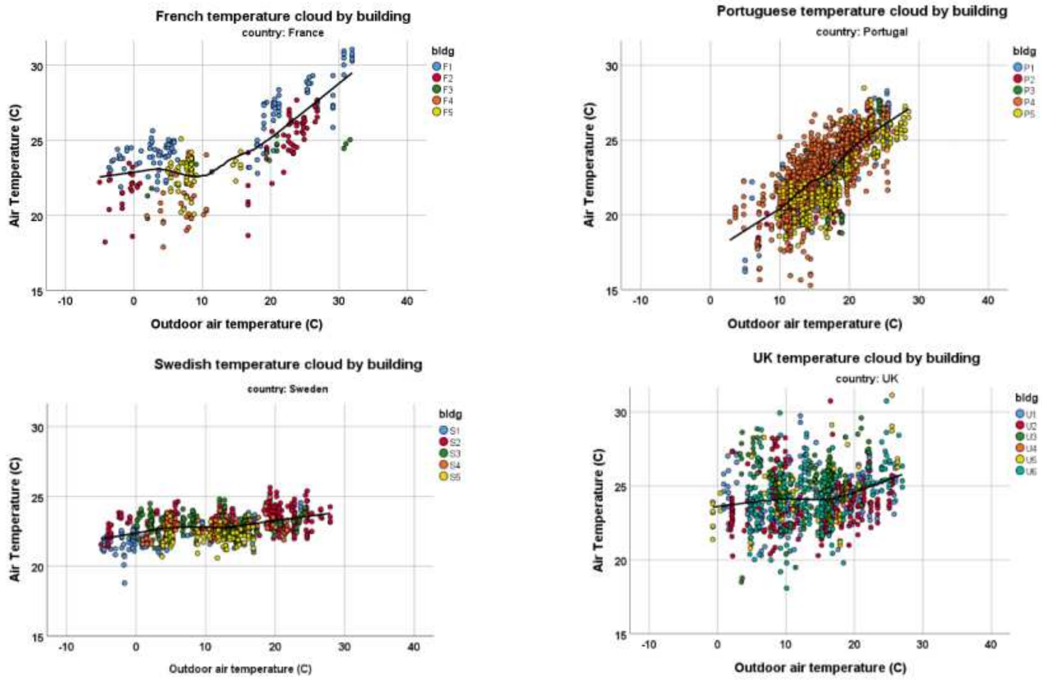



Figure 11 temperature clouds for France (Lyon), Portugal (Porto and Lisbon) Sweden Gothenburg/Malmo and UK (London)

The clouds shown in Figure 11 illustrate the variation which can occur in the temperature clouds from offices. Each includes its loess regression line for reference.

1. The French cloud is characteristic of buildings which have different modes of operation in cold and warm weather. In warm weather the indoor temperature increases in concert with the outdoor temperature. This is characteristic of buildings in free running mode. However, at outdoor temperatures below about 10°C, the mean indoor air temperature

remains almost constant at 22-23°C despite changing outdoor temperature suggesting that controlled heating or air conditioning was used

2. Figure 12 shows that windows and clothing are active adaptive opportunities in Portugal.

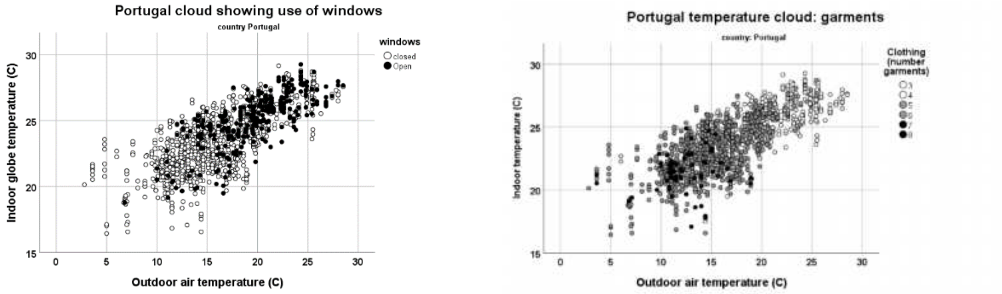


Figure 12. pattern of window and clothing use in Portugal (cf. figures 7 & 9)

The cloud from Portugal also shows the shape which can be associated with buildings which are effectively free running. The 'sloping cigar' shape is similar to that for buildings in Pakistan. Work by Nicol (2020) has suggested that for free-running buildings there is continuity between the clouds for different climates. This has been tested in Figure 13 where the outline of the cloud from Karachi has been compared to the cloud for Portugal. Karachi has been chosen for the comparison because, like Lisbon and Porto, its climate is influenced by proximity to the sea.

3. The cloud for Sweden is a classic line for buildings which are closely air conditioned. The spread of the cloud (which has a small (0.05) slope) follows the recommendations of European standard EN 15251 [BSI, 2017] which calls for indoor temperatures in mechanically conditioned offices of 20-25°C in winter and 23-26°C in summer
4. The cloud for the UK has a less defined shape than those from other countries. There is no obvious explanation as the clouds for the individual buildings are similarly shapeless, all having a wide range of indoor temperatures. The construction of the UK buildings is generally lightweight without centralised controls. There is a slight tendency in all buildings for the temperature to rise as outdoor temperatures increase above about 15°C.

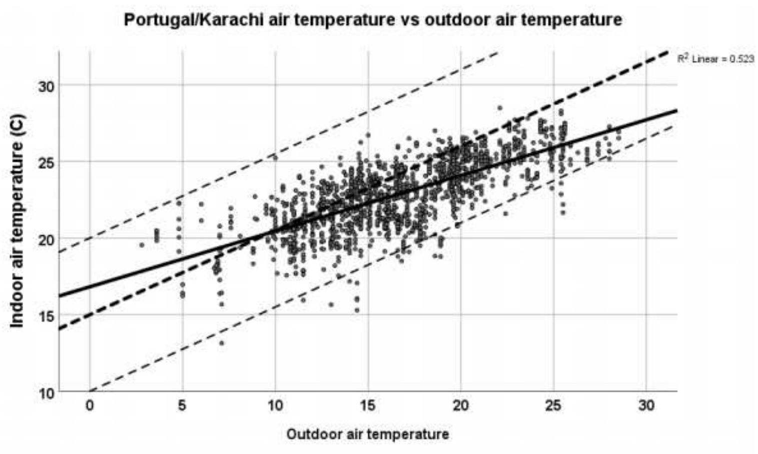


Figure 13. Comparison between the cloud for Karachi thick dashed regression line and its approximate limits (thinner dashed lines) and the cloud for Portugal with (solid) regression line.

## 3. Discussion and conclusions

The basic aim of most field surveys of the thermal environment is to answer a fairly closely delimited question. For instance: what is the temperature at which the largest proportion of people are comfortable in a particular type of building or climate or doing a particular type of work? Once a decision has been taken (and the finance collected) then the range of measurements to be made or questions asked is decided.

There is a natural tendency to collect information on a wider variety of factors than is strictly necessary. Why not collect information about noise and light for instance while you are about it? It may turn out to be important (are people more (or less) sensitive to heat in a noisy office?). Also, if there is a short-lived heatwave should you dash in to collect some data about the response of occupants in these relatively extreme circumstances?

This is a presentation of various uses of the cloud approach where the data can be interrogated, before any is excluded. We have concentrated on the temperature clouds based in the indoor/outdoor temperature space. This can allow us to assess which of the two is predominant and whether this interrelationship should consider the role of windows, fans, doors etc on the overall thermal landscape. Taking these factors as, in effect, a third dimension in the cloud. But clouds can also be used to demonstrate relationships beyond the purely thermal, as was demonstrated in the analysis of the dependence of skin moisture on water vapour pressure, as well as temperature, in figure 9.

The use of fans for cooling is shown to follow a different pattern to the use of windows, or the use of clothing because windows can make matters worse when the outdoor air is hotter than that indoors. They can also improve indoor air quality.

In all the figures presented in this paper testify to the active use of both mechanical and passive controls by the occupants to adapt the buildings to their comfort targets.

In a recent paper (Nicol 2020) a problem was encountered where the database from Japan (Rijal et al. 2019) exhibited a strangely shaped temperature cloud which turned out to be caused by a misunderstanding by the subjects who counted a building as free running which was found to effectively to be heated.

Lastly, the above analyses had clearly demonstrated that the thermal comfort experiences of citizens of one city in a country or continent can be radically different from others in different geographic, or climatic, zones, even when they are as close together as Quetta and Multan. It may be convenient for sizing heating or cooling systems or simulating the thermal performance of buildings to have one simple number to feed into the calculations, but such a number may not reflect the actual thermal experience and preferences of the majority in a region. Why would one specify the same indoor optimal operating temperature in winter, or summer, in Sweden as in Spain, let alone Islamabad or Multan? The resulting compromising thermal setting can not only result in discomfort for parts of the population but will also result in significant extra energy used to force indoor temperatures across the region. Much better to identify the actual thermal preferences for every major population grouping and use them to inform really energy efficient design and servicing solutions. Exploration of the comfort clouds of different cities at different times of year will be an effective tool to inform optimal design solutions for comfortable buildings in any climate.

**Acknowledgements**

My thanks to Prof Sue Roaf for her useful comments and criticisms

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## ANNEXE A Experimental design of the surveys

**European Survey (SCATs)**

The basic experimental design for these surveys was the repeated transverse survey. This is a transverse survey carried out at monthly intervals among the same group of subjects. The European subjects were 850 office workers from five countries (France (5 buildings in Lyon), Greece (5 buildings in Athens), Portugal (4 buildings in Porto and one in Lisbon), Sweden (3 buildings in Gothenburg and one each in Malmö and Halmstad) and the UK (5 buildings in SW London)).

Physical measurements made near the subject were globe temperature, air temperature, relative humidity and air speed. In Europe measurements were also taken of desktop Illuminance and noise level at the desk. Estimates were also made of clothing insulation and activity level as well as use subjects made of various controls which may influence the thermal environment - doors, windows, heating, air conditioning, curtains or blinds, artificial lighting, and fans or other localised cooling.

In addition to the repeated transverse surveys, longitudinal and background surveys were made. The longitudinal surveys were taken four times daily by a small subsample of the subjects in each building answering a limited range of survey questions. The background surveys asked more general questions to be filled in by each subject covering topics about the buildings and the individual subject's attitudes – questions which only need to be answered once. The results from these surveys were used to develop the temperature limits for free running buildings in European Standard BS EN 15251 (2007) (Nicol and Humphreys, 2010)

**Pakistan surveys**

The surveys were undertaken in Pakistan in the late 1990s (Nicol et al. 1999). These surveys were more straightforward, and the environmental measurements were basic. 846 subjects took part in surveys in 5 Pakistani cities (see Figure 1) spread over 12 months in 1995-1996. The characteristic climate for each was different: with almost parallel mean temperature profiles with a mean annual range of about 20K apart from Karachi where the sea damps the temperature swing. The regions represented were: Coastal region (Karachi), Hot desert (Multan), Cold desert (Quetta) Composite climate Islamabad) Mountain climate (Saidu Sharif) (see Figure 1b). Indoor air and globe temperatures, Relative Humidity and air movement were measured at the time of the survey. Subjective scales were thermal comfort (Bedford Scale), preference (5- point scale), Skin moisture (4-point scale) and then estimates of activity, Clothing and use of controls (doors, windows, ventilators heaters fans and AC).

# Whole year evaluation of thermal comfort using international standards EN16798-1 and TR16798-2

**Bjarne W. Olesen**[1], **José Joaquín Aguilera**[1], **Ongun B. Kazanci**[1] **and Daniel Coakley**[2]

[1] Intl. Centre for Indoor Environment and Energy, Technical University of Denmark;
[2] Mitsubishi Electric R&D Centre Europe

**Abstract**: There is an increasing interest in evaluating the indoor environment on a yearly basis. The technical report (TR16798-2) to EN16798-1 recommend criteria for thermal comfort evaluation based on heating and cooling seasons, but do not give clear indications of how to manage the transition between them. This study used dynamic simulations to evaluate the thermal comfort level and energy use when the heating-cooling seasons are defined either by a pre-fixed date, by identifying the periods with energy requirements for heating-cooling or by considering prevailing outdoor conditions. The results show that a better thermal comfort level was obtained when the heating-cooling seasons were defined by using prevailing outdoor conditions, without a significantly higher energy use compared to the other two cases. Including a transition period between seasons where only heating is available was observed to optimize both energy use and thermal comfort. The study also evaluated the thermal comfort level in buildings with and without air-conditioning systems using categories of indoor environment and a yearly thermal comfort score. The results showed that the latter yielded to similar conclusions when assessing the annual thermal comfort but in a much simpler manner than using indoor environmental categories.

**Keywords:** Thermal comfort, heating, cooling, performance evaluation.

## 1. Introduction

Indoor environmental quality (IEQ) is becoming an increasingly important concern, along-side energy consumption, for both new and existing buildings. Building energy performance, even for buildings utilising multiple disparate fuel sources, is generally expressed as a single annual value, either as primary energy (kWh/m$^2$/yr.) or carbon intensity (kg$CO_2$/yr.). As a consequence, in order to compare energy performance with the corresponding indoor environmental performance, there is a need to also express the indoor environmental performance on a yearly basis, referring both to each separate environmental factor (thermal comfort, air quality, light and noise) and to a combination of these factors.

If the indoor environmental criteria in existing standards have to be met 100% of occupied periods, the amount of heating, cooling and/or ventilation capacity of any HVAC installation would be significantly increased. Economic and/or environmental considerations lead to a more pragmatic position of allowing the indoor environmental conditions to exceed the recommended ranges for a limited time: this can be verified both by computer simulations (design stage) and by the field monitoring (post-occupancy phase). This paper will focus on the issues related to perform a whole year evaluation of the performance of HVAC systems, under a range of climatic conditions and operational scenarios. The aim is to evaluate the consequences, in terms of annual energy use and thermal comfort, when the heating-cooling seasons are defined based on a pre-defined date; based on previously identified periods when the energy requirements for heating or cooling are higher; or based on prevailing outdoor temperature conditions. The transition period between heating-cooling seasons will be also analysed, considering cases with and without heating or cooling available during that period. This paper also aims to compare methods to evaluate thermal comfort on a yearly basis, considering buildings with and without air-conditioning systems.

## 2. Issues with Thermal Comfort Evaluation Methods in Current Standards

The main issues that will be analysed in the present paper is whole year evaluation method for thermal comfort and how to define heating (winter) and cooling (summer) season, especially focused on definitions and guidance provided in EN16798-1. To illustrate and analyse the issues, a dynamic simulation of the thermal comfort and energy use in an example office building will be used.

### 2.1. Thermal comfort evaluation methods

Both the Adaptive method (ACM) (De Dear & Brager 1998) and the PMV-PPD method (Fanger 1970) for mechanical heated and cooled buildings, use categories are to define input parameters for design of buildings and systems, as well as for input to energy calculations. However, the intent is not that the buildings must always be operated within one category. Instead the distribution of time in the different categories during a year (or another time interval) can be used to express the long-term performance. For example, even if a system is designed for Cat. II, it may operate a significant part of the year in Cat I. According to Khovalyg et al. 2020, standards like EN 16798-1 give acceptable exceedance hours to allow for variations under real weather conditions compared to the simulation results using weather data files and to avoid the design of oversized HVAC systems. The required operative temperature categories for sedentary office work are shown in Table 1. For the adapted approach, the criteria for the operative temperature categories are taken from Figure B.1. in EN16798-1.

Table 1: Temperature ranges consider for the four categories of indoor environment defined for offices in EN 16798-1. Air velocity is assumed below 0.1 m/s and the relative humidity is 40% for heating seasons and 60% for cooling seasons.

| Category | Temperature range for heating seasons, °C (1.0 clo) | Temperature range for cooling seasons, °C (0.5 clo) |
|---|---|---|
| I | 21.0 - 23.0 | 23.5 - 25.5 |
| II | 20.0 - 24.0 | 23.0 - 26.0 |
| III | 19.0 - 25.0 | 22.0 - 27.0 |
| IV | 17.0 - 25.0 | 21.0 - 28.0 |

### 2.2. Definition of heating (winter) and cooling (summer) season.

For the PMV-PPD method for mechanically conditioned buildings the comfort requirements are divided in heating and cooling season with an assumed clothing change. The definition of heating-cooling season can be made in different ways:

- Based on date
- Based on outdoor temperature
- Based on calculated needs by dynamic building simulations

In the standards, it is recommended to define heating season (winter) at running mean outside temperatures below 10 °C. Cooling (summer) season is defined at running mean outdoor temperatures higher than 15 °C. It is assumed that in the heating season it is not possible to use mechanical cooling and vice-versa for the cooling season. However, it is a question whether heating-cooling should be assumed in the transition period between winter and summer, one of the focus areas for this paper. Using the adapted method, the thermal comfort requirements for the heating season (below 10 °C running mean outdoor temperature) are the same as for mechanical conditioned buildings.

## 3. Method

To study the issues outlined above dynamic building simulations was used for a typical office building in four different geographical areas Edinburg, Copenhagen, Zurich and Palermo.

### 3.1. Boundary building conditions

The model corresponded to a module of an office building, originally developed by Olesen and Dossi (2004). The building was composed of two identical offices with a floor area of 19.8 m² (length/height/width = 5.5/2.8/3.6 m) and a corridor section with a floor area of 8.6 m² (length/height/width = 2.4/2.8/3.6 m) between them. Each office had one 10 m² external wall with a window area of 5 m² (height/width = 1.65/3 m). One of the external walls was facing south and the other one facing north. All the internal walls of the building model were assumed adiabatic, except for the walls in between the corridor and the offices. The thermo-physical properties of the building components are shown in Table 2. Windows were equipped with automatically controlled solar shading devices. For incident radiations higher than 100 W/m² on the external glazing, internal blinds were drawn. When the internal blinds were active, the transmittance was multiplied with a factor of 0.09 and the solar gain was multiplied with a factor of 0.14.

Table 2: Characteristics of the building components of the simulation model

| Component | Material | Thickness (mm) | Density (kg/m3) | Heat conductivity (W/mK) | Specific Heat (Wh/kg K) | Emissivity, (-) |
|---|---|---|---|---|---|---|
| Opaque component | | | | | | |
| Floor/ceiling | Floor coating | 5 | 1100 | 0.18 | 0.26 | 0.95 |
| | Concrete | 150 | 2300 | 1.7 | 0.24 | |
| | Air gap | 500 | 1.2 | 2.8 | 0.28 | |
| | Ceiling panels | 20 | 970 | 0.22 | 0.3 | |
| Outside wall | Plaster | 8 | 1000 | 0.7 | 0.28 | 0.82 |
| | Insulation | 80 | 40 | 0.04 | 0.42 | |
| | Sand lime brick | 240 | 1200 | 0.56 | 0.28 | |
| | Plaster | 15 | 1200 | 0.35 | 0.28 | |
| Internal wall | Plaster | 15 | 1200 | 0.35 | 0.28 | 0.82 |
| | Sand lime brick | 115 | 1800 | 0.99 | 0.28 | 0.93 |
| Glazing component | | | | | | |
| Windows | Heat transfer coefficient for the frame, W/m2 K | | | | | 2.1 |
| | Heat transfer coefficient for the glazing, W/m2 K | | | | | 1.1 |
| | Overall heat transfer coefficient, W/m2 K | | | | | 1.4 |
| | Solar heat gain coefficient, -. | | | | | 0.58 |

### 3.2. Simulated weather conditions

For each location, a 3-day running mean outdoor air temperature was calculated from January to December according to equation (1), defined in EN 16798-1.

$$T_{rm} = \frac{1}{(1+\alpha+\alpha^2)} \cdot (T_{ed-1} + \alpha \cdot T_{ed-2} + \alpha^2 \cdot T_{ed-3}) \qquad (1)$$

where $T_{rm}$ is the daily running mean outdoor temperature for a specific day; $T_{ed-1}$, $T_{ed-2}$ and $T_{ed-3}$ represent the daily mean outdoor air temperatures from the previous three days and $\alpha$ is a constant with the value 0.8 (recommended in EN 16798-1).

In Figures 1 to 4 it is shown the running mean outdoor air temperature as well as the lower criteria for operative temperature during the heating season (Trm<10°C) and the upper criteria for operative temperature during the heating season ($T_{rm}$>15°C).

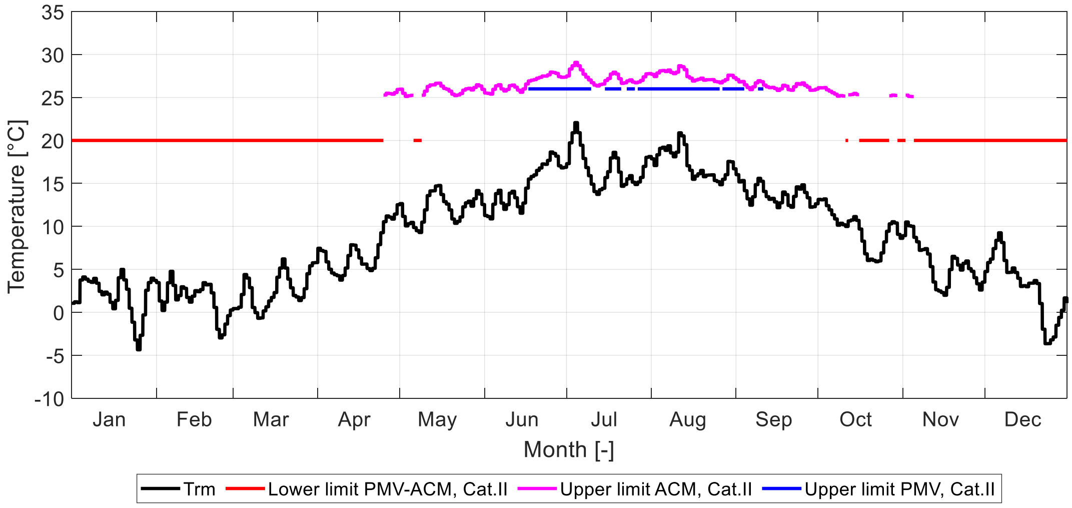


Figure 1: Daily running mean outdoor temperature ($T_{rm}$) as well as upper and lower limits for the PMV-PPD method and the ACM method for Category II, EN 16798-1 in Copenhagen.

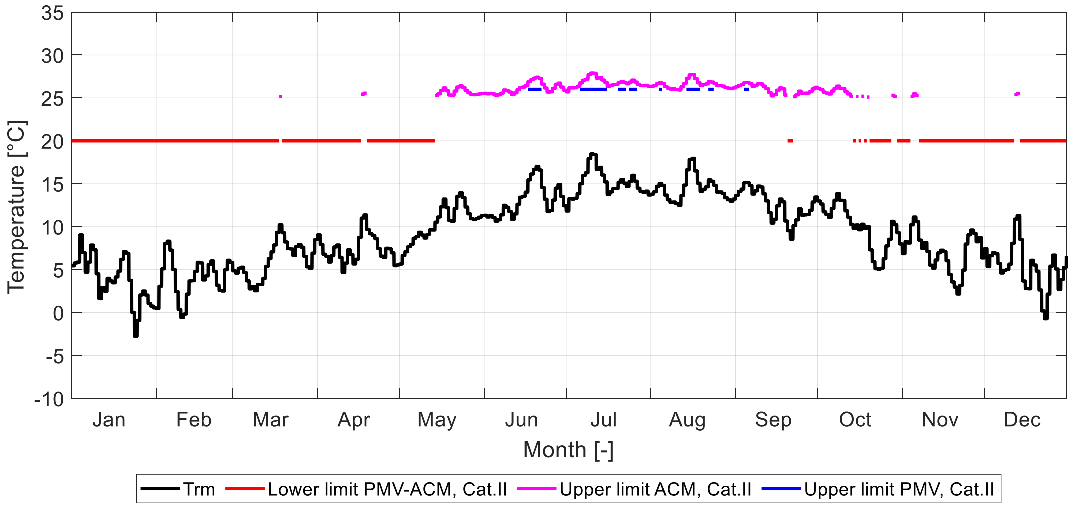


Figure 2: Daily running mean outdoor temperature ($T_{rm}$) as well as upper and lower limits for the PMV-PPD method and the ACM method for Category II, EN 16798-1 in Edinburgh.

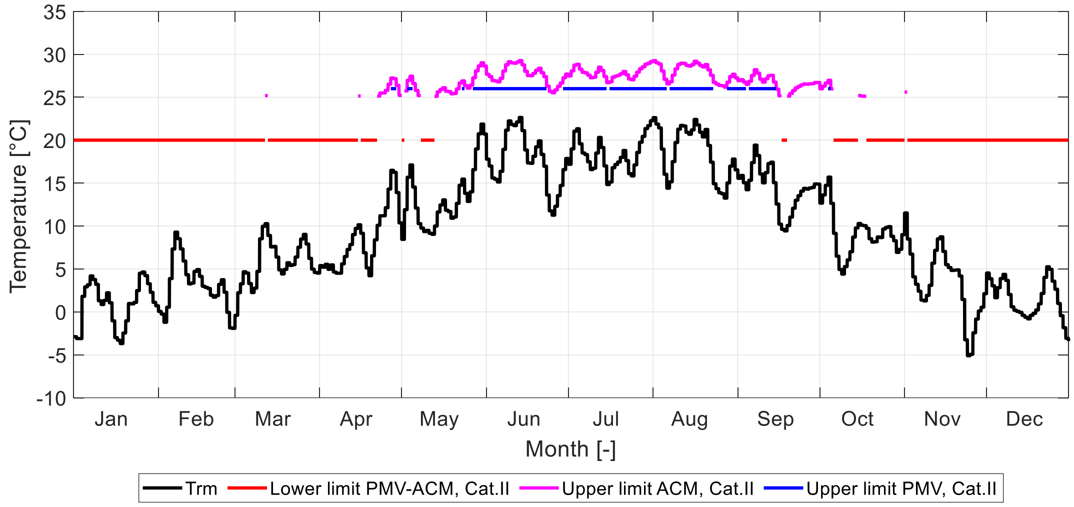


Figure 3: Daily running mean outdoor temperature ($T_{rm}$) as well as upper and lower limits for the PMV-PPD method and the ACM method for Category II, EN 16798-1 in Zurich.

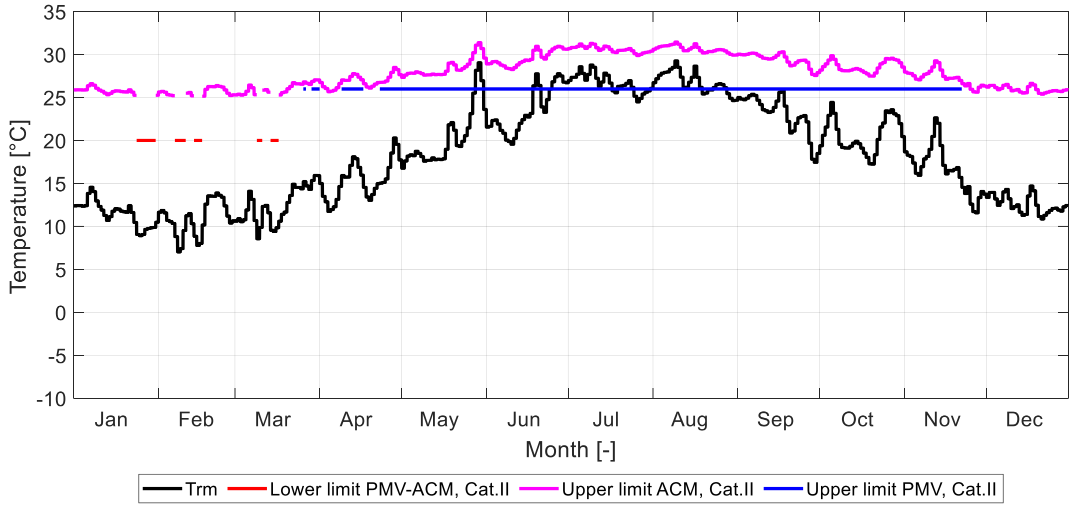


Figure 4: Daily running mean outdoor temperature ($T_{rm}$) as well as upper and lower limits for the PMV-PPD method and the ACM method for Category II, EN 16798-1 in Palermo.

### 3.3. Boundary system conditions and internal heat gains

As internal heat gains, each office had 2 occupants with a metabolic rate of 1.2 met, which were estimated to produce 238 W (12 W/m²). The occupancy level was based on the schedule defined in EN 16798-1 for single offices, where occupants are present only during weekdays from 08:00 to 13:00 and from 14:00 to 17:00. The equipment on each office corresponded to two computers and one printer, which altogether produced 350 W (17.7 W/m²). Ceiling lighting accounted for 50 W (2.5 W/m²), with a convective fraction of 50%. The schedules for the equipment and lighting were the same as for the occupants. The internal heat gains in the corridor corresponded only to a 100 W (11.6 W/m²) ceiling light, which had the same schedule as occupants in the offices.

The building was equipped with an all-air system, where a central air-handling unit (AHU) provided both heating and cooling to all zones. The supply temperature was proportionally controlled in the AHU between 16°C to 34°C based on the outdoor air temperatures between 22°C to -12°C respectively. The office rooms were equipped with a Variable Air Volume (VAV) system, where the air flow was controlled based on operative temperature, with a minimum supply airflow of 1.4 [L/sm²] (1.8 ACH) and maximum supply airflow of 10 [L/sm²] (13 ACH). The ventilation system in the corridor was controlled by a Constant Air Volume (CAV) control, with a constant airflow of 0.5 [L/sm²] (0.6 ACH). The operation time of the all-air system was continuous from 08:00 to 17:00 for all zones.

### 3.4. Cases considered for the evaluation

In order to analyse the implications of the seasonal operation of heating and cooling on thermal comfort and energy use, seven cases were considered in the evaluation: cases A, B, C, D, E and F. In case A, the change between the heating and cooling seasons is given by a fixed date. The change between the heating and cooling seasons was considered to occur on the 1st of April and the opposite change occurred on the 1st of October, without transition periods between seasons. In case B, the seasons were based on prevailing outdoor temperature levels. The heating season was defined as the period with $T_{rm}$ below 10°C, the cooling season as the period with $T_{rm}$ above 15°C and the transition between seasons occurred when $T_{rm}$ was between 10°C and 15°C. In case C, the seasons were defined based on a fixed date obtained from building dynamic simulations, without considering a transition period between seasons. The simulations to define the duration of the heating and cooling seasons were based on the same boundary conditions mentioned in Section 3.1, 3.2 and 3.3, using as set points 20.5°C and 25.5°C for heating and cooling respectively. The period when the energy use for cooling was observed to overpass the period when heating was used was defined as the cooling period, without applying any specific guidelines for its definition. The same approach was used to define the heating period. An additional case was added to analyse the yearly performance of a building without any mechanical cooling systems installed, named case D. The heating season was considered as the period where the running mean outdoor temperature was below 10°C, as presented in EN 16798-1. However, the cooling season and transition period where not considered in case D, as no mechanical cooling was applied during the year. Finally, two additional cases were added in the analysis to evaluate the effects on thermal comfort when heating and/or cooling is available during transition period between seasons. Those cases are: only heating was applied during the transition period (case E) and neither heating nor cooling were available within that period (case F). A summary of the cases is presented in Table 3.

Table 3: Characteristics of the cases considered in the evaluation, showing how the seasons were defined and whether heating and/or cooling was present in each season. HA: Only heating was available; CA: Only cooling was available; NHC: neither heating nor cooling were available.

| Case | Season definition | Heating season (winter) | Cooling season (summer) | Transition period |
|---|---|---|---|---|
| A | Fixed date, defined arbitrarily | HA | CA | Not considered |
| B | Based on $T_{rm}$ | HA | CA | HA and CA |
| C | Fixed date, based on simulations | HA | CA | Not considered |
| D | Based on $T_{rm}$ | HA | Not considered | Not considered |
| E | Based on $T_{rm}$ | HA | CA | HA |
| F | Based on $T_{rm}$ | HA | CA | NHC |

## 4. Results

### 4.1. Analysis of heating and cooling seasons

The results in Figures 5, 6, 7 and 8 show that the operative temperature differed for the three cases A, B and C for the south room in each location. In Copenhagen, Edinburgh and Zurich, the lowest temperature levels were observed for case A, when the seasons were defined based on an arbitrary date. In that case, the heating season finished too early, leaving a period within April, May and September without heating supply. In Palermo, the operative temperature reached the highest values for case A, right after the beginning of the heating season. The case when the seasons were defined based on outdoor temperatures (case B) and building simulations (case C) showed operative temperature values between 20°C and 26°C for all the locations.

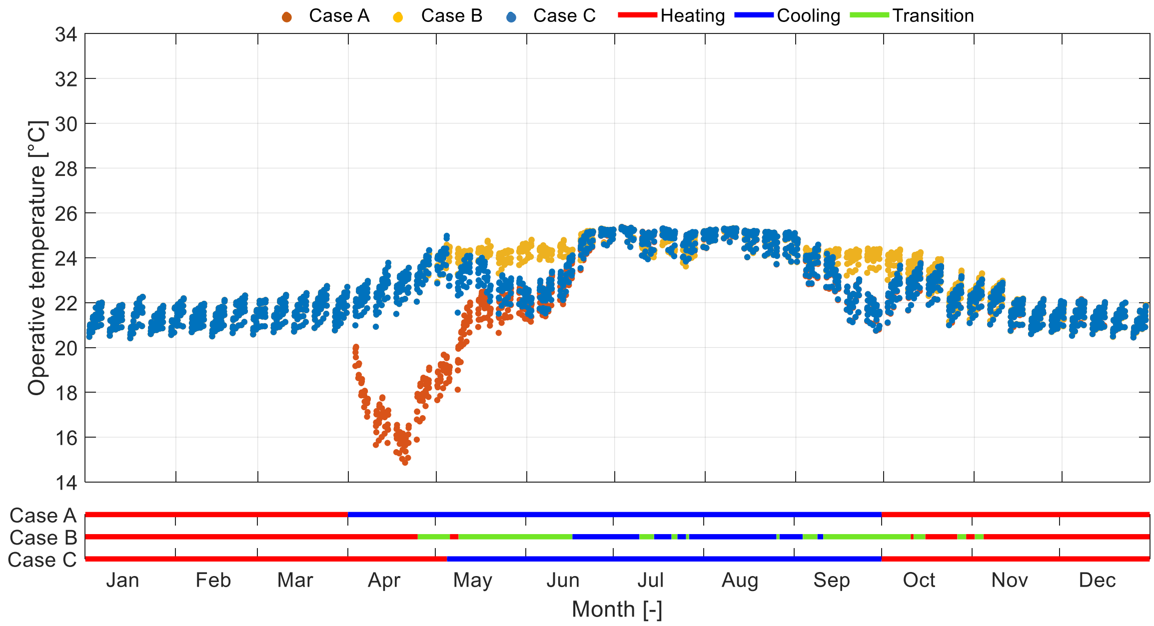


Figure 5: Operative temperatures obtained from the south room in Copenhagen for the cases A, B and C, during occupied hours

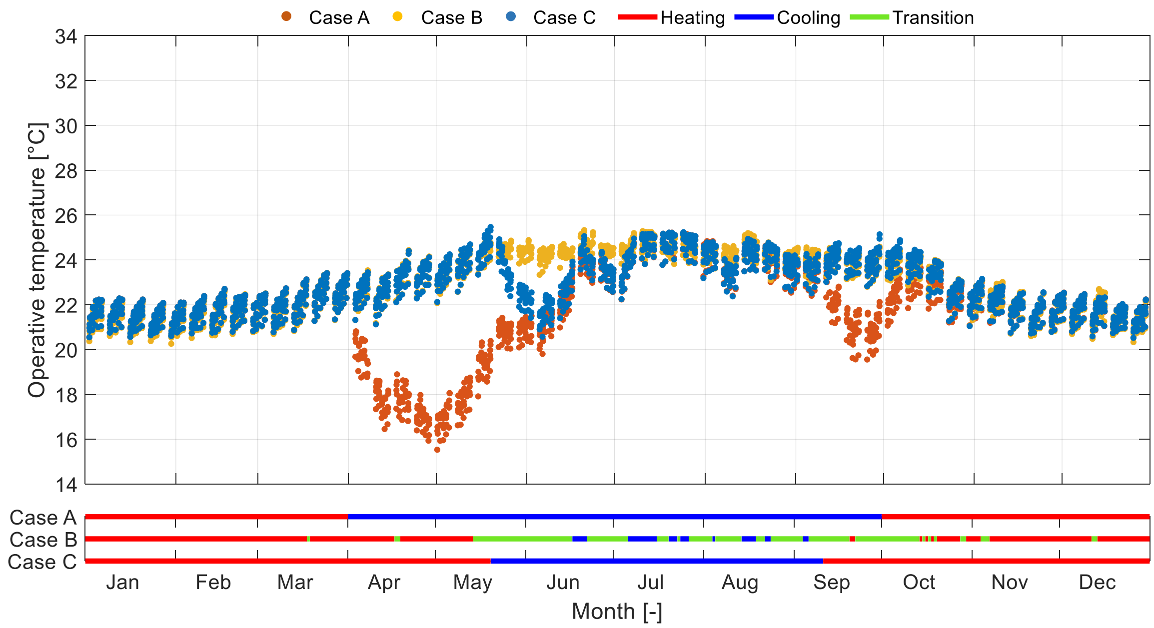


Figure 6: Operative temperatures obtained from the south room in Edinburgh for the cases A, B and C, during occupied hours

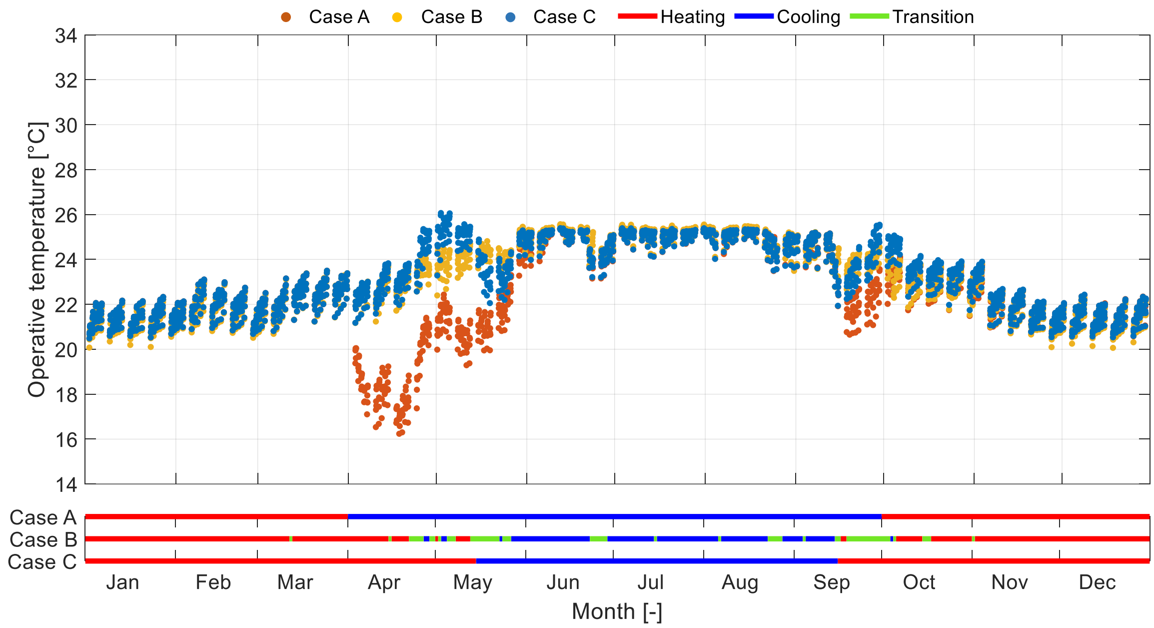


Figure 7: Operative temperatures obtained from the south room in Zurich for the cases A, B and C, during occupied hours

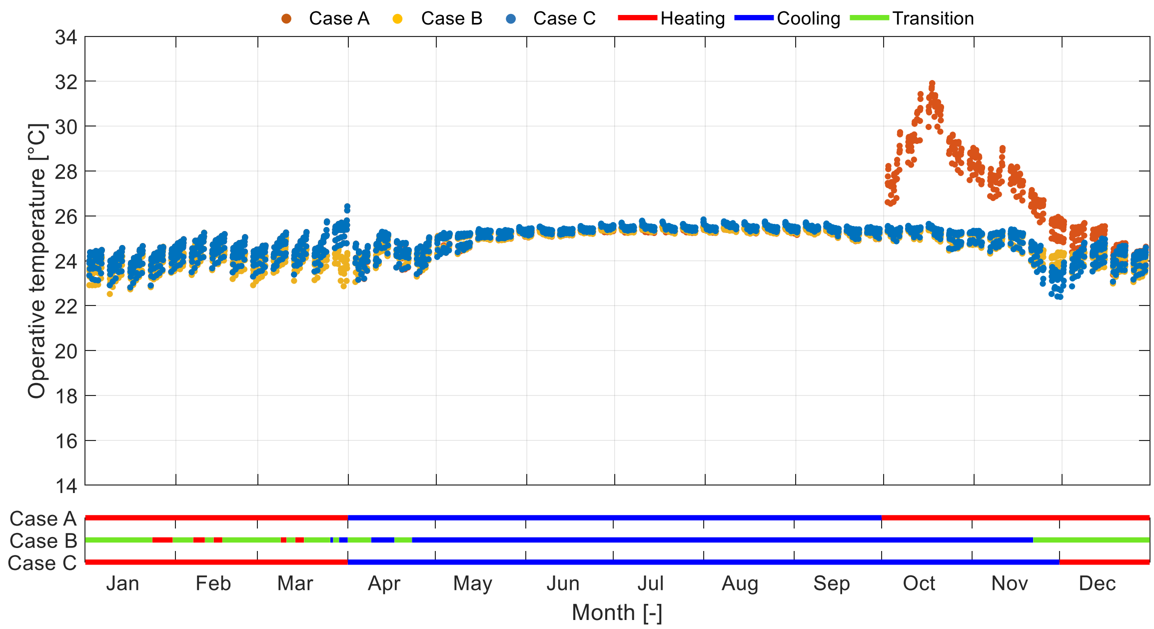


Figure 8: Operative temperatures obtained from the south room in Palermo for the cases A, B and C, during occupied hours

### 4.2. Thermal comfort evaluation

Figure 9 shows how the operative temperatures during time of occupancy from each studied case were distributed into the four categories of indoor environment presented in EN 16798-1, Table B.5. The limits defined for heating and cooling season were applied for the assessment of cases A and C. For case B, additional limits between heating and cooling seasons were added to account for the transition period between seasons, considering 0.75 clo, 1.2 met and 50% relative humidity. The percentage of occupied hours inside Cat. I was the highest in case B for all four locations (CPH-Copenhagen, ED-Edinburgh, ZH-Zurich, PA-Palermo). The period outside all categories was near zero for case B in all locations. The results show that when the heating and cooling seasons are defined based on a date (cases A and C), the thermal comfort level of the building is lower than when they are defined based on outdoor temperature levels (case B). The lowest thermal comfort was observed when the change between seasons occurred on a date determined arbitrarily (case A). The thermal comfort is improved when the date for changing from heating to cooling is based on the local climate and estimated based on a building simulation (case C).

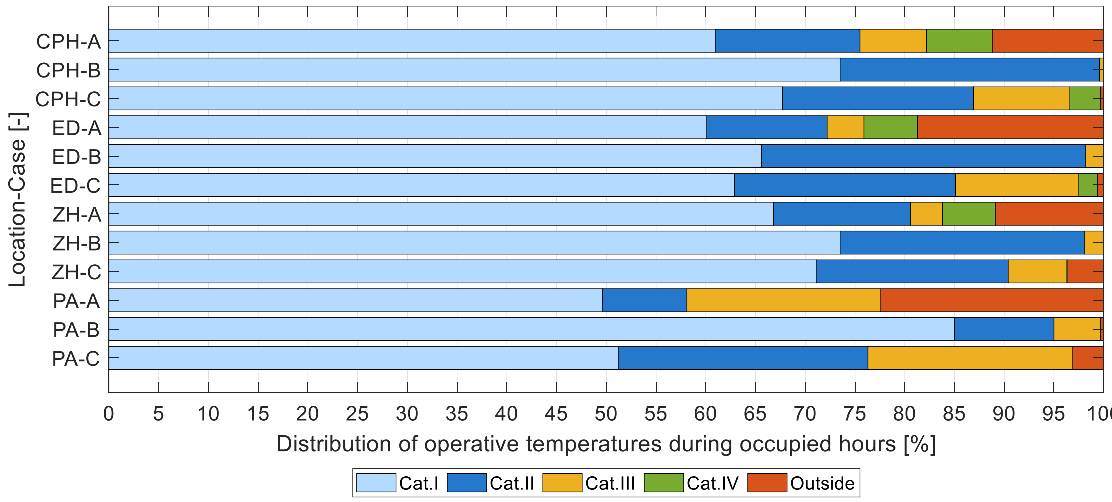


Figure 9: Distribution of the operative temperatures from the south room in the IEQ categories from EN 16798-1 during occupied hours, evaluated based on heating, cooling seasons for cases A and C and adding the transition period between seasons for the evaluation of case B.

The Adaptive Comfort Method (ACM) was used to evaluate the thermal comfort in four additional simulations for each location, defined as case D. In this case, only mechanical heating was used, which was only available during the heating season. Figure 10 shows how the operative temperatures were distributed during the year in the three categories defined for the ACM defined in EN 16798-1. For Palermo, the number of hours with operative temperatures outside all categories was negligible. Locations with colder average outdoor temperatures such as Copenhagen, Edinburgh and Zurich showed less hours inside all categories, compared to the simulation for Palermo.

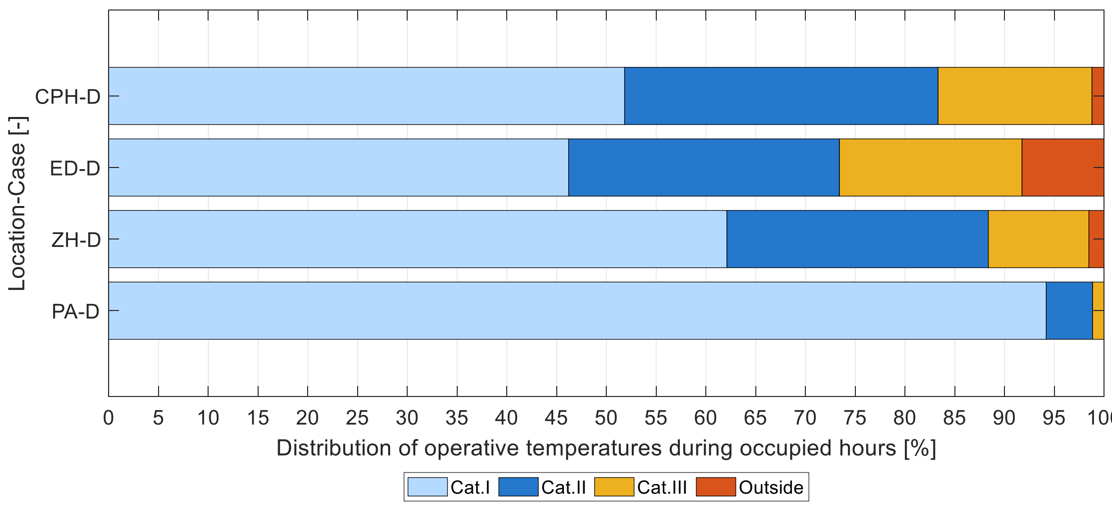


Figure 10: Distribution of the operative temperatures from the south room in the IEQ categories from EN 16798-1 during occupied hours.

The energy performance of a building is expressed with one number in kWh/m$^2$. To compare thermal comfort for different heating-cooling concepts and for expressing comfort with a single value, the yearly thermal comfort score (TCS) was introduced. This value was calculated based on the percentage of occupied hours (Figure 9 and 10) inside the categories of indoor environmental quality defined in EN 16798-1. The score assigned weighted values for % time spent in each category, and provides a single value from 1 (Best) to 5 (Worst) as an overall assessment of a zone or a building in each case. Equation (2) was used for the calculation of the weighted score for cases A, B and C.

$$TCS = \%Cat.I * 1 + (\%Cat.II - \%Cat.I) * 2 + (\%Cat.III - \%Cat.II) * 3 + (\%Cat.IV - \%Cat.III) * 4 + \%outside * 5 \quad (2)$$

The percentages inside each category (%Cat.I, %Cat.II, %Cat.II, %Cat.IV and %outside) correspond to the results showed in Figure 9.

For case D, the approach to calculate the weighted score was different, since the adaptive comfort method (ACM) accounts only for three IEQ categories. The yearly thermal comfort score for case D ($TCS_{ACM}$) was calculated using the ACM categories and percentage of time outside them as shown in equation (3).

$$TCS_{ACM} = \%Cat.I * 1 + (\%Cat.II - \%Cat.I) * 2 + (\%Cat.III - \%Cat.II) * 3 + \%outside * 5 \quad (3)$$

The highest TCS from cases A, B and C was obtained for case A, whereas the lowest value was observed for case B, as presented in Table 4. This is in agreement with the results from Figure 9, since the yearly thermal comfort score represents a weighted score of the IEQ categories based on the PMV-PPD method. For case D, the highest TCS was observed from the simulation in Zurich, where the number of occupied hours outside all categories was higher than for the other locations (see Figure 10). The highest TCS was observed in case D for Palermo.

Table 4: Yearly thermal comfort score (TCS) calculated for cases A, B, C and D. Higher score-lower comfort

| Location | Copenhagen | | | Edinburgh | | | Zurich | | | Palermo | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Case | A | B | C | A | B | C | A | B | C | A | B | C |
| TCS | 1.93 | 1.27 | 1.49 | 2.11 | 1.36 | 1.55 | 1.80 | 1.28 | 1.46 | 2.37 | 1.21 | 1.79 |
| Case | D | | | D | | | D | | | D | | |
| TCS,ACM | 1.71 | | | 2.00 | | | 1.56 | | | 1.10 | | |

The same approach to evaluate the category distribution for case B (see Figure 9), was used to calculate the percentage of time inside the four IEQ categories for cases E and F. That is to say, the percentage of hours inside each category was calculated for the heating season (clo=1, RH=40%), the cooling season (clo=0.5, RH=60%) and the transition period between them (clo=0.75, RH=60%). Figure 11 shows that the percentage of occupied hours with temperatures outside the IEQ categories was significantly higher when neither cooling nor heating were available during the transition period (case F), compared to the case only with heating (case E). For the latter case, the period inside Cat. II was approximately the same compared to case B in Palermo and 4% lower for Copenhagen (see Figure 9).

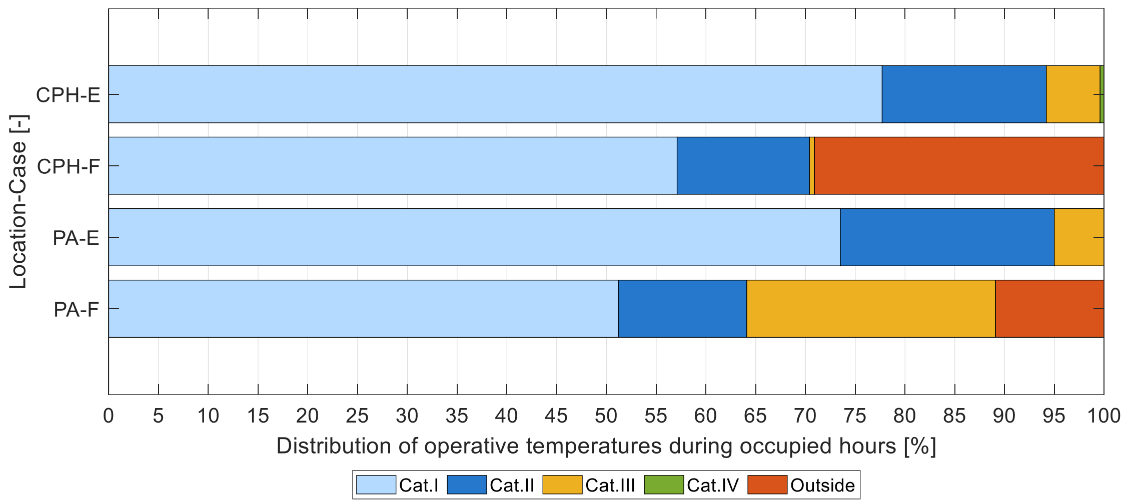


Figure 11: Distribution of the operative temperatures from the south room in the IEQ categories from EN 16798-1 during occupied hours, evaluated based on heating, cooling seasons and transition period. Two cases were considered for the transition period, where only heating was provided (case E) and neither cooling nor heating was available (case F).

The yearly thermal comfort score was calculated considering the distribution of operative temperatures presented in Figure 11, by applying equation (2). The results shown in Table 5 evidence that the overall thermal comfort level decreased significantly when neither heating nor cooling was available during the transition period, compared to the case only with heating applicable during that period. When comparing cases B and E, it was observed that the TCS for case B in Copenhagen was approximately the same for cases B and E. However, the TCS was higher for case B in Palermo. This suggests that allowing cooling during the transition period did not have an appreciable effect on the yearly thermal comfort level for Copenhagen, but it had a small improvement for Palermo.

Table 5: Yearly thermal comfort score (TCS)

| Location | Copenhagen | | Palermo | |
|---|---|---|---|---|
| Case | E | F | E | F |
| TCS | 1.28 | 2.31 | 1.30 | 2.06 |

### 4.3. Energy evaluation

The results presented in Figure 12 show that case B had the highest level of energy used in each location. This was due to a greater energy use for heating in colder climates (Copenhagen, Edinburgh and Zurich) and for cooling in warmer climates (Palermo) compare to the other cases. When cooling (case E) or heating and cooling (case F) were not available during the transition period, the total energy use was lower than having both during that period. The lowest energy use in each location was from case D, as no cooling was considered along the year and no heating outside the heating period. The difference between the total energy use when changing the heating and cooling seasons based on a date defined arbitrary (case A) and grounded on building dynamic simulations (case B) was below 2 kWh/m² for cold climates (Copenhagen, Edinburgh, Zurich) and approximately 3 kWh/m² for warm climates (Palermo).

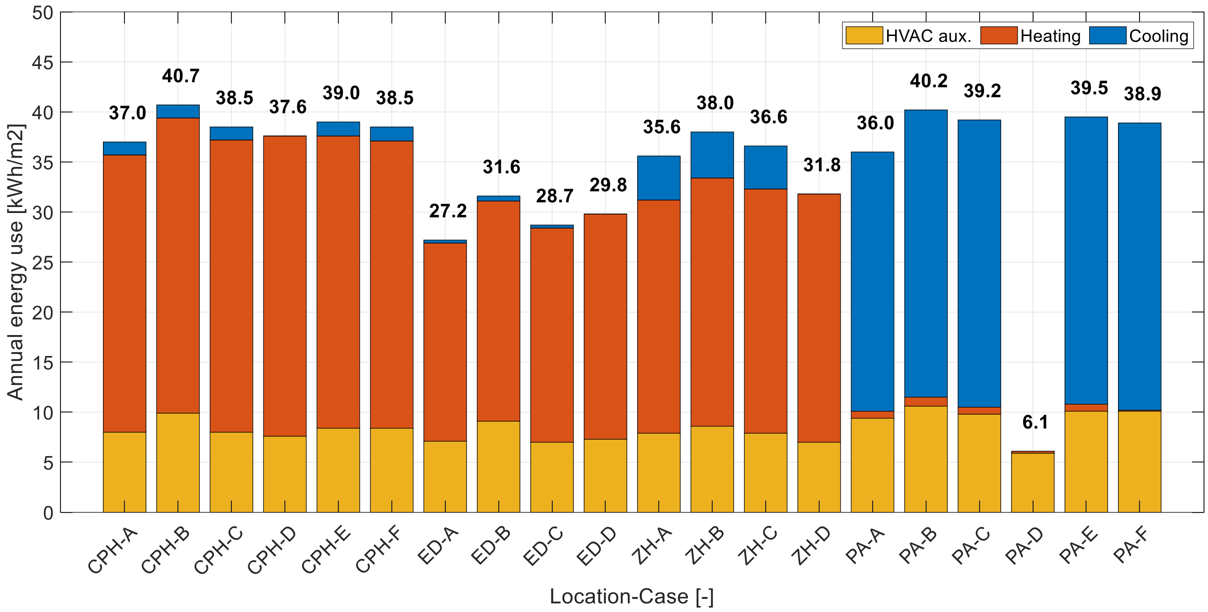

Figure 12: Annual energy use for each simulated case for heating, cooling and auxiliary energy used by the HVAC equipment (HVAC aux.).

## 5. Discussion

### 5.1. Definition of the heating-cooling period

The definition of heating (winter) and cooling (summer) period for mechanical cooled buildings has a significant influence in the overall comfort. Using the definition in EN16798-1 based on an outdoor running mean temperature of 10 °C and 15 °C seems to work well under all four climatic zones. To optimize the date for the change based on a pre-simulation will not give much improvement in the comfort (see Figure 9). It is however still an open question how the systems should be operated in the transition period. Should both heating and cooling be available or only heating or cooling? The running mean outdoor temperature will fluctuate and there will be days where it goes below 10 °C after it has passed 10 °C the first time. In reality, it is not likely that during the cooling period heating will be available and cooling will be applied during the period of the year when heating is normally used. Therefore, it is a difficult task to suggest consistent guidelines to define a transition season that is not intermittent in time and accounts for the seasonal variations of the outdoor climate. Again, it does not make sense to have both heating and cooling available in the transition period. A concept could be to have heating available in the spring until 15 °C running mean is reached the first time and again in fall when 10 °C running mean is reached the first time. This is supported by the results in figure 9 and Figure 11. Figure 11 show that providing heating during the transition period (Case E) provide about better comfort than Case F, with no heating and cooling in the transition period. The figures also show that the comfort with case E is very similar to case B, where heating and cooling is available in the transition period. This is also confirmed by comparing the Thermal Comfort Scores in Table 4 and 5.

The distribution of the energy use in the four cities (Figure 12) were, as expected, different between the four cities. In Edinburgh, Copenhagen and Zurich, the energy for heating was dominating while in Palermo it was for cooling. The energy use in all locations was larger for case B, where heating and cooling were considered during the transition period. The difference between the energy use between that case and case E, when only heating was as available in the transition period, was moderate (4% lower for Copenhagen and 2 % lower for Palermo). The reduction of the energy use when heating was not available (case F) compared to the case when it was available during the transition period was even lower (1% for Copenhagen and Palermo).

**5.2. Yearly thermal comfort evaluation**

The thermal comfort has been evaluated by looking at the temperature distribution in the different Categories as seen in Figure 9. It can still be difficult to compare the thermal comfort between the three cities and for the three definitions of heating and cooling season. Therefore, a method to combine the values into one number by a weighing factor for each category is shown in equations 2 and 3. In all cases A with a fixed date for switching between heating-cooling has the least comfort. For Edinburgh, Copenhagen and Zurich the difference between Cases B and C is very small; but for Palermo case B is significant better. The yearly thermal comfort score (TCS) gives an overall assessment of the thermal comfort in a building, therefore is not capable of analysing slight differences between temperature distribution in categories. For instance, when comparing the distribution of operative temperatures from Copenhagen and Palermo for case B (Figure 9), in the first case the period with temperatures above Cat.II was nearly zero, whereas for the second was approximately 5% of the occupied hours. However, the TCS is lower (better) for the second case than for the first one. This example demonstrates the penalty of using a single index to represent the yearly thermal comfort score.

Figure 11 shows the results with different concepts for the transition period regarding heating and cooling. When only heating was considered during that period, the yearly thermal comfort score estimated with the proposed methodology was approximately the same compared to the case when cooling was also available in that period. However, TCS increased significantly (40-80%) when heating was not available in the transition period, indicating a much poorer performance in terms of thermal comfort.

For buildings where the Adaptive approach can be applied to characterize the thermal comfort level, the cooling season does not exist as no mechanical cooling is available. The question is however when heating should be available. Only the period where the running mean is below 10°C? or until 15°C?. In the present simulation study, only heating for running mean outdoor temperatures below 10°C was assumed. The results showed that the operative temperatures for the simulation in Palermo had higher percentages inside the limits from the ACM, compared to the other locations (see Figure 10). The limits for the ACM from Palermo could be applied for a longer fraction of the year as presented in Figure 4. This suggests that, outside the heating period, the ACM limits can be used to evaluate the thermal comfort level in buildings without mechanical cooling, but the overall thermal comfort will be better in cases with warmer climates. It should be noted that in the current study the ventilation level was not increased for the adapted method, which could possibly provide more cooling during periods where outside temperature were lower than room temperature.

**5.3. Suggested revision of the standards**

The applicability of the temperature ranges considered for the indoor environmental categories defined in EN 16798-1 depends on the definition of the heating and cooling seasons. This study demonstrated that the definition of the period of the year when heating and cooling is available has a significant influence on thermal comfort and energy use. The definition of the heating and cooling seasons based on a running mean outside temperature of 10 and 15 seems to work well for the different climatic zones studied. However, the authors recommend that Guideline TR 16798-2, should provide more specific design guidance regarding the transition period. Should this period be evaluated using the adapted method as it seems cooling is not needed or should it be evaluated, as done in this paper, by using a clo-value of 0.75 clo? The standard defines three categories of indoor environment for the Adaptive method, when mechanical cooling is not available, and four categories for the PMV-PPD method. It is recommended to include an index that summarizes the overall comfort level described by the IEQ categories, which allows to compare in a simple manner scenario with different boundary conditions.

## 6. Conclusions

This study aimed to analyse how the heating and cooling seasons can be defined throughout a year, such that the thermal comfort level is adequate, and the energy use is minimized. The evaluation was performed by analysing the results from the dynamic simulation model of an office building for four locations: Copenhagen, Edinburgh, Zurich and Palermo. Defining the heating-cooling seasons based on outdoor temperature conditions with a transition period between them showed a better thermal comfort level compared to their characterization based on a date defined arbitrary or from dynamic simulations. No significant benefits in terms of thermal comfort and energy use were observed when operating the transition period with mechanical cooling available.

It was also the aim of the study to evaluate and compare different methods to analyse the thermal comfort level of a building throughout a year. The approaches recommended in EN 16798-1 and the technical TR16798-2 were used to assess the thermal comfort level by looking at the distribution of room temperatures in the different categories of indoor environment, based on the results from building dynamic simulations. The analysis was carried out in buildings with air-conditioning systems, where temperature limits of the comfort zone are calculated from the PMV-PPD method and buildings without air-conditioning, where the Adaptive Comfort model is used to define the limits of the comfort zone. A methodology to calculate an overall yearly thermal comfort score based on the IEQ categories of indoor environment, was also applied to evaluate the thermal comfort in buildings with and without air-conditioning. The results from the thermal comfort score allowed to have a simpler overview of the thermal comfort level from each simulation, compare to the categorization of thermal comfort.

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# Rethinking resilient comfort – definitions of resilience and comfort and their consequences for design, operation, and energy use

**Marcel Schweiker[1,2]**

[1] Building Science Group, Karlsruhe Institute of Technology, Karlsruhe, Germany
[2] Institute for Occupational, Social and Environmental Medicine, RWTH Aachen University, Aachen, Germany, mschweiker@ukaachen.de

**Abstract:** The usage of "resilient" increased over the last decade reflecting anticipated changes in our climate and resulting necessary changes in our energy system. While resilience is popular, its usage varies to such extent that opposing consequences for the building design are promoted: robustness or flexibility. This paper questions whether resilient buildings support the resilience of their occupants and presents a framework for human-building resilience, pointing to distinctive aspects like "toughness", "ability to cope", or "capacity to recover". In addition, this framework includes a wider definition of thermal comfort, which considers not only thermal relief as provided by thermoneutral conditions, but thermal encouragement, related to adaptation, and thermal enjoyment, pointing to thermal alliesthesia. Based on previously published and new data from laboratory studies, the presentation of first attempts analysing individual parameters of human resilience is followed by a discussion of the consequences of the new framework for future pathways of design and operation. Should we continue searching for ways to predict "optimal" conditions or shift our focus towards those design and operation concepts, which optimise encouragement and enjoyment and consequently lead to a higher human resilience and a lower dependence on building resilience or intensive energy use?

**Keywords:** Thermal resilience, building resilience, adaptation, alliesthesia, experimental study

## 1. Resilient comfort – background and definitions

Resilient design, resilient buildings, resilient energy systems, resilient comfort… The usage of 'resilient' has been increasing over the last decade reflecting anticipated changes in our climate and resulting necessary changes in our energy system and design practices (Figure 1).

Research related to resilience and buildings is related either to the urban or to the building scale. As an example for the urban scale, Albers et al. (2015) mention resilient housing as strategies for resilient cities. On the building scale, resilience of buildings is considered as the ability of a building to keep indoor temperatures within pre-set limits or to permit peoples adaptability. Lomas and Giridharan (2012) treat resilience as a measure of avoidance of overheating and account for the ability of an occupant to cope with change by proposing fans to increase air speed. Short et al. (2012) criticize that resilience to overheating is often assigned to mechanical ventilation, and argue for passive building design options such as shading. Trebilcock-Kelly, Soto-Muñoz and Marín-Restrepo (2019) understand resilient buildings as designed and operated flexibly, so that the buildings can adapt to their occupants' requirements and promote the adaptability of the occupant. Coley and Kershaw (2010) present climate change amplification coefficients ($C_T$) to judge the resilience of a building to climate change. In contrast to the previous work, they assign a higher resilience to buildings, which are characterized by a smaller relationship between the mean and maximum indoor temperature and the mean and maximum outdoor temperature at different climate change scenarios.

However, are resilient buildings supporting the resilience of their occupants?

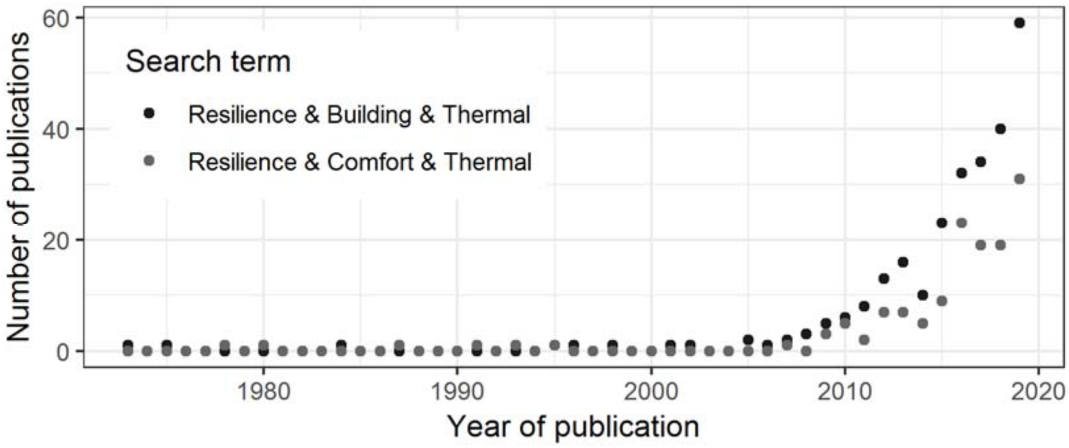



Figure 1. Number of publications per year based on a search on scopus using the search terms “resilien* AND building* AND thermal*” ($N_{total}$ = 265) and “resilien* AND comfort* AND thermal*” ($N_{total}$ = 138) on title, abstract, and keywords.

While the number of publications found with the search string “comfort” instead of “building” increases as well over the last decade, most of these studies mention thermal comfort as a result of a resilient building. At the same time, research looking at the resilience of persons themselves is scarce. Fernandez, Milan, and Creutzig (2015) mention that the education level affects an individual’s resilience “due to higher awareness and better knowledge of hazard prevention”. Daanen and Herweijer (2015) tried to increase resilience of persons over 75 years for heat waves using an indoor training program. Their 5-day one hour each training program did not lead to differences between the heat strain test on the first and 5$^{th}$ day in gastrointestinal temperature, mean skin temperature, heart rate, weight loss (due to sweating), or thermal sensation. In contrast, studies conducted at the Maastricht University found positive benefits of cold and warm exposures on acclimatization and health (van der Lans et al., 2013; Hanssen et al., 2015; Pallubinsky et al., 2017).

Overall, a holistic approach to building resilience is missing, which includes human resilience and knowledge on variables influencing human resilience. Therefore, the objectives of this paper are a) questioning the existing concept of resilience for buildings and humans, b) developing a framework combining resilience with existing paradigms of thermal comfort, and c) demonstrating two preliminary attempts to analyse individual aspects of human thermal resilience and influences on its variability.

### 1.1. Reviewing definitions of resilience

As outlined above, the usage of the word *resilience* is increasing, while its meaning varies between authors. In this context, it would be interesting, but beyond the scope of this paper, to look at the etymology of *resilire,resiliois* (interested readers are referred to Alexander (2013)).

Relevant for the following discussion are the definitions and translations of resilience found in dictionaries. Dictionaries list meanings of resilience such as a) “*the capacity to recover quickly from difficulties; toughness*”, or b) “*the ability […] to spring back into shape; elasticity*” (Oxford, 2019), while it is often related to c) “*the ability to cope*” in health- and psychology-related literature. Translations include the term toughness, but in contrast to the definition above, relate it to d) “*the robustness*”, which will be used in the following.

Reviewing these meanings in light of human thermal comfort in buildings leads to interesting research questions requiring the inclusion of different concepts related to thermal comfort. Beforehand, it is meaningful reviewing also definitions of comfort.

### 1.2. Reviewing the definition of thermal comfort

The most widespread definition within the field of thermal comfort is that of ASHRAE, which defines comfort as "the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation" (ASHRAE, 2017). Less known is a definition of comfort in the Merriam-Webster Dictionary of English Language (Merriam-Webster, 2019), which notes comfort in relation to *relief*, *encouragement*, and *enjoyment* (this definition is mentioned in Bubb, 2003). Because the latter definition appears more comprehensive, it will be considered in the following.

## 2. A holistic framework for resilient thermal comfort

Based on above review of definitions for resilience and thermal comfort, a holistic framework for resilience of buildings and humans in relation to thermal comfort is presented in Figure 2 and discussed in the following.

### 2.1. Parameters and phases of human-building resilience

In Figure 2a, the time course of a thermal load is shown. This thermal load could be internal (e.g. related to a high number of occupants or high equipment load) or external (e.g. high outdoor temperature or solar radiation). At time, tL2, the thermal stressor could be removed either by an occupants' action (e.g. switching of equipment, closing blinds) or external conditions (e.g. clouds, sunset) or continuous. The following subfigures show the case for a removed thermal load.

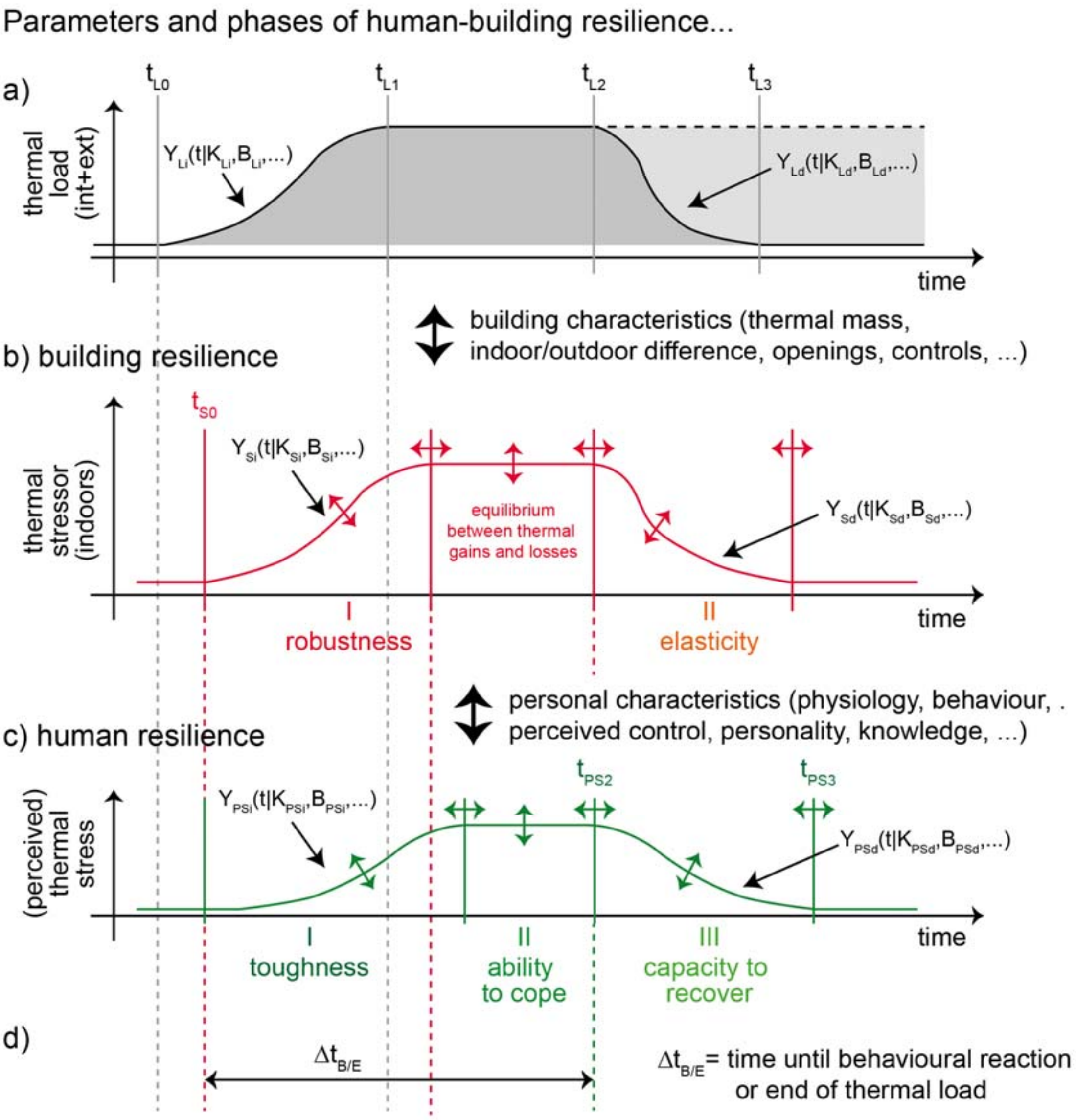
The increase and decrease of this thermal load could be described with a generalised logistic function, which was originally developed for the modelling of the growth rate of plants (Richards, 1959), in the form:

$$Y(t) = A + \frac{K-A}{(1+Q*e^{-B(t-M)})^{1/\nu}} \quad (1)$$

with the parameters Y(t) = the thermal load at time, t, A = the lower asymptote, K = the upper asymptote, Q = the relative position in the time dimension, B = the rate of growth, M = the starting time, $t_0$, and 1/v = a value affecting whether the maximum growth takes place at the beginning or end of the growth curve.

Figure 2b shows the time course of a physical indoor thermal stressor (e.g. an increased operative temperature) as a result of the thermal load shown in Figure 2a. The relationship between thermal load and thermal stressor depends on the type of load and largely on the buildings' characteristics such as thermal mass or window-to-wall-ratio. Increase and decrease could be described with a growth function again. The classic way to define the resilience of a given building, i.e. its ability to reduce thermal stressors, can be based on the parameters of growth functions such as Y(t), shown in eq. 1. For increase and decrease, especially the parameters K, the upper asymptote (e.g. the maximum indoor operative temperature), and B, the growth rate (e.g. the temperature gradient), then form the basis for the comparison of different building concepts according to their robustness (increase) and elasticity (decrease). The values of these parameters can differ between robustness and elasticity.

However, as mentioned introductory, such definition for the buildings' resilience does not consider the effect on the thermal resilience of the human occupant. Figure 2c shows the time course of (perceived) thermal stress as a reaction to the thermal stressor shown in Figure 2b. While only one curve is drawn for reasons of clarity, note that thermal stress (e.g. physiological) can differ largely from perceived thermal stress. The relationship between thermal stressor and (perceived) thermal stress depends on the personal characteristics such as




e) ... and their relationship to comfort paradigms for building design and operation

| | | | |
|---|---|---|---|
| definition | relief | encouragement | enjoyment |
| related paradigms | thermo-neutrality | adaptive comfort | alliesthesia |
| relationship to human-building resilience | no support of human resilience; relying on a low value for $K_{Si}$ for the robustness and high $B_{Sd}$ for elasticity (and potentially high energy use) | supporting toughness (e.g. physiological adaptation), ability to cope (e.g. behavioural or psychological adaptation), and capacity to recover (physiological and behavioural adaptation) | supporting ability to cope (e.g. through memory of activities/ actions causing alliesthesia), and capacity to recover (e.g. through positive alliesthesial perception) |

Figure 2. Parameters and definitions of resilience in relation to comfort definitions and paradigms. Red and green arrows indicate that the position of the curve depends in building and personal characteristics.

the physiological constitution (e.g. level of fitness), behaviour (e.g. reducing work load to adjust metabolic rate), perceived control, which was found to be related to perceived thermal stress and physiological reactions (Schweiker and Wagner, 2015), personality, or knowledge (e.g. that the stressor will end soon). The time course is split into three phases, each presenting a different parameter of human resilience: I) toughness, II) ability to cope, and III) capacity to recover. While the toughness related to thermal stress largely depends on physiological processes, the toughness related to perceived thermal stress might depend on other influences such as distractions by a heavy workload. Phase II can be non-existing in case the occupant removes the thermal stressor before the thermal stress reaches its upper asymptote. Otherwise, phase II describes that period during which the occupant endures the thermal stress, so that perceived stress remains stable. Also here, growth functions in the form of eq. 1 and their parameters can be utilized to describe individual aspects of human resilience as well as for inter- and intrapersonal comparisons.

**2.2. Relationship to comfort definitions and paradigms**

As described introductory, previous researchers promote the flexibility of buildings and adaptive capability of occupants as a key factor for overall resilience. The question remains, how such elements relate to individual phases of human-building resilience. A preliminary answer is shown in Figure 2e, which shows the relationship between definitions of comfort, corresponding building design and operation paradigms, and human resilience.

Considering comfort of buildings as providing "relief" is in line with the paradigm of thermoneutrality (e.g. inherent in the concept of the predicted percentage of dissatisfied (PPD) (Fanger, 1970)). According to this definition and paradigm, a building should be designed and operated in a way that it provides maximum relief and minimum thermal stress. Thereby it is relying on a high robustness and elasticity of the building likely causing intensive energy use, because of tight comfort bands (Hoyt et al., 2005). At the same time, it is hypothesized that such paradigm does not support human resilience, which is supported by findings showing smaller temperature ranges by occupants of tightly controlled buildings.

In line with the demand for flexibility by Trebilcock-Kelly, Soto-Muñoz and Marín-Restrepo (2019) is the definition of comfort to provide encouragement. This definition can be related to building design and operation according to the paradigm of adaptation (De Dear and Brager, 1998; Hellwig et al., 2019; Schweiker and Wagner, 2015). Related to the three adaptive mechanisms,

a) daily and seasonal temperature variations support physiological acclimation (van der Lans et al., 2013; Hanssen et al., 2015; Pallubinsky et al., 2017),
b) a higher level of perceived control due to adaptive opportunities increases psychological adaptation (Schweiker and Wagner, 2015), and
c) the frequent behavioural interactions with personal clothing level and the building interfaces likely increases behavioural adaptation.

Such increase in adaptive capacity increases the toughness, the ability to cope, and the capacity to recover as presented in Figure 2e.

The third part of the definition of comfort, enjoyment, can easily be linked to the paradigm of alliesthesia or thermal pleasure (de Dear, 2011; Cabanac, 1971; Parkinson, de Dear and Candido, 2012; Schweiker et al., 2020). The effect on human resilience can only be speculated. Building design and operation concepts offering opportunities to experience alliesthesial situations permit the "training" of the capacity to recover. Alliesthesia will likely play a role in occupants' acquisition of knowledge. Actions, which successfully led to pleasure are likely executed again; a learning process known as operant conditioning in psychology originating from work on animals (Thorndike, 1898). In addition, positive effects of alliesthesia might speed up recovering processes through a combination of emotional and physiological reactions.

In order to demonstrate the applicability of this framework, the following section describes exemplary analyses of

a) the time between the onset of the thermal stressor until a person's reaction, $\Delta t_B$ (see also Figure 2d), which includes the durations of the phases I) toughness and II) ability to cope, and
b) the capacity to recover.

## 3. Methods

Data from two datasets is taken for two exemplary analyses of two parameters of human resilience included in above described framework. The first dataset, data set M, will be used to analyse $\Delta t_B$ and originates from a previously published study (Meinke et al., 2017). The second dataset, data set D, is unpublished, and is applied to the analysis of the capacity to recover, $B_{PSd}$.

Both datasets were collected by means of experimental studies in the field laboratory LOBSTER (Schweiker et al., 2014).

### 3.1 Dataset M

In total 77 participants (44 female, 29±14 years of age, 173±10 cm height, 68±14 kg weight) were balanced across morning and afternoon sessions.

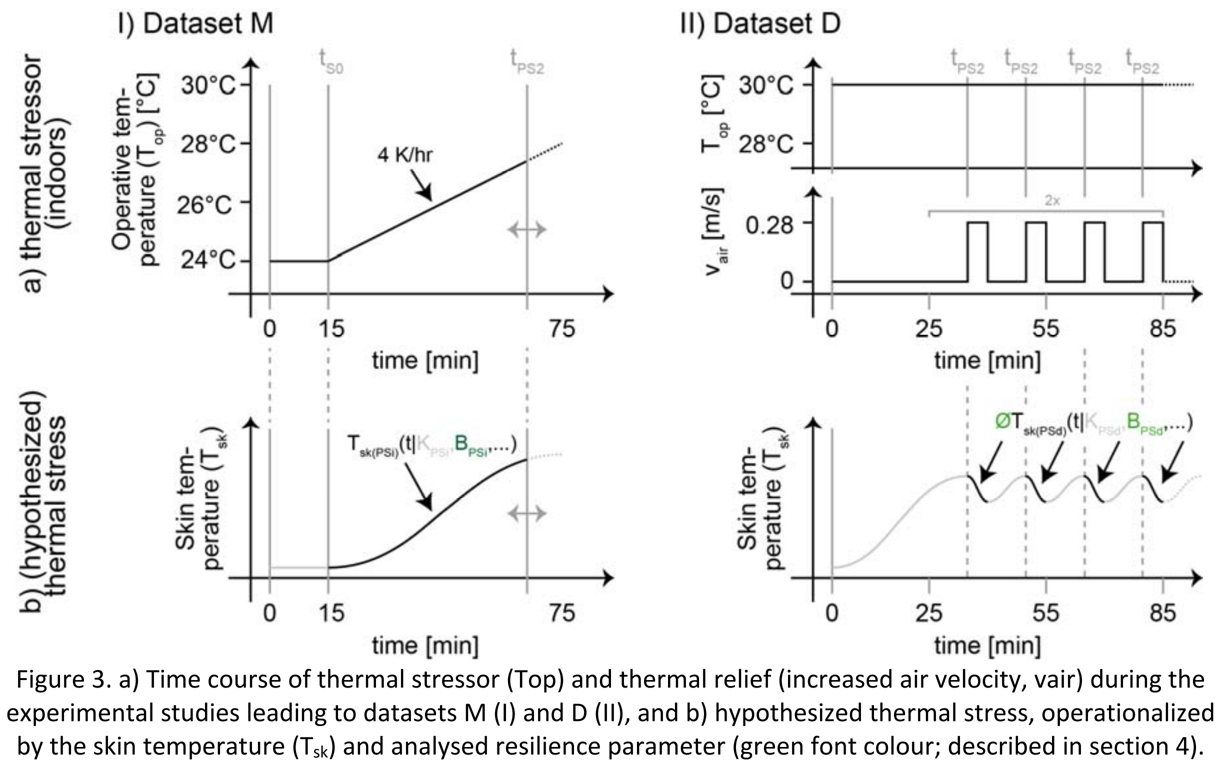



Figure 3. a) Time course of thermal stressor (Top) and thermal relief (increased air velocity, vair) during the experimental studies leading to datasets M (I) and D (II), and b) hypothesized thermal stress, operationalized by the skin temperature ($T_{sk}$) and analysed resilience parameter (green font colour; described in section 4).

The experimental protocol relevant for the analysis presented here consists of the following steps (see also Figure 3-I). Participants were welcomed, received instructions, gave written informed consent, and received sensors for measuring skin temperature (iButton (van Marken Lichtenbelt et al., 2006)) logging at a 1-minute interval in the front room. This first phase took 20 minutes. Afterwards, they entered one of the office-like test rooms conditioned to an operative temperature ($T_{op}$) of 24°C and were asked to fill out a first questionnaire. After 15 minutes, $T_{op}$ increased continuously by 4K/hr until participants pressed a marked button on their keyboard. They were instructed to press this button once they feel warm and would like to change the indoor environment. Upon pressing the button, they were asked to fill out a second questionnaire assessing their thermal perception of sensation, preference, and comfort as well as the type of interaction they would like to perform.

### 3.2 Dataset D

Dataset D was collected in autumn 2018. In total 61 participants started the experiment, of which one participant could not finish it due to health problems. The remaining 60 participants were balanced according to sex (31 female) and age (N = 33 below 32 years of age compared to N = 27 above 50 years of age).

The experimental protocol consists of three phases lasting in total three hours. First, participants were welcomed as described in dataset M. They then entered one of the offices conditioned to a $T_{op}$ of 30°C (see also Figure 3a-II). Clothing item instructions required participants to wear long trousers, a short-sleeved T-shirt and an additional long-sleeved upper part. After entering the office, the acclimation phase of 25 minutes started, during which participants received further instructions and filled out a background questionnaire. The third and fourth phase were nearly identical and lasted each one hour. In both phases, periods with a running ceiling fan were followed by periods without the ceiling fan running. The ceiling fan was switched off for 10 minutes, followed by 5 minutes being switched on. This 15-minute period was repeated four times in each phase. During this 15-minute period, participants were asked four times about their thermal perception of sensation, preference, and pleasure: 4 and 8.5 minutes (fan off), 10.5 minutes (fan just on), and 13 minutes (fan on for three minutes) after the start. The difference between both phases is the amount of control. In the no-control condition, the ceiling fan switched on according to the pre-set protocol automatically. In the control-condition, participants were given control of the ceiling fan and could decide themselves after 10 minutes when to switch the ceiling fan on. The ceiling fan-off signal was not under control of the participants in both conditions. Note that in order to reduce predictability, the automated on-/off-signal was jittered ±10 seconds around the above described timing. The order of conditions was balanced across participants. The ceiling fan used in this experiment is extremely silent, so that participants could watch the ceiling fan starting to run in case they looked up, but there was no perceptual increase in noise level. The ceiling fan is described in more detail in Rissetto et al. (2020).

### 3.3 Data analysis

Despite hypothesizing the suitability of a generalized logistic function to characterise the increase and decrease of thermal load, stressor, and stress in the previous section, the time-resolution of the available data-points was too low to apply the complete function in the analysis with all available parameters. Therefore, the data analysis is based on the analysis and discussion of a linear slope.

# 4. Results

## 4.1. Time between the onset of the thermal stressor until a person's reaction, $\Delta t_B$ (toughness and ability to cope)

Participants pressed the button indicating their preference to change conditions, i.e. their thermal discomfort, in average after 58 minutes (sd: 34, median 46, min 13, max 123). Until this point, $T_{op}$ increased from 24°C in average by 3.9 K (sd: 2.1, median 3.6, min 0.45, max 8.4). For each participant, the $T_{op}$ gradient and $T_{sk}$ gradient were calculated. The $T_{sk}$ gradient is the change in $T_{sk}$ per minute and is used as a simplified parameter for the growth rate, $B_{Psi}$ (see also Figure 3b-I). For dataset M, the time-span considered for the calculation of $T_{sk}$ gradient is the period between the start of the temperature gradient and the moment the participant pressed the button, i.e. a value between 13 min and 123 min as described above. Descriptive statistics for $T_{op-}$ and $T_{sk}$ gradients between the start of the temperature gradient and the time, the button was pressed, are shown in Table 1. The relative variance of $T_{sk}$ gradient is two times higher than that of $T_{op}$. At the same time, correlation between both variables is low (r = .26).

Figure 4 shows the relationship between Tsk gradient and the time until participants pressed the button. Based on linear regression of $T_{sk}$ gradient on the time, $T_{sk}$ gradient is a significant predictor of time ($p < .001$, $R^2 = 0.24$), while the $T_{op}$ gradient is significant at $p = .03$ ($R^2 = 0.07$). Multiple regression analysis on the time difference and $T_{sk}$ gradient as dependent variables revealed that none of the dependent variables tested, i.e. sex, height, weight, BMI, age, level of perceived control, actual level of thermal sensation, preference, and comfort at time of pressing the button, neuroticism, openness, and extraversion, had a significant effect on $T_{sk}$ gradient (all $p > .13$, $R^2 = 0.18$, $R^2_{adj} = 0.0076$). Among all independent variables, only the $T_{sk}$ gradient ($p < .001$) and neuroticism ($p = .021$) had a significant effect on the time difference (all other $p > .16$, $R^2 = 0.38$, $R^2_{adj} = 0.23$).

Table 1. Descriptive statistics of temperature gradient for operative ($T_{op}$) and skin temperature ($T_{sk}$) in dataset M between the start of the thermal stressor and the moment, when participants pressed the button.

| | Mean | Std. dev | 5% | 50% | 95% |
|---|---|---|---|---|---|
| **$T_{op}$ gradient [K/min]** | 0.071 | 0.021 | 0.035 | 0.070 | 0.107 |
| **$T_{sk}$ gradient [K/min]** | 0.021 | 0.014 | 0.0047 | 0.020 | 0.043 |

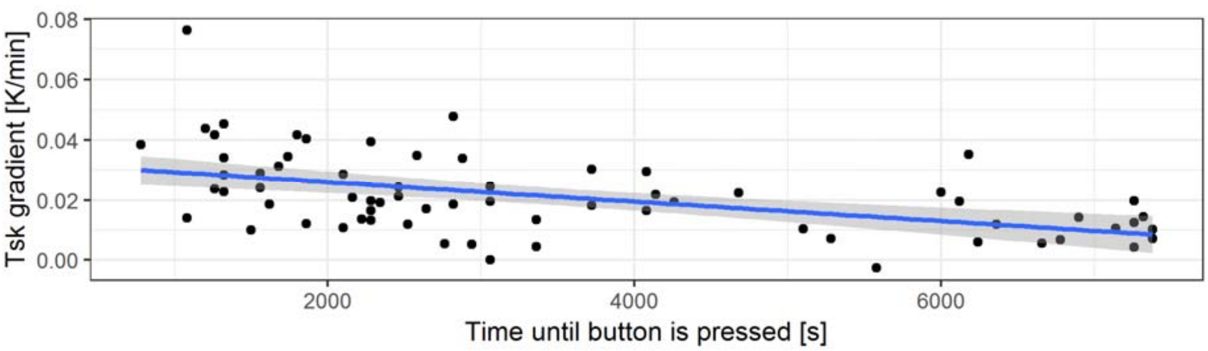



Figure 4. Relationship between the time difference until button is pressed and $T_{sk}$ gradient.

## 4.2. $T_{sk}$ gradient after reduction of thermal stressor (the capacity to recover)

In order to analyse the capacity to recover, first, the average $T_{sk}$ gradient of each participant over the four periods with the ceiling fan running (reduced thermal stressor) was calculated. For dataset D, the time-span considered for the calculation of $T_{sk}$ gradient is the period from

30 seconds after the fan started to run until 3 minutes after the fan started to run and from 1.5 minutes before the fan started to run and 0.5 minutes after the fan started to run. This linear slope serves as a representative of the resilience parameter $B_{PSd}$ (see Figure 3b-II). The $T_{sk}$ gradient was then set in relation a) to the actual thermal perception votes 0.5 minutes after the fan started to run and 3 minutes after the fan started to run, and b) to the difference in thermal perception 1.5 minutes before the fan started to run and 0.5 minutes after the fan started to run, i.e. the same period used to calculated $T_{sk}$ gradient. Note that the a priori calculated difference in PMV with and without the elevated air speed due to the running ceiling fan is 0.5 votes.

Figure 5 shows the relationship between $T_{sk}$ gradient and the absolute values for thermal perception votes. The higher the absolute value of the $T_{sk}$ gradient, i.e. the faster the decrease of $T_{sk}$, the warmer and less pleasant participants voted, but at the same time, their preference for cooler conditions was less strong. However, none of these relations was significant (all $p > .10$) nor had they a substantial effect ($0.003 < R^2 < 0.045$).

The relationship between Tsk gradient and the difference in thermal perception votes before and after the fan started is overall weak (Figure 6). Based on linear regression analysis, $T_{sk}$ gradient has no significant effect on the difference in thermal sensation ($p = .27$, $R^2 = 0.03$) thermal pleasure ($p = .97$, $R^2 < 0.01$), and thermal preference ($p = .08$, $R^2 = 0.06$). In addition, the explained variance with $R^2$ values below .1 is very low.

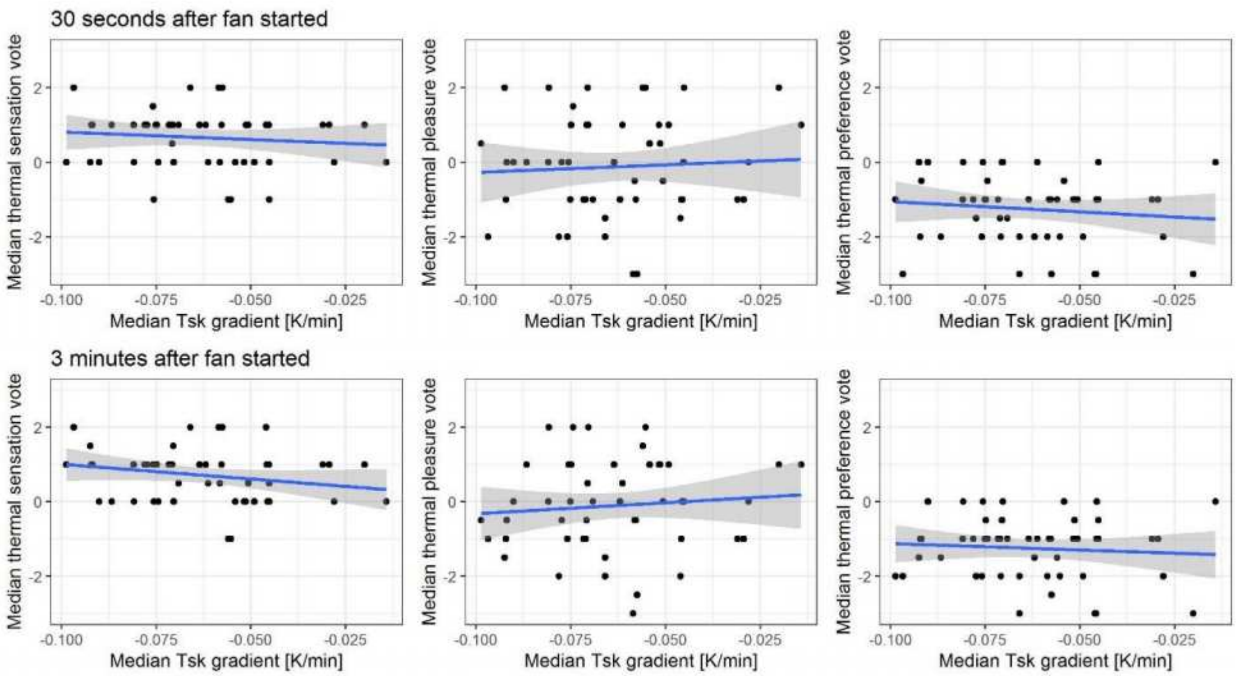



Figure 5. Relationship between median $T_{sk}$ gradient and median thermal perception votes 30 seconds and 3 minutes after fan started. Thermal sensation: -3 = cold, +3 = hot; thermal pleasure: -3 = very unpleasant, +3 = very pleasant; thermal preference: -3 = prefer much cooler, +3 prefer much warmer.

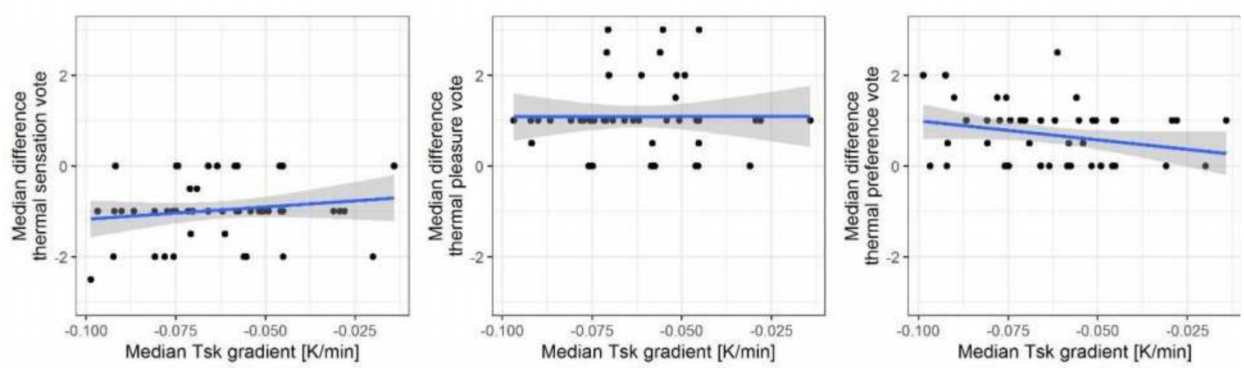



Figure 6. Relationship between median $T_{sk}$ gradient and median difference of thermal perception votes 3 minutes after and 1.5 minutes before fan started. Positive differences mean that thermal sensation votes were lower (cooler), thermal pleasure votes were less pleasant, and thermal preference was less extreme before fan started.

## 5. Discussion

### 5.1. Toughness and ability to cope

Analysing the relationship between the time until participants pressed the button, because of warmth perception, and their Tsk gradient revealed that a lower gradient is related to a longer time period. Transferring this result to the human-building resilience framework, the $T_{sk}$ gradient can be interpreted as a parameter of toughness and ability to cope for the human component. The lower the $T_{sk}$ gradient, the longer participants withstand the increasing thermal stressor. Multiple regression analysis showed that none of the observed parameters affected neither the time difference nor the $T_{sk}$ gradient. Therefore, other variables have to be found, which may explain the inter-personal variance in the $T_{sk}$ gradient, i.e. the toughness.

It is hypothesized that a complex combination of personal and life style related variables affects the toughness. In addition, studies looking at the influence of building characteristics and related parameters of their indoor thermal environment would be meaningful in order to draw conclusions whether and how building design and operation can support the aspects toughness and ability to cope of human resilience.

### 5.2. Capacity to recover

The repeated decrease of a thermal stressor by elevated air speed affected thermal perception in the expected direction However, $T_{sk}$ gradient, taken here again as a parameter of resilience, had no significant effect on the inter-personal variations in thermal perception or the perceived thermal stress.

At the same time, this result has to be taken with great caution. Explanations can be found in aspects such as the low time resolution in measuring $T_{sk}$ and perception votes or that the effect of the elevated air speed was too low to have a substantial effect on physiology and thermal perception. At the same time, comparing the values of the $T_{sk}$ gradient between data set M (M = 0.02±0.01 K/min) and D (M = -0.06±0.02 K/min) shows that physiological reaction was not lower in its gradient, but had less relative variance.

Limitations have to be seen in the circumstance that both datasets were not collected for the analysis conducted here. iButtons used to collect skin temperature values have a time delay (van Marken Lichtenbelt et al., 2006), therefore temperature gradients of skin temperature can be expected to be higher in reality than measured with the iButtons. Related to this is the low time-resolution of a 1-minute interval in comparison to the human bodies' physiological reaction. Future studies need be designed specifically to challenge one or more aspects of the framework and need to acquire a higher time-resolution for a richer dataset.

### 5.3. Human building resilient comfort and consequences for building design, operation, and thermal comfort research

The presented framework, connecting building resilience, human resilience, and paradigms of comfort opens several opportunities to scrutinise building design and operation practices together with research on thermal comfort.

The framework itself offers the potential to structure the variety of research applying the same term resilience, but looking at different parameters for it. Still, there is a need to discuss and define measures for the individual parameters of human thermal resilience in order to be able to assess influencing factors. The analyses presented here, which operationalized thermal stress with the $T_{sk}$ gradient, seem promising to evaluate aspects of toughness and ability to cope, but failed to explain differences in perceived thermal stress.

Discussing consequences, the paradigm of thermoneutrality is related to the concept of relief, however, it is hypothesized that such building design and operation practice does not support the strengthening of human resilience. Therefore, latest advancements in predicting thermal perception using for example machine-learning approaches should be applied with great caution and not in a way to remove any encouragement, i.e. temporary discomfort. Designing for encouragement and enjoyment offer the potential to increase human resilience. At the same time, it can be expected, that all three components, i.e. relief, encouragement, and enjoyment, are important and that none should be neglected. Resulting research questions are: When, under which circumstances, for which activities, do we need which component, for how long and how often? Moreover, even in case we know the answers to these questions, will occupants accept such conditions?

Related to research on thermal comfort, another discussion resulting of these thoughts is whether we should continue putting our emphasis on finding so-called optimal conditions with increasing efforts in terms of data collection and analysis. This paper suggest to shift our focus to find those concepts for design and operation, which lead to the right dose of encouragement and enjoyment and consequently a higher overall human resilience relying less on building resilience and/or intensive energy use.

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# A new building model in urban climate simulation: Indoor climate, energy demand, and the interaction between buildings and the urban climate

**Jens Pfafferott[1], Sascha Rißmann[1], Björn Maronga[2], Matthias Sühring[2]**

[1] Institute of Energy System Technology, Offenburg University, 77652 Offenburg, Germany;
[2] Institute of Meteorology and Climatology, Leibniz Universität Hannover, 30419 Hannover, Germany

**Abstract:** There is a strong interaction between the urban and the building energy balance. The urban climate affects the heat transfer through exterior walls, the longwave heat transfer between the building surfaces and the surroundings, the shortwave solar heat gains and the heat transport by ventilation. Considering also the internal heat gains and the heat capacity of the building structure, the energy demand for heating and cooling and the indoor thermal environment can be calculated based on the urban climate. According to the building energy concept, the energy demand results in an (anthropogenic) waste heat, this is directly transferred to the urban environment. Furthermore, the indoor temperature is re-coupled via the building envelope to the urban environment and affects indirectly the urban climate with a time shifted and damped temperature fluctuation. We developed and implemented a holistic building model for the combined calculation of indoor climate and energy demand based on an analytic solution of Fourier's equation. The building model is integrated via an urban surface model into the urban climate model.

**Keywords:** urban climate, building simulation

## 1. Building indoor model for urban climate simulation

Buildings strongly affect the urban climate. And the urban climate strongly affects the indoor climate and energy demand of buildings. A good review on experimental and numerical studies from the 1960s to today is given by Helbig et al. (2013). Hence, urban climate simulation models should contain a powerful building indoor model in order to evaluate the strong interaction between the building and the urban climate.

In a preliminary simulation study, Jacob and Pfafferott (2012) applied different test reference years (Deutscher Wetterdienst, 2014) on different building concepts and operation strategies. These test reference years consider both the climate change and the urban climate effect. The study clearly revealed that the urban heat island effect has a stronger effect on the building energy balance than the climate change. As expected, the building physical parameters of the building envelope (i.e. heat transfer coefficients, window area related to façade and floor area, fabric, solar shading) and the user behaviour (i.e. attendance, ventilation, use of shading device) strongly affects energy demand in summer and winter and indoor environment for both residential and office buildings. Results from monitoring campaigns confirm these findings, (Kalz et al., 2014) and (Pfafferott and Becker, 2008).

## 2. Building indoor model for urban climate simulation

The building indoor model is based on an analytical solution of Fourier's law considering a resistance model with five resistances R [K/W] and one heat capacity C [J/K]. The solution is based on a Crank-Nicolson scheme for a one-hour time step. Since the whole programming is based on heat transfer coefficients, all figures and equations are based on heat transfer coefficients H [W/K]. This is the reciprocal value of R and takes short wave, long wave, convective and conductive heat transfer and heat transport (by air) into account. The model considers four driving heat fluxes:

- $\Phi_{hc}$ heating and cooling energy,
- $\Phi_{conv}$ convective internal heat gains,
- $\Phi_{rad,s}$ radiative internal and solar heat gains to the room-enclosing surfaces, and
- $\Phi_{rad,m}$ radiative internal and solar heat gains to the room-enclosing building structure.

All heat sources and sinks are coupled with

- $\vartheta_i$ indoor air,
- $\vartheta_s$ interior surface temperature, or
- $\vartheta_m$ temperature of the room-enclosing building structure, respectively.

These interior temperatures are coupled with three exterior temperatures:

- $\vartheta_n$ façade near temperature for the incoming air,
- $\vartheta_e$ ambient air temperature for the calculation of the heat transfer through the window, and
- $\vartheta_w$ wall temperature from the urban surface model.

Figure 1 shows all temperatures and heat fluxes in this R5C1 network.

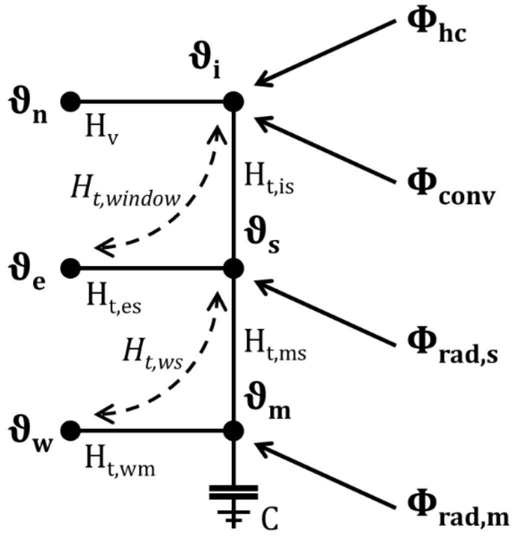


Figure 1. Heat flux and temperature in the R5C1 network. The heat flux Φw between ϑm and ϑw is calculated additionally as input value for the urban surface model, not shown in this diagram. Furthermore, the anthropogenic waste heat Φhc,w from the heating and cooling system is calculated additionally as output value to the urban climate simulation, not shown in this diagram. (The dashed lines are for information only.)

From a numerical perspective, this network consists of five reciprocal heat-transfer resistances H and one heat storage capacity C:

- $H_v$ [W/K] for heat transport by ventilation between surface-near exterior air $\vartheta_n$ and indoor air $\vartheta_i$
- $H_{t,is}$ [W/K] for convective heat transfer between indoor air $\vartheta_i$ and interior surfaces $\vartheta_s$ with specific heat transfer coefficient $h_{is}$=3.45 W/(m² K) considering all room-enclosing surfaces
- $H_{t,es}$ [W/K] for heat transfer through windows between exterior air $\vartheta_e$ and interior surfaces $\vartheta_s$

– $H_{t,ms}$ [W/K] for conductive heat transfer between interior surfaces $\vartheta_s$ and interior mass node $\vartheta_m$ with specific heat transfer coefficient $h_{ms}$=9.1 W/(m² K) considering room-enclosing surfaces
– $H_{t,wm}$ [W/K] for conductive heat transfer between wall $\vartheta_w$ and interior mass node $\vartheta_m$
– C [J/K] heat storage capacity of all the whole room-enclosing building structure

Based on the building energy concepts and the input parameters from the model database, the electrical energy demand (e.g. for lighting, ventilation and office / residential equipment), the heating energy demand (e.g. heat pump systems, boilers, cogeneration or solar thermal energy) and the cooling energy demand (e.g. compression or thermally driven chillers, adiabatic cooling, cooling towers, ground cooling) are calculated. Considering this electrical or thermal energy demand, the anthropogenic heat production is calculated and is passed back to the urban climate model.

The model according to DIN EN ISO 13790 (2008) was validated with monitoring data (simulation-measurement validation) and other simulation programs (cross-model validation). The accuracy of the advanced analytical model has been compared repeatedly with numerical simulation models with special respect to uncertain input parameters, different building technologies, and stochastic user behaviour (Burhenne et al., 2010).2

## 3. Model database

A model database is used for the parametrization of the building indoor model and the urban surface model. The database provides building physical parameters of the building envelope, geometry data and operational data (incl. user behaviour, control strategies and technical building services). The only available building information is often the age of the building, its construction material of façade and coating, the façade and window area, and the cubature. Hence, the model database defines all building physical parameters and operational data based on those basic parameters according to a building typology (IWU, 2018). The model database contains four areas:

1. The building description is based on geometry, fabric, window fraction and ventilation models.
2. The user description is based on (stochastic) user models regarding window opening and use of solar control, and user profiles regarding attendance and internal heat gains.
3. The person description is based on the metabolic rate and the clothing value.
4. The HVAC energy supply system is simulated with simplified models based on characteristic line models (considering the applicable standards) for different air-conditioning concepts. The model database contains also operation strategies for the energy supply system.

The input information on building physical parameters from a regional survey or an urban planning tool is often uncertain and inconsistent. The model database is well-structured and includes sub-models which process information on different levels of accuracy and precision. Hence, the database is built up on a standardized building topology and can manually be adapted in order to evaluate measures with regard to the façade or to the building energy supply.

The standard database contains six building types according to the German building topology (IWU, 2018), i.e. building age from the 1920s, 1970s and the 1990s for residential and non-residential buildings. The summer heat protection corresponds to the minimum requirements with regard to DIN 4108-2 (2013). Typical attendance and internal heat gains are taken from DIN V 18599 (2011) and empirical values (Voss et al., 2006).

**4. Integration into the urban climate model**

The building indoor model has been implemented into the PALM platform. The building geometry and the resolution given by the urban simulation model define both the volume of the building and the number of façade elements. Each building indoor model contains as many indoor volumes as façade elements. Thus, all global parameters (i.e. air change per hour, internal heat gain per net floor area and heat capacity) are referred to this virtual room volume:

Figure 2 shows simulation results for a summer and a winter simulation run. Both graphs show the (local) temperature distribution in the building and around the building and the anthropogenic waste heat from heating and cooling at 11 a.m. in a typical urban situation with street canyons, block development and high-rise buildings, parks and water: Ernst-Reuter-Platz, Berlin (Germany). These simulation results clearly show that the combined simulation of urban climate, energy balance at the wall surface, and the indoor energy balance yield detail information on indoor and outdoor temperatures, surface temperatures and energy demand (not shown in the graph) and heat fluxes from the building's energy system to the urban environment:

- The outdoor temperature $\vartheta_e$ is around +24 °C in the summer scenario (above) and -10 °C in the winter scenario (below) and is locally calculated by the urban canopy model that represents the fluid dynamic and thermodynamic effects of the urbanized area around Ernst-Reuter-Platz in Berlin on the atmosphere.
- The operative room temperature $\vartheta_i$ is around 26 °C in the summer scenario (in buildings with active cooling) and around 20 °C in winter due to active heating. There is a remarkable temperature range in buildings with no active cooling: In this summer scenario, the operative room temperature in some buildings rise to 33 °C due to high solar and internal heat gains while other buildings stay at 22 °C due to their high thermal inertia and passive cooling strategies.
- The (use) energy demand for heating and cooling of each volume element depends strongly on the temperature difference between inside and outside, the wind speed at the façade, the building construction and window-to-façade ratio, and the solar radiation and the orientation of the building. The (final) energy demand considers the building's energy supply system. Based on the energy conversion factors for each heating or cooling system, the anthropogenic waste heat from the building $\Phi_{hc,w}$ is calculated for each façade element separately and is transferred to the urban area via the outside surface. Façade elements with no anthropogenic waste heat (i.e. buildings with district heating in winter or passive cooling in summer, respectively) are shown in black. The anthropogenic waste heat from the building $\Phi_{hc,w}$ due to energy losses of the heating supply system ranges between 2 and 7 W/m²facade in winter and due to the recooling systems of the cooling supply system between 20 and 60 W/m²facade.

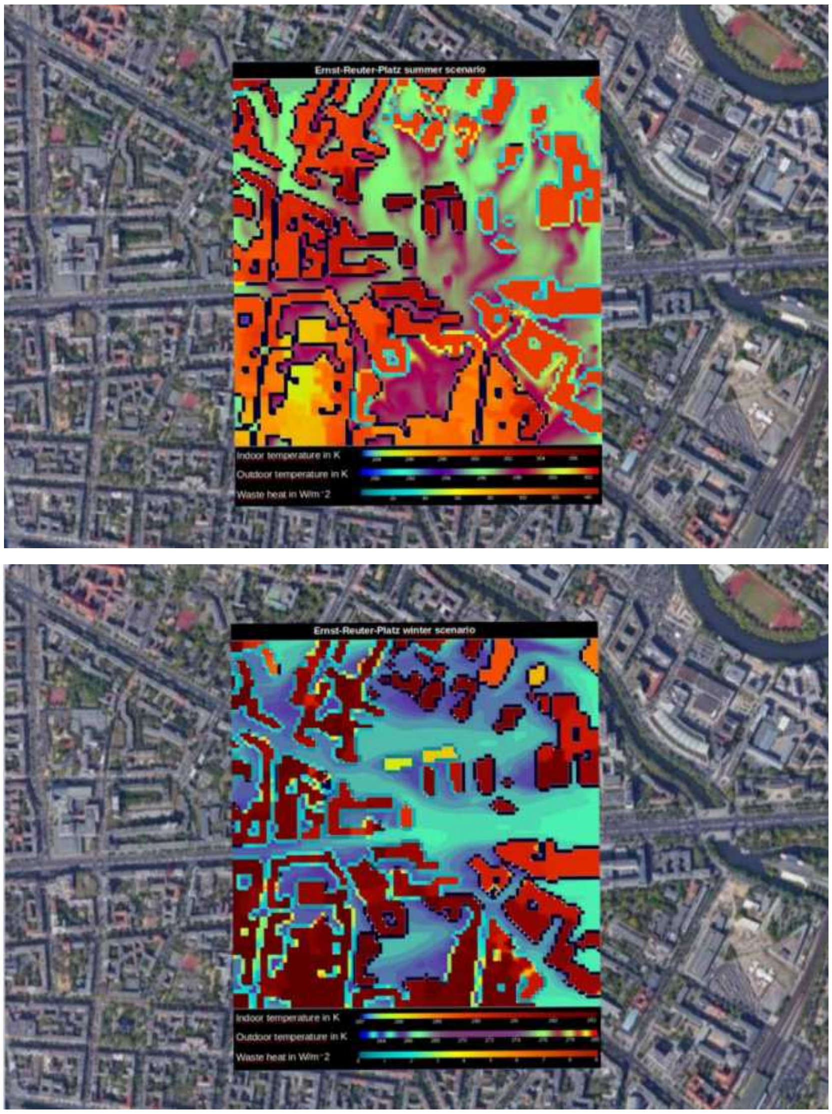


Figure 2. Urban climate and building model in a test setup: The Ernst-Reuter-Platz connects five urban street canyons and is surrounded by high-rise buildings. The simulation runs with a resolution of 1 m x 1 m x 1m. The graphs show the operative room temperature $\vartheta_i$, the ambient air temperature $\vartheta_e$ and the anthropogenic waste heat $\Phi_{hc,w}$ at the outside surface. The outdoor temperature is around +24 °C in the summer scenario (above) and -10 °C in the winter scenario (below). Façade elements with no anthropogenic waste heat (i.e. buildings with district heating in winter or passive cooling in summer, respectively) are shown in black.

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# Designing buildings today adapted to a changing climate

**Anaïs Machard[12], Christian Inard[1], Jean-Marie Alessandrini[2], Charles Pelé[2], Jacques Ribéron[3]**

[1] LaSIE - Laboratoire des Sciences de l'Ingénieur pour l'Environnement (UMR CNRS 7356) La Rochelle Université, 23 Avenue Albert Einstein, 17000 La Rochelle, France, correspondance email : amachard@univ-lr.fr

[2] Département Energie et Environnement, Centre Scientifique et Technique du bâtiment (CSTB) 84 avenue Jean-Jaurès, Champs-sur-Marne, 77447 Marne-la-Vallée cedex 2, France

[3] Département Santé et Confort, Centre Scientifique et Technique du bâtiment (CSTB) 84 avenue Jean-Jaurès, Champs-sur-Marne, 77447 Marne-la-Vallée cedex 2, France

**Abstract:** This paper proposes an analysis of the summer thermal comfort in a residential building case-study, evaluated with dynamic thermal simulation using EnergyPlus as software. Different building designs that combine reducing heat gains with providing cool air via natural ventilation are tested in three French cities. The proposed solutions include thermal inertia, proper use of solar shading, selective materials, reducing glazing percentage and natural ventilation. The building's resilience to overheating is assessed under three sets of future climate files built using Regional Climate Model (RCM) data: a historical typical-summer, a future typical-summer and a future "intense-heatwave-period". The future heatwave is selected according to the French criteria and is chosen to be more intense than the 2003 heatwave to assess if the building could maintain safe indoor conditions. The design approach is evaluated through a sensitivity analysis of the key building design input parameters, conducted for each of the two future climate files.

**Keywords:** Future climate data, summer thermal comfort, overheating, sensitivity analysis, passive cooling

## 1. Introduction

Historically, buildings in central Europe were designed to withstand cold winters and natural ventilation would be sufficient to cool the buildings during the summer. Until now, in France the buildings Thermal Regulation has focused efforts on designing very energy-efficient new buildings. However, due to the changing climate, overheating problems have started happening more and more frequently in recent years. The PassivHaus standard from Germany has also been questioned in its capability to not overheat in future summers (McLeod et al., 2013). In France, the summer thermal comfort of buildings built today is assessed under a warm day of the historical climate. It is now necessary to assess the overheating limits and potential health heat-related risk of new buildings built today under future climate.

Modelling buildings with future climate files has been the interest of the building research community for almost fifteen years now. However, most authors have been assessing the resilience of buildings under future typical summers, but not under future extreme conditions. Assessing the resilience of buildings to future climate with future weather files containing warm years, extreme hot years or heatwaves is a very recent practice. Some authors have been using recorded hot years or heatwave weather data to assess the resilience of the building to hot external temperatures (Alessandrini et al., 2019)(Synnefa et al., 2018)(Pyrgou et al., 2017), while others have been using future weather files to assess the resilience of buildings to overheating. (Nik, 2016) has used data from regional climate models to reconstitute future extreme hot years, whereas Liu has used the UKCP09 British weather generator to generate future years containing extreme hot temperatures (Liu et al., 2019).

To maintain a safe indoor environment during hot weather, the use of air-conditioning seems to be an efficient and common solution. However, the International Energy Agency has announced in 2018 that "the world is facing a looming cold crunch" as the use of air conditioners worldwide has been increasing tremendously over the last thirty years. By 2050, the global energy demand from air conditioners is expected to triple (International Energy Agency, 2018). In China, air-conditioning in households was about 1% in 1990 and is almost at 100% in 2010, whereas in Europe air-conditioning has penetrated only 8% households but this number is growing fast (Santamouris, 2016).

In France, the buildings thermal regulation is promoting the use of natural cooling solutions in residential buildings, to limit the penetration of air-conditioning. However, according to Givoni, for a high thermal mass building with efficient solar control, the potential of nocturnal ventilation to maintain indoor temperatures below 28°C is limited to exterior temperatures under 36°C (Givoni, 1992). If future air temperatures in France were to exceed 36°C, air-conditioning or alternative natural cooling strategies and systems would be needed. Many passive cooling systems exist and have proven to reduce indoor temperatures considerably and limit overheating problems (Givoni, 1994) (Fergus et al., 2007). In this paper, the resilience to overheating of a residential building in France will be assessed in three cities under future weather conditions. Combinations of the following passive techniques will be investigated: solar control via external shading, thermal inertia, cool paints, glazing percentage and natural ventilation. Will these solutions be enough to maintain safe indoor temperatures during future typical summer conditions and future heatwave events in French climate? Should we design for future typical summer or future heatwaves? Which parameters would have the most impact on the building overheating?

## 2. Methodology

There is a need to develop a methodology for designing buildings adapted to future climate with mitigated solutions. The research presented in this paper is a proposal for such a methodology. First, future hourly summer temperature data from different regional models are presented, then the methodology to reconstruct historical typical, future typical and future weather files including future intense heatwaves is explained. These weather files will be used to simulate indoor building conditions under future climate. Secondly, the building case-study modelled with the software EnergyPlus for the analysis is introduced with the comfort and health indicators used to assess the indoor conditions of the building. The selected input parameters for the sensitivity analysis are also presented in this section. The methodology could be applied with different weather files, for a different building type, and for different cities.

### 2.1. Future climate data

During the past fifteen years in the building community, most researchers have been using data that were statistically downscaled using the Morphing method. The method has the advantage to provide hourly data available in epw format at a very low computational time. However, it presents many limitations, one of them is that climate change is considered through monthly temperatures averages, therefore it is not possible to detect future extreme events. For the purpose of this case study, we have decided to use data from regional climate models to assess the indoor building conditions both under future typical summer conditions and under a future heatwave period. The thermal summer discomfort of the building will be analysed in three French cities: Paris, Carpentras, and Strasbourg. Paris is located in a modified oceanic climate, with a high urban heat island effect and high population density. Carpentras is in a Mediterranean climate where record maxima's temperatures were registered. Strasbourg is a city in a semi-continental climate, located in the East of France.

**Historical & future typical weather year**
We compared temperature data from different climate models with the climate file currently used by the French Thermal Regulation, which consists of observations made during the 1994-2008 period (Figure 1). Climate data are from regional models from the EURO-CORDEX project with a grid resolution of 12.5 km. Typical years were reconstituted following the NF EN ISO 15927-4 standard (ISO, 2006). For the comparison, the historical reference period was chosen to be from 1991 until 2005 and the future period 2041-2070 under the scenario RCP 8.5. The data used in Figure 1 presents hourly summer temperatures distribution of historical and future typical years in Paris. The data were not bias adjusted because bias-adjusted data could not be found for all climate variables. However, previous analysis showed that bias-adjusted data for this climate and for these climate models were actually warmer than non-bias-adjusted data. It can be observed that the typical-year summertime hourly temperatures predicted by the models CNRM_RCA4, MPI_RCA4 and IPSL_RCA4 over the historical period 1991-2005 are lower than the observed temperatures (RT-2012_type) over the historical period 1994-2008. Also, future temperatures over the period 2041-2070 predicted by the models CNRM_RCA4 and MPI_RCA4 are really close to the data from RT-2012 over the historical period. For our case study, the model IPSL_RCA4 that seem to conservatively represent the observations of Paris typical summer temperatures during the reference period and present warmer temperatures over the future period was selected. The summer hourly temperature distribution of the typical year from the model ISPL_RCA4 suggests that there is an increase of around +2.5°C for 50% of the summer temperatures, whereas the increase is more pronounced for the hottest temperatures, as the maximal temperature in Paris over the historical typical year was of 34°C and will be of 41°C in the future. The hourly temperature distribution of the summer months (June, July, and August) from the typical years during the historical and future period is presented in Figure 2. Average values are shown in green triangles. From Figure 2, the following observations can be made: The summer temperature rise has a similar trend in Paris and Strasbourg. For both cities, the mean temperature increase is around +3.5°C between the present and future climate, and the maximal temperature increase is about +6.5°C. In Carpentras, the mean temperature increase is about 4.5°C and the maximal temperature increase almost +8°C. Regarding minimal temperatures, in Paris the increase is of +2°C, in Strasbourg, it is almost inexistent and in Carpentras, the increase is of 5°C.

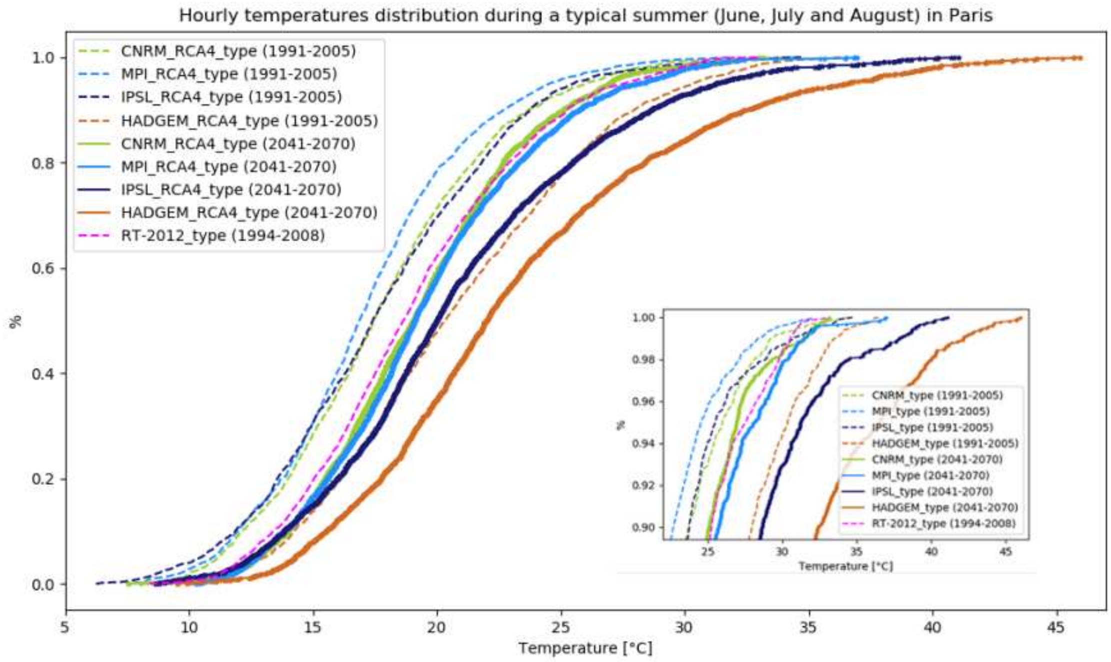


Figure 1 – Statistical Distribution of Hourly Summer (June, July, August) Temperatures over the period 2041-2070 (scenario RCP 8.5) from different climate models in Paris. Models are presented under the name GCM_RCM. RT-2012 is an historical typical year (compiled with EN ISO 15927-4) from observations

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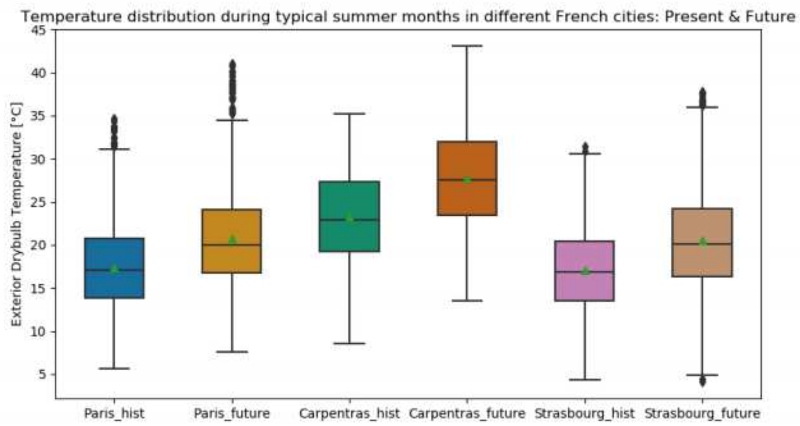



Figure 2 – Hourly dry-bulb temperature distribution during typical summer months in Paris, Carpentras and Strasbourg. Climate data are from the RCM model RCA4 driven by the GCM IPSL. The historical period is 1976-2005 and the future period is 2041-2070 under the RCP 8.5 scenario. The green triangles on the box plots are the average values.

**Future intense heatwave**

Using data from regional climate models allowed us to select heatwaves over the future period 2041-2070. We followed the methodology used by the French health-warning system to detect heatwaves (Laaidi et al., 2006). The temperatures during the future heatwave selected for Paris, compared to the heatwave in 2003 are presented on Figure 3. Both maximal temperatures (from 40°C to 44°C) and minimal temperatures (from 22°C to 26°C) are higher in the future. The observations from the airport station Orly and the temperatures from the IPSL_RCA4 model do not consider the urban heat island effect, which we know will exacerbate strongly the night time temperatures. The French health-warning system uses 3-day moving-average exterior temperature daily maxima (IBMx) and minimal (IBMn) to detect heatwaves. For each department, Sx and Sn, the respective thresholds maxima and minima were calculated based on mortality data from past heatwaves. These thresholds are presented on Figure 3 with the hourly temperatures for the observed 2003 data heatwave and the future modelled heatwave with the climate model IPSL-RCA4. The future heatwave chosen for the analysis was selected from the year 2056. From all detected future heatwaves, this one was chosen because its intensity and duration were more intense than the 2003 heatwave. In order to compare with observations, bias-adjusted data are usually used. On Figure 3 non-bias-adjusted data and bias-adjusted data are compared. It can be seen there is no significant difference for this period of time, therefore using non-bias-adjusted data for our analysis seem acceptable.

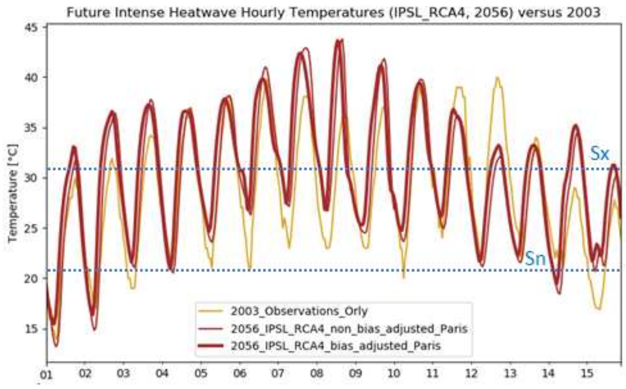



Figure 3 – Future Intense Heatwave Hourly Temperatures in Paris: 2003 vs. 2056 (IPSL)

### 2.2. Building case-study

The building case-study is a low-rise residential building. In this study we focused on a flat located on the top floor on the Westside. The apartment can accommodate five people, the living space has a surface area of 120m² with an additional 50m² veranda oriented South, which contributes to reducing the winter heating needs with solar gains. A glazed cavity zone of 0.6m width is located on the North façade, as the original design of the apartment is fully glazed on the North and South façade to allow a lot of daylight in the house. On Figure 4, a rendering of the apartment is shown. The living space is located in between the veranda and the glazed cavity zone, which is an interesting bioclimatic design as the two external thermal zones act as buffer spaces between the living space and the exterior environment. The configuration of the windows favors cross-ventilation, to enhance summer natural ventilation. All the flats have exterior balconies beyond the glazed façades which act as overhangs for the flats under them, to reduce solar heat gains in the summer (0.5m on the North façade and 1m on the South façade). In addition, light-colored external shutters are placed on the south-facing windows of the veranda to provide supplementary shading during the summer.

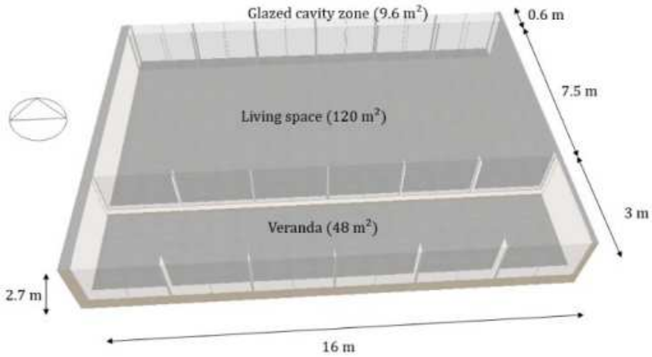



Figure 4 - Representation of the apartment case-study

The building constructions are presented on Table 1. The interior wall and the floor are considered adiabatic as they are supposed to be in contact with an adjacent apartment.

Table 1 - Description of the building case-study materials properties

| | Construction layers from interior to exterior | U-value [W/m².K] | Solar factor |
|---|---|---|---|
| **Exterior wall** | 20cm concrete + 14cm polystyrene insulation | 0.23 | |
| **Interior wall** | 20 concrete | Adiabatic | |
| **Floor (intermediate) of the living space** | 20cm concrete + 3cm polyurethane insulation | Adiabatic | |
| **Ceiling of the living space** | 20cm concrete + 15cm polyurethane insulation | 0.16 | |
| **Exterior glass of the living space and of the glazed cavity** | Double glazing 16mm filled with Argon | 1.1 | 0.33 |
| **Exterior glass of the veranda** | Single glazing | 5.5 | 0.67 |

Regarding occupancy, four persons are at work during the day, but one person stays in the apartment all day. The averaged heat produced by the individuals is assumed to be equal to 81 W. According to the occupancy schedule proposed by the French Thermal Regulation, we multiplied the heat gain produced by each individual by 0.7 at night (10pm-7am), by 1 in the mornings and the evenings (7am-9am and 7pm-10pm) when the flat is fully occupied, and by 0.2 during the day (9am-7pm) when only the elderly person is in the apartment. Their vesture is about 1 clo in the winter and 0.3 clo during the summer. For the historical period internal gains are about 5.7 W/m² for electric equipment and 1.4 W/m² for the lights according to the French Thermal Regulation. However future predictions were used to calculate future internal gains, which are predicted to be lower: 2.7 W/m² and 0.7 W/m² for the lights (RTE, 2017). Similar to the occupancy schedule, the electric gains are fully used only at times when the apartment is fully populated.

### 2.3. Building model

The apartment was modeled with the software EnergyPlus. It was divided into three thermal zones: the glazed cavity, the living space, and the veranda. The heat balance algorithm chosen was the conduction transfer function. The interior convection model algorithms were chosen to be TrombeWall for the glazed cavity and TARP (Walton, 1983) for the two other zones. The natural ventilation was modeled with the Airflow Network that takes into account stack pressure and wind-driven air exchanges (Gu, 2007). All windows were modelled as large vertical openings through which airflow can be bi-directional. Discharge coefficients were chosen equal to 0.65. The wind pressure on the façades was determined by Bernoulli equation. Wind pressure coefficients (Cp) on the building envelope were calculated using Swami and Chandra correlation for low-rise rectangular buildings (Swami and Chandra, 1988). The wind speed inside the city was calculated by EnergyPlus using ASHRAE coefficients for towns and cities (ASHRAE, 2001).

### 2.4. Discomfort indicator

Since the building is naturally ventilated and without air-conditioning, the adaptive comfort model is applicable to assess the indoor thermal comfort. Only the upper comfort categories of the EN-15251 standard (CEN-EN 15251, 2007) were analysed, above the neutral comfort line. Operative temperatures falling under the neutral comfort line were not be considered into the summer thermal comfort assessment. On Figure 5, the different comfort categories are presented. The neutral comfort line is drawn in olive. Trm is the daily running-mean outside temperature. According to the EN-15251 standard, category I a comfort zone with a high level of exigence, recommended for vulnerable people such as young children or the elderly. Category II represents the normal level of comfort that can be expected in new and refurbished buildings. Category III is the “moderate” expected level of comfort, that can be used in existing buildings. Category IV is accepted only for short periods of the year. In this paper, the discomfort criterion is chosen to be the number of hours above the upper limit of category II.

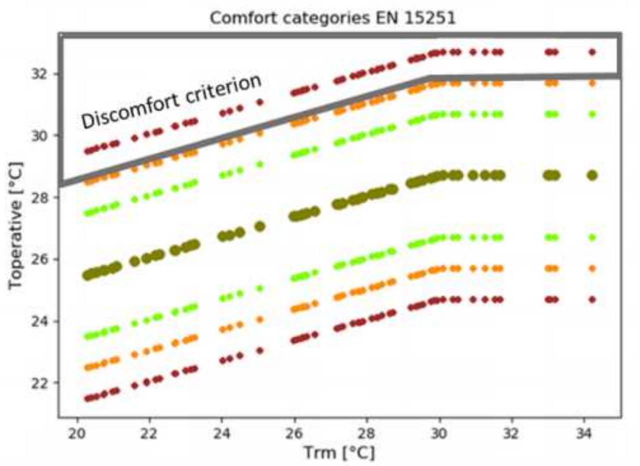



Figure 5 – Upper comfort categories from EN-15251 and selected discomfort indicator

### 2.5. Design input parameters

The design input parameters were selected according to the potential impact they could have on the building’s overheating, summer thermal discomfort, and health risk. A range was selected for each parameter, delimited by low and high values. The choice was made to select an extended range, exploring all the feasible values each parameter could take.

Table 2 – Design input parameters selected for the parametric and sensitivity analysis, lower and higher limits

| Parameter | Lower limit | Higher limit | Unit |
|---|---|---|---|
| **Density of materials with thermal inertia** | 650 | 2300 | kg/m$^3$ |
| **Glazing % of North and South facades** | 15 | 90 | % |
| **Absorptivity (SW) & Emissivity (LW) of exterior coatings** | 0.05 | 0.95 | |
| **Set-point temperature controlling windows opening for the natural ventilation** | 15 | 24 | °C |
| **Solar radiation on façade controlling the use of the external shutters** | 5 | 500 | W/m$^2$ |

### Thermal inertia of the living space envelope

In order to vary the thermal inertia of the living space envelope, materials with inertia within the envelope (exterior and interior wall, floor and ceiling of the living space) were modified. Four materials were considered: concrete (high limit, density of 2300), brick (density of 1750), earth (density of 1200) and wood (density of 650). For a specific material density, the associated thermal capacity, thermal conductivity and thickness of that material were modified in conjunction and in order to keep constant the U value of the wall. For the wood material, the thermal insulation was moved from exterior to interior.

### Glazing % on North and South facades

Regarding the glazing percentage, it was modified only on the North and South façade in order to maintain the initial design from the architect, allowing cross-ventilation. A minimum glazing percentage of 15% was chosen in order to ensure minimal daylight into the apartment. The RT-2012 standard imposes a minimal glazing ratio of a sixth of the conditioned space floor area. For the apartment case-study, the minimum recommended surface is about 20 m². The North and South façade represent a total of 86.4 m², so the minimum glazing % should be of 23%. However, in order to consider an extended range of possible values, we decided to extend this minimal glazing percentage and to consider a design with less glazing than recommended by the French regulation.

**Absorptivity & Emissivity of exterior coatings**
The best selective material should have a low absorptivity in the solar short-wave length combined with a high emissivity in the infrared long-wave length. In order to examine the potential of these selective materials, we decided to change these two parameters simultaneously. This way, the best material for our case study would have an absorptivity of 0.05 in the solar wave-length and an emissivity of 0.95 in the infrared long-wave, whereas the worst material would have an absorptivity of 0.95 combined with an emissivity of 0.05. The exterior coatings were applied on the exterior surfaces of the exterior walls and ceilings of the living space, glazed cavity and veranda for all simulations.

**Set-point temperature controlling windows opening for natural ventilation**
The condition for windows opening is based on a set-point interior operative temperature from which the windows open. The assumption that windows will never be open if the interior temperature is above the exterior temperature was made. The minimal set-point temperature was chosen to be 15°C, in order to maximize the nocturnal ventilation. The assumption that people could always open windows and were not restrained by noise, pollution or security concerns was made. The set point temperature was the same for all windows (living space, exterior windows of the veranda and of the glazed cavity zone) to prevent overheating in the buffer zones and allow cross ventilation.

**Solar radiation on façade controlling the use of the external shutters**
The shades on the exterior Southern façade are controlled in function of the incoming solar radiation on the windows. A control at 500 W/m² would only use the shades during the warmest hours of sunny days, whereas a control at 5 W/m² would use the shades most of the time except in the early mornings and late evenings. As the shades are placed only on the South façade, daylight is still be provided by the North facade.

### 2.6. Sensitivity Analysis

The sensitivity analysis was conducted with the Morris method. It is the most engineering-used screening method based on the “one factor at a time” (OAT) design (Morris, 1991) (Saltelli et al., 2004). The Morris method allows to identify the input parameters $j$ that have an impact on an output variable F. In this study, the chosen output variable is the discomfort criterion presented in section 2.4. The five design parameters chosen for the sensitivity analysis were presented on Table 2. The method allows to calculate for each input parameter and in between two simulations the elementary effects EE. $\Delta$ is the change in input $j$, and corresponds to $\Delta\mathrm{F}$, the change in output. The absolute mean μ* and the variance σ of the elementary effects can then be calculated for each input parameter $j$, $r$ is the number of trajectories. A high value of μ* is an indication of a high influence of the input parameter $j$ on the output F, a small value of $\sigma$ indicates that the input parameter $j$ has a linear effect, whereas a high value of $\sigma$ indicates that the input parameter has interactions with other input parameters, or that the parameter does not behave linearly.

$$EE_j^i = \frac{\Delta \mathrm{F}}{\Delta}$$

$$\mu_j^* = \frac{1}{r} \cdot \sum_{i=1}^{r} \left| EE_j^i \right|$$

$$\sigma_j = \sqrt{\frac{1}{r-1} \cdot \sum_{i=1}^{r} \left( EE_j^i - \mu_j \right)^2}$$

The simulations were conducted from the 1st of June until the 30th of September.

## 3. Results

### 3.1. Simulations settings

Simulations were conducted for 10, 20, 30, 40, 50, and 500 trajectories with the weather file Paris-future-typical-summer. The convergence of each parameter was assessed with their respective absolute mean μ*. From Figure 6, it seems that the convergence was obtained fairly quickly, thus we conducted the simulations with the other weather files with 50 trajectories each time (300 simulations). Among the 300 simulations, 31 duplicates were found. For five parameters, the full factorial design is about 1024 combinations (simulations), therefore the Morris matrix design allowed to divide the number of simulations by around four (269 non-duplicate simulations/1024). The simulations were conducted for the extended summer period, from the 1st of June until the 30th of September. For the heatwave weather files, the simulation time was reduced to the month during which there was the heatwave. The sensitivity analysis was conducted for the three cities, and for each city under the three climate files (nine analyses). For each analysis, the same design matrix was followed for consistency. Simulations were run in parallel with 15 processors, resulting in a simulation time per climate file of around 30 minutes.

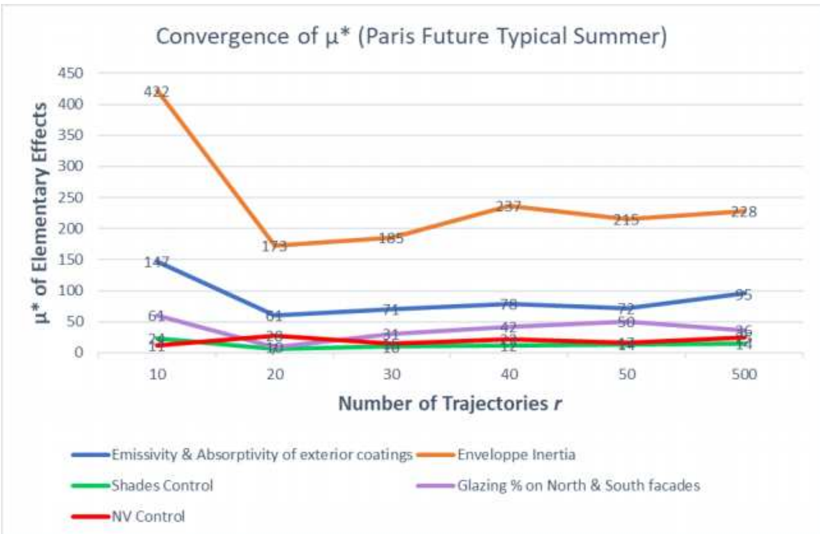



Figure 6 - Convergence of input parameters depending on the number of trajectories

### 3.2. Operative temperature under future typical summer months & Discomfort analysis

On Figure 7 and Figure 8, statistics of the operative temperature from the 300 simulations are shown for the typical historical and future climate and for the future heatwave in Paris and Carpentras respectively. Results for the city of Strasbourg were found very similar to the city of Paris, therefore they are not shown here. The median operative temperature of all simulations is shown, as well as the max, min, 75% and 25%, which allow comparison with the upper limit of the category II from the EN-15251 standard. In Paris (Figure 7), under the historical typical climate, almost all simulations showcase operative temperatures under the discomfort limit, except for a few hot days (never beyond 5 consecutive days) for the worst case, Top_max. Under the future typical climate, around 25% of the simulated combinations showcase operative temperatures above the limit. However, under the future heatwave, more than half of the combinations result in operative temperatures beyond the comfort limit (and above 30°C). In Carpentras (Figure 8), the increase in absolute temperatures between the historical and future typical summer is important: In the future summer, more than half of the simulated combinations exhibit operative temperatures above the limit for 30 consecutive days, and some days for more than 75% of the combinations, whereas in the historical less than 25% of combinations were above the limit. Regarding the worst case (Top_max), night operative temperatures are above 32°C and the day temperatures above 40°C which would result in great heat-related health issues. Moreover, the upper limit of the comfort II category is at its maximum for most days of the future typical summers, revealing the norm's limitation in terms of applicability range. Under the future mega-heatwave, and at the end of it (end of July), even the best combination (Top_min) has an operative temperature above the comfort limit, meaning no proposed combinations allow the building to remain comfortable under future climate. The upper limit is at its maximum during the entire duration of the heatwave. Beyond discomfort, health related issues might occur at such high temperatures, and a health-related heat indicator would be needed to asses health risks.

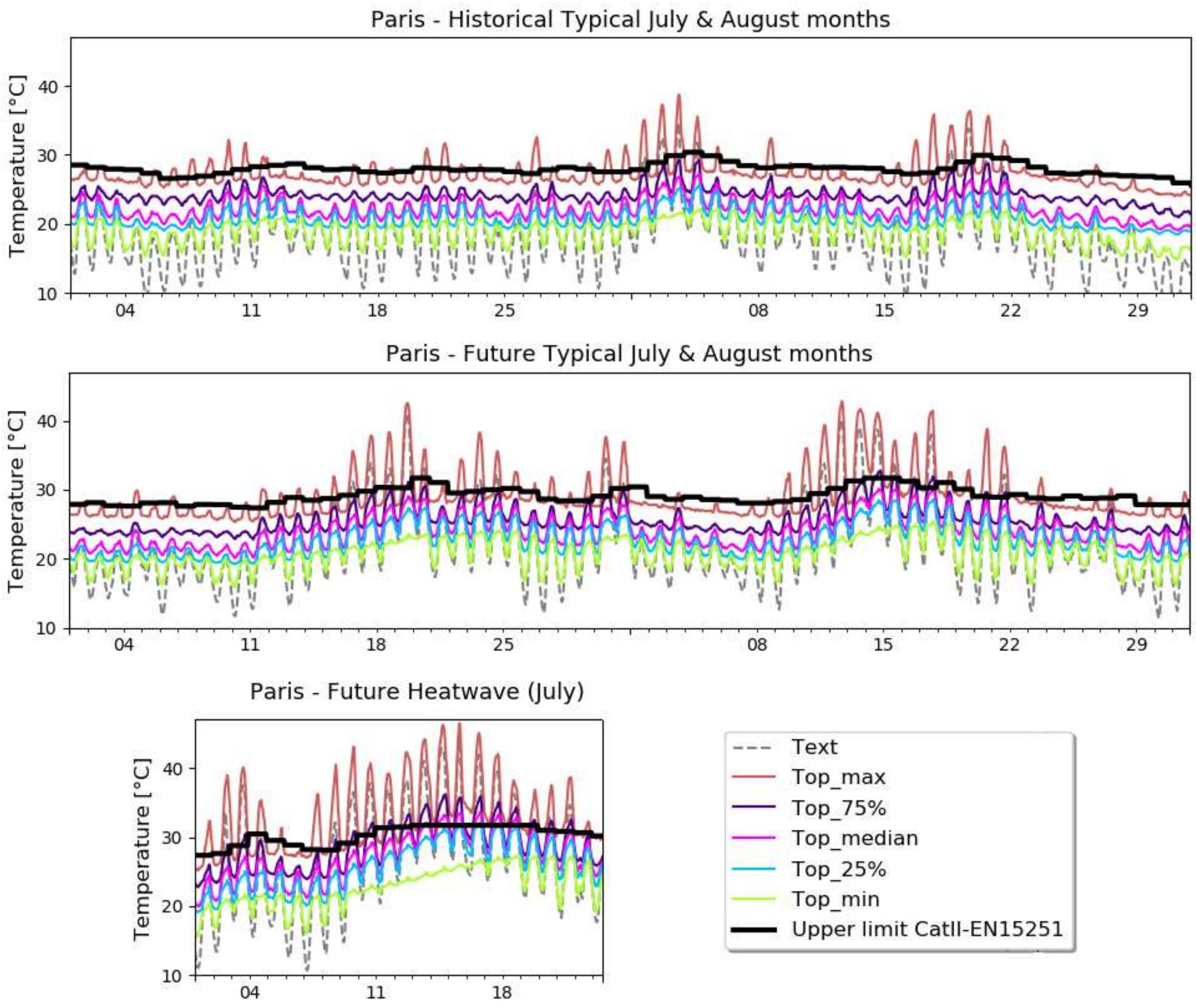



Figure 7 - Operative temperatures in Paris for the historical & future typical July and August months and for a future heatwave (climate data from the model IPSL_RCA4) from the 300 simulations following the matrix

From the 300 simulations, the worst and best configurations of input parameters on the hottest day of each future typical summer, for the three cities were investigated (Table 3). From Figure 7, each data point (one data point per hour) of the Top min, 25%, median, 75% and max are from independent simulations, meaning that during each hour of the day, there are several worst and best combination of input parameters. All the worst combinations have in common the E & A input parameter, that is about 0.95. During the day, all worst combinations have 650 for density (wood) whereas during the night hours, the worst material for inertia can be another material, but it is never 2300 (the concrete). The other input parameters (shades control, glazing % and natural ventilation) vary in between their range, depending on the configurations. Among all the best combinations, similarly and opposite to the worst, all configurations have an E & A input parameter of 0.5. Regarding the thermal inertia, it seems that during the night a low inertia (density of 650) is preferred, whereas during the day high inertia (density of 2300) is better. Most best configurations have a shades control of 5 (all configurations in Carpentras where it is sunnier warmer). Best configurations can have a low or high glazing percentage, however they all have a low set-point at 15°C of operative temperature for windows opening, indicating that they are ventilated at their maximum.

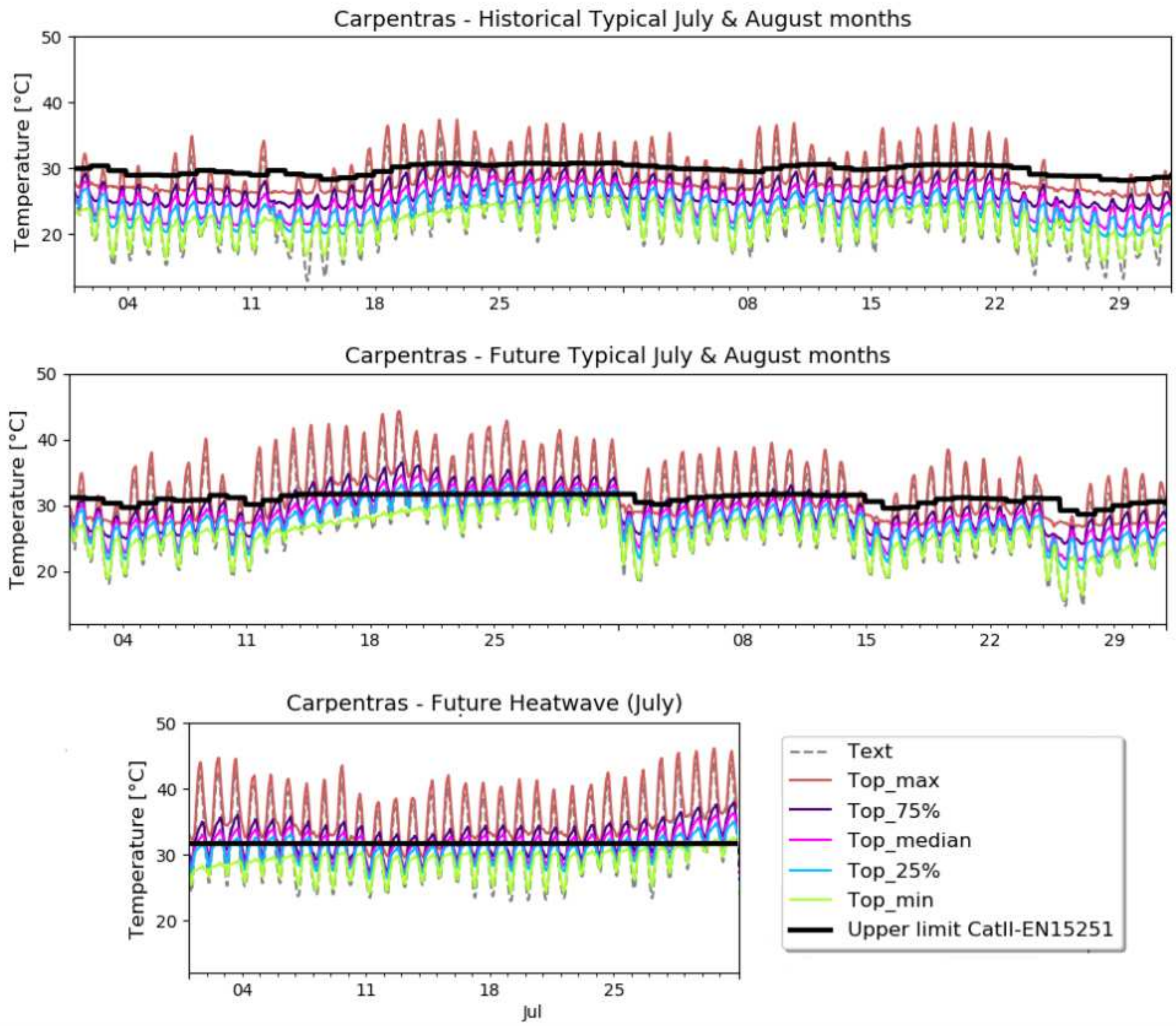



Figure 8 - Operative temperatures in Carpentras for the historical typical, future typical July and August months and for a future heatwave (climate data from the model IPSL_RCA4) from the 300 simulations following the design matrix

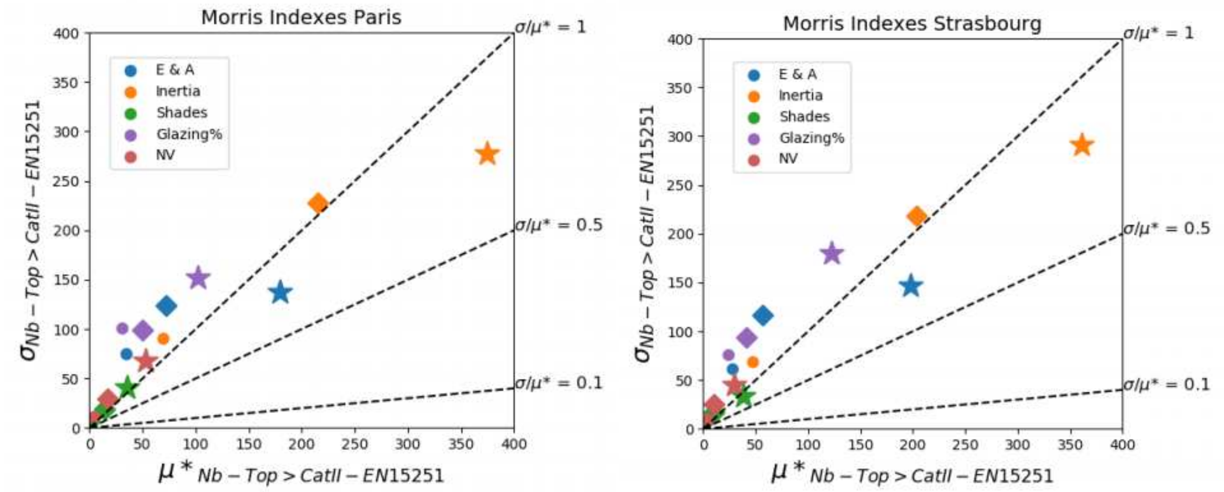
Table 3 – Worst and best combinations of input parameters for the hottest day of each weather file. C stands for Carpentras, P for Paris and S for Strasbourg

| **WORST** | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | N° | E & A | Inertia | Shades | Glazing % | NV |
| **Night** | 00h-09h & 23h (C) & 01h-08h (P) | 198 | 0.95 | 1200 | 500 | 0.15 | 21 |
| | 02h-09h (S) | 185 | 0.95 | 1750 | 170 | 0.15 | 24 |
| | 18h-23h (S) & 21h-22h (C) & 19h-00h (P) | 268 | 0.95 | 650 | 500 | 0.15 | 15 |
| | 18h-20h (C) | 269 | 0.95 | 650 | 170 | 0.15 | 15 |
| **Day** | 16h-17h & 00h-01h (S) | 174 | 0.95 | 650 | 170 | 0.15 | 24 |
| | 10h-15h (S) | 197 | 0.95 | 650 | 335 | 0.9 | 18 |
| | 10h-14h (C) & 09h-15h (P) | 151 | 0.95 | 650 | 500 | 0.9 | 15 |
| | 15h (C) | 120 | 0.95 | 650 | 170 | 0.65 | 24 |
| | 16h (C) | 289 | 0.95 | 650 | 335 | 0.15 | 18 |
| | 17h (C) & 16h-18h (P) | 167 | 0.95 | 650 | 5 | 0.15 | 21 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **BEST** | | | | | | | |
| **Night** | 03h-05h (C) & 04h (P) | 169 | 0.05 | 650 | 5 | 0.9 | 15 |
| | 05h-06h (C) | 168 | 0.05 | 650 | 5 | 0.4 | 15 |
| **Night & Day** | 00h-02h & 07h-23h (C) & 02h-03h & 05h (P) | 81 | 0.05 | 2300 | 5 | 0.4 | 15 |
| | 00h-02h & 06h-23h (P) & 00h-23h (S) | 119 | 0.05 | 2300 | 335 | 0.15 | 15 |

### 3.3. Results of the Sensitivity Analysis

On Figure 9, results of the Morris sensitivity analysis are presented for each city. On each Figure, results for the historical climate are in dots, for the future typical in diamonds and for the future heatwave in stars. In all cities, and for all climate files, the parameter ranking goes as follow (μ*): The thermal inertia is the most important parameter, then the absorptivity and emissivity of exterior coatings has a strong effect as well, followed by the glazing percentage. In contrast, the control of windows opening for natural ventilation and of the shades to reduce heat gains only have a low impact. A strong effect of the absorptivity and emissivity of exterior coatings (A & E) can be explained by the fact that the apartment is located under the roof, so the best case (with A = 0.05 and E = 0.95) is a typical cool roof configuration. A low effect of the shades control could be because the direct solar gains enter the veranda, but only diffuse solar gains enter the living space (please see EnergyPlus Documentation, Engineering Reference, 2016). Finally, the impact of the windows opening control for natural ventilation (NV) might not be seen because the discomfort criterion analyses hours maxima above a threshold but does not analyse in particular night hours, when it is directly effective. It could also be because air flows inside the building are reduced, more analysis is needed to understand this parameter. Moreover, the ratio $\sigma/\mu^*$ is a measure of linearity or effects with another input parameter. As well explained in Garcia Sanchez et al, and from a statistical point of view, if $\sigma/\mu^* > 0.5$, the input parameter is non-linear, or has interactions with other input parameters, which is the case for all parameters (Garcia Sanchez et al., 2014).



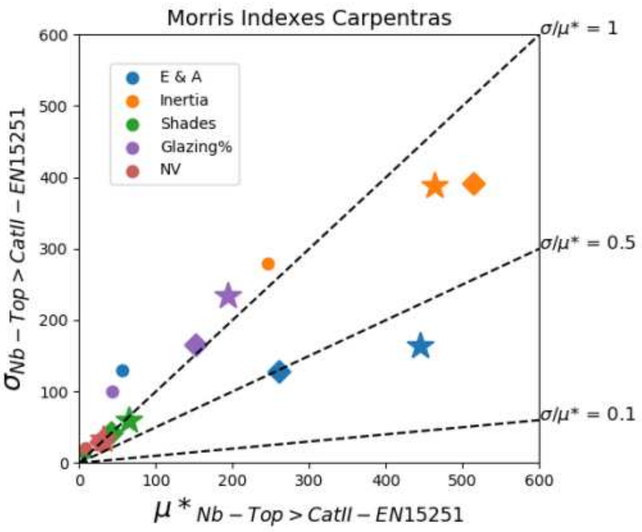



Figure 9 – Morris indexes from the sensitivity analysis for the cities of Carpentras, Paris and Strasbourg. Stars represent results for the future heatwave, diamonds for the future typical year, circles for the historical period.

## 4. Discussion and perspectives

Using future weather files allowed us to assess the discomfort risk under future climate conditions for three cities in France. Simulations were only conducted with one weather file but uncertainty analysis could be conducted using more climate model and future concentration pathway scenarios. The building case-study presented an interesting bio-climatic design, enhancing cross-ventilation and with two buffer zones around the living space from the outdoor conditions. Analyzing operative temperatures inside the building for the different building combinations allowed to understand the overheating, discomfort and potential health risk under future climate, especially under future heatwaves, and especially for the city of Carpentras which will experience an increase in temperature maxima of +8°C, already being the city of France with the highest maxima. The results from the Morris sensitivity analysis allowed to rank the thermal inertia as the most important parameter, followed by the absorptivity and emissivity of exterior walls and ceiling, the windows percentage on the North and South façade. The two behavioural adaptations proposed (control of the windows opening and of the windows shades) resulted in being less significant. Important input parameters were found to be sensibly the same for all cities investigated, and under both historical and future climate, but to different magnitudes. This suggest that adaptation measures, design either for future typical of future heatwave might be similar. However, in Carpentras, no proposed combination was enough to prevent hot discomfort, suggesting the need for additional adaptations. Finally, more understanding of the behaviour of the input parameters is needed, as they were found to either show interactions between them, either behave non-linearly. This case-study is part of a methodology proposal for building practitioners, to help them to make the right decisions in the early stages of the building design. Using future weather files ensures that buildings built today will provide safe indoor conditions under future climate. The proposed methodology can be adapted and used for any building type, in any city, under various future conditions, with different climate models.

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# No escape from the heat? Bedroom temperatures during England's hottest summer.

**Paul Drury[1*] and Kevin J Lomas[1]**

[1]School of Architecture, Building and Civil Engineering, Loughborough University, Ashby Road, Loughborough, Leics., LE11 3TU, ***corresponding author**: P.Drury@lboro.ac.uk

**Abstract:** Numerous monitoring studies have demonstrated overheating of bedrooms in English homes during summer. Elevated bedroom temperatures can degrade sleep quality and impinge on health and well-being. This paper examines Public Health England's advice to 'move into a cooler room, especially for sleeping' in hot conditions. Temperatures were monitored in 33 dwellings across the English Midlands between 1 May and 30 August 2018: the joint hottest English summer on record. The bedroom temperatures were analysed using the recommended CIBSE criterion that there should be no more than 1% of annual occupied hours over 26°C; adaptive comfort criteria are deemed inappropriate for sleeping persons. In half of the main bedrooms, temperatures exceeded 24°C for more than a third of sleeping hours. The CIBSE overheating criterion was exceeded in 78% of master bedrooms. Even if everybody in a household slept in the coolest bedroom, 70% would still experience overheating. Assessing the living room as a bedroom led to a substantial reduction in homes classed as overheating. It is concluded that, whilst public health advice to seek cooler spaces during hot weather is well founded, such 'safe havens' for sleeping may exist only for a minority of English households. Further work is, however, needed.
**Keywords**: Overheating, monitoring, bedrooms, dwellings, England

## 1 Introduction

There is growing evidence from monitoring studies that UK homes exhibit indoor overheating in summer, with up to 1 in 5 overheating even in a cool summer (Beizaee et al., 2013). The summer of 2018 was the joint hottest on record for the UK (Met Office, 2018). McCarthy et al. (2019) report that a 2018-like summer could be more common than not by mid-century. With this predicted rise in summer temperatures and the likelihood of longer, more frequent and intense heatwaves (Christidis et al., 2015) the spatial extent and severity of overheating in homes will increase.

It is acknowledged that very high ambient temperatures are linked to an increase in mortality and other health effects (Murage et al., 2017). For example, the 2003 heatwave led to 2,091 excess deaths in England (Johnson et al., 2005). There are concerns that these heat related deaths could rise to over 7,000 by the 2050's (Hajat et al., 2014). At night, indoor conditions will be most relevant for people's health, thermal comfort and sleep quality. High indoor temperatures were noted as a key factor in heat related deaths during the 2003 European heatwave (Kenny et al., 2019). Understanding the temperatures that people are exposed to in their homes during night-time hours, especially in hot summers, will add to the evidence base on overheating risk.

The protection against outdoor heat is key to a well-functioning dwelling. Notwithstanding the potential health impacts, higher indoor temperatures will affect occupants through reduced thermal comfort and difficulty sleeping. There are also concerns that the current low adoption of domestic air conditioning in the UK will increase to maintain comfort (Peacock et al., 2010), impacting on peak electricity demand and carbon emissions.

Moreover, equity issues are raised in households being unable to pay for the increased energy needed to keep homes cool (Maller and Strengers, 2011).

Several UK monitoring studies (Beizaee et al., 2013; Gupta et al., 2019; Mavrogianni et al., 2017; Vellei et al., 2017) have highlighted that bedrooms, in general, are more likely to be assessed as overheating. High temperatures at night can limit a person's ability to recover from heat stress experienced in the day (Kovats and Hajat, 2008) and is identified as a significant contributing factor to heat-related mortality (Anderson et al., 2013). Bedroom temperatures are, therefore, judged to be perhaps the most important metric in domestic overheating assessment (Peacock et al., 2010).

There are still challenges in establishing clear relationships between temperature, sleep and health outcomes (Anderson et al. 2013). Guidance given within the 7th edition of CIBSE guide A (CIBSE, 2006) suggests that sleep may be impaired above 24°C. There is still, however, some debate about the most appropriate overheating metric to use for bedrooms (Lomas and Porritt, 2017) with Lan et al. (2017) suggesting that the current thermal comfort theories and standards are not appropriate for sleeping people. The guidelines in CIBSE TM59 (CIBSE, 2017) accept that adaptive behaviour whilst sleeping is limited and adopt a static threshold of no more than 1% of annual occupied hours over 26° C for bedrooms. This threshold is also adopted by Public Health England as being a temperature that 'cool areas' in care homes and hospitals should be kept below (PHE, 2018).

The concept of a 'safe haven' or a 'cool retreat' is proposed as a critical component in adapting housing for future heatwave scenarios (Zuo et al., 2015). Similarly, Ormandy and Ezratty (2016) state that relief and cooling can be achieved where there is a cool room available in the dwelling. At present, however, there is very little evidence of whether such a safe haven might exist in English homes in a hot summer.

This paper sought to evaluate Public health England's advice during heatwaves: "if possible, move into a cooler room, especially for sleeping" (PHE, 2018:28) by assessing the temperatures in 33 semi-detached houses across the English Midlands in one of England's hottest summers. The study sought answers to the following questions:

1. What is the extent of overheating in bedrooms during a hot summer?
2. Do homes that are classed as overheating have a 'safe haven' to escape the heat, especially for sleeping?
3. Are the cool rooms cool enough to enable high-quality sleep?

## 2 Methods

### 2.1 Data collection

This paper uses data obtained from the DEFACTO field trial (Haines et al., 2019). Room temperature was monitored at five-minute intervals over three years in 188 semi-detached homes located across the East Midlands as part of a study into smart heating controls. This paper uses a sub-sample of 33 homes to investigate the temperatures monitored for a 122-day period between 1 May and 30 August 2018. Where possible, the homes had a sensor installed in every room[1], with between five and eleven in each home.

The raw data on a five-minute timestep went through a phased cleaning process and was resampled to a half-hourly time step (Haines et al., 2019). Further post processing

[1] The sensors were placed by installers, where possible, at mid-room height to replicate the temperature experienced by occupants (Nicol et al., 2012). Although attempts were made to verify the location of sensors during the study period, this was not always possible.

involved visual inspection of the data for erroneous or missing values. Where the sensor data appeared 'suspect' or there was evidence of heating from direct solar radiation, all data from the sensor was discarded for the whole monitoring period. In common with previous monitoring studies (Lomas and Kane, 2013; Vellei et al., 2017) there were occasional issues with wireless connections and loss of data, with all sensors experiencing some periods of missing data. This was identified, however, as being random and not related to factors such as high temperatures. In total, the sensors recorded data for a mean value of 97% of occupied hours during the monitoring period.

The half-hourly data was resampled to an hourly reading and then to a time series that considered occupancy hours. As no information was available regarding actual occupancy schedules, the occupied hours were chosen to align with previous studies (Beizaee et al., 2013; Lomas and Kane, 2013; McGill et al., 2017). For bedrooms, occupancy was assumed from 22:00 (first hourly measurement recorded at 23:00) to 07:00 the following day (last hourly measurement): a total of nine hours.

In common with the majority of domestic monitoring studies, the temperatures monitored are air temperatures rather than operative temperatures referred to within overheating criteria. Hughes and Natarajan (2019), however, suggest that air temperature can be taken as a good approximation of operative temperature. Moreover, Lomas and Porritt (2017) propose that the sensors commonly used are likely to record an undetermined mix of air and radiant temperatures making them closer to those experienced by room occupants.

## 2.2 Weather data

Outdoor temperature data was obtained from the Centre for Environmental Data Analysis (Met Office, 2012) website for the seven weather stations (Table 1) located nearest to the respective study homes. In common with previous use of external weather station data (Beizaee et al., 2013; Lomas and Kane, 2013) it is assumed that the study homes experience the same external temperature as recorded at the specific weather stations.

The summer of 2018 was the joint warmest on record with the mean outdoor temperature across the Midlands region being 2.8°C higher than the 1981-2010 long-term average (Met Office, 2018). Using the Nottingham Watnall weather data there were two periods that classified as a heatwave, i.e., at least three consecutive days with daily maximum temperatures meeting or exceeding the heatwave threshold of 27°C for East Midlands (Met Office, 2019). The first period was from 5 to 8 July and the second from 5 to 7 August. The hottest day fell on the 26 July but did not appear within a set of days to classify as a heatwave.

*Table 1. Weather stations closest to the study homes*

| County | Station name | Src-id | Latitude | Longitude | Postcode |
|---|---|---|---|---|---|
| Leicestershire | Market Bosworth: Bosworth Park | 30529 | 52.6228 | -1.394 | CV13 0 |
| Nottinghamshire | Nottingham: Watnall | 556 | 53.0053 | -1.24969 | NG16 1 |
| | East Midlands | 18919 | 52.8829 | -1.2777 | NG10 3 |
| Northamptonshire | Northampton: Moulton Park * | 578 | 52.2732 | -0.87937 | NN2 7 |
| Oxfordshire | Wellesbourne** | 596 | 52.2054 | -1.60345 | CV35 9 |
| West Midlands | Coventry: Coundon | 24102 | 52.4241 | -1.53498 | CV1 |
| Staffordshire | Keele | 622 | 52.9986 | -2.2688 | ST5 5 |
| Warwickshire | Coleshill | 19187 | 52.4798 | -1.68925 | B46 3 |
| *Until 22/7/18 23:00<br>**From 23/7/18 00:00 | | | | | |

It was important for this study to establish how the summer of 2018 compares to previous hot summers, notably 2003, and how it compares to the predicted temperatures within CIBSE's future climate files. The CIBSE files chosen were the current Test Reference Year (TRY) and Design Summer Year (DSY1[2]). These files represent the "statistically typical scenario" and "near-extreme scenario of natural variability" respectively (Lee and Steemers, 2017: 65). Future weather files for Nottingham in the 2050's and 2080's under a medium carbon emissions scenario were also analysed.

The period from 1 May to 31 August was compared for the number of hours that temperatures exceeded temperature thresholds (Figure 1). The profile for Nottingham 2018, although not identical, closely follows the predicted profile of the 2080 CIBSE DSY1, 50$^{th}$ percentile weather file. Thus, the performance of homes in the summer of 2018 can be judged as a good benchmark for summers that are predicted to be more frequent by the 2050's and beyond (McCarthy et al., 2019).

[2] There are three different DSY files available from CIBSE which represent summers with different types of hot events. The DSY1 represents a moderately warm summer.

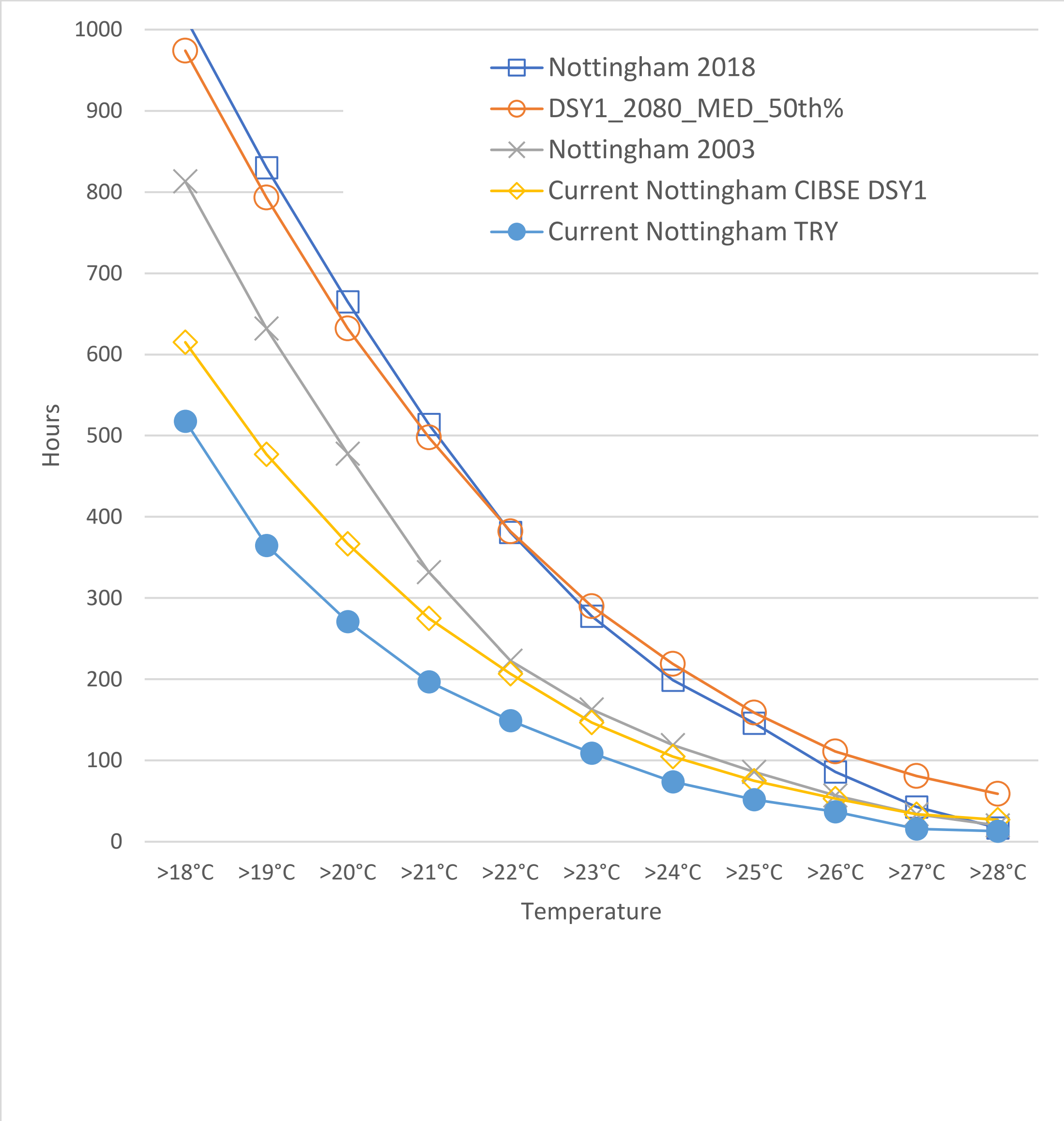


*Figure 1.Hours over threshold temperatures during summer period (1 May to 31 August) for Nottingham in 2003, 2018 and CIBSE current and future weather files*

### 2.3 Sample data

All houses in the sample were semi-detached. The study of this dwelling type is merited as they represent 25.3% or approximately 6 million properties across all tenures in the English housing stock (MHCLG, 2018). Moreover, the semi-detached dwelling type is not particularly identified as being at increased risk of overheating in previous monitoring studies. Dwelling and household information for the 33 study homes was obtained from the DEFACTO field study archive. Each home had a floorplan detailing the location and orientation of the rooms. Where bedrooms were not explicitly identified as the master bedroom, the largest bedroom on the floor plan was chosen for analysis purposes. Among the 158 rooms with temperature data, there were 32 master bedrooms and 46 non-master bedrooms monitored during summer 2018. A comparison of the study sample and the English housing stock is given in Table 2.

*Table 2. Comparison of sample and English Housing Stock*

| | | D33 sample %* | English Stock 2017-18 % | Data source |
|---|---|---|---|---|
| Dwellings: age and construction | | | | |
| Usable floor area | <50m$^2$ | 0 | 2.9 | MHCLG (2019) Table AT2.1 floor area, owner occupied dwellings |
| | 50-69 | 6 | 15.8 | |
| | 70-89 | 33 | 27.2 | |
| | 90-109 | 27 | 20.6 | |
| | >110m$^2$ | 33 | 33.5 | |
| House age | Pre 1900 | 3 | n/a | Categories don't align with age bands in English Housing survey |
| | 1900-1929 | 27 | n/a | |
| | 1930-1949 | 18 | n/a | |
| | 1950-1966 | 18 | n/a | |
| | 1967-1975 | 30 | n/a | |
| | 1976-1982 | 3 | n/a | |
| | Post 1982 | 0 | n/a | |
| Wall construction and insulation | Cavity wall no insulation | 6 | 20.6 | MHCLG (2019) Table AT2.13, owner occupied homes of all types |
| | Cavity wall insulated | 55 | 49.6 | |
| | Solid wall not insulated | 30 | 25.8 | |
| | Solid wall insulated | 3 | 2.2 | |
| | Other | 6 | 1.8 | |
| Loft insulation | 0-200mm | 55 | n/a | MHCLG (2019) Table AT2.11, all tenancies |
| | 200mm or more | 42 | 37.5 | |
| | Other (insulation. at rafters) | 3 | n/a | |
| SAP rating band | A/B | 3 | 1.0 | MHCLG (2019) Table AT2.7, owner occupied homes, rating bands |
| | C | 27 | 24.0 | |
| | D | 55 | 53.2 | |
| | E | 15 | 16.3 | |
| | F | 0 | 4.3 | |
| | G | 0 | 1.3 | |
| Households: number of occupants and age of Household Representative Person (HRP) | | | | |
| Number in household | 1-2 | 58 | 63 | ONS (2018) |
| | 3-5 | 42 | 37 | |
| | >5 | 0 | | |
| Age of HRP | 16-24 | 3 | 0.7 | MHCLG (2019) Table AT1.4 Owner occupied homes |
| | 25-34 | 0 | 8.3 | |
| | 35-44 | 10 | 15.3 | |
| | 45-54 | 16 | 20.5 | |
| | 55-64 | 42 | 19.2 | |
| | 65 or over | 29 | 36.0 | |
| *The percentages ignore null responses, which were: Age of HRP 2 responses; Number in household 2 responses | | | | |

## 2.4 Overheating assessment

The methods adopted for this study use the static criteria exemplified by those in the Chartered Institution of Building Services Engineers (CIBSE) guide A (CIBSE, 2006), i.e., no greater than 1% of annual occupied hours over 26°C for bedrooms. This criterion is also adopted as criterion 1B in CIBSE TM59 (CIBSE, 2017) in the assessment of overheating using dynamic thermal modelling. The study also analyses against the threshold of no more than 5% of annual hours exceeding 24°C, which is commonly applied in previous monitoring studies (Beizaee et al., 2013; Lomas and Kane, 2013). This threshold also aligns with the guidance that temperatures over 24°C in bedrooms may impact sleep quality. Statistical analysis to produce descriptive statistics and assess differences between groups was carried out using SPSS v24 software package.

## 3 Results

### 3.1 Observed temperatures

The mean temperatures recorded in the master bedrooms (n=32) between 23:00 and 07:00 in the 122-day monitoring period ranged from 20.6°C to 25.3°C with an average mean of 22.8°C. The maximum temperatures recorded ranged from 26.7°C to 31.1°C with a mean of 28.6°C. In the 32 homes that had temperature measurements in both living room and master bedroom, there were twenty homes where the mean temperature of the bedroom during occupied hours (night-time) was warmer than the respective living room during occupied hours (day-time).

### 3.2 Prevalence of overheating using CIBSE static criteria

The results in this section will be presented in two different but connected ways. Firstly, the percentage of occupied hours that temperatures exceeded the 24°C threshold and 26°C threshold. Secondly, the data is presented differently by plotting actual number of hours exceeding the thresholds for each room. As the monitored period is not a complete year this allows a direct comparison with the annual hourly exceedance according to the CIBSE static criteria.

The main finding from analysis of master bedroom temperatures was that they were very warm during the occupied hours of 23:00 to 07:00 (Figure 2). All the 32 master bedrooms exceeded the 5%/24°C threshold; nearly 50% were over 24°C for a third of occupied hours. One house experienced temperature over 24°C for 71% of occupied hours. This is concerning for the occupants if we accept the premise that bedroom temperatures above 24°C may cause sleep impairment (CIBSE, 2006) and have an impact on health.

A total of 97% of master bedrooms- all but one home- exceeded the 1% of occupied hours over 26°C. In one home, the master bedroom experienced temperatures over 26°C for nearly 40% of occupied hours. This represents 440 hours or nearly 49 nights if a nine-hour bedroom occupancy is assumed.

It is useful to compare the observed number of hours over the thresholds with the annual hours 'allowable' for each threshold. Figure 3 shows that 29 master bedrooms (91%) had monitored temperatures above 24°C for more occupied hours than the 5% annual hours threshold of 164 hours. Furthermore, when considering the 1% of annual hours over 26°C, 25 master bedrooms (78%) exceeded the threshold of 33 hours.

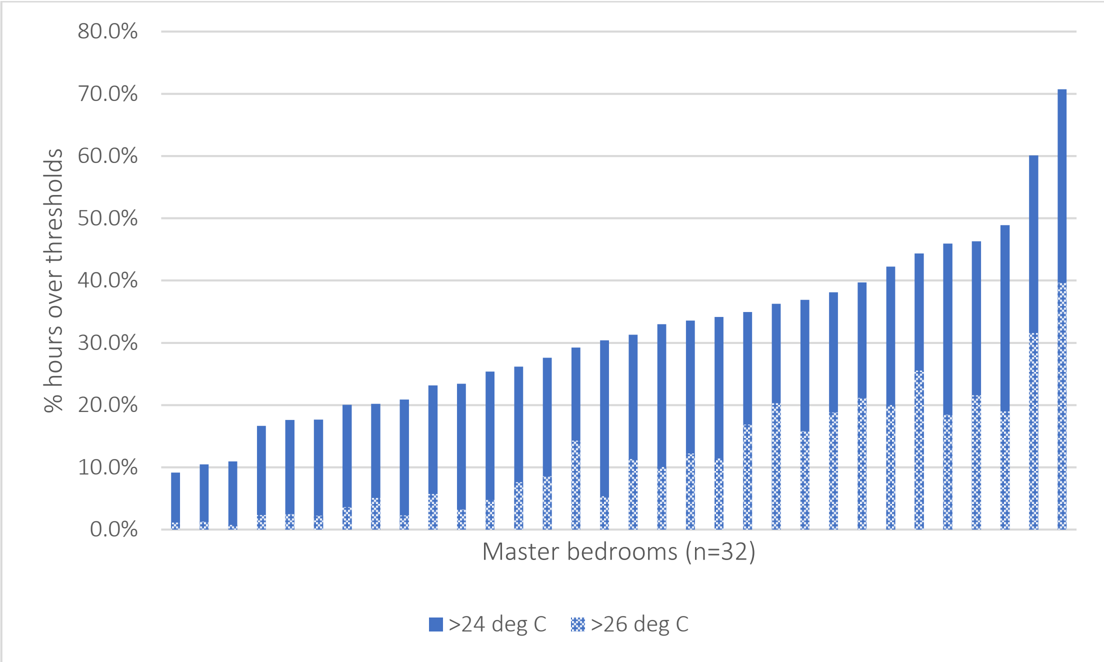


*Figure 2. Percentage of occupied hours (23:00 to 07:00) the temperature exceeded 24°C and 26°C in master bedrooms during 122-day monitoring period*

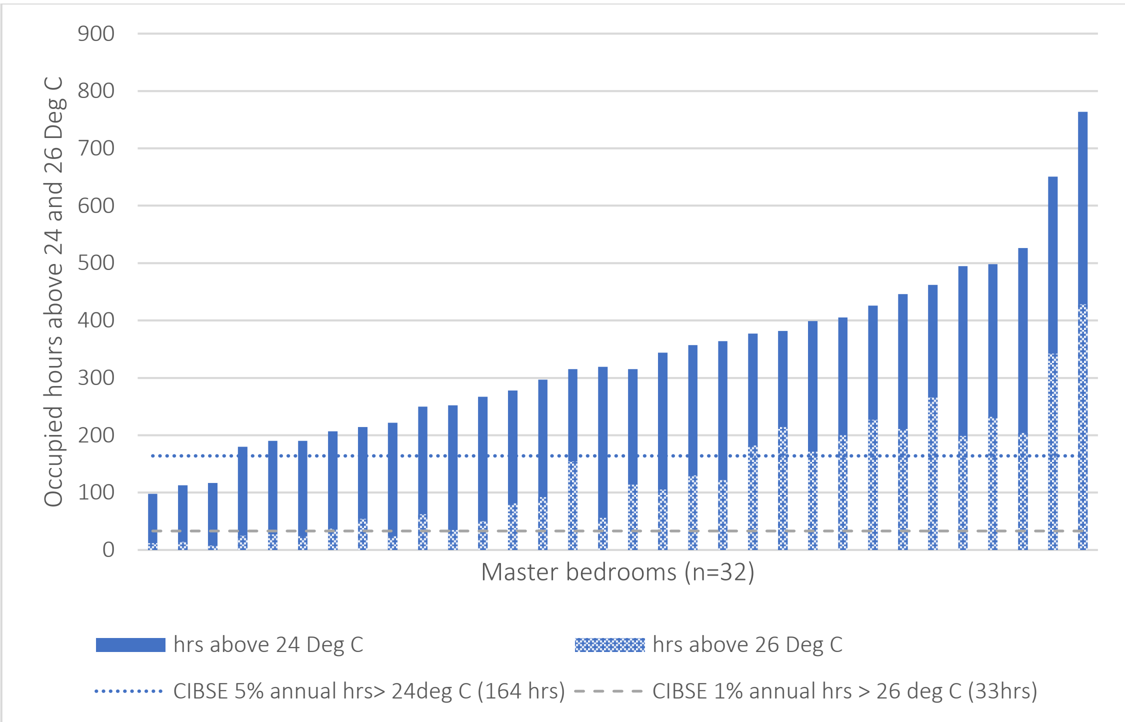


*Figure 3. Number of hours the temperature exceeded 24°C and 26°C in master bedrooms during 122-day monitoring period compared to CIBSE annual hours thresholds*

The above charts show that there is considerable variation in experienced bedroom temperatures considering that the sample is composed of a single dwelling type and experiencing similar weather conditions. These findings align with those of Mavrogianni et al. (2012) where greater temperature variation was discovered within dwelling type than between dwelling types. This suggests that caution must be exercised in assuming that certain building types are not at undue risk of summer overheating.

### 3.3 Search for a 'safe haven'

The concept of a 'safe haven' or a cool retreat within a home relies on the fact that the behaviour of people might be to seek out a cooler room within their home to maintain their thermal comfort if such a room exists. Research by Wright et al. (2018) suggests that this is a credible 'adaptive' behaviour of people to high bedroom temperatures. Moreover, advice given to homeowners by Public Health England in their heatwave plan for England (PHE, 2018: 28) advises that people "move into a cooler room especially for sleeping". The following analysis therefore considers the homes where monitored temperatures were available for bedrooms other than the designated master bedroom. The analysis was based on an alternative 'cooler' bedroom for sleeping in the dwelling. It doesn't consider the practicalities of another room for sleeping (e.g. number of occupants in the home, is the room used as an office, etc.) but attempts to evaluate the thermal conditions that people would experience overnight should they sleep in this room. The CIBSE static criteria of 5% occupied hours over 24°C and 1% occupied hours over 26°C was applied to determine the coolest bedroom for each home over the monitoring period.

The master bedroom was the coolest bedroom in only 9 out of the 33 homes (i.e. 27%). 32 bedrooms (97% of sample) had more than 5% of occupied hours over 24°C with 31 exceeding the 1% of occupied hours 26°C threshold (Figure 4). When considering actual hours, a total of 27 bedrooms (82% of sample) had occupied hours greater than the CIBSE 5% of annual hours (164 hours) over 24°C threshold. Also, 23 bedrooms (70%) had occupied hours greater than the CIBSE 1% of annual hours (33 hours) over 26°C (Figure 5), indicating that a large percentage of homes would still be classed as overheating.

Comparing the results for the coolest bedroom with results for master bedrooms over the 122-day monitoring period (Table 3) shows that the exceedance of the 1%/26°C and 5%/24°C threshold is only marginally reduced; from 97% to 94% of homes for the former, 100% to 97% for the latter. If actual numbers of hours exceeding the CIBSE annual limits for both 24°C (164 hours) and 26°C (33 hours) are considered, two fewer homes would be categorized as overheating basing the analysis on the coolest bedroom in the property. Furthermore, the average percentage of hours over 26°C is reduced from 12% to 9%, representing approximately 27 fewer hours.

*Table 3. Number of rooms with master bedroom and coolest monitored bedroom exceeding the fixed thresholds (1%/26°C, 5%/24°C) and number exceeding the annual hours thresholds*

| **Number (%) of rooms** | **>1% OH[a] with temp>26°C** | **>5% OH with temp>24°C** | **Mean % of hours> 26°C** | **Mean % of hours> 24°C** | **OH> CIBSE 1% annual hrs (33 hours) >26°C** | **OH> CIBSE 5% annual hrs (164 hours) >24°C** |
|---|---|---|---|---|---|---|
| **Master Bedroom (n=32)** | 31 (97%) | 32 (100%) | 12.0 | 31.4 | 25 (78%) | 29 (91%) |
| **Coolest bedroom (n=33)** | 31 (94%) | 32 (97%) | 9.6 | 26.8 | 23 (70%) | 27 (82%) |

**[a]OH: Occupied hours**

Of course, the analysis presented above over the whole study period of 122 days may not adequately determine whether a safe haven exists on a particular hot day. It does, however, suggest that over a hot summer period it might be more difficult to find a cooler bedroom to sleep.

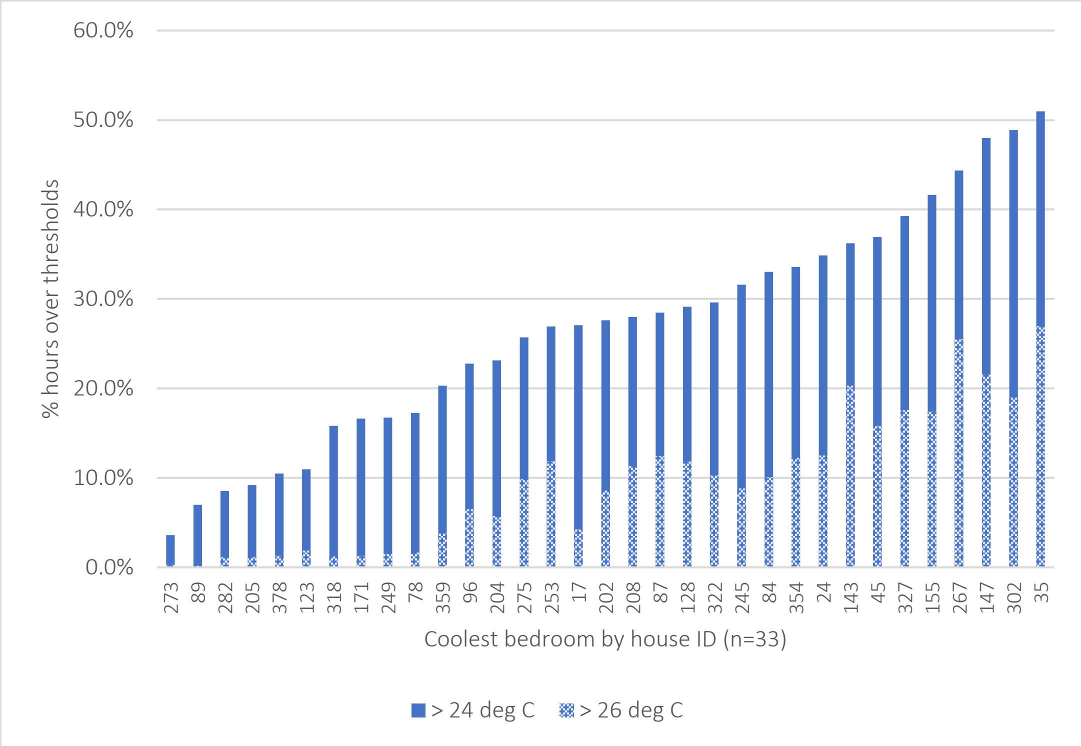


*Figure 4. Percentage of occupied hours (23:00 to 07:00) the temperature exceeded 24°C and 26°C in coolest bedroom during 122-day monitoring period*

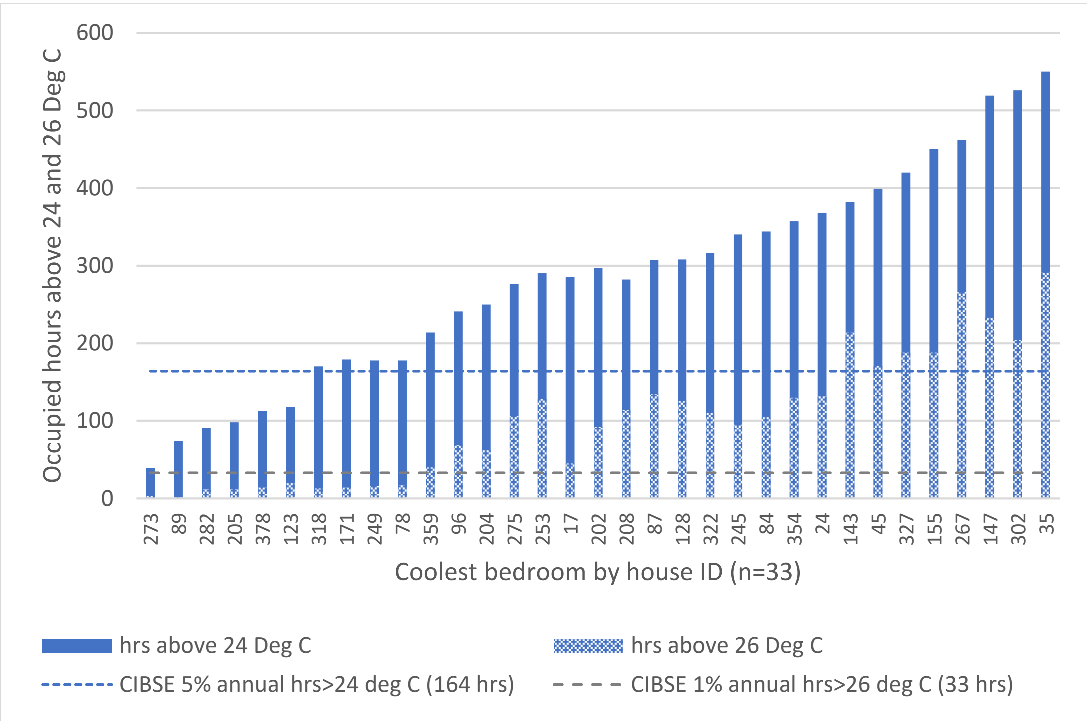


*Figure 5. Number of hours the temperature exceeded 24°C and 26°C in coolest bedroom during 122-day monitoring period compared to CIBSE annual hours thresholds*

For master bedrooms the average percentage of hours above 24°C was significantly higher ($p<0.1$) for homes occupied by 3 or more people compared with 1-2 people. For these homes the potential to sleep in a different (cooler) bedroom will be more limited.

To investigate other rooms within the dwellings. The temperatures in the living room during night-time hours (23:00 to 07:00) were analysed against the 24°C and 26°C thresholds, i.e., as if they were to be used as a bedroom. This provided quite different results. Figure 6 and Figure 7 show the master bedrooms arranged from least to most overheated and thus allows comparison with the number of hours exceeding the thresholds for the respective living room.

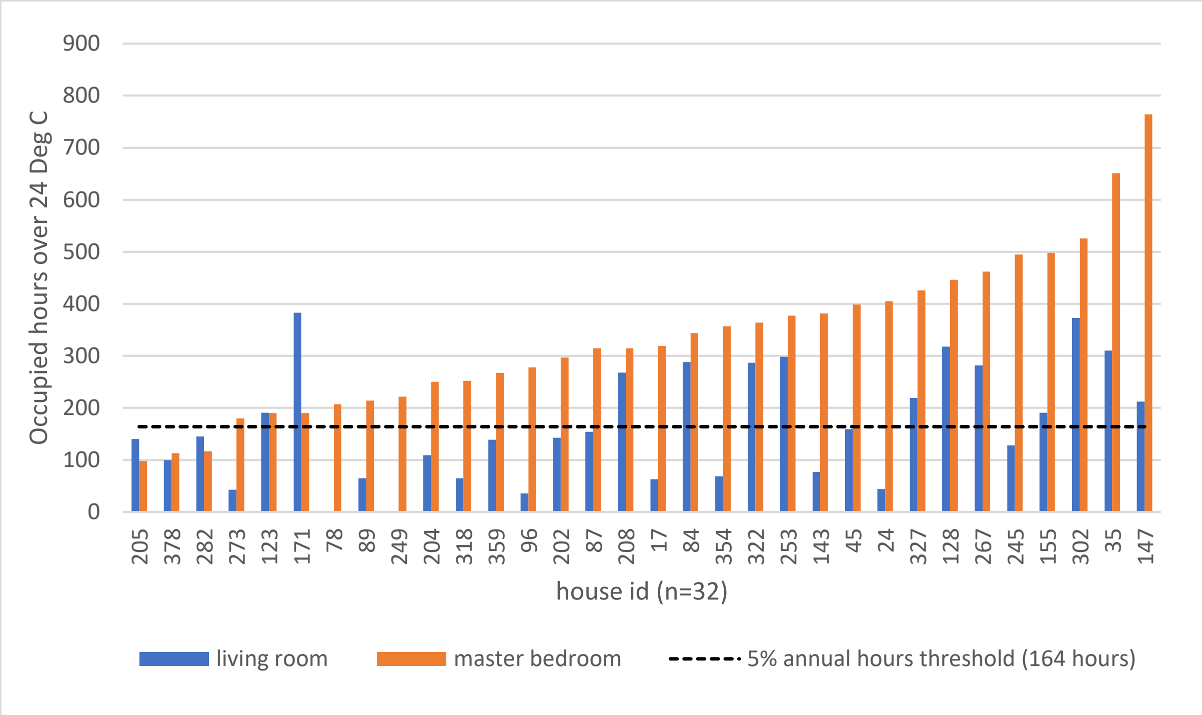


*Figure 6.Number of occupied hours exceeding 24°C in living room and master bedroom during night hours (23:00 to 07:00) in 122-day monitoring period*

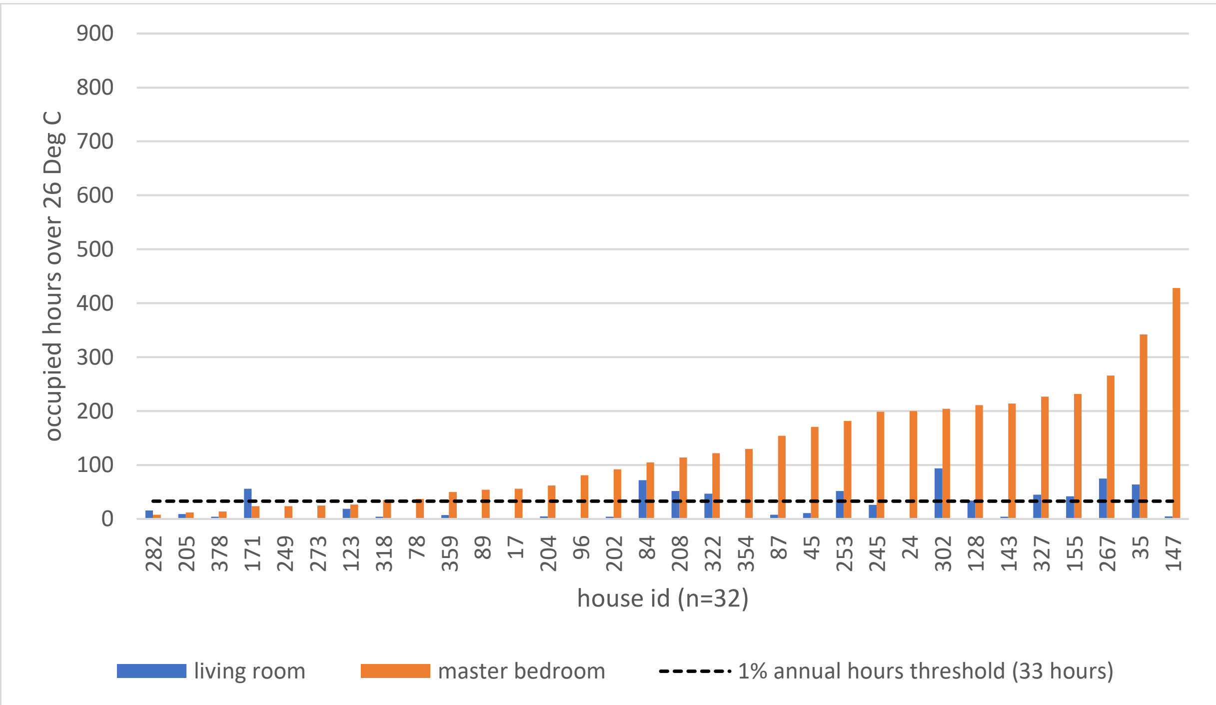


*Figure 7. Number of occupied hours exceeding 26°C in living room and master bedroom during night hours (23:00 to 07:00) in 122-day monitoring period*

The results show that living rooms if re-categorized as a bedroom experienced considerably fewer hours over both the 24°C and 26°C thresholds. When judged against the 26°C annual hours threshold the number of homes classed as overheating falls from 25 out of 32 (78%) to 11 out of 32 (34%). Similarly, the average percentage of hours over 26°C shows a substantial decline from 12% in master bedrooms to 2% in living rooms. This suggests that, despite the obvious practicalities, people in over two thirds of the homes will be able to find a safe haven from heat overnight by sleeping in a downstairs room.

## 4 Discussion

Of the 32 master bedrooms, only one was found not to exceed 1% of occupied hours over 26°C. With 25 out of 32 (78%) failing against the 1% of annual hours greater than 26°C threshold it indicates that many occupants were subject to temperatures that might disrupt sleep and impact on their health. This study showed comparable results to dwellings studied in 2018 by Hughes and Natarajan (2019) where 94% of bedrooms failed CIBSE TM59 criterion 1B. The hot summer of 2018 can be considered atypical in the current climate but could be more common than not by mid-century. Overheating in bedrooms may therefore become a chronic problem in future summers as the climate warms.

The concept of a safe haven was predicated on the idea that people will seek out the coolest bedroom to sleep. The research sought to evaluate Public Health England's advice to move to a cooler room in hot weather and to answer the question of whether homes that overheat have these safe havens. The research highlighted two noteworthy results. Firstly, the reduction in the number of homes classed as overheating considering the coolest bedroom was only marginally reduced (70% cf. 78%), although there was a reduction in the number of hours exceeding 24°C; indicating some respite from elevated temperatures for the occupants. Secondly, ground floor living rooms were considerably cooler during night-time hours. Two-thirds of the study homes would not be classed as overheating if the living room was a functional bedroom. The summer of 2018 was hotter, but also sunnier than average (McCarthy et al., 2019). As bedrooms are typically located on the first floor perhaps this represents greater solar irradiance in bedrooms contributing to higher temperatures and therefore a need to consider external shading of some form.

The finding that master bedrooms in homes with 3+ people had significantly greater percentage of hours above 24°C than those with 1-2 people indicates that those in most need of a cooler bedroom may not have access to one.

There were only nine homes where the master bedroom was the coolest, which perhaps indicates that occupants are not carrying out different practices to keep their sleeping room cooler than other bedrooms, or if they are then these practices are insufficient to significantly reduce temperatures in the main bedroom. There are, however, many confounding factors that might contribute to overheating of these specific bedrooms.

Moving to another room can be considered an adaptive behaviour. Survey evidence from Raw (2018), however, suggests that this might not be common behaviour; less than 5% of respondents would avoid using certain rooms in the home in response to warm conditions. A limitation of this study is that there is no way of telling whether people actually did choose to sleep downstairs. Even the presence of a cooler room on the ground floor would provide some respite from an overheating bedroom, even if only used for a short period. The lead author of this paper adopted this very strategy during a short heatwave in 2019. Further study using occupant diaries, or some form of occupancy detection could shed more light on the issue.

This still leaves the question of the most suitable metric for assessing overheating in bedrooms unresolved. Research by Nicol and Humphreys (2018) proposes that more work needs to be done to assess the relationship between bedroom air temperature and the close-to-body temperature achieved by the sleeping person. It seems likely that neither the static 26°C temperature nor the adaptive comfort approach of TM52 adequately describes overheating risk in bedrooms. It is suggested (Sharpe et al., 2014) that bedrooms overnight represent 'steady-state' conditions with little or no adaptive behaviour taking place. But 'adaptive' behaviours are likely to be enacted when people first go to bed as they set in place the room they might choose to sleep in, the nightwear and bedding they will use and any windows they might want to leave open. A further accepted criticism of a static threshold is that it does not consider the severity of overheating on any particular day. Furthermore, a run of consecutive hot nights could impact on health much more than a 'steady' accumulation of hours over the whole summer period (Brooke Anderson and Bell, 2011; Rocklöv et al., 2011). Considering the need to build new houses and adapt existing ones it will be essential and urgent to determine what criteria to judge these bedrooms against to ensure conditions that aren't detrimental to health.

## 5 Conclusions

This study used temperature data from 33 semi-detached homes located across the English Midlands to determine the extent of bedroom overheating during a 122-day period in the summer of 2018: one of the hottest summers on record. Advice given in heatwave plans suggest that people move to a cooler room, especially for sleeping in hot conditions. This study sought to determine if such a cooler room exists in homes that might be classed as overheating. The overheating levels in the homes were assessed using existing static criteria of no more than 1% of occupied hours over 26°C. Occupied hours over 24°C, which is suggested as being a temperature above which sleep can be disrupted, were also determined. The key findings from this study are:

- All master bedrooms had more than 5% of occupied hours above 24°C. Furthermore, when judged against the annual hours threshold of 33 hours above 26°C, 25 out of 32 (78%) master bedrooms would be classed as overheating.
- Basing the overheating assessment on the coolest bedroom led to a slight decline in homes failing the criteria, but still meant that 70% of homes would be classed as overheated; there was, however, a slight reduction in the average percentage of hours over temperature thresholds, offering some respite to people sleeping in the coolest bedroom.
- The living room during night-time hours offered people more chance of achieving respite from the heat; two-thirds of the sample homes would not be classed as overheating during sleeping hours. More work is needed to establish if this is a pattern replicated in different dwelling types. It does, however, suggest that occupants in single floor dwellings, such as bungalows and flats, might struggle more to find safe havens.

In conclusion, although the advice given by Public Health England to choose a cooler room is well founded, the findings from this study suggest that in a hot summer, a significant majority of bedrooms have considerable levels of overheating offering limited escape from the heat during sleeping hours. Living rooms were considerably cooler during night-time but the practicalities of people being able to sleep in these rooms may limit it as a credible adaptive behaviour to overheating bedrooms.

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# The impact of future UK heatwave mitigation strategies in office and residential buildings-a comparison

**Asif Din [1] and Hala El Khorazaty [2]**

[1] London Metropolitan University, UK, aud0034@my.londonmet.ac.uk;
[2] Human Experience Lab, Perkins&Will, UK, Hala.ElKhorazaty@perkinswill.com

**Abstract:**
Heat waves are abnormal effects within the UK but significantly increase discomfort for building occupants. This study expands a previous residential unit study (Din and Brotas 2016) to include an office building. Heat wave periods were identified for 3 locations in the UK and overheating contrasted against a whole cooling season for different building characteristics. A future weather file from 2080 was used to increase the incidents of heat wave events using TM52 to define overheating. The criteria were modified to 3 factors to allow contrasts to be made between short and long-term overheating.

No heat wave events occur in Aberdeen in 2080 and so only London and Birmingham were assessed. A combination of a heavyweight and shading (or elevated air velocity) mitigates against heat wave events in both building typologies.

In heat wave periods a greater number of overheating hours and heat stress hours occurs in a residential unit compared to an office building. Heat stress peaks for a lightweight building construction without shading or elevated air velocity. During heat wave events, offices only experience part of their overall overheating factors but residential units experience all (or lack) of their overheating factors during the identified heat wave periods.

**Keywords:** Future climate, Heat Waves, Overheating office, TM52

## 1. Introduction

The severe effects of Global warming had been internationally recognized in the Rio Earth Summit in 1992 (United Nations, 1992), Since then, there has been many efforts to fight global warming, but despite these efforts, global surface temperatures are still projected to rise by up to 4.8 °C by the end of this century (IPCC, 2013) (Liu, C., 2017). Such warming increases the risk of heat waves and the problems of high summer temperatures in urban areas such as London are likely to become worse in the future because of climate change (Oikonomou, E, 2012).

Some of the potential climate change impacts on London. (Source: London Climate Change Partnership, 2002) Issue Key impacts such as:

- Higher Temperatures
- Intensified urban heat island, especially during summer nights
- Reduced comfort and productivity of workers

Reports have identified that most of the global warming over the past 50 years is attributed to human activities; such activities will continue to change the composition of the atmosphere; and that global mean temperatures and sea levels will continue to rise for many centuries to come (IPCC, 2001). The Third Assessment Report (TAR) of the Intergovernmental Panel on Climate Change (IPCC) sets out a strong case linking human emissions of greenhouse gases to climate change (Wilby, R.L., 2007).

Climatologists are already beginning to detect and attribute changes in extreme events to human influences on the global climate system (Zwiers and Zhang, 2003), as one of the most extreme overheating events was recorded in August 2003, where 14,729 excess deaths occurred in France (Fouillet et al., 2006) and 2,139 in England and Wales, due to a severe heat wave, primarily in large urban centres (Johnson et al., 2005). Current projections suggest a heatwave of similar magnitude may occur as frequently as every third year by the 2050s (Oikonomou, E, 2012). The risk of other extremes such as intense precipitation (Groisman et al., 1999), destructive tropical cyclones (Emanuel, 2005) and flooding (Milly et al., 2002) is also expected to increase.

Heat wave definitions vary widely. These definitions include weather periods in urban centres, which have a trigger temperature that when increased an emergency services plan is to be put in place (Diaz et al, 2015). Heat Island Effect in major urban cities is the result of dese built up areas that result in an average rise of nighttime temperatures (Lemonsu et al, 2014). These criteria is the basis of the current heat wave plan for England (NHS, 2015) requiring a preceding night to exceed a threshold temperature for a heat wave event to occur.

A range of differing parameters exist in defining what constitutes a heat wave. A heat wave is an external weather event but has a significant impact on buildings and their occupants. As an abnormal event, it is advantageous to use a future weather file that highlights warm periods in the future to increase the frequency of heat wave events experienced.

Due to the increased number of urban heat health warning systems; managing existing weather-related risks has become an area for concern, key activities include the growing measures for countering excessive temperatures in urban centres through improved planning and building design (e.g., Shimoda, 2003). Some other studies have been conducted to classify Inhabitants by location and social demographics to identify their venerability to temperatures above 28oC (Wolf and McGregor, 2012) which could be defined as a heat wave event

A range of differing mitigation measures have been defined in reducing the amount of overheating discomfort felt over these periods but the evaluation of the significance of the heat wave events compared to the whole cooling season needs to be evaluated. By using two of the most common building typologies; that of an office and a residential unit allows an evaluation of mitigation against differing building usage.

There is a need to assess the quantity of overheating experienced by the differing buildings contrasting a few UK locations to see the impact of geography on the frequency of heat wave events experienced.

## 2. Aim

The study aims to investigate that factors that impact overheating in heat wave events in two differing building typologies within the UK. The main part of the study assesses the varying of the parameters of TM52 including the mass of the building, air velocity and shading using factors inputted into simulation software (Energy Plus v9.1.0). These characteristics have been shown to be the most influential mitigation factors within a previous dwelling study (Din and Brotas, 2016).

In the evaluation of the criteria in the TM52 protocol, the contrast between heat wave events and a cooling season can be established. This requires the investigation of current definitions of heat waves and the identification of when overheating occurs in available weather files.

## 3. Background

Previous studies have established the probabilistic weather for future years on established climate change models (Eames et al, 2012). To maximise the incidences of heat waves, a 2080 file was used. This 2080 date coincides with the anticipated dwelling life of 60 years (RICS, 2017) and long-life office building to assess its fitness of purpose towards the end of its design life. Given the slow rate of progress of the global tackling of climate change a high scenario (a1fi under IPCC modelling) was used with a 50% probability profile. More extreme files were not used as they produce an unrealistic escalation in temperatures (Din and Brotas 2017).

The Design Summer Year (DSY) uses 20 years of the peak summer condition to weight the weather file is used as the input data in the simulations as specified in TM52.

### 3.1. CIBSE TM 52 2013

The evaluation of overheating is defined by the proportion of uncomfortable conditions that is experienced by building occupants. This is defined by TM52 which establishes a methodology to assess a naturally ventilated building. This methodology cannot be assessed simply on when a set of internal temperatures is exceeded. Therefore, updating the previous BS EN 15251 standard.

TM52 has more of a relationship between the outside temperature, the occupant's behaviour, activity and adaptive opportunities, which affect comfort. Overheating in the TM52 is defined in terms of three distinct criteria, which has some interdependency in their calculation method:

1. The amount of degree hours above 1K over the limiting comfort temperature. Assessed from 1st May to 30th September. This amount must not exceed 3% of occupied hours.
2. The relationship between the high temperature and its significant effect. This test quantifies the severity of temperature daily. The weighted excess of temperature must be less than 6K on any one day for comfort to be achieved.
3. Reports heat stress events 4K above the limiting comfort temperature.

Occupants are likely to experience overheating if two or more of these conditions are not met.

The Chartered Institute of Service Engineers (CIBSE) Technical Memorandum TM52 (2013) is used to establish overheating in naturally ventilated buildings. TM52 expands on BSEN 15251 (BSi, 2007) by using other factors than the proportional hours in occupation when the temperature is above an operative temperature.

The Chartered Institute of Building Service Engineers (CIBSE) Technical Memorandum TM59 (2017) adds to the previous methodology the definition of the parameters for equipment, occupancy and occupancy hours. However, since TM59 assesses the risk of overheating for a range of units within a housing development, it cannot be effectively used to evaluate two differing building typologies.

### 3.2. Overheating in offices

Other more long-term effects of overheating in the built environment mainly effect human health and comfort. Exposure to warm conditions in excess of approximately 25°C is associated to increased health risks, with thermal stresses affecting the performance of our body, productivity, and mood (Sehizadeh & Ge, 2014).

Effects of overheating is expected to increase in inner-city London, in which maintaining thermal comfort in summer will become more challenging (Sehizadeh & Ge, 2014). Such challenges create a risk in managing the quality of the indoor environment where providing thermal comfort can improve productivity of the users especially in educational and office buildings (Hauge et al., 2011).

In a recent assessment of the risks of overheating in office buildings, it appeared that lightweight office buildings were more prone to internal heat gain with the increase in external air temperature and a minimum heat capacity temperature (Brambilla and Jusselme, 2017). This resulted in the increase of indoor air temperature over the maximum heat band. Therefore, in order to prevent the overheating in indoor environments, it is important to consider the capacity of the building materials in retaining the internal heat (Aste et al., 2015) which will vary depending on the building structure and geographic location.

The latest release of CIBSE weather data in early 2016 (Virk & Eames 2016) was following the updated method discussed in TM49 – Design Summer Years for London (CIBSE TM49 2014). The term “weighted cooling degree hours (WCDH)” was defined to judge the outdoor warmth. As a result, three complete weather years were selected from a much larger source weather dataset (1950 to 2006). The three complete weather years are intended to represent: inner urban (1976 – a year with a long period of persistent warmth), rural (2003 – a year with a more intense single warm spell) and intermediate urban & sub-urban (1989 – a moderately warm summer). WCDH is based on adaptive comfort temperature (CIBSE Guide A 2006; BS EN 15251 2007), and it is closely related to the likelihood of thermal discomfort (Smith & Hanby 2012).

CIBSE and Arup investigated how typical existing buildings would cope with future rising summer temperatures. The results of the study existing buildings are already failing to meet comfort levels (25°C and 28°C). The study showed that as the century progresses and external temperatures rise, summertime comfort will deteriorate further (Gething, B., 2010.)

### 3.3. Overheating in houses

The future climate conditions must be considered when designing for the future built environment. This was proven by many Architects such as Bill Dunster and Arup, which have already started to design homes with energy efficiency features; these features main goal was to balance the expected increase in air temperatures (Sehizadeh & Ge, 2014). Through their R&D department (2005) Dunster Architects and Arup also demonstrated the importance of mitigating climate change effects. They demonstrated that lightweight homes would result in discomfort caused by higher internal temperature (Bill Dunster Architects, 2005).

Other efforts have been put forward by the built sector as a result of these future climate challenges; such efforts include developing regulations to reduce energy consumption by increasing the buildings’ envelope energy performance. This is found in the German standard entitled PassiveHaus (PH). which is a well-known standard that attempts to reduce energy consumption by 90% within dwellings.

One of the main goals of PassiveHaus (PH) standard, is that a building that demands low energy requirements must also maintain appropriate comfort for occupants (Sehizadeh & Ge, 2014). In order to achieve the PH certification, buildings must meet the PassiveHaus standard requirements of: High insulation, extremely air tight envelope, passive solar gain, heat recovery, day lighting, shading, energy efficient appliances and lighting, and high performing windows are issues that are stringently considered in the PassiveHaus standard (Straube , 2009).

Another challenge appeared after further assessment of European dwellings that achieved PassiveHaus standard (Psomas et al,. 2016). It was found that dwellings refurbished to improve the thermal performance in winter are now facing overheating problems in summer (Psomas et al., 2016)

A PassivHaus single dwelling has also been previously assessed against the overheating used in building regulation methodology (McLeod et al, 2013) but this study is limited in its results as this regulatory tool results in a crude overheating assessment, using historic climate data ,not evaluating the residence's fitness for purpose in the future.

The impact of the significant overheating variables has been analysed by Mavrogianni et al (2013) but there is no clear statement of the significance of factors under the BS EN 15251 overheating criteria chosen.

Some further Research has also focused on the impact of the UHI on indoor summer temperatures in the housing stock. For example, high temperatures were measured in five occupied houses in London and four occupied houses in Manchester during the August 2003 heatwave, and found to be associated with a high level of discomfort in most dwellings (Oikonomou, E, 2012).

## 4. Methodology

Three differing locations analysed in the UK Aberdeen, Birmingham, London. Within the future weather files selected heat waves were identified. The heat wave definition used was based on the threshold temperatures from the UK heat wave plan for England (NHS, 2015). This was contrasted against the cooling season as defined in TM52 as the run period for the dynamic models.

Two differing Energy plus model geometries were devised for the differing building typologies. These are illustrated in figure 1 and figure 2 showing a south facing office bay of 7 m and living room of 6 m width respectively.

A TARP algorithm was used as the calculation algorithm which has been validated to account for thermal storage from heavyweight materials (Henninger and Witte, 2014). Windows openable during occupied hours. The office model additionally had top light windows which, opened automatically when it is beneficial for cooling (by setting the rule of opening when there was a 2K differential between the inside and outside temperature).

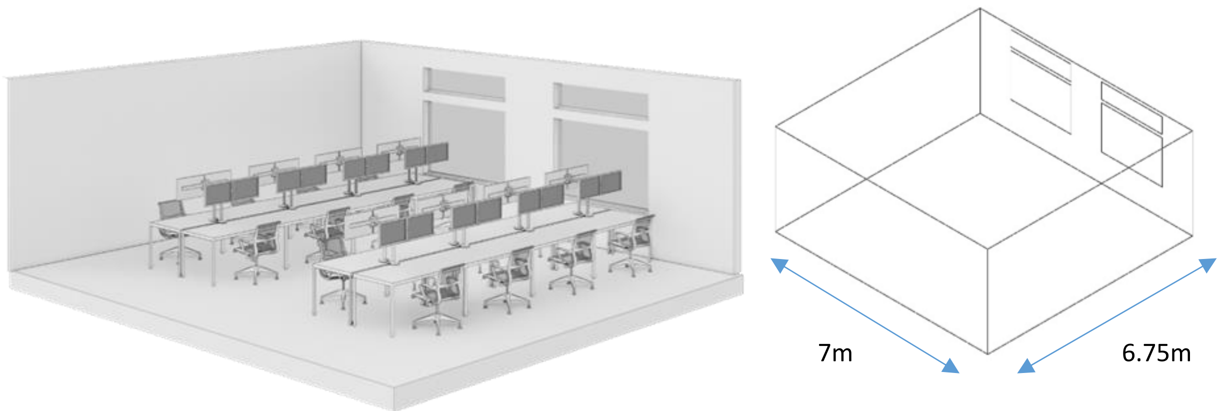


Figure 1. south facing office model

The office was modelled with a floor to ceiling height of 3.0 meters. The occupancy of 16 people based on the internal floor areas and desk layout typical for commercial spaces. LED lighting used continuously during occupation as the incidental gain of this was low compared to the incidental people load in the space. The equipment loads used in the model was based upon each person with a laptop and 2 LED monitors, typical of an office.

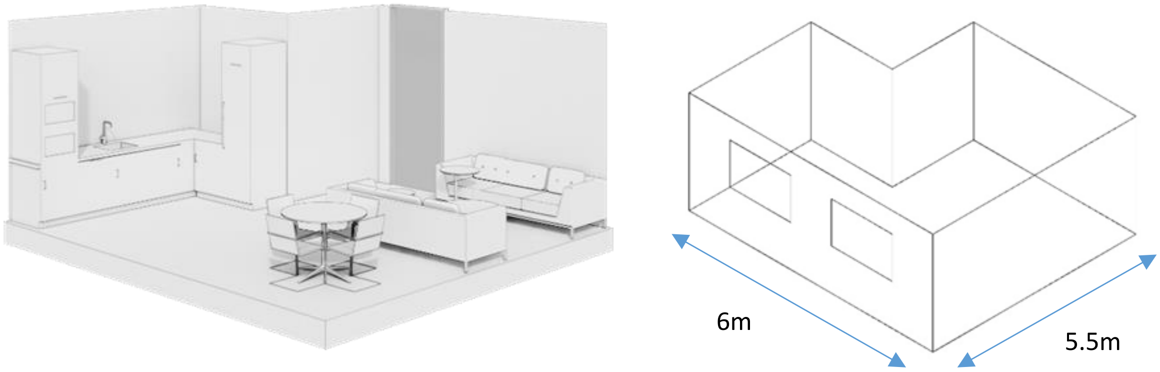


Figure 2. south facing residence model

For residential units the floor to ceiling height is 2.7 meters. The occupancy is 3 people scheduled with 2 people in occupancy during the day to simulate a working family. Cooking loads were accounted for using two hobs for 30 mins for each meal. LED lighting was used early in the morning and in the evening. Internal gains were defined by a LED TV and games system used during the evenings.

As can be seen the scheduling of loads was dictated by building usage and occur at differing points during the day. The parameters for mitigation taken from previous study (Din and Brotas 2016) as being the most effective on domestic properties and then applied to the office model. This includes thermal mass, shading and air velocity (elevated air movement but within acceptable comfort bounds). The dynamic simulations were conducted as a Monte Carlo structure of models to ensure all options are considered individually and their impact evaluated.

The baseline model used was of a lightweight construction 700kg/m3 on all surfaces which held no thermal storage. In contrast the heavyweight model was 100mm of 2000kg/m3 concrete on all surfaces in line with CIBSE recommendations for using thermal mass within buildings. This is recognised as an overestimate as the thermal mass only acts when in view of the occupant. It is acknowledged that a large degree of blockage will occur from internal furniture. This model uses the extreme case as the maximum differentiation that could be obtained for passive thermal storage in buildings.

Of the mitigation aspects modelled the air velocity was elevated to 3.5 m/s. This level of air movement would be uncomfortable in most situations but acceptable in periods of elevated temperatures in both living and office areas. This may not be the same however in rooms of differing usage such as bedrooms where there would be more sensitivity. This is calculated separately from the dynamic energy model to align with the calculation in the TM52 methodology.

The office and residential models have a similar amount of window wall ratio on their south elevations of 38%. A shading device of 1 meter on the horizontal and vertical to each side of the windows have been placed to be a reasonable structural proposition. It is recognised that slightly differing shading outcomes due to differing geometries will result for each building typology.

Rather than TM52 assessing when 2 of the criteria are broken to determine overheating, each criterion is quantified with values compared between differing models and differing assessment periods. For criterion 1, this was quantified as the number of overheating hours, and for criterion 2, it was the number of overheating incidents. Criterion 3 is evaluated on the number of hours that the heat stress temperature is exceeded. Each of the models was evaluated for heat wave periods and the whole cooling season. As illustrated by the list of models in table 1.

Table 1. dynamic models with nomenclature and features

| Model no | Typology | Location | Building mass | Features | Time period |
|---|---|---|---|---|---|
| 1 | Office | Birmingham | Lightweight | none | Cooling season |
| 2 | Office | Birmingham | Lightweight | none | Heat wave |
| 3 | Office | Birmingham | Heavyweight | none | Cooling season |
| 4 | Office | Birmingham | Heavyweight | none | Heat wave |
| 5 | Office | Birmingham | Lightweight | velocity | Cooling season |
| 6 | Office | Birmingham | Lightweight | velocity | Heat wave |
| 7 | Office | Birmingham | Heavyweight | velocity | Cooling season |
| 8 | Office | Birmingham | Heavyweight | velocity | Heat wave |
| 9 | Office | Birmingham | Lightweight | shading | Cooling season |
| 10 | Office | Birmingham | Lightweight | shading | Heat wave |
| 11 | Office | Birmingham | Heavyweight | shading | Cooling season |
| 12 | Office | Birmingham | Heavyweight | shading | Heat wave |
| 13 | Office | London | Lightweight | none | Cooling season |
| 14 | Office | London | Lightweight | none | Heat wave |
| 15 | Office | London | Heavyweight | none | Cooling season |
| 16 | Office | London | Heavyweight | none | Heat wave |
| 17 | Office | London | Lightweight | velocity | Cooling season |
| 18 | Office | London | Lightweight | velocity | Heat wave |
| 19 | Office | London | Heavyweight | velocity | Cooling season |
| 20 | Office | London | Heavyweight | velocity | Heat wave |
| 21 | Office | London | Lightweight | shading | Cooling season |
| 22 | Office | London | Lightweight | shading | Heat wave |
| 23 | Office | London | Heavyweight | shading | Cooling season |
| 24 | Office | London | Heavyweight | shading | Heat wave |
| 25 | Residential | Birmingham | Lightweight | none | Cooling season |
| 26 | Residential | Birmingham | Lightweight | none | Heat wave |
| 27 | Residential | Birmingham | Heavyweight | none | Cooling season |
| 28 | Residential | Birmingham | Heavyweight | none | Heat wave |
| 29 | Residential | Birmingham | Lightweight | velocity | Cooling season |
| 30 | Residential | Birmingham | Lightweight | velocity | Heat wave |
| 31 | Residential | Birmingham | Heavyweight | velocity | Cooling season |
| 32 | Residential | Birmingham | Heavyweight | velocity | Heat wave |
| 33 | Residential | Birmingham | Lightweight | shading | Cooling season |
| 34 | Residential | Birmingham | Lightweight | shading | Heat wave |
| 35 | Residential | Birmingham | Heavyweight | shading | Cooling season |
| 36 | Residential | Birmingham | Heavyweight | shading | Heat wave |
| 37 | Residential | London | Lightweight | none | Cooling season |
| 38 | Residential | London | Lightweight | none | Heat wave |
| 39 | Residential | London | Heavyweight | none | Cooling season |
| 40 | Residential | London | Heavyweight | none | Heat wave |
| 41 | Residential | London | Lightweight | velocity | Cooling season |
| 42 | Residential | London | Lightweight | velocity | Heat wave |
| 43 | Residential | London | Heavyweight | velocity | Cooling season |
| 44 | Residential | London | Heavyweight | velocity | Heat wave |
| 45 | Residential | London | Lightweight | shading | Cooling season |
| 46 | Residential | London | Lightweight | shading | Heat wave |
| 47 | Residential | London | Heavyweight | shading | Cooling season |
| 48 | Residential | London | Heavyweight | shading | Heat wave |

## 5. Results

Figure 3 shows that no heat wave events occur in Aberdeen in year 2080 on a 50% probability. This was subsequently excluded from subsequent modelling at an early stage and is reflected within table 1. As heat wave events are linked to the urban Heat Island Effect (Lemonsu et al, 2014) an examination on the number of heat wave event based on the NHS (2015) definition was conducted evaluating not only peak daytime temperatures but the previous night temperatures as well. The number of events was plotted against the population of cities as an indicator of urban density and the link to hard surfaces. These two factors are defined as significant factors in causing the Heat Island characteristics.

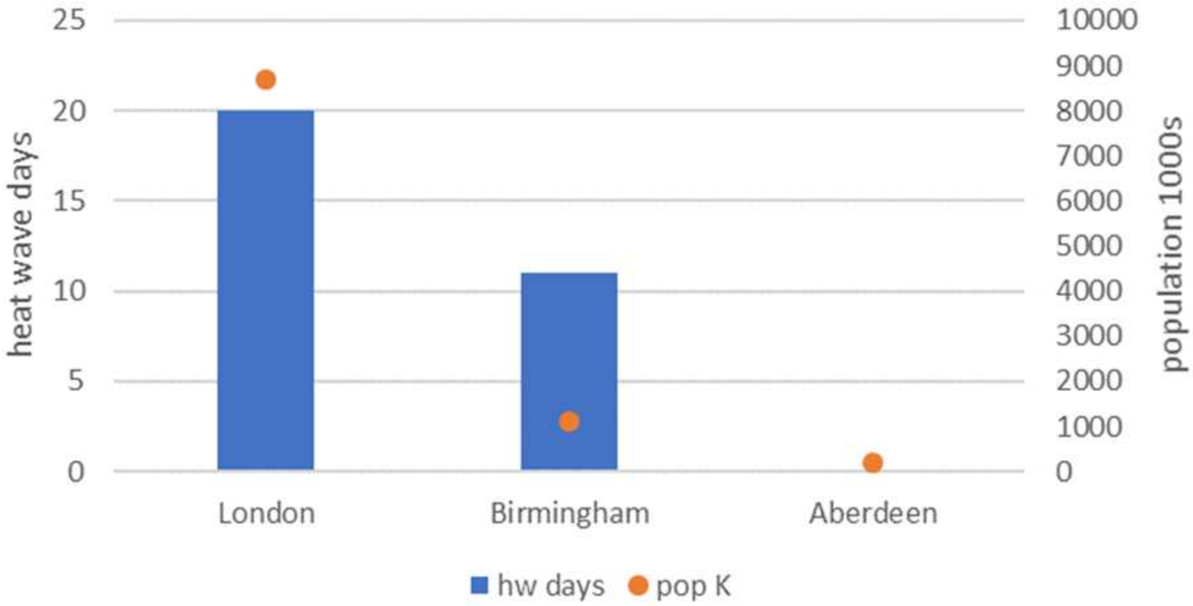


Figure 3. Heat wave events against population for 3 UK locations

The number of overheating hours experienced for all models during the identified heat wave periods for the two locations are illustrated in Figure 4. There are more overheating hours in residential than the office model. This is partially a reflection of the occupancy. While the residential occupancy was 17 hours, occupancy was 10 hours for office buildings, and they were not occupied during late evenings. The occupancy hours and the number of overheating hours is largely in proportion to the results obtained.

The overheating threshold for criterion 1 of TM 52 was 24oC. Above this temperature the number of hours were accumulated as overheating periods regardless the magnitude of overheating. This threshold was used for both offices and dwellings.

There are more overheating hours in London than Birmingham, which is reflective of the number of heat wave days in each location.

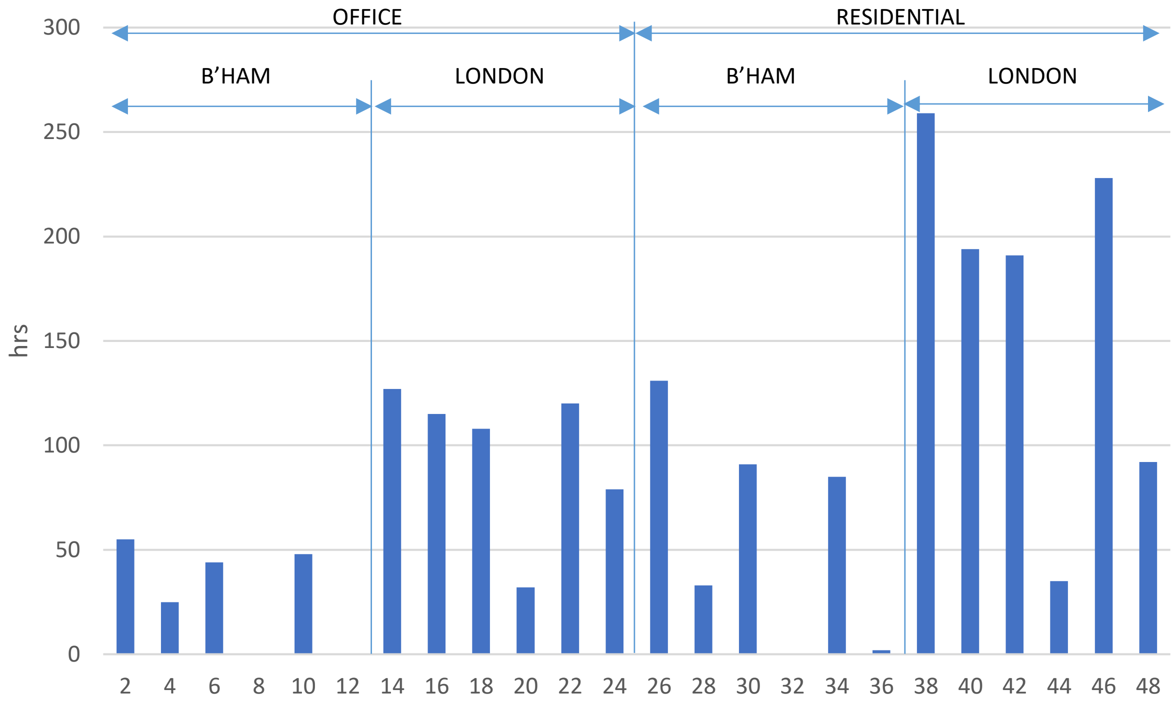


Figure 4. Heat wave overheating hours against building model

There is a larger difference in the reduction of the number of hours of overheating in London due to mitigation aspects applied in London compared to Birmingham. The largest difference is between residential models 38 and 44 both located in London of 225 hours (Figure 5).

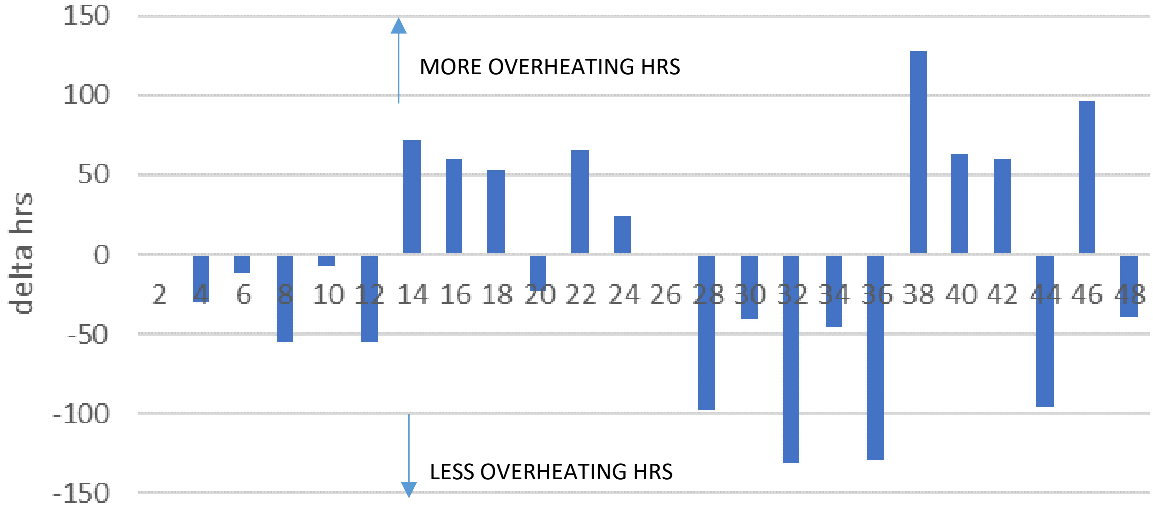


Figure 5. Difference of heat wave overheating hours compared to model 2

The difference to base case is shown in Figure 5 being a Lightweight office building in Birmingham. The results clearly show where more overheating hours occur (results above the above the line) compared to less overheating (results below the line). Those models of a lightweight construction generally experiencing more overheating hours as do models located in London.

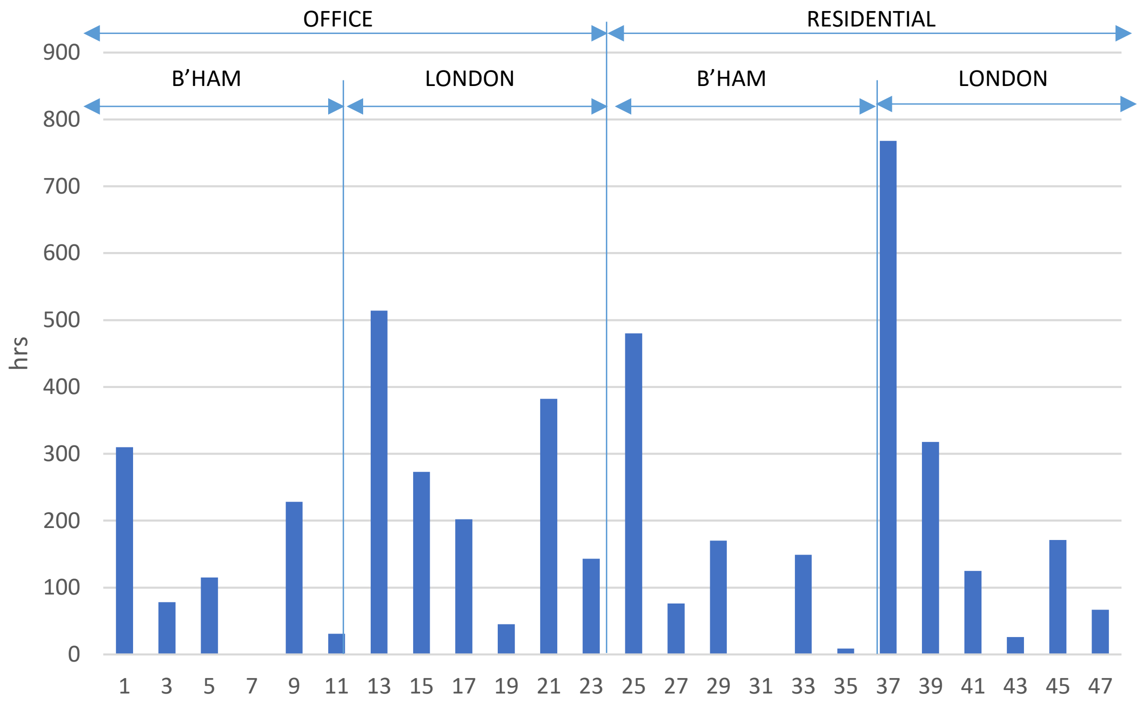


Figure 6. Cooling season overheating hours against model

For the overheating hours, in Figure 6, for the cooling season the largest differences are again experienced in the London residential model of about 700 hours. Overall, the pattern is similar the heatwave characteristics, but the results look less coherent compared to the smaller heat wave timeframe.

There are more pronounced peaks for lightweight structures showing that mitigation impacts are more effective over the whole season whether this is in combination with thermal mass or not. Thermal mass seems to have more impact in London than Birmingham.

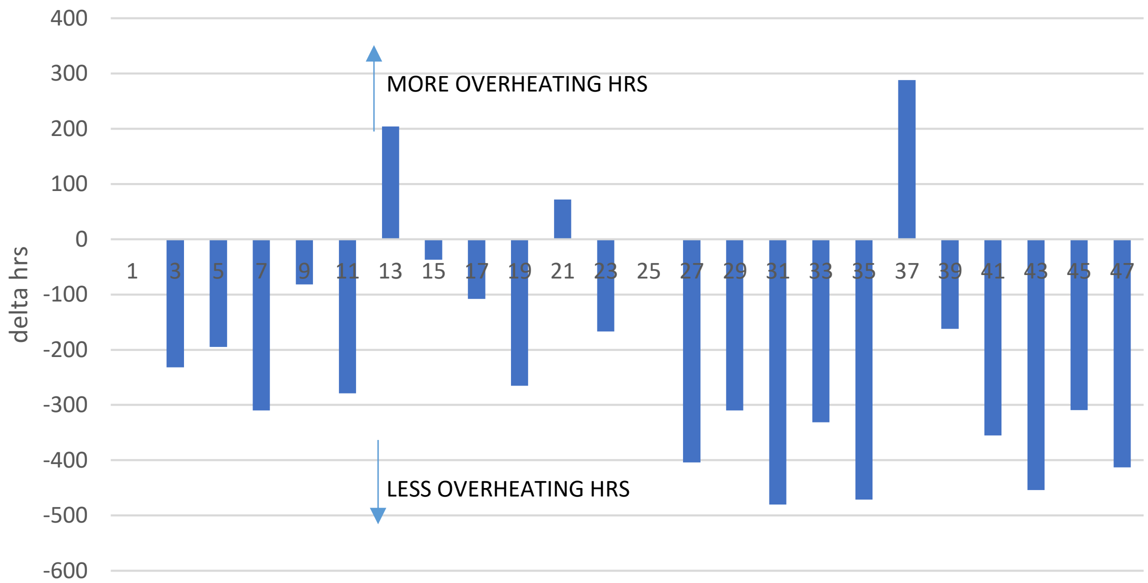


Figure 7 Difference of cooling season overheating hours compared to model 1

Mitigation has more impact for both heavyweight and lightweight construction and within both locations (Figure 7). The lightweight constructions have more frequency of overheating hours.

The other overheating factors in TM52 can be split up similarly according to heat wave and cooling season. As shown in Figure 8, there are very few incidents of overheating factor 2 is equating criterion 2 in TM52. In considering very short heat wave periods, a one-day increase is not a significant measure.

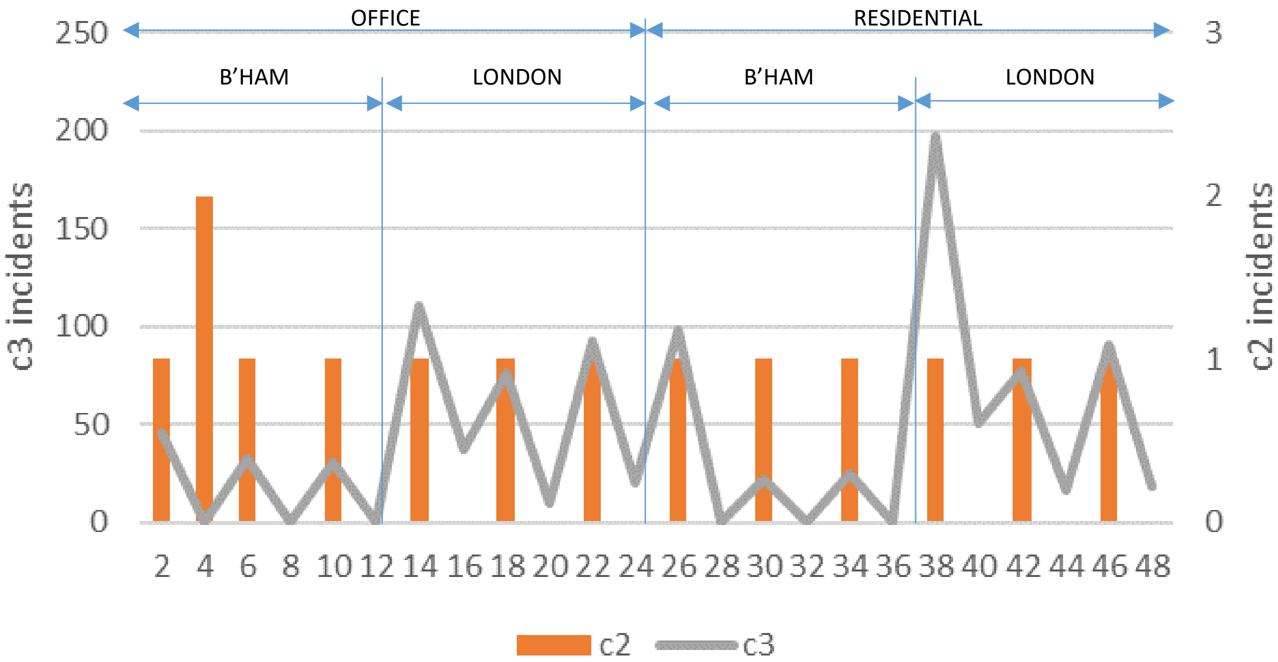


Figure 8. overheating according to factors 2 and 3 during a heat wave

The heat stress hourly events for lightweight offices and residences show up as peaks. Model 38 being a lightweight residence is shown as a peak as it is assessed for more heat wave days than its Birmingham counterpart (model 26). The difference between lightweight and heavyweight is marked showing the capacitance of the building structure being an important factor in considering heat stress hourly events. There is less heat stress in offices in Birmingham than London overall.

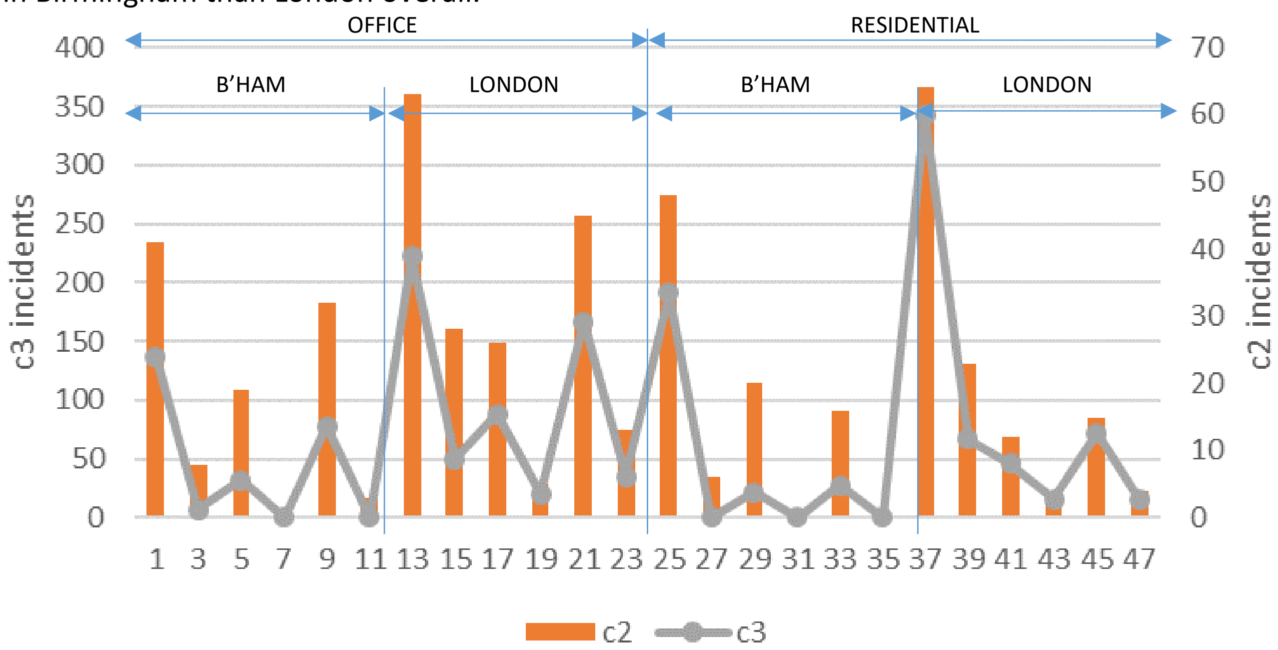


Figure 9. overheating according to factors 2 and 3 during a cooling season

In Figure 9 there is around 5 times less overheating factor 2 daily events rather than hourly heat stress events (factor 3). The profile however broadly similar for heat stress to a heat wave event although this is 1.5 times the amount compared to the heat wave periods

Lightweight structures create significant spikes in heat stress events and daily average events (factor 2) when compared to a lightweight office building in Birmingham. A heavyweight structure with an additional mitigation feature creates the most significant difference between models.

In the comparison between heat wave and cooling season the proportion of the two time periods of the overheating factors identified. There is less of a pattern with the office typology, shown in Figure 10, but a pattern does emerge with London offices having higher percentages the more mitigation occurs as can be seen by models 14, 16 and 18 being lightweight, heavyweight and heavyweight with increased velocity respectively.

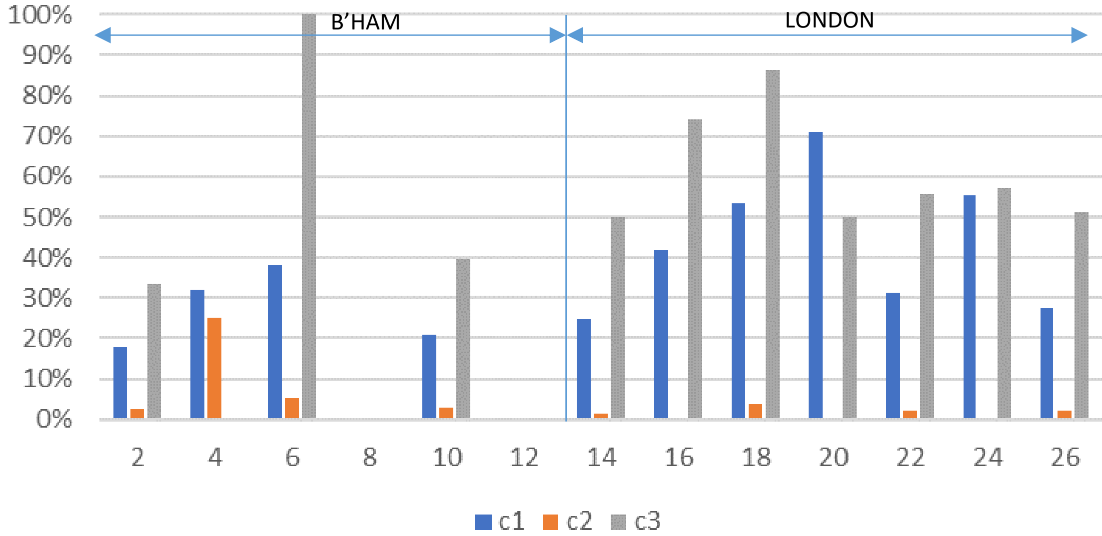


Figure 10. Comparison between heat wave events and cooling season for offices

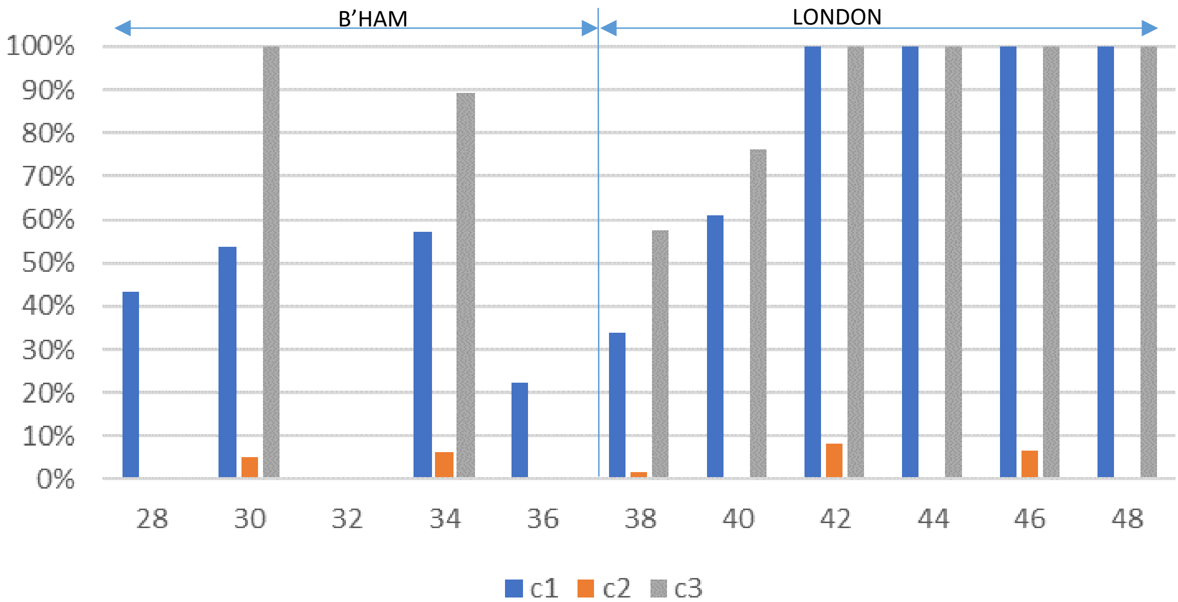


Figure 11. Comparison between heat wave events and cooling season for residential units

In the residential units shown in Figure 11, higher levels of mitigation the representativeness of heat wave events on the overall cooling season increases. The residential in London is most represented by heat wave events rather than over the whole cooling season

## 6. Conclusion

Overall the results demonstrate that heavyweight buildings perform better for both typologies and act as the best form of mitigation against overheating. Shading and air velocity add significantly to the mitigation effect both in heat waves and during the whole cooling season but there is not enough data to classify which is better.

Residential mitigation is more effective in London than Birmingham through the demonstration of the heat wave event being more representative of the whole cooling season excluding overheating factor 2. In Birmingham this varied from 20% to 100% depending on the factor being evaluated.

Thermal mass is equally important to residences and offices in terms of thermal capacitance and coolth storage. The combination of thermal mass with a mitigating feature makes buildings fit for purpose at the end of a 60-year life cycle and eliminates the risk of air conditioning being installed in a naturally ventilated building.

Definite rules on mitigation to be given to designers or to be used as overall building strategies in both building typologies are difficult to fully define without a certain amount of risk.

## 7. Further work

These results should be matched with daylight availability in offices to see what fraction of internal loads can be saved. As LED lighting is highly efficient other parameters such as productivity or health benefits to occupants should be evaluated.

The life cycle carbon of concrete needs to be more carefully assessed to show cost effectiveness in designing new buildings for the future with thermal mass. Adequate levels of climate mitigation can be achieved through different construction selection, not requiring air conditioning (and the replacement factors and energy that these use). This will have the resultant reduced impact of energy and carbon expended over the service life of the building making naturally ventilated buildings a lower risk proposition to deal with climate change.

The paper used a single zone model which has its limitations as larger cells are more prone to error in evaluating overheating results. This is due to the variation of temperature within the internal spaces from the façade to the back of the plan. The size of the cell should be varied to show the sensitivity to air flow and natural ventilation of the spaces considered.

Although a range of surfaces were classified as adiabatic this is rarely the case. A range of adjacent insulation conditions should be used to evaluate the influence of transfer of heat to adjacent zones to determine the sensitivity of the modelling assumptions made.

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# Resilient Design in The Tropics: An Overheating Assessment Method for Naturally Ventilated Buildings

**Daniel Zepeda-Rivas[1] and Jorge Rodríguez-Álvarez[1,2]**

[1] Universidade A Coruña, A Coruña, Spain, daniel.zepeda@udc.es
[2] Architectural Association School of Architecture, London, UK, jorge.ralvarez@udc.es

As a consequence of global warming, overheating has become the main source of discomfort when speaking about the thermal performance of buildings. On the one hand, energy consumption together with the risk of heatstroke rises during warm periods and in extreme situations such as heatwaves. On the other hand, there is no broadly accepted method to measure overheating. Most of the literature is limited to a simple count of hours above comfort limit, disregarding the intensity and temporal extent of the periods, whereas other methods have a limited application since they were developed for a certain type of building and location. This paper proposes a novel method for overheating assessment in existing and projected buildings based on 5-step criteria. The objective of the process is to assess the intensity and the total time extent of overheating following adaptive theory and established limits of human comfort. The method consists in hourly counts of overheating hours divided into five segments (i.e. hours above 0.1°K, 1°K, 2°K, 3°K, and 4°K) using the upper comfort limit as a threshold. The output of the method thus provides a quantitative answer regarding overheating in a building, assessing not only the intensity but the range of the problem, allowing to evaluate different strategies to regain comfortable conditions for the occupants.

**Keywords:** thermal comfort, overheating, tropics

## 1. Introduction

There is compelling evidence that the climate across the globe is changing. Yearly temperature averages, as well as absolute peaks, have been rising and they are expected to reach even higher marks in the near future. As a consequence, there will be longer and more intense heatwaves during warmer summer and spring seasons (de Wilde and Coley, 2012). The consequences of overheating in the human body are many, and they vary depending on different factors. Nevertheless, the starting point is always heat stress induced thermal discomfort, and sadly, for the most vulnerable occupants, the endpoint may be death or life-threatening diseases. Speaking about building performance, the main problem with this temperature increases is the fact that space cooling requires more energy than space heating.

While global warming is happening everywhere around the globe, recent studies have found that the developing world is suffering the worse part of it (Chen and Chen, 2013). Climate change has triggered a worldwide desertification phenomenon that is mostly occurring in the tropical and subtropical areas, encompassing the most populated countries in the world such as Brazil, Mexico, Indonesia, Nigeria, Pakistan India, and China (Figure 1). Temperature peaks are constantly escalating above 40°C and becoming a real threat to the wellbeing of the population in these regions in which, unlike other developed countries, the only available solution to overcome the overheating problem is restricted to passive means due to the socio-economic limitations (IPCC, 2013).

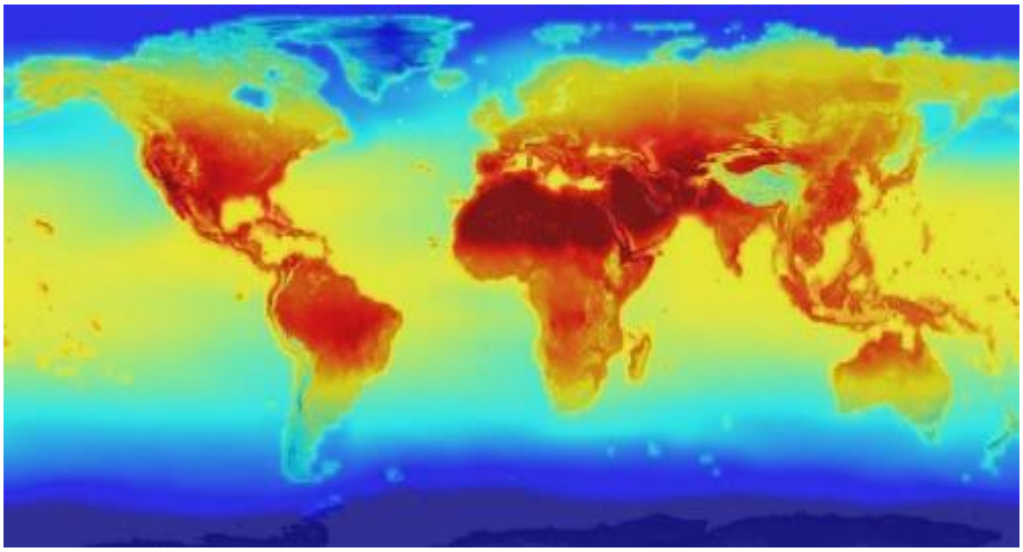

Figure 1. Map representation of future forecasted temperatures where is possible to appreciate how the highest temperatures are concentrated in the tropical and subtropical areas (Image source: NASA)

It is understood that the tropics are the immediate regions surrounding the equator. On the Northern Hemisphere, these are delimited by the tropic of Cancer at the coordinates 23°26’12.0” and by the Tropic of Capricorn at the coordinates 23°26’12.0” in the Southern Hemisphere. The subtropics are the areas between the tropics of Cancer and the tropic of Capricorn, and the latitude marks of 66.5° north and south. Nine of the ten most populated countries in the world fall within this area, which are also catalogued as developing regions (Figure 2).

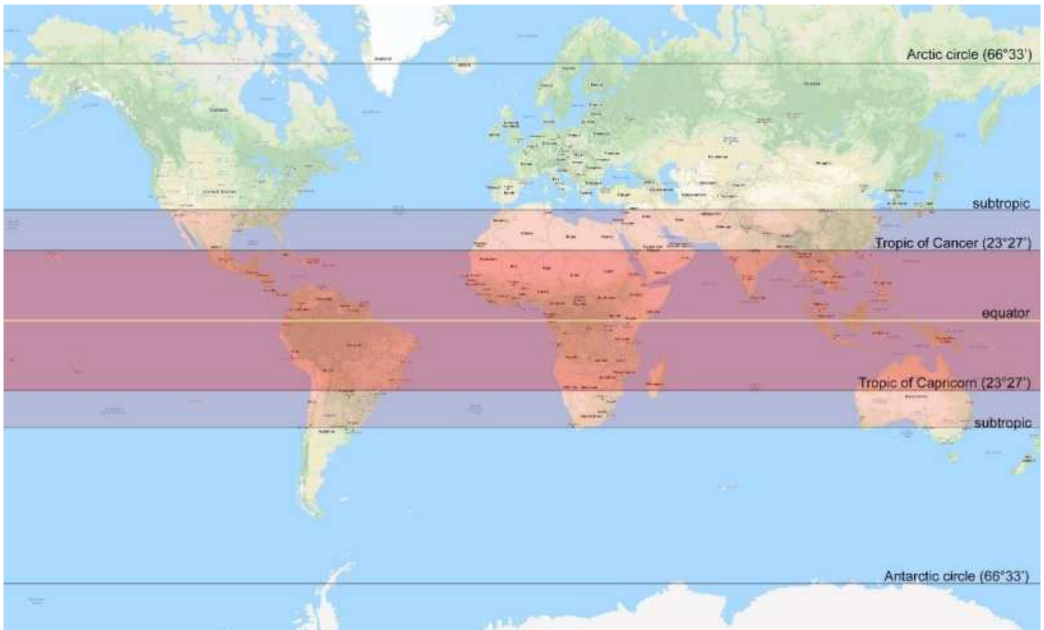


Figure 2. Global location of tropical and subtropical areas.

As part of a global effort to reduce energy consumption and therefore, $CO^2$ emissions, energy-saving policies for buildings have been implemented in many countries across the globe (Walsh, Cóstola and Labaki, 2017). In recent years, thermal comfort models have been used as the foundation to create healthy and comfortable spaces, while reducing their energy consumption. Meanwhile, comfort models for active or mechanically climatized buildings have been broadly developed and discussed for several decades. The current performance limits for passive or free-running buildings are relatively new, and for some specific cases, they remain unknown. Moreover, it is important to consider that two of the most relevant and most used comfort models, the ASHRAE standard 55 and the CEN Standard BS EN 15251 (renamed to EN 16798), were developed considering very specific survey and climatic data, which would have differ from that on a tropical or subtropical context (Nicol, Humphreys and Roaf, 2012). Thus, some modifications need to be addressed before assuming their effectiveness in a warmer context. Although some other comfort models seem to be more suited for this contexts, such as the ones developed by Humphreys and Szolokolays-Auliciems (Szokolay, 2008; Nicol, Humphreys and Roaf, 2012), the current implementation of energy standards such as BREEAM and LEED in developing countries, are somehow forcing the implementation of ASHRAE's and CEN Standard's comfort models, since this countries lack energy-saving regulations of their own.

There is not a broadly accepted method or formula to measure or quantify the possible overheating of a free-running building in a tropical or subtropical context. Most published literature is limited to a simple count of overheating hours above 0.1 or 1.0 °K, completely disregarding the intensity and length of the overheating phenomena. Other documents, such as the CIBSE's TM-52 (CIBSE, 2013), were written keeping in mind its implementation in a high latitude context (such as the UK ), Nowadays, this document is being studied more as an early out-dated approximation to solve the problem rather than as a possible answer, partly because of the yearly progressive overheating due to climate change, but also due to their impractical application in other European settings where temperatures frequently rise above 30°C, such as the south of Portugal, Spain, and Italy.

This paper presents a new method to measure and assess overheating in free-running naturally ventilated buildings in tropical and subtropical climates. It was developed to measure the intensity and chronological length of overheating as means to determine the possible effectiveness of one or many adaptive opportunities and passive strategies to maintain or regain indoor comfort. Additionally, based on the theoretical principles of adaptive thermal comfort, this method intends to stablish the theoretical base to consider a possible limit of overheating to ensure comfort for the occupants and the effective applications of adaptive opportunities.

## 2. Method

Comfort models are limited by different factors according to their specific application. The width of a comfort band, thus its upper limit, is defined by the building class or acceptable limits (Carlucci *et al.*, 2018).Adaptive comfort theory suggests that a comfort band of ±4K, would ensure an 80% of acceptability limit on a predicted mean vote (PMV) scale, One of the reasons for this comfort width of ±4K, is that it can be possible when considering the previously experienced temperature of the user, therefore, the thermal history would be encompassed and taken into account (Nicol, Humphreys and Roaf, 2012).

There is not a common agreement between comfort models or literature regarding the highest possible temperature limit in which occupants of a free-running building would still be comfortable and fully operable. The ASHRAE standard 55 suggest an upper limit of 33.5°C for the U.S. while the original EN 15251 suggest 30.5°C for Europe. The reason for this is because both standards are based on user’s satisfaction questionnaires from which thermal expectations of the occupants were pre-established, as well as the common limit of what could be considered comfortable at those specific locations (CIBSE, 2013). The same applies to relative humidity levels Early work by (Lee and Givoni, 1971; Fanger, 1972) established that the optimum operative range of relative humidity is between 20 and 80% according to the findings in their experiments and fieldwork. Nevertheless, in tropical locations close to the equator such as Puerto Rico, Cuba or Barbados, occupants are constantly experiencing higher levels than the suggested 80% during daytime throughout the year. In a similar way, sub-tropical desert locations such as Egypt and Saudi Arabia, as well as most of the subtropical African countries, experience extreme dry conditions during great part of the daytime for most of the year. Despite of such conditions, building occupants in these areas are still functioning and most dwelling and workplaces are naturally ventilated, free running, relying on passive strategies to procure thermal comfort.

There is no further research that establishes the actual limits of thermal comfort for workspaces or living spaces in a tropical or subtropical setting. Research by (Gómez-Azpeitia *et al.*, 2012) and (Mishra and Ramgopal, 2015), reached different and apparently opposed conclusions, mainly because they followed different objectives and methodologies, obtaining incomparable results, but still, it is possible to say that they both agree when stating that there should be a different comfort limit corresponding to each location as a consequence of the thermal history, expectations and cultural background of the subjects. In most cases, those limits are different than the original suggested by the standards In a similar manner, research by (Vellei *et al.*, 2017) concluded that those limits are not only variable based on temperature but also on relative humidity. In line with this, they propose a method that significantly extends the relative humidity range for acceptable indoor conditions in naturally ventilated buildings, according to the thermal history and expectations of the users.

Adaptive opportunities are an efficient solution to achieve and maintain comfort. However, they are not necessarily faultless whenever they are applied. Adaptive theory suggests that the correct use of passive strategies together with adaptive opportunities may improve the thermal sensation and therefore push further the upper comfort limit (Nicol, 2017) (Figure 3).Still, the effectiveness of these strategies and opportunities is variable depending on the conditions in which they are applied, they are more efficient when preventing overheating rather than when solving overheating (Oropeza-perez, 2019). Thus, it is important to anticipate its application in the early design stages and analysis.

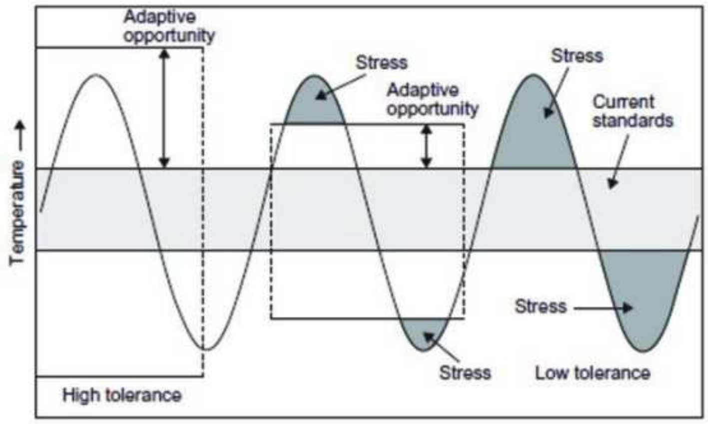


Figure 3. Effect range of passive strategies on a temperature curve with respect to the comfort zone and thermal stress (Taslim, Parapari and Shafaghat, 2015)

When speaking about tropical and subtropical locations, it is important to keep in mind that despite of what comfort models and adaptive thermal comfort theory suggest, most of the building stock of developing countries are solely depending on passive strategies as means to create and maintain comfortable conditions. Users maintain a closer relationship with outdoor spaces and therefore, they easily acclimatize and closely relate to exterior conditions, resulting in a more uniform thermal history (Humphreys and Nicol, 2002). This means that, according to some of the comfort models, people in these regions may have lived and will be living under what could be considered overheating conditions for most of their time. Nevertheless, regardless of the possible location of the comfort limit, in order to pursuit a better understanding and to evaluate the threat, it is necessary to quantify and fully appreciate the extent of this overheating phenomenon.

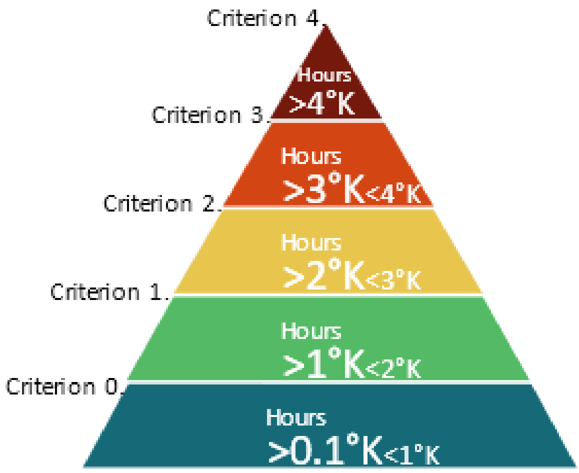


Figure 4. Graphical representation of overheating hours subdivision criteria

This paper proposes a method based on 5-step hourly subdivision criteria to assess the intensity and frequency of overheating in a sensitive manner. The method divides overheating temperatures depending on how far they are from the upper comfort limit. Each criterion could be described as follows:

- Number of hours above 0.1K. The total amount of hours where temperature is strictly above comfort but less than 1°K. The number of hours may represent in a rigorous way time outside of the comfort limit but not an overheating problem since a temperature change of less than 1°K is almost imperceptible to the body. (Nicol, Humphreys and Roaf, 2012).
- Number of hours above 1°K. The total amount of hours where temperature is one whole degree or more above comfort but less than 2°K. This specific distance from the upper comfort limit is taken as a starting point since sensitive subjects would start feeling thermal stress, although it would still not represent a problem or a significant thermal stress.
- Number of hours >2°K. The total amount of hours where the temperature is 2°K or more above comfort limit, but less than 3°K. This is where thermal stress is already manifested, and something should be done to regain comfort.
- Number of hours >3°K. The total amount of hours where the temperature is three degrees or more above comfort but less than 4°K. This is where thermal stress is clearly present, but still it is possible to be solve and re-gain comfort.
- Number of hours >4°K. The total amount of hours where the temperature is four degrees or more above comfort. The last step before severe overheating where conditions may still be bearable for the less sensitive subjects.

Once the overheating hours corresponding to a reading or a simulation result are distributed across the five division method, it is possible to appreciate the frequency of overheating hours, as well as their distance from the upper comfort limit. Figure 3 provides a graphical representation of this.

### 3. Interpretation of results

With the interest of providing a better understanding of the method, six different examples were elaborated. The same building was simulated with six different weather files corresponding to three tropical locations and three subtropical locations.These locations are spread across 3 different continents, at different conditions and with variations on latitude, longitude, climate and altitude. Table 1 provides an overview of location specifics, climate generalities and simulation results.

| | City | Country | Lat. | Long. | m.a.s.l. | Type of climate | Class. | Avrg. Yearly Temp. | Max. Temp. | % in comfort | % Above upper comfort limit | % Below lower comfort limit |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Cancun | Mexico | 20.03 | -86.86 | 5 | tropical | Aw | 26 | 35.3 | 92.99 | 6.88 | 0.13 |
| 2 | Sao Paulo | Brazil | -23.5 | 46.617 | 792 | subtropical | Csc | 20.2 | 33.5 | 91.55 | 0.65 | 7.80 |
| 3 | Lagos | Nigeria | 6.58 | 3.33 | 40 | tropical | Aw | 27.5 | 34.9 | 94.16 | 5.84 | 0.00 |
| 4 | Cairo | Egypt | 30.083 | 31.283 | 36 | subtropical | BWh | 22.5 | 41.8 | 83.49 | 7.59 | 8.92 |
| 5 | Jakarta | Indonesia | -6.15 | 106.85 | 5 | tropical | Af | 26.3 | 34.5 | 96.55 | 3.45 | 0.00 |
| 6 | New Delhi | India | 28.583 | 77.2 | 212 | subtropical | BSh | 24.9 | 44.4 | 78.14 | 17.53 | 4.33 |

Table 1. Specifications and details of the locations and their simulation results.

The simulation file was setup assuming a completely passive, naturally ventilated building, excluding any possible neighbouring or contextual buildings. The average U-Value for the building envelope is 3.06 $W/m^2K$ and is composed by single glazing windows, plastered brick walls and a concrete slab cover. It considered a infiltration airflow of 0.75 air-changes per hour , as well as an automated window operation according to the interior and exterior temperature, imitating the potential user's behaviour.

The yearly hourly temperature of each of the locations is represented in Figure 5, where it is possible to appreciate the chronological occurrence of temperature peaks according to the weather files. In a similar way, the simulation hourly results are plotted in Figure 6, following the BS EN 15251 standard for naturally ventilated office buildings with a ±4K width comfort band. Following the established standard limits, everything that falls outside the upper comfort limits is considered as overheating despite the distance from the upper comfort limit. It is possible to appreciate in the results that the buildings located in tropical locations suffered only occasional overheating while the ones in subtropical climates experienced both overheating and underheating., In Table 1, it is possible to appreciate the percentages of comfort and overheating corresponding to the simulation results of Figure 6. With the purpose of focusing only in the overheating analysis, underheated periods will be excluded from examination.

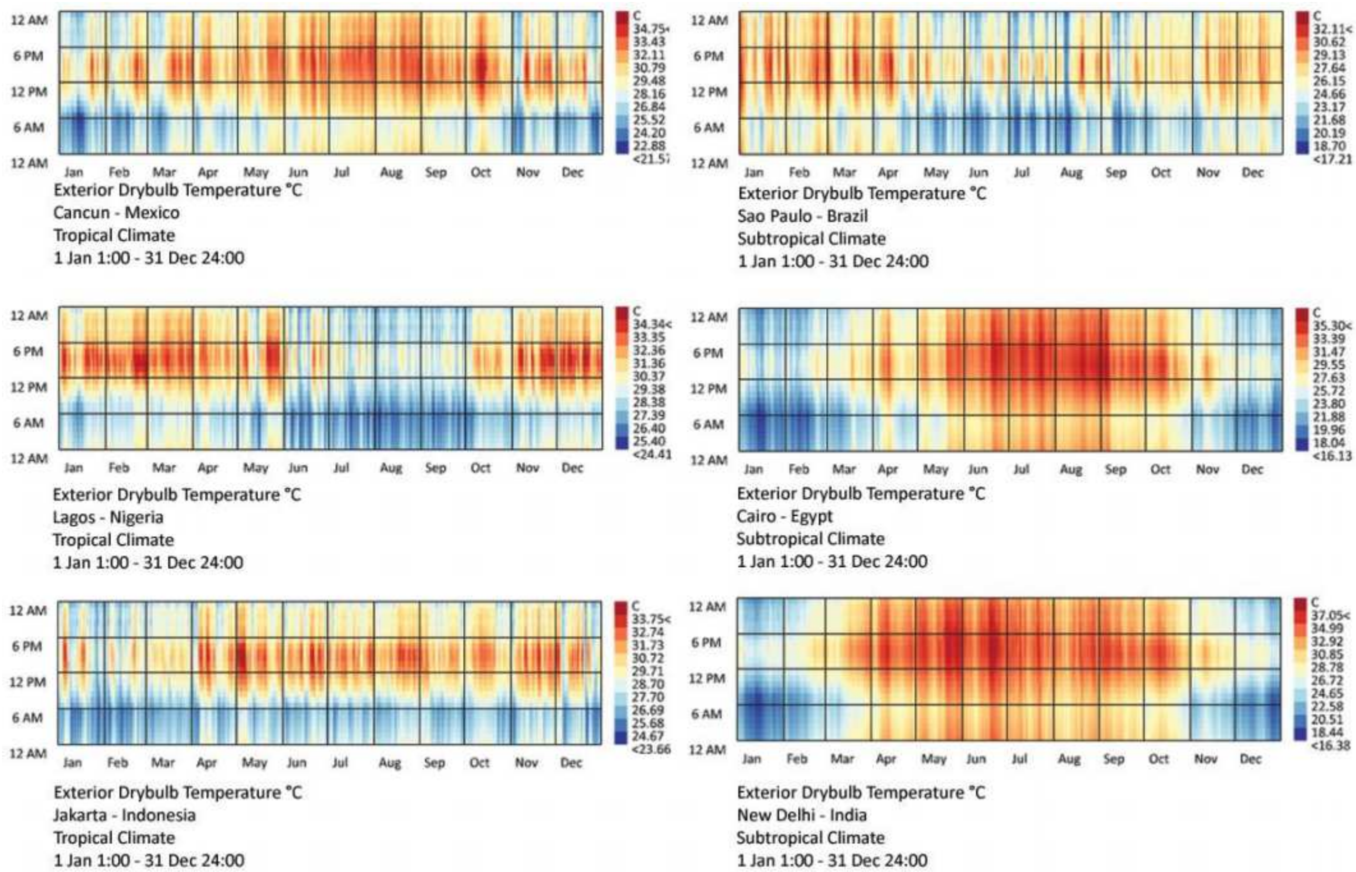


Figure 5. Hourly temperatures during the year of the 6 test locations

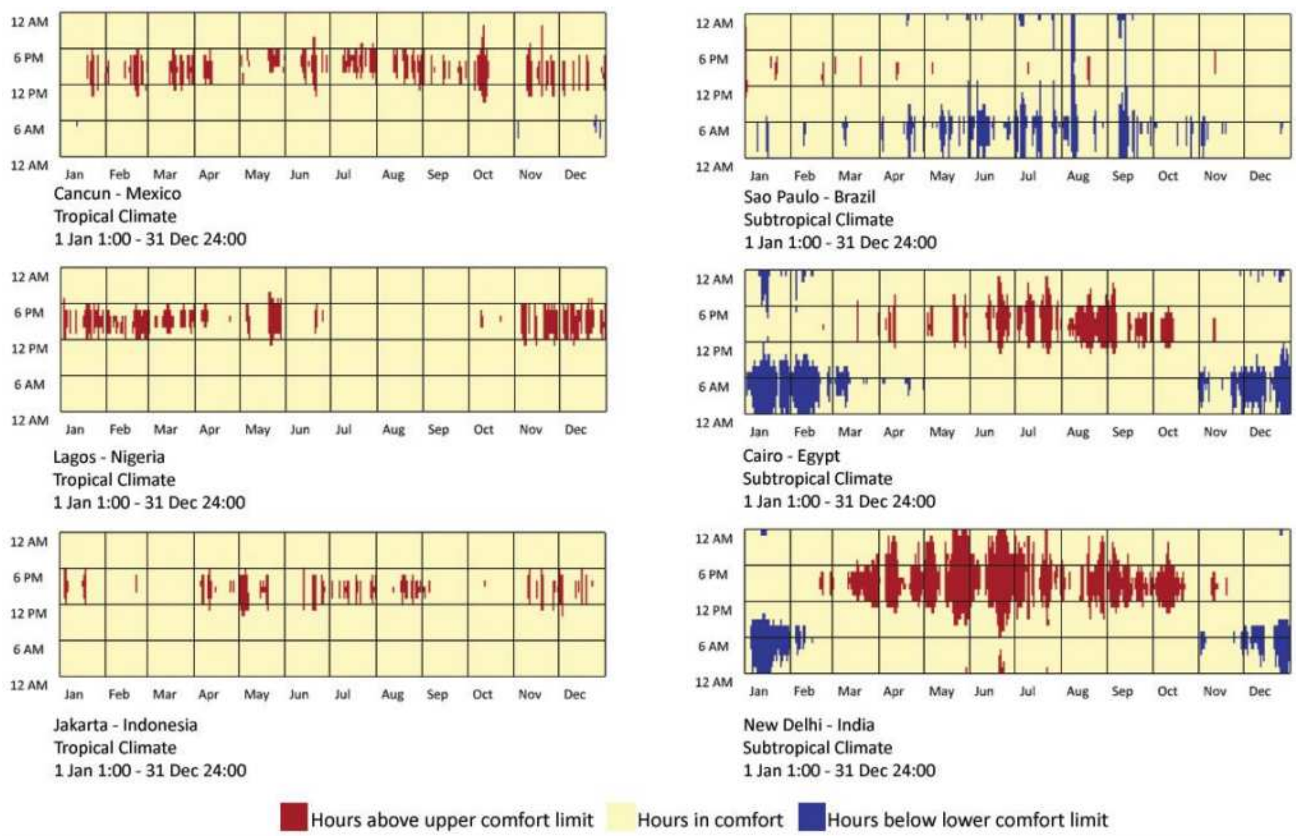


Figure 6. Simulations hourly results. Hours in yellow are in comfort, red are overheated, and blue are cold hours

Following the methodology proposed, the simulation results were distributed across the different criteria. The data of each criterion was interpreted in the following way:

- Criterion 0, hours >0.1°K but <1°K: the total amount of hours where overheating is occurring but still imperceptible to the human body. This step provides a sensible representation of how prone to overheating a building might be, even when it does not necessarily represent a problem or require a solution, a high number means that in a particularly hot season, the building is in danger of displaying a constant overheating problem that will escalate further.
- Criterion 1, hours >1°K but <2°K: the total amount of hours where temperature is one whole degree above comfort but less than two. This number of hours represent the total time outside the comfort limit, where overheating can be perceived by sensitive users, but not necessarily indicate an overheating problem since the temperature rise is only 1°K. Yet, not all that time can be accounted for as effective time overheated since it depends on the sensitivity of the occupants. This is where thermal stress begins to be present and one single adaptive opportunity can be highly effective against thermal stress. It can be summarized as the possibility of changing the surrounding environment by, for example, access to cold drinks, airflow improvement or clothing adjustments.
- Criterion 2, hours >2°K but <3°K: the total amount of hours where temperature is two degrees or more above comfort but less than three. This is where thermal stress is already present and something should be done in order to regain comfort. These are the number of hours where access to more than one passive opportunity would be psychologically relieving since the effect of multiple passive opportunities can be accumulative.
- Criterion 3, hours >3°K but <4°K: the total amount of hours where temperature is three degrees or more above comfort but less than four. At this distance from the upper comfort limit, thermal stress is a problem for occupants and depending on the context and the subjects, it may not be possible to be endured for long periods without experiencing discomfort and performance reduction. During short periods of exposure, multiple adaptive opportunities can be relieving and efficient against thermal stress, but they can be rendered useless if overheating persist for longer periods.
- Criterion 4. hours >4°K: the total amount of hours where temperature is four degrees or more above comfort. This means that there are at least 8 °K or the same length of the comfort band between the current temperature and thermal neutrality. Overheating is occurring, and depending on the subjects and the context, it might not be possible to be endured, human performance is decreased, and physiological manifestations of thermal stress will be present. This condition should be avoided in all possible cases, the access of passive strategies can be helpful to provide psychological relief and decrease the thermal stress, although they may not increase the human performance of the users.

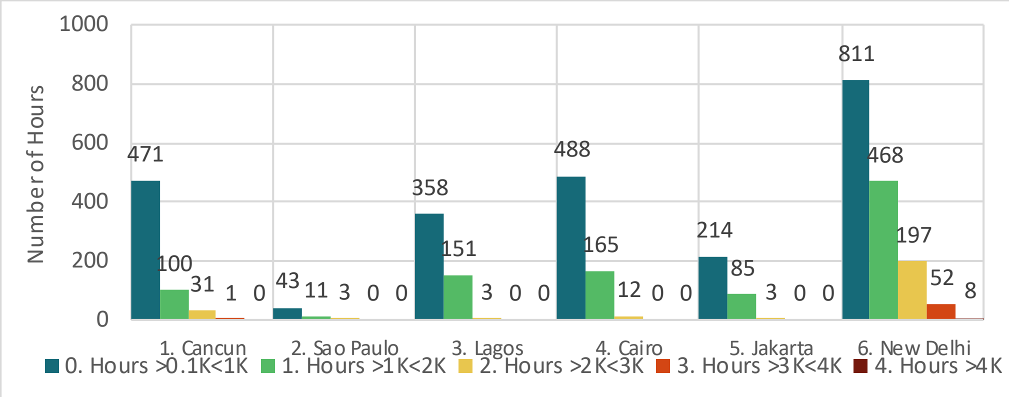


Figure 7. Yearly accumulative count of overheating hours according to each criterion in every location.

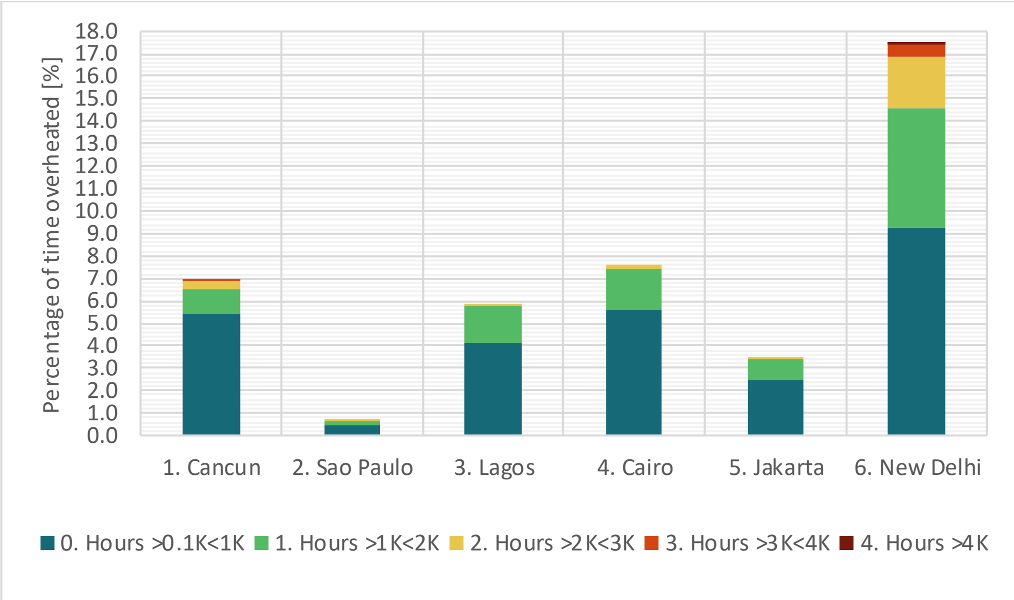


Figure 8. Yearly percentage of time overheated according to each criterion during the year

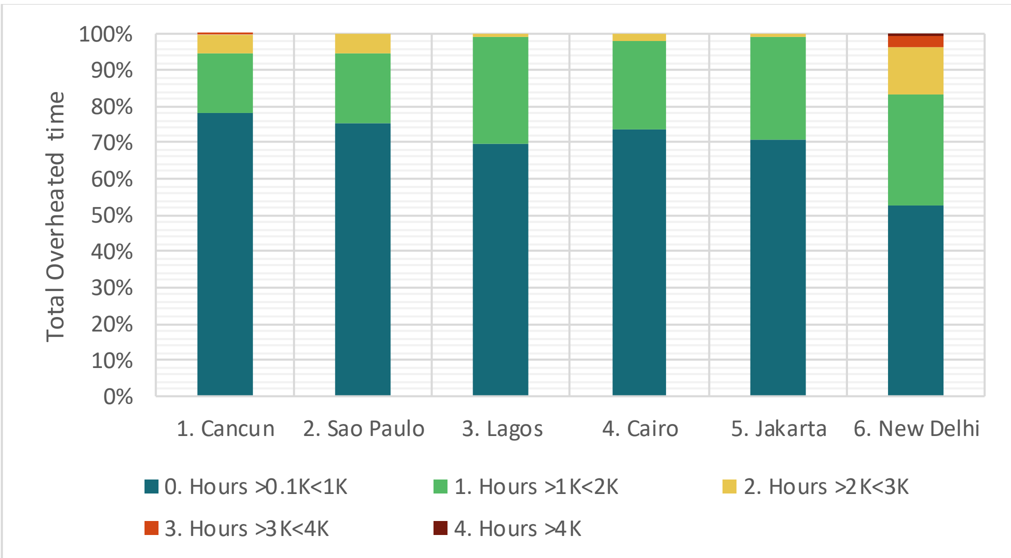


Figure 9. Distribution of the intensity of overheating according to each of the criteria within total overheating time

In figures 7 to 9 overheating hours in the simulation results of every location are plotted according to the criteria. The yearly accumulative count in Figure 7, the yearly percentage of time overheated in figure 8, and in Figure 9 the distribution of the intensity of overheating according to each of the criteria within total overheating time, or in other words, out of the total overheated time, what percentage of it corresponds to each of the criteria.

It is possible to appreciate that, while Jakarta performs best among tropical locations remaining 96.55% of the time in comfort, Cancun has the lowest percentage of time in comfort (92.99%). However, none of the three tropical locations (Cancun, Lagos or Jakarta) presents a persistent or threatening overheating problem since none them show hours above 3°K or 4°K. Jakarta and Lagos have only 3 hours of discomfort above 2°K during a year, which is perfectly manageable with adaptive opportunities, and even when Cancun has 31 hours of discomfort above 2°K, it only represent the 0.35% of time during a year, which is as well still manageable with adaptive opportunities. In figure 10 it is possible to see the concurrence and intensity throughout the year of these overheating events.

Speaking about sub-tropical locations, it is possible to appreciate that Sao Paulo is the best performing sub-tropical location, remaining 91.55% of the time in comfort with a 0.65% of time overheated, while New Delhi has the lowest percentage of time in comfort with a 78.14% of time and a 17.53% of time overheated, and Cairo in the middle of the two with a 83.49% of time in comfort and 7.59% of time overheated. It is possible to say that Sao Paulo does not have an overheating problem of any kind since all its numbers in every criteria are low and the very few it has, are mainly in criterion 0 and 1. In the case of Cairo, despite of the high number of overheating hours within criterion 0 and 1 , these are fully manageable through adaptive opportunities, and the 12 hours during the year corresponding to overheating hours >2°K, can be considered quite insignificant in a broader perspective since the overheating does not escalate any further, as it is shown in Figure 10. In the case of New Delhi, even when the graphs may apparently indicate the contrary, it does not necessary have a significative overheating problem, the numbers of the criterion 0 and criterion 1 does not necessarily represent a constant problem during the year since they can be manageable with adaptive opportunities. The numbers of the last 3 criterions do represent a recurrent problem, but given the amount of hours or percentage of time, it can be argued that they are manageable events spread during the year, in the number of hours above 2°K limit or criterion 2 is translated as 32.5°C, meaning that temperature has escalated that for 2.25% of the occupancy time. And .6% of the time 33.5°C or 52 hours, and 0.10% of the time 34.5°C or 8 hours, the original CIBSE TM-52 (CIBSE, 2013) suggest that a non-domestic building can be safely free-running or naturally ventilated if temperature never exceeds a maximum of 4°K and the 1°K limit is not exceed for more than 3% of occupancy time during the hottest 5 months of the year, even when these limits where drawn for buildings in the UK and the building in New Delhi would fail to pass these, and all the criteria in the CIBSE TM-52. People in New Delhi would still be occupying and using the building, and they would only consider having a recurrent overheating problem during the months of May and June when is frequent. (Mishra and Ramgopal, 2015).

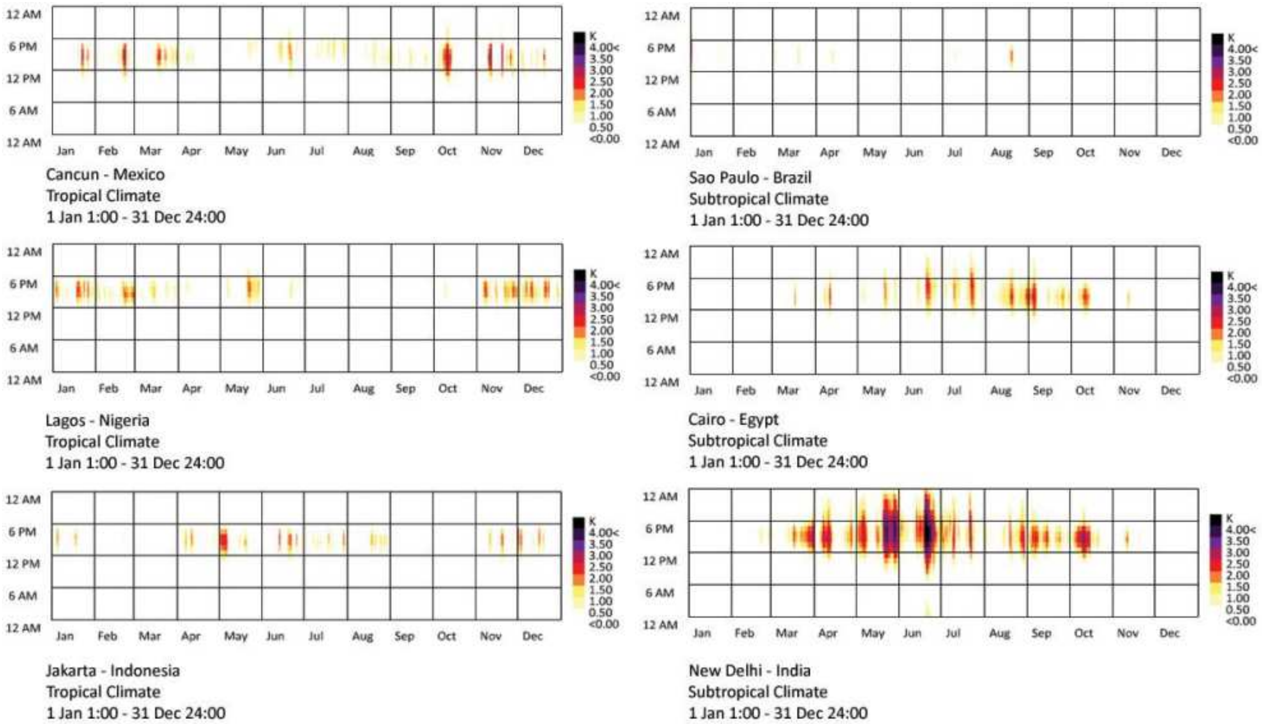

Figure 10. Yearly distribution of overheating hours and their distance to thermal neutrality

## 4. Conclusions

This method provides a novel approach to visualize and understand overheating hours. The first three criteria prove useful sensible information regarding what could be interpreted as "the beginning of overheating", where adaptive opportunities are highly effective as means to remain in comfort and address thermal stress. The fourth criterion represents the theoretical limit of overheating for sensible subjects, while the fifth criterion could be interpreted as the beginning of unbearable temperatures. Nevertheless, further research needs to be conducted specifically focused in every location to establish the possible overheating limits in a clear and exact way according to the specifics of the users, since this methodology is case-sensitive.

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# The Future of Thermal Comfort in a Warming World

**Abdulla Alnuaimi[1] and Sukumar Natarajan[1]**

[1] University of Bath, UK, Department of Architecture & Civil Engineering

## Abstract:
Building cooling energy demand in the warmer climates of the world is increasing due to population growth and built environment expansion. Currently, cooling energy demand is increasing at a rate of 8% per annum, and this is projected to increase more rapidly with global warming. However, much of this demand is driven by unsustainably low indoor building temperature set points, that are also fundamentally seen as undesirable by most building occupants. In this study, we examine the effect of this "overcooling" in a changing climate using data from Qatar as a case study of a location with high average and peak external temperatures. Field data from 4 buildings in public and private settings demonstrate that cold discomfort is about 20 percentage points higher than warm discomfort due to excessive air-conditioning. Computer energy simulations using morphed future weather data and the extrapolated effect of observed low internal building temperatures, demonstrate that overcooling exacerbates the effect of a warming world by 16 percentage points. In other words, the use of more climatically appropriate thermal comfort standards that avoid unnecessary overcooling could reduce 28% of global carbon emissions in a future warmed world. As anecdotal evidence of excessive cooling in other warm climates demonstrates that the effects of overcooling are true, the reduction of building overcooling results in a greater achievement of thermal comfort, a decrease in cooling energy consumption, and a decline in carbon emissions across the warm climates of the world.

**Keywords:** Thermal Comfort, Warm Climates, Overcooling, Building Energy, Space Cooling

# 1 Introduction

## 1.1 Environmental Crisis

Environmental degradation is the negative change of the environment through actions that result in an undesirable environmental change, which is caused by actions such as the pollution, destruction, and depletion of the natural resources (UNEP, 2007). The rate at which the environment has been deteriorating is increasing yearly. Negative impacts such as climate change, global pollution, and the loss of biodiversity are linked to environmental degradation (Stocker et al., 2013). Current biodiversity loss is a thousand times larger than the natural level. The documented loss is roughly three quarters of wild animals and half of plant life as a result of habitat destruction and over-usage of natural resources (Stocker et al., 2013). Increased air, land and sea contamination is observed globally as a result of pollution. The increase in pollution has led to larger occurrences of diseases, allergies, and in some cases death (I. C. Change, 2014). The current change in the climate is correlated with endangering environmental phenomena such as increased precipitation changes, rising sea levels, and global warming. Researchers explain that the current trend in climate change is a direct result of the increase of greenhouse gas production such as carbon dioxide, which has increased 40% within the last century and a half (I. C. Change, 2014).

## 1.2 Human Population and Built Environment Expansion

The human population globally is experiencing rapid growth facilitated by advances in health care, food production, material manufacturing, transportation, and construction. The rapid population growth and the shift from a rural to urbanized life contributes to the large built environment expansion. As a result of the growing urbanized human lifestyle, human-made carbon emissions increase yearly resulting in global warming (UN, 2011). By 2050, the urban population is estimated at 85% for developed regions and 60% for developing regions (Stocker et al., 2013).

## 1.3 Global warming

Global warming is the gradual rise in the average surface temperature of the Earth’s climate system. Global warming is a key aspect of climate change, as it has been observed by direct temperature measurements. Climate change and global warming are terms that are frequently used interchangeably (I. C. Change, 2014). The increase in global surface temperatures and its forecasted continuation that is caused by human-made greenhouse gas emissions is considered as global warming, while climate change involves both global warming and its impacts, such as shifts in precipitation. Greenhouse gases such as methane, nitrous oxide, and most importantly carbon dioxide are concluded to influence global warming directly. Simulated climatic modelling projects an increase in global surface temperature by a lower 1.5°C or a higher 4.5°C, depending on the growth rate of greenhouse gas emissions (Stocker et al., 2013).

## 1.4 Energy Consumption and Cooling

More than half of the global population lives in urban built environments. The built environment accounts for the consumption of roughly 40% of the total energy produced primarily from non-renewable energy sources (EIA, 2019). The non-renewable energy focused consumption generates about a third of global carbon emissions (Stocker et al., 2013) (IEA, 2018).

In the built environment, space conditioning is a significant energy use sector about 16% globally (IEA, 2018). Space cooling is the largest end-use of energy consumption in warm climates, consumption as high as 40% of the building energy could be used for space cooling, (IEA, 2018). Space cooling energy demand globally is projected to triple by 2050 (IEA, 2018). As the largest expansion of the built environment will be in inherently warmer climate developing regions. Space cooling energy demand in warmer climatic regions will witness the greatest increase. As space cooling is a means of establishing habitable built environments, understanding space cooling and the associated energy consumption through thermal comfort in a warming world presents the opportunities for its optimization.

## 2 Background

### 2.1 Measuring Thermal Comfort

Thermal comfort is a significant component of building design in the context of the built environment. Thermal comfort impacts building occupant satisfaction and energy demands. Standards exist for achieving and maintaining thermal comfort throughout the built environment. The International Organization for Standardization (ISO) 7730 (ISO, 2005), the ASHRAE Standard 55 (ASHRAE, 2010), the European Standard (EN) 15251 (CEN, 2007), and the CIBSE (The Chartered Institution of Building Services Engineers) Environmental Design Guide (CIBSE, 2015) are examples of entities that address the guidelines and regulations of thermal comfort in the built environment. Assessing thermal comfort involves the combination and evaluation of physical and subjective metrics. The physical metrics evaluate the thermal environment of a space. Physical parameters such as the air temperature, the mean radiant temperature, the air velocity, the relative humidity, the occupant clothing insulation value, and the metabolic rate, are considered in assessing the thermal comfort within a building (ASHRAE, 2010; CEN, 2007; CIBSE, 2015; ISO, 2005). Additionally, the thermal sensation and preference votes are subjective metrics for assessing thermal comfort within a building. Thermal comfort models such as the predicted mean vote attempt to identify the thermal sensation of a building's occupant through evaluating physical parameters (ASHRAE, 2010; CEN, 2007; CIBSE, 2015; Fanger, 1970; ISO, 2005; Toftum & Ole Fanger, 2002). Assessing thermal comfort in principle depends on assessing subjective thermal comfort metrics such as the thermal sensation and preference vote through occupant responses or calculations.

In thermal comfort studies, subjectively assessing building occupant’s thermal sensation in each environment involves gathering the thermal sensation vote given by occupant responses. The thermal sensation vote as a metric most accurately describes the occupant’s thermal sensation response as it takes into consideration any prejudices based upon age, sex, body mass, metabolic rate, clothing, and thermal adaptation (ASHRAE, 2010; CEN, 2007; ISO, 2005). The thermal sensation vote is most commonly gathered on a seven-point thermal scale from cold (-3) to hot (+3) (ASHRAE, 2010; CEN, 2007; ISO, 2005). In addition, a subjective metric like the thermal sensation vote is the thermal preference vote. The thermal preference vote assesses the occupant’s thermal preference by indicating the desire to be warmer, cooler, or to have no change. The thermal preference vote conveys an accurate description of the occupant’s thermal preference as it directly indicates their thermal preference in the given environment. The thermal preference vote is gathered on a preference scale of warmer, cooler, and a no-change (ASHRAE, 2010; CEN, 2007; ISO, 2005). The thermal sensation gathers the building occupant’s response on a thermal scale. The thermal preference vote can either represent a desire of cooler, warmer, or no change either aligning with the thermal sensation vote or not. The agreement of both the thermal sensation and preference vote on either the cold or hot thermal discomfort identifies the occupant’s thermal attitude towards a given space.

### 2.2 Comfort Temperature

Evaluating a groups’ thermal sensation votes in relation to the existing internal temperature through the Griffiths method can establish the proposed comfort temperature for that group (Baker & Standeven, 1997; Griffiths, 1990; Humphreys, 1998; F Nicol et al., 1994; Fergus Nicol & Roaf, 1996; Oseland et al., 1998). The Griffiths method assumes that the comfort temperature represents a neutral vote (0) on a thermal scale. The relationship between the comfort temperature on a thermal sensation scale in relation to the internal temperatures is represented by a coefficient in the Griffiths method (Griffiths, 1990). The Griffiths coefficient is identified as the Griffiths constant with the values for the constants generally applied being 0.25, 0.33 and 0.50 (F Nicol et al., 1994; Rijal et al., 2010). The size of the group of votes and the Griffiths constant affect the accuracy of the evaluated comfort temperature. Thermal comfort studies evaluate the comfort temperatures by employing several Griffiths constants (Bouden & Ghrab, 2005; Indraganti, 2010; F Nicol et al., 1994; Rijal et al., 2010).

### 2.3 Energy Performance Simulation

EnergyPlus is a software that simulates whole building performance through building systems operations and thermal equations in an energy model under given parameters. EnergyPlus facilitates the manipulation of parameters such as the building schedule, the envelope of the building, the systems for space conditioning, etc. Through these manipulations, EnergyPlus allows for the evaluation and optimization of the performance of buildings (Crawley et al., 2000). Additional parameters are constants in the energy simulations as effects of the environment, such as climatic conditions included in simulations as weather data (Crawley et al., 2000). In the building energy simulations, weather data are common parameters. Weather data files contain for an annual period, hourly combined weather trend data (Crawley, 1998). To correctly evaluate the associated building energy demand for maintaining habitable building conditions the weather data reflects the existing climatic conditions in the energy model.

Global warming presents a change in the climatic conditions resulting in changes in building energy demand. With the change of the climate, space conditioning demands in either cooling or heating can be significantly altered. To assess future impacts on energy demand in the built environment the morphing method of current weather data to suggest future climatic conditions based on carbon emission data is applied (Belcher et al., 2005). The morphing method joins the existing weather data with global emission scenarios to reflect the average weather in the future while maintaining the existing weather patterns from the source weather data. The morphing method results in morphed weather data that are considered in building thermal simulations of future climatic conditions (Belcher et al., 2005).

## 3 Methods

The field study conducted collected thermal comfort data in Doha through field visits of various buildings. Buildings were selected that represent a large office working environment which range from private to public organizations. The timing of the field data collection was scheduled during the summer of 2019 as the summer periods within warmer climates heavily rely on active cooling systems to offset the heat. Data collection started on June 14$^{th}$ and ended on August 20$^{th}$ of 2019, with a total of 4 visits to 4 buildings during this period.

Qualitative metrics such as the thermal sensation vote and the thermal preference vote were collected in questionnaires. The questionnaires collected were presented to the occupants in an English and Arabic format. Explanations of the data collection and procedures of input were made available upon the beginning of the data collection. Consent of the building's occupant was acquired for their participation.

A questionnaire incorporating standardized thermal comfort questions found in ISO 7730 was used for collecting occupant responses. The questionnaire was made anonymous for the occupants to maintain anonymous responses. Additionally, the questionnaire established the use of a continuous scale on several thermal comfort questions. The distribution of the questionnaire was made to occupants of the building that have been in a prolonged seated position to ensure a stable metabolic level that corresponds to seating.

The environmental parameters collected within the field study were the air temperature, mean radiant temperature, relative humidity, and air velocity. The environmental parameters are measured using calibrated thermal environment measurement sensors which conform to ISO 7730. The air temperature and relative humidity measurements are collected using the Swema HC2A-S air humidity probe, mean radiant temperature measurements are collected using the Swema 05 767370 globe temperature sensor, and the air velocity measurements are collected using the Swema 03 767360 anemometer. The measurements of the environmental parameters are taken as spot readings at the desk of each building occupants' workplace. This is conducted for each occupant that is included in the study. In addition, to the physical measurement, a note of the time, date, building setpoint temperature, and external weather conditions are made. Further, images are captured of any observable indications of excessive cooling in additive clothing or alteration to cooling system equipment.

### 3.1 Establishing the Thermal Discomfort Classifications

Combining warm or cool thermal discomfort votes in the thermal sensation and preference vote metrics establishes the thermal discomfort classification. The location of the thermal sensation vote on a seven-point thermal scale describes the votes discomfort. A thermal sensation vote above (+1) is warm thermal discomfort, below (-1) is cool thermal discomfort, and in between represents neutral thermal comfort. Additionally, the identification of the thermal preference vote on a thermal preference scale describes the vote's discomfort. A thermal preference vote of cooler is warm thermal discomfort, a vote of warmer is cool thermal discomfort, and a vote of no change represents neutral thermal comfort. The combination of both the warm thermal discomfort occurrences in the thermal sensation and preference votes account for a definite warm thermal discomfort classification as identified by the occupant. In addition, the combination of both the cool thermal discomfort occurrences in the thermal sensation and preference votes account for a definite cool thermal discomfort classification as identified by the occupant. For each study, the warm and cool thermal discomfort classifications are evaluated for the definite combinations ignoring periphery and contradicting combinations.

### 3.2 Establishing the Thermal Discomfort Distributions

The warm and cool thermal discomfort distributions within a given building are evaluated by accounting for the warm and cool thermal discomfort classification percentages in each building respectively. Calculating the warm thermal discomfort distribution percentage involves accounting for all responses that are classified as a warm thermal discomfort against the total responses in the study. Moreover, calculating the cool thermal discomfort distribution percentage involves accounting for all responses that are classified as a cool thermal discomfort against the total responses in that study. For each building, the warm and cool thermal discomfort distributions are calculated.

### 3.3 Comfort Temperature Calculations

The Griffiths method is used to evaluate the proposed comfort temperature for each building using equation (1) (Griffiths, 1990; F Nicol et al., 1994).

$$Tcg = Tg + (0 - TSV) / G \tag{1}$$

The evaluated comfort temperatures Tcg 0.25, Tcg 0.33, and Tcg 0.50 are the comfort temperature by Griffiths' method (°C) with the associated Griffiths coefficient (G) respectively (Griffiths, 1990). The Griffiths coefficient applied is 0.50 as it conforms with thermal comfort research and represents the lowest comfort temperature (F Nicol et al., 1994; Rijal et al., 2010). The internal temperatures are taken from Tg (°C). The thermal sensation vote (TSV) is collected from each occupant's response.

### 3.4 Building Energy Simulations in Current and Morphed Climatic Conditions

Applying EnergyPlus as a whole building energy simulation program and the ANSI/ASHRAE/IES standard 90.1 large office prototype building model, comparative simulations are conducted (DOE, 2019). The ASHRAE climate zone variant of the ANSI/ASHRAE/IES standard 90.1 large office prototype building model is selected for Doha based upon the classification in the ASHRAE climate zone and subtype (DOE, 2018). Additionally, the weather data for Doha's climate is acquired from the ASHRAE weather data center (ASHRAE). The weather data is imported from the data center in EnergyPlus Weather Format (EPW) in the simulation for each model (Crawley, 1998). The comparison study is conducted by simulating the operation of a building in Doha in the initial temperature conditions from the collected setpoint temperatures and the proposed comfort temperature conditions by use of Griffiths method rounded to the nearest 0.5°C. The application of the temperature conditions is through creating different building cooling setpoint schedules. The schedule uses the initial temperatures and the proposed comfort temperatures with a two-degree (°C) setback after working hours for each building respectively. The buildings are simulated in the current climatic conditions to represent the energy demand for both the initial and comfort temperature schedules. The simulated building energy demand is calibrated to current building energy use intensities for cooling demand and whole building energy demand provided by the Qatar national energy provider's calculated energy use intensity averages (Kahramaa, 2014, 2017).

Comparing the simulations for the buildings represents the energy demand difference between the two scenarios. Further, the same process is followed with the morphed climatic conditions. Representing future climatic conditions to assess the projected energy demand requires the morphing of current weather data (Belcher et al., 2005) Current weather data in an EnergyPlus Weather Format (EPW) is morphed based on emission projections to represent the future climatic conditions in 2050 using the climate change world weather file generator tool (CCWorldWeatherGen) (Jentsch et al., 2013). The (CCWorldWeatherGen) tool relates the Intergovernmental Panel on Climate Change Third Assessment Report (IPCC TAR) model summary data of the Hadley Centre Coupled Model version 3 (HadCM3) experiment (C. Change, 2001) to generate the climatic conditions. This application facilitates the application of the "morphed" weather data that represent the climatic conditions in 2050 in energy simulations. Comparably, the comparison simulation in the morphed climatic conditions is conducted by simulating the operation of the buildings in Doha in the initial temperature conditions from the setpoint temperatures and the rounded comfort temperature conditions by use of Griffiths method. Furthermore, The building energy demand difference between the morphed and unmorphed scenarios are evaluated based upon the calibration of the unmorphed simulations to known building energy use intensities in Qatar (Ayoub et al., 2014; Kahramaa, 2014, 2017; Krarti et al., 2017).

## 4 Results

### 4.1 Thermal Comfort Conditions in the Doha Built Environment

The buildings examined during the filed visit of Doha represent typical buildings in Qatar. All buildings are actively cooled and heated through building centralized air conditioning systems and maintain non-operable windows throughout as dust is an issue in desert climates. During the data collection period from June 14th to August 20th of 2019, the average external temperatures ranged from 42°C to 45°C as the high dry bulb temperature and from 39°C to 43 °C as the low dry bulb temperature (Table 1). The total occupant response collected was 165, 40 female responses and 125 male responses are included from the buildings surveyed (Table 1). The average age of the building occupants was 38 years.

**Table 1 Doha Buildings Study Summary**

| Study Name | Code | Occupants Surveyed | Occupants Responses | Average Age | Day of Visit | Setpoint (°C) | High Tdb (°C) | Low Tdb (°C) |
|---|---|---|---|---|---|---|---|---|
| Public Building 1 | BPU1 | 39 | 11 (F) 28 (M) | 38 | 6/17/2019 | 22.0 | 42 | 39 |
| Public Building 2 | BPU2 | 36 | 24 (F) 12 (M) | 39 | 7/17/2019 | 22.0 | 45 | 39 |
| Private Building 1 | BPR1 | 55 | 5 (F) 50 (M) | 36 | 8/20/2019 | 23.5 | 43 | 39 |
| Private Building 2 | BPR2 | 36 | 1 (F) 35 (M) | 48 | 7/15/2019 | 24.0 | 45 | 43 |

Observing the thermal comfort conditions in the Doha built environment identifies slight variations in the public and private buildings (Table 2). The mean internal temperatures recorded in the study are observed to be in range with the temperature setpoints with minimal deviation (Table 1,2). In public buildings, the observed internal temperatures are cooler than private buildings which is also observed in the average TSV and TPV values as cooler votes. The PMV values for the buildings are in majority within acceptable ranges and the PPD does not exceed 15% (Table 2). Clothing values recorded in the study are observed to be in the range of 1.27 to 0.94 CLO with slight deviation (Table 2). As the study involved seated occupants within office settings the assumed MET value is 1.20 (Table 2).

**Table 2 Doha Buildings Study Thermal Comfort Summary**

| Study Name | Size | TSV | TPV | PMV | PPD | Ta (°C) | Tg (°C) | Rh (%) | Av (m/s) | CLO | MET |
|---|---|---|---|---|---|---|---|---|---|---|---|
| BPU1 | 39 | -0.76 | -0.11 | 0.35 | 11.45 | 22.10 | 22.42 | 52.03 | 0.13 | 1.18 | 1.20 |
| Std. Dev. | | 1.42 | 1.43 | 0.43 | 5.58 | 1.60 | 1.42 | 6.18 | 0.14 | 0.23 | 1.20 |
| BPU2 | 36 | -1.31 | -0.16 | 0.24 | 9.03 | 21.65 | 21.47 | 58.22 | 0.20 | 1.27 | 1.20 |
| Std. Dev. | | 1.40 | 1.27 | 0.38 | 2.74 | 0.31 | 0.20 | 4.73 | 0.21 | 0.31 | 1.20 |
| BPR1 | 55 | -0.31 | 0.06 | 0.66 | 15.00 | 24.75 | 24.84 | 38.77 | 0.18 | 1.09 | 1.20 |
| Std. Dev. | | 1.36 | 1.03 | 0.19 | 4.72 | 0.76 | 0.64 | 1.91 | 0.22 | 0.14 | 1.20 |
| BPR2 | 36 | -0.67 | 0.15 | 0.31 | 9.61 | 23.74 | 24.02 | 43.64 | 0.12 | 0.94 | 1.20 |
| Std. Dev. | | 1.06 | 0.90 | 0.35 | 4.43 | 0.86 | 0.81 | 2.07 | 0.09 | 0.25 | 1.20 |

### 4.2 Thermal Discomfort Conditions in the Doha Built Environment

Observation of the thermal comfort conditions of the buildings in the Doha built environment identifies several indications of excessive active building cooling. An elevated cool thermal discomfort in contrast to warm thermal discomfort is observed in all buildings based on the collected occupant responses. The elevated cool thermal discomfort percentage is greater in public buildings compared to private buildings (Figure 1-8). Considering the highest evaluated comfort temperatures by the Griffiths method, the suggest comfort temperatures evaluated are on average higher from the building setpoint temperature by a range of 1.5-2 °C (Table 3). The PMV observed in the buildings predicts the thermal sensations to be on average in the acceptable PMV range. However, the PMV illustrates higher thermal sensation in contrast to the range of observed thermal sensation votes (Table 3).

**Table 3 Public Building 1 Thermal Comfort Summary**

| Study Size | Item | TSV | TPV | PMV | Ta (°C) | Tg (°C) | Tc 0.50 (°C) | Tc 0.33 (°C) | Tc 0.25 (°C) |
|---|---|---|---|---|---|---|---|---|---|
| 39 | Mean | -0.76 | -0.11 | 0.35 | 22.60 | 22.42 | 23.95 | 24.74 | 25.48 |
| | Std. Dev. | 1.40 | 1.42 | 0.43 | 1.40 | 1.40 | 2.29 | 3.61 | 4.91 |
| | Max | 3.00 | 2.40 | 0.93 | 24.67 | 25.63 | 28.47 | 31.56 | 34.47 |
| | Min | -3.00 | -3.00 | -1.08 | 19.81 | 19.63 | 17.50 | 14.41 | 11.50 |

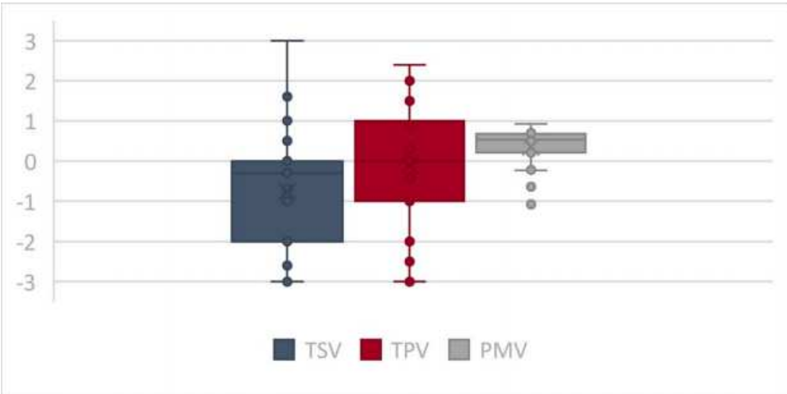



Figure 1, Thermal sensation vote, thermal preference vote, and predicted mean vote distribution on the seven-point thermal scale for Public Building 1

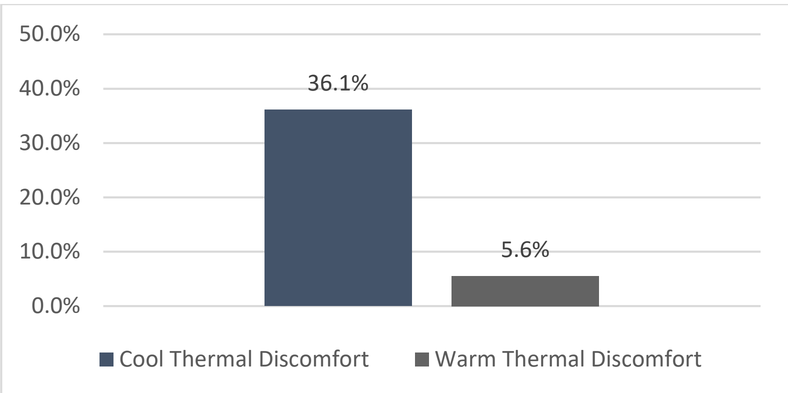



Figure 2, Percentage comparison of thermal discomfort based upon the combined thermals sensation and preference metric for Public Building 1

## Table 4 Public Building 2 Thermal Comfort Summary

| Study Size | Item | TSV | TPV | PMV | Ta (°C) | Tg (°C) | Tc 0.50 (°C) | Tc 0.33 (°C) | Tc 0.25 (°C) |
|---|---|---|---|---|---|---|---|---|---|
| 36 | Mean | -1.31 | -0.16 | 0.24 | 21.65 | 21.47 | 24.09 | 25.45 | 26.72 |
| | Std. Dev. | 1.38 | 1.26 | 0.37 | 0.31 | 0.20 | 2.76 | 4.18 | 5.51 |
| | Max | 3.00 | 2.00 | 0.65 | 22.71 | 21.89 | 27.77 | 30.86 | 33.77 |
| | Min | -3.00 | -3.00 | -0.65 | 21.24 | 21.09 | 15.64 | 12.55 | 9.64 |

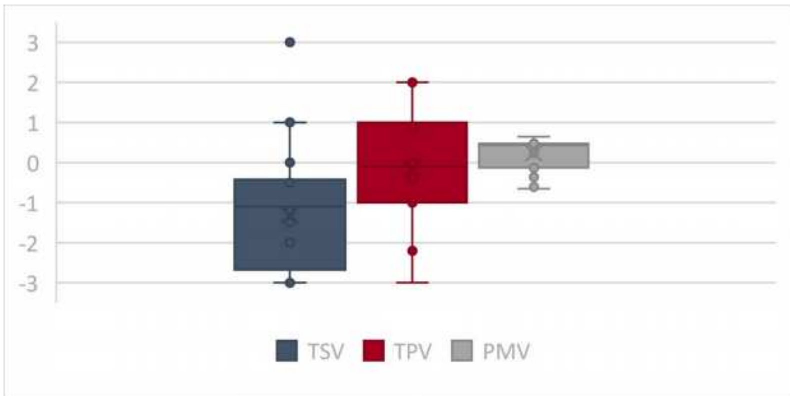



Figure 3, Thermal sensation vote, thermal preference vote, and predicted mean vote distribution on the seven-point thermal scale for Public Building 2

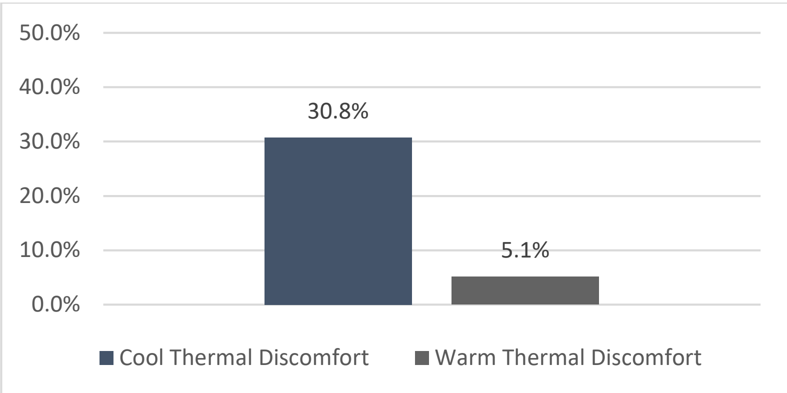



Figure 4, Percentage comparison of thermal discomfort based upon the combined thermals sensation and preference metric for Public Building 2

## Table 5 Private Building 1 Thermal Comfort Summary

| Study Size | Item | TSV | TPV | PMV | Ta (°C) | Tg (°C) | Tc 0.50 (°C) | Tc 0.33 (°C) | Tc 0.25(°C) |
|---|---|---|---|---|---|---|---|---|---|
| 55 | Mean | -0.31 | 0.06 | 0.66 | 24.75 | 24.84 | 25.46 | 25.78 | 26.09 |
| | Std. Dev. | 1.35 | 1.02 | 0.19 | 0.75 | 0.63 | 2.76 | 4.12 | 5.42 |
| | Max | 3.00 | 2.00 | 0.94 | 25.76 | 25.71 | 31.63 | 34.72 | 37.63 |
| | Min | -3.00 | -2.00 | 0.08 | 23.64 | 23.98 | 18.40 | 15.31 | 12.40 |

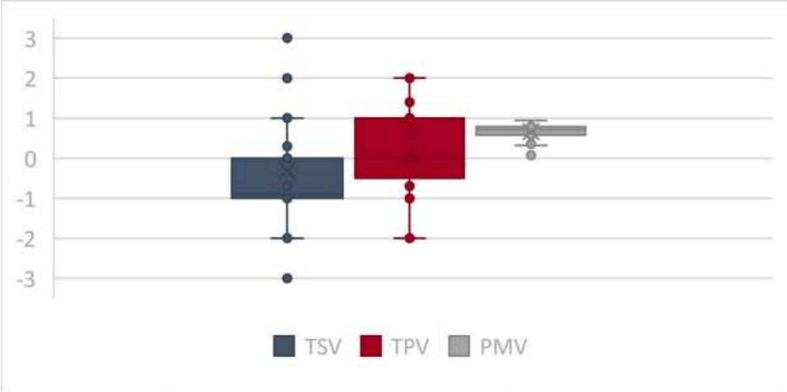



Figure 5, Thermal sensation vote, thermal preference vote, and predicted mean vote distribution on the seven-point thermal scale for Private Building 1

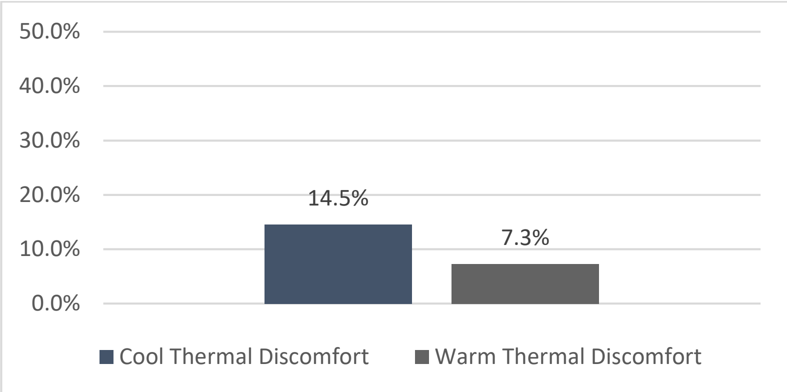



Figure 6, Percentage comparison of thermal discomfort based upon the combined thermals sensation and preference metric for Private Building 1

### Table 6 Private Building 2 Thermal Comfort Summary

| Study Size | Item | TSV | TPV | PMV | Ta (°C) | Tg (°C) | Tc 0.50 (°C) | Tc 0.33 (°C) | Tc 0.25 (°C) |
|---|---|---|---|---|---|---|---|---|---|
| 36 | Mean | -0.67 | 0.15 | 0.31 | 23.74 | 24.02 | 25.35 | 26.04 | 26.68 |
| | Std. Dev. | 1.05 | 0.89 | 0.35 | 0.85 | 0.80 | 2.26 | 3.29 | 4.29 |
| | Max | 1.00 | 2.00 | 0.79 | 24.73 | 24.99 | 30.81 | 33.90 | 36.81 |
| | Min | -3.00 | -2.00 | -0.31 | 22.34 | 22.30 | 21.41 | 20.48 | 19.61 |

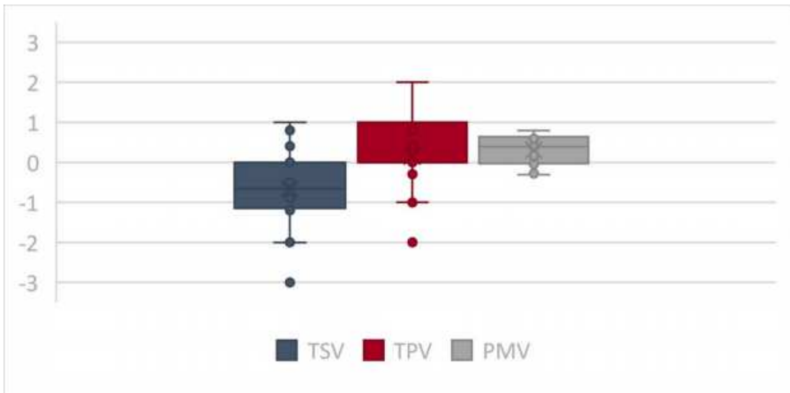



Figure 7, Thermal sensation vote, thermal preference vote, and predicted mean vote distribution on the seven-point thermal scale for Private Building 2

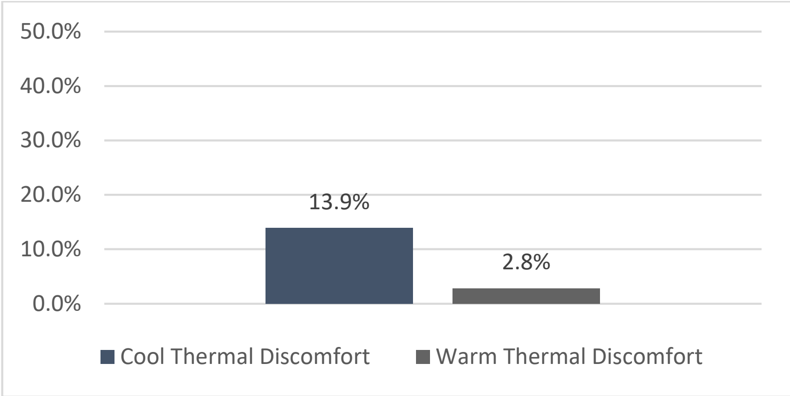



Figure 8, Percentage comparison of thermal discomfort based upon the combined thermals sensation and preference metric for Private Building 2

### 4.3 Unconventional Observations of Overcooling

Observing the thermal comfort conditions through thermal comfort metrics in the buildings have identified hints of excessive cooling. In addition, unconventional evidence of excessive cooling is observed during the field visits. Observed alterations of the cooling system equipment are attempts by occupants to minimize the cooling in the offices they occupy. Elements such as napkins, papers, and cardboard are used to reduced or block the cooler airflow from the ducts (Figure 9).

Figure 9, Images of observed occupant alterations to building air cooling distribution systems

Also, additional garments and jackets are used frequently in the cold office setting as methods of warming. These garments and jackets can be found in offices as if they are part of the permanent office fixtures. Further, the garments would also remain in the offices and not be taken home later once the occupant left the office at the end of the day (Figure 10).

Figure 10, Images of occupant's garments in offices as additional insulation for warming when needed

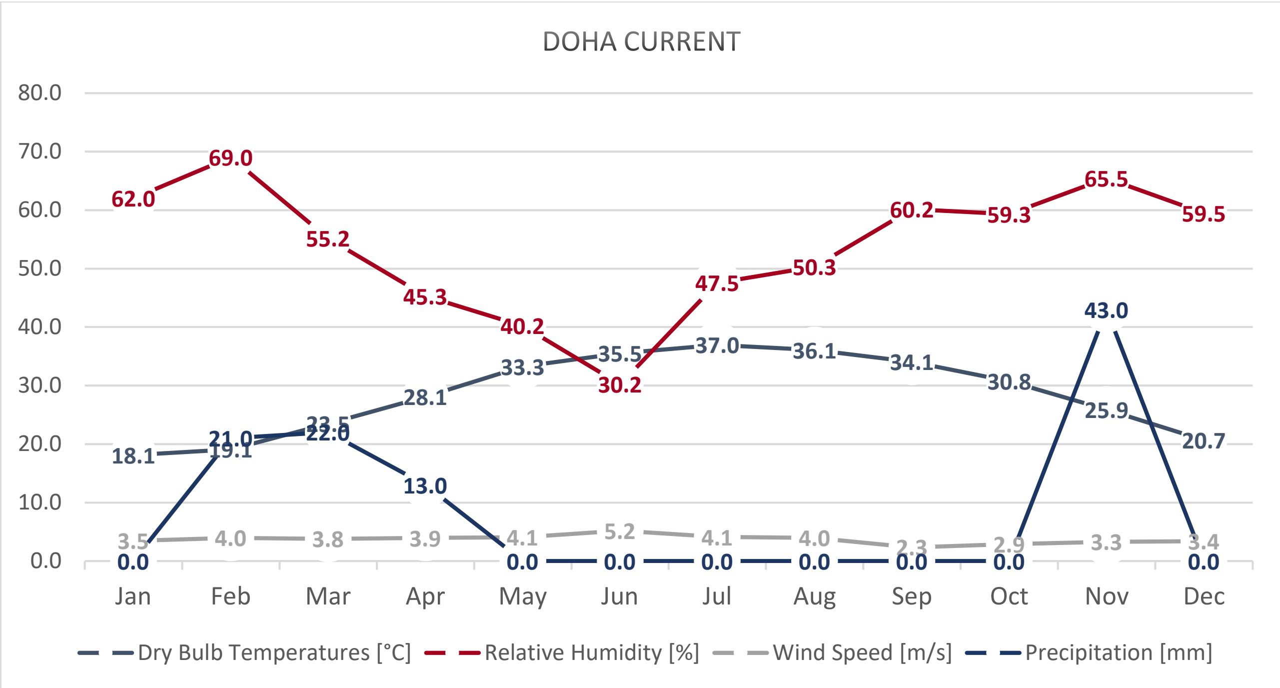
Discussions with the building occupants during the field visits have noted accounts of behavioural adjustments as measures of gaining heat in the cold environment. Occupants resort to taking several breaks throughout the workday outside the building to heat their bodies. In addition, occupants have stated relying on hot beverages to keep warm.

### 4.4 Current and Morphed Climatic Conditions

Observing the current and morphed climatic conditions of Doha depicts the climatic warming in 2050. The current climatic conditions of Doha represent an average external temperature ranging from 35.5 - 37.0 °C during the summer season and 18.1 – 25.9 °C during the winter season (Table 7). The relative humidity follows an opposite pattern of higher humidity range from 59.5 – 69.0 % during the winter season and lower humidity range from 30.2 – 50.3 % in the summer season (Table 7). As Doha is a desert climate, precipitation is minimum throughout the year increasing slightly in the winter monsoon season (Table 7).

**Table 7 Doha Current Monthly Climatic Conditions**

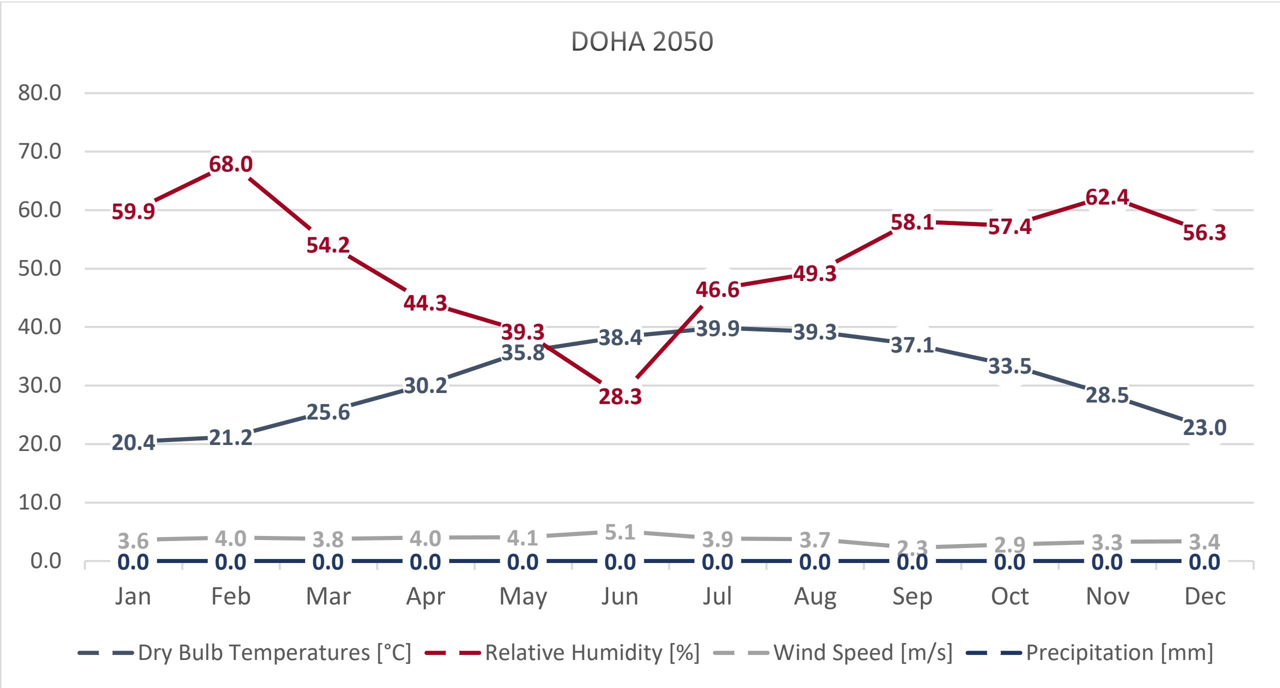
| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Dry Bulb Temperatures [°C]** | 18.1 | 19.1 | 23.5 | 28.1 | 33.3 | 35.5 | 37.0 | 36.1 | 34.1 | 30.8 | 25.9 | 20.7 |
| **Relative Humidity [%]** | 62.0 | 69.0 | 55.2 | 45.3 | 40.2 | 30.2 | 47.5 | 50.3 | 60.2 | 59.3 | 65.5 | 59.5 |
| **Air Velocity [m/s]** | 3.5 | 4.0 | 3.8 | 3.9 | 4.1 | 5.2 | 4.1 | 4.0 | 2.3 | 2.9 | 3.3 | 3.4 |
| **Precipitation [mm]** | 0.0 | 21.0 | 22.0 | 13.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 43.0 | 0.0 |




The morphed climatic conditions of Doha illustrate an increase in the average external temperatures ranging from 35.8 - 39.9 °C during the summer season depicting an average increase in temperature by 2.70 °C from the current conditions. The winter season temperatures range from 20.4 – 28.5 °C during the winter season depicting an average increase in temperature by 2.45 °C from the current conditions (Table 8). The relative humidity follows a similar opposite pattern of higher humidity during the winter season and lower humidity in the summer season with an average of 2 % decrease in relative humidity as temperatures are higher throughout the year and can hold more moisture (Table 8). Moreover, precipitation is minimum throughout the year increasing slightly during the monsoon season (Table 8).

**Table 8 Doha Morphed Monthly Climatic Conditions**

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Dry Bulb Temperatures [°C] | 20.4 | 21.2 | 25.6 | 30.2 | 35.8 | 38.4 | 39.9 | 39.3 | 37.1 | 33.5 | 28.5 | 23.0 |
| Relative Humidity [%] | 59.9 | 68.0 | 54.2 | 44.3 | 39.3 | 28.3 | 46.6 | 49.3 | 58.1 | 57.4 | 62.4 | 56.3 |
| Air Velocity [m/s] | 3.6 | 4.0 | 3.8 | 4.0 | 4.1 | 5.1 | 3.9 | 3.7 | 2.3 | 2.9 | 3.3 | 3.4 |
| Precipitation [mm] | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |




### 4.5 Energy Consumption in Warm and Warmer Conditions

Examining the simulated energy use for the initial setpoint temperature scenario results in an average energy use intensity of 127.7 KWh/m$^2$ for the total building energy demand and roughly 38.3 KWh/m$^2$ for a 30% cooling energy demand (Table 9). Qatar's national energy provider Kahrama's annual energy statistics report states an average energy use intensity of 131.9 KWh/m$^2$ for typical office buildings (Kahramaa, 2014, 2017). In addition, the U.S. Department of Energy (DOE) Standard Benchmark Energy Utilization Index states an average of 115.6 KWh/m$^2$ for office buildings within the 1A, 2A, and 2B ASHRAE climate zones. The difference between the simulated energy use for the initial setpoint temperature scenarios and the Qatar and DOE averages for office buildings is below 10%. The proximity of the simulated energy use to measured averages validates the energy models for further comparisons.

**Table 9 Doha Buildings Energy End-Use Summary in Current Climatic Conditions**

| Building Designation | BPU1 | BPU2 | BPR1 | BPR2 | Qatar 2014 | Qatar 2017 | USDOE 1A | USDOE 2A | USDOE 2B |
|---|---|---|---|---|---|---|---|---|---|
| Average Total Energy Use (KWh/m2) | 133.8 | 133.8 | 123.0 | 120.1 | 135.3 | 128.5 | 113.5 | 119.8 | 113.5 |
| Average Cooling Energy Use (KWh/m2) | 40.1 | 40.1 | 36.9 | 36.0 | 40.6 | 38.6 | 34.1 | 35.9 | 34.1 |

Observing the simulated energy demand for the initial and comfort temperature scenarios in both current and morphed climatic conditions of Doha represents the current and projected energy impact of excessive building cooling in Doha. The average cooling energy end-use for the buildings in current climatic conditions is 284.4 MWh accounting for an average of 44.6 % of the total energy demand (Table 10).

**Table 10 Doha Buildings Energy End-Use Summary in Current Climatic Conditions**

| | BPU1 | | BPU2 | | BPR1 | | BPR2 | |
|---|---|---|---|---|---|---|---|---|
| Energy End Use | Energy (MWh) | Portion (%) | Energy (MWh) | Portion (%) | Energy (MWh) | Portion (%) | Energy (MWh) | Portion (%) |
| Heating | 6.3 | 0.95% | 6.3 | 0.95% | 0.9 | 0.15% | 0.6 | 0.09% |
| Cooling | 306.0 | 45.90% | 306.0 | 45.90% | 268.6 | 43.82% | 257.0 | 42.96% |
| Interior Lighting | 83.7 | 12.55% | 83.7 | 12.55% | 83.7 | 13.65% | 83.7 | 13.99% |
| Exterior Lighting | 12.5 | 1.88% | 12.5 | 1.88% | 12.5 | 2.05% | 12.5 | 2.10% |
| Interior Equipment | 208.4 | 31.25% | 208.4 | 31.25% | 208.4 | 33.99% | 208.4 | 34.83% |
| Exterior Equipment | 3.3 | 0.49% | 3.3 | 0.49% | 3.3 | 0.53% | 3.3 | 0.55% |
| Fans | 46.6 | 6.98% | 46.6 | 6.98% | 35.6 | 5.80% | 32.8 | 5.48% |
| Pumps | 0.0 | 0.01% | 0.0 | 0.01% | 0.0 | 0.01% | 0.0 | 0.01% |
| Total End Uses | 666.8 | | 666.8 | | 613.0 | | 598.2 | |

Comparing the initial and comfort temperature building cooling scenarios illustrates an increase in energy demand on average by 16.1% with the associated average of 2.0 °C increase in internal temperature (Table 11). In addition, the average increase in the internal temperature by 1.5 °C is associated with a 12.6% increase in energy demand for cooling (Table 11).

**Table 11 Doha Buildings Initial and Comfort Temperature Cooling Energy Demands in Current Climatic Conditions**

| | Initial Temperature | | Comfort Temperature | | Difference | | |
|---|---|---|---|---|---|---|---|
| | Temperature (°C) | Energy (MWh) | Temperature (°C) | Energy (MWh) | Temperature (°C) | Energy (MWh) | Change (%) |
| BPU1 | 22.0 | 306.0 | 24.0 | 257.0 | 2.0 | 49 | 16.01% |
| BPU2 | 22.0 | 306.0 | 24.0 | 257.0 | 2.0 | 49 | 16.01% |
| BPR1 | 23.5 | 268.6 | 25.5 | 224.6 | 2.0 | 44 | 16.38% |
| BPR2 | 24.0 | 257.0 | 25.5 | 224.6 | 1.5 | 32.4 | 12.61% |

In morphed climatic conditions, comparing the initial and comfort temperature scenarios represent an average energy demand increase by 14.5% associated with an average of 2.0 °C increase in internal temperature (Table 12). Additionally, the increase in the internal temperature by 1.5 °C is associated with an energy demand increase by 11.4% for cooling (Table 12).

**Table 12 Doha Buildings Initial and Comfort Temperature Cooling Energy Demands in Morphed Climatic Conditions**

| | Initial Temperature | | Comfort Temperature | | Difference | | |
|---|---|---|---|---|---|---|---|
| | Temperature (°C) | Energy (MWh) | Temperature (°C) | Energy (MWh) | Temperature (°C) | Energy (MWh) | Change (%) |
| BPU1 | 22.0 | 386.6 | 24.0 | 331.1 | 2.0 | 55.5 | 14.36% |
| BPU2 | 22.0 | 386.6 | 24.0 | 331.1 | 2.0 | 55.5 | 14.36% |
| BPR1 | 23.5 | 344.3 | 25.5 | 293.1 | 2.0 | 51.2 | 14.87% |
| BPR2 | 24.0 | 331.1 | 25.5 | 293.1 | 1.5 | 38 | 11.48% |

Comparing the initial temperature scenarios in current and morphed climatic conditions represent an average cooling energy demand increase by 27.4% associated with the warming of the climate alone (Table 13).

**Table 13 Doha Buildings Initial Temperature Cooling Energy Demands in Current and Morphed Climatic Conditions**

| | Current Climate | | Morphed Climate | | Difference | | |
|---|---|---|---|---|---|---|---|
| | Temperature (°C) | Energy (MWh) | Temperature (°C) | Energy (MWh) | Temperature (°C) | Energy (MWh) | Change (%) |
| BPU1 | 22.0 | 306.0 | 22.0 | 386.6 | 0 | 80.6 | 26.34% |
| BPU2 | 22.0 | 306.0 | 22.0 | 386.6 | 0 | 80.6 | 26.34% |
| BPR1 | 23.5 | 268.6 | 23.5 | 344.3 | 0 | 75.7 | 28.18% |
| BPR2 | 24.0 | 257.0 | 24.0 | 331.1 | 0 | 74.1 | 28.83% |

## 5 Discussion

Through the collection of the thermal sensation vote and the thermal preference votes, it is observed that the thermal sensation and preference vote depict an elevated cold thermal discomfort level in the buildings surveyed. These are indications of the occupants representing a cold thermal discomfort through the physical manipulation of the environment. In addition, Elevated levels of excessive cooling are apparent through the occupant’s clothing and manipulation of the cooling systems within the buildings. This result aligns the findings in the questionnaire to the occupant’s manipulation of the environment to maintain a warm body temperature in additive clothing and cooling system alterations.

The comfort temperatures found for the selected buildings all represented internal temperatures that are higher than the observed internal temperatures. This is an initial indication that occupants prefer warming internal temperatures. Additionally, the observed cooler thermal discomfort votes in the thermal sensation and preference metric align with the notion of a cold internal building temperature. Further, the observation of increased cooling is the underlying logic for the ongoing cultural conversations around occupants being cold in their workspaces. The increased level of cold thermal discomfort is associated with an excessive cooling of the building located within the warm climate of Doha. As the climate of Doha is a warm climate the only means of cooling is from active systems, therefore the excessive cold thermal discomfort is a result of resource use in a form of energy. Considering the increased warming phenomena of the globe, warmer temperatures imposed on buildings will increase resulting in additional energy use to cool the building. The current wasteful use of energy in overcooling buildings in the warm climate of Doha consumes as much energy as predicted by the effect of global warming alone. The understanding of cooling in the expanding warm climate built environment is considered relativity recent and requires additional research.

As the majority of developed regions are concentrated in heat demanding cooler regions, cool demanding warmer climates have been historically overlooked. There exists a shortage in complete current thermal comfort studies within warmer climates. Further research representing current space cooling culture is called for as current urbanization trends within developing warm climate regions are expected to significantly increase the issues of overcooling. In addition to being the largest sector of energy consumption within warm climate built environments, space cooling is likewise the fastest growing. Research around global space cooling projects a significant increase in future cooling demand. This increase is linked to population growth, the built environment expansion, and the increase in the availability and affordability of space cooling systems. Without a proper interpretation of overcooling within the built environment, attempts in its reduction would be unfeasible. Unresolved, overcooling will result in increased building occupant thermal discomfort and contribute to developing regions' energy consumption, considerably increasing its associated environmental degradation.

## 6 Conclusion

A field study is conducted in buildings of Doha to understand the thermal comfort conditions that exist within them. Elevated levels of cold thermal discomfort are observed through physical observations and collected occupant responses. Observing physical manipulations made by the occupants to keep warm to the environment highlights the excessive cooling within the building. Using the combined thermal sensation and preference metric, increased building overcooling in Doha are observed. The impact of overcooling on energy is estimated to be significant as the majority of the built environment expansion will see a focus in warmer climates where cooling demand is greater. In a warming world, global warming and the built environment expansion are expected to raise cooling demand even further. Without the means to reduce overcooling in warm climate buildings, occupant thermal discomfort, wasteful resource consumption, and increased global carbon emissions would persist.

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# Summertime indoor temperatures and thermal comfort in nursing care homes in London

**Rajat Gupta[1] and Alastair Howard[2]**

[1] Low Carbon Building Research Group, School of Architecture, Oxford Brookes University, UK, rgupta@brookes.ac.uk
[2] Low Carbon Building Research Group, School of Architecture, Oxford Brookes University, UK, ahoward@brookes.ac.uk

**Abstract:** The UK Government's 2018 National Adaptation Programme identified summertime overheating in care settings as a key risk and research priority for the health and social care system. This paper empirically investigates the risk of overheating during summer 2019 by monitoring indoor temperatures and thermal comfort in three purpose-built nursing care homes in London. The methodological approach combined continuous monitoring of indoor and outdoor temperature (objective data) with thermal comfort surveys of residents and staff (subjective data). The average indoor temperature during the monitoring period across the three care settings was measured as 25.8°C between 8am and 8pm, exceeding 30°C frequently, much above the Public Health England's recommended threshold of 26°C. Despite this, majority of residents found their thermal conditions 'neutral' even at high temperatures, while the responses of care staff were on the 'warm/hot' end of the thermal sensation scale. This difference was likely to be due to staff being more active that residents. Nevertheless staff were willing to put up with up with uncomfortably hot temperatures if they felt it was in the residents' best interest. Given that care settings are hybrid buildings (residential and offices), it is vital to provide adequate comfort to staff and residents through better management of the indoor environment.

**Keywords:** Care home, overheating, temperature, thermal comfort, monitoring

## 1. Introduction

The UK care home population is around 410,000 (CMA, 2017) and is increasing as the population continues to age. The Office for National Statistics predicts a 36% growth in persons aged 85+ between 2015 and 2025 (CMA, 2017), which will likely lead to a significant demand for care home services. Current climate predictions indicate that temperatures will continue to rise, bringing heatwaves more often and with greater severity. Research has shown that heat wave periods coincide with increased levels of mortality, and that elderly are vulnerable to heat-related deaths (Kovats et al., 2006). A study of heat-related mortality throughout England and Wales found the strongest correlation between heat and mortality in elderly people, particularly women, in nursing and care homes (Hajat et al., 2007). Medical conditions linked to excessive heat include cardiovascular and respiratory disease, heat stroke (leading to cell, organ and brain damage) and dehydration (leading to bloodstream infections) (PHE, 2014, Al-Hasan et al., 2009). High temperatures can also affect sleep, with studies finding that at least half of over-65-year-olds experience difficulty in sleeping (Martin et al., 2000), and those with dementia can experience 40% of their bedtime hours awake (Dewing, 2003).

During a ten-day heat wave in 2003, mortality in England and Wales increased by 13.5% in the under-75's, but by 33% in those aged 75 and over. In nursing homes, mortality increased by 42% (Kovats et al., 2006). Heat-related mortality could increase by more than 250% by 2050, the majority of which would be in vulnerable groups such as the elderly (Hughes and Natarajan, 2019). This is why the UK Government's 2017 Climate Change Risk Assessment report and the 2018 National Adaptation Programme has identified summertime overheating in care homes as a key risk and research priority for the health and social care setting (DEFRA, 2017, DEFRA, 2018).

Care homes in the UK have historically been designed to keep residents warm, and often have features such as heated corridors which are distinctive to residences for the elderly (Lewis, 2014) and heating systems which are designed to operate all year round. Care Quality Commission (the independent regulator of all health and social services in England) inspections include checking room temperatures and questioning staff on how they deal with residents feeling cold (Neven et al., 2015). Consequently, care homes can find themselves ill-prepared to regulate indoor temperatures during periods of high outdoor temperatures.

Given this context and the limited research on summertime performance of care homes in the UK, this study assessed three London-based care homes over the summer of 2019, combining temperature monitoring (indoor and outdoor) and repeated thermal comfort surveys with residents and staff. The overall aim of the study was to better understand the prevalence and severity of summertime overheating in care settings, and the perception of indoor temperature by those who live and work there.

## 2. Evidence to date

Extensive literature review was conducted to identify studies investigating the effects of hot environments on elderly people and their carers in the UK and internationally, as shown in Table 1 below. A study of nursing homes in the Netherlands found a correlation factor of $R^2$=0.9 for mortality rates and weekly average maximum daily temperature (Luscuere and Borst, 2002). Analysis of the 2003 heatwave in France found that it was the least physically fragile residents in nursing homes that were the most susceptible to heat-related illness, potentially because carers focussed their attention on more dependent residents, leaving the 'healthier', more independent residents to self-care, possibly unaware of the onset of their own heat-related illness (Anderson et al., 2013). In a study by Luff et al., residents were found to spend nearly 11 hours per night in bed, but a significant amount of this time was spent awake, with bedtimes and getting-up times often determined by staff shift patterns rather than resident choice (Luff et al., 2011).

Table 1 Selected studies investigating the effects of hot environments on elderly people and their carers in the UK and internationally.

| No. | Study | Methods | Key findings |
|---|---|---|---|
| **UK studies** | | | |
| 1 | (Abrahamson and Raine, 2009) | Interviews with older people and their carers (not in care homes) (London, UK). Themes included perception of vulnerability in relation to heat-related risks, likely actions in extreme heat and factors that may impede/promote protective behaviour. | Some respondents acknowledged that older people might be adversely affected by the heat, but they did not perceive themselves to be particularly vulnerable. Most respondents reported changing their behaviour during previous heatwaves and described taking 'common sense' actions, such as alterations to their routine. |
| 2 | (Guerra-Santin and | One care home (UK). Summer environmental and energy | Most staff considered the building to be too warm and reported to be |

| | | | |
|---|---|---|---|
| | Tweed, 2013) | monitoring in various locations (including bedrooms lounge, dining room, nurse station). 14 interviews (staff, not residents) concerning staff and resident comfort and the operation of the building. | (thermally) uncomfortable most of the time. |
| 3 | (Brown and Walker, 2013) | One residential care building (UK). Observation of care and conversations with residents and carers. Outdoor environment also monitored. | Residents encouraged to be dependent on staff. When hot weather arrived, residents therefore relied upon nursing staff to carry out preventative measures. Staff were not fully aware of how to manage heat effectively. |
| 4 | (Mavrogianni et al., 2015) | Three case study social housing dwellings (London, UK) occupied by vulnerable individuals (elderly/ill health/mobility impairment). Environmental monitoring used to inform modelling for future climates. | Temperature monitoring showed overheating in the current climate. Modelling suggested that improved natural ventilation strategies could help to reduce overheating in future climates. Night cooling and shading were found to be more effective than all-day rapid ventilation, but high outdoor temperatures could limit the effectiveness of this in future climates. |
| 5 | (Tweed et al., 2015) | Five extra-care homes and six care homes (UK). Interviews investigated influence of thermal conditions on use of space, preferred thermal environments and spaces, understanding of the thermal environment. | Interviews revealed that when conditions were not considered extreme, preferences for spaces were not usually determined by thermal conditions. However, the thermal environment was often cited as an important factor in the interviews. |
| 6 | (Lewis, 2015) | 13 interviews with those involved in the design, development and management of extra-care housing (UK). | Participants characterised the typical occupants of their buildings as vulnerable to cold, at risk from fuel poverty, at risk of being burned by hot surfaces or falling from high windows. These ideas were inscribed into the design of extra-care housing schemes (e.g. under-floor heating, restricted window opening and heated corridors). |
| 7 | (Walker et al., 2016) | Six care homes (UK). Interviews with care home owners, managers and staff. | Respondents understood the core function of care homes was to provide thermal comfort. Much more emphasis was placed on keeping residents warm than cool. Consequently, carers were routinely overheated, particularly when doing more physical work. Respondents consistently stressed cold as a risk to residents, with little discussion about risk of residents becoming too warm. |
| 8 | (Gupta, Barnfield and Gregg, 2017) | Two care and two extra-care homes (UK). Temperature monitoring, building surveys, interviews with design and | Summertime overheating was found to be a current and prevalent risk in the case study schemes, yet currently little awareness or preparedness existed to |

| | | | |
|---|---|---|---|
| | | management teams. | implement suitable adaptation strategies. There was a perception that cold represents a bigger threat to older occupants' health than excessive heat. A lack of effective heat management was found that included unwanted heat gains from the heating system, confusion in terms managing indoor temperatures, and conflicts between window opening and occupant safety. |
| 9 | (Gupta and Gregg, 2017) | Two care and two extra-care homes (UK). Dynamic thermal simulation. Interviews with design team. | Dynamic thermal simulation results demonstrated the magnitude of projected summertime overheating in care and extra-care schemes, yet there was little awareness amongst designers about the risk of overheating and implementation of long-term adaptation approaches such as external shading, provision of cross-ventilation. |
| **International studies** | | | |
| 10 | (Hwang and Chen, 2010) | Older people at home (not care home) (Taiwan). Questionnaires conducted alongside concurrent indoor environmental monitoring. Questions included thermal sensation and thermal preference votes, level of clothing and what thermal adaptation behaviours were used when thermally dissatisfied. | Only 8% of respondents used mechanical cooling (air-conditioning) as an adaptive strategy, compared to 34% using electrical fans and 90% using window-opening. The temperature range corresponding to 80% thermal acceptability in the summer was 23.2–27.1°C (around 2°C warmer than in the winter). |
| 11 | (Mourits, 2012) | Two nursing homes (Netherlands). Questionnaires/interviews for residents, family members, staff, volunteers and visitors. 5-point Likert scale used to investigate aspects of the building including accessibility, safety, space and indoor environment. | Staff found indoor temperatures uncomfortable; either too hot or too cold. Respondents had problems regulating temperature and ventilation. Both buildings used concrete core heating and cooling, so temperature adjustments were small and slow to respond. The cooling system meant staff were asked by facility managers to not open windows or doors on hot days, which was unpopular with staff and residents. |
| 12 | (Mendes et al., 2013) | Six elderly care centres (Portugal). Environmental monitoring in dining rooms, medical offices and bedrooms. Thermal comfort surveys conducted on residents. | Dissatisfaction with thermal conditions was lower in summer than in winter. Analysis showed that medical offices and bedrooms had the highest percent of dissatisfied residents in both summer and winter. |

Another common theme that emerged from the studies was the understanding that older people are more vulnerable to cold than excessive heat. This was seen in those who designed care homes (Lewis, 2015), managers and frontline carers (Walker et al., 2016) and residents (Abrahamson and Raine, 2009). Brown and Walker's observational research revealed institutionalisation whereby residents were encouraged to be dependent on staff to meet many of their needs (Brown and Walker, 2013). Consequently, when periods of hot weather came, residents did not take initiative themselves, even if they were cognitively and physically able to do so, because there was an expectation that their carers would deal with it. They also observed that some residents felt uncomfortable at the prospect of wearing lighter clothing during hot weather because it exposed more flesh, suggesting dignity may trump thermal comfort for some.

In a more recent study on care and extra-care settings in the UK, Gupta, Barnfield and Gregg (2017) and Gupta and Gregg (2017) study found summertime overheating was found to be a current and prevalent risk in the case study schemes, yet currently little awareness or preparedness existed to implement suitable adaptation strategies. The perception that older people 'feel the cold' was again prevalent.

Some studies have found that thermal comfort models (both PMV/PPD ISO 7730 and the adaptive ISO 15251) did not match the occupant responses, with occupants feeling comfortable at temperatures where the models predicted they should feel warm/hot (Hughes and Natarajan, 2019). However, at the same temperatures, carers have felt overheated (Walker et al., 2016, Guerra-Santin and Tweed, 2013, Mourits, 2012). This discrepancy between thermal comfort/preference for residents and carers is a fundamental issue that care homes face on a regular basis. This difference between thermal sensation of residents and staff will be empirically investigated in this study.

## 3. Methods and case studies

### 3.1. Environmental monitoring

The research methods used in this study were socio-technical and combined continuous monitoring of temperature and relative humidity (RH) (objective data) with a thermal comfort survey (subjective data). Indoor temperature and RH were recorded using Hobo UX100 and iButton loggers (logging at 5- and 10-minute intervals respectively). Outdoor temperature and RH were recorded at each case study using Hobo MX2300 loggers. Specifications for these devices are given in Table 2. Environmental monitoring was conducted during June, July and August 2019.

Table 2 Specification, accuracy and resolution of data loggers used in the study.

| Device | Measures and details | Specification | | |
|---|---|---|---|---|
| | | Range | Accuracy | Resolution |
| Hobo UX100 | Indoor temperature and RH | *Temperature:* -20 - +70 °C *RH:* 15 - 95% | *Temperature*: ±0.21 °C *RH*: ±3.5% | *Temperature*: 0.024 °C at 25 °C *RH*: 0.07% |
| iButton DS1922L | Indoor temperature | -40 - +85 °C | ±0.5 °C | 0.0625 °C |
| Hobo MX2301 | Outdoor temperature and RH | *Temperature:* -40 to +70 °C *RH:* 0 - 100% | *Temperature:* ±0.2 °C *RH*: ±2.5% | *Temperature:* 0.04 °C *RH*: 0.05% |

Devices were deployed in a number of locations within the care homes, categorised as 'offices' (staff-only locations), 'lounge/dining rooms' (communal areas used by residents and staff), and 'bedrooms'. The characteristics of the locations within the three case study care homes (AL, AS and VI) are shown in Table 3.

Table 3 Location characteristics of data loggers.

| Case study | Location type | Location code | Floor | Orientation | Temperature | RH | CO2 |
|---|---|---|---|---|---|---|---|
| AL | Office | ALO1 | G | south | ✓ | ✓ | ✓ |
| | | ALO2 | G | east | ✓ | | |
| | Lounge/ dining room | ALL1 | G | north + west | ✓ | ✓ | ✓ |
| | | ALL2 | 1 | north + east | ✓ | ✓ | ✓ |
| | | ALL3 | 1 | south + east | ✓ | | |
| | Bedroom | ALB1 | G | south | ✓ | ✓ | ✓ |
| | | ALB2 | 1 | | ✓ | ✓ | ✓ |
| | | ALB3 | 1 | east | ✓ | ✓ | ✓ |
| | | ALB4 | 1 | | ✓ | | |
| | | ALB5 | 2 | | | | ✓ |
| | | ALB6 | 2 | west | ✓ | | |
| | Outdoor | AL-outdoor | outdoor | outdoor | ✓ | ✓ | |
| AS | Office | ASO1 | G | west | ✓ | | |
| | | ASO2 | G | internal | ✓ | ✓ | ✓ |
| | | ASO3 | 2 | | ✓ | ✓ | ✓ |
| | Lounge/ dining room | ASL1 | G | west | ✓ | ✓ | ✓ |
| | | ASL2 | 1 | east | ✓ | ✓ | ✓ |
| | | ASL3 | G | | ✓ | | |
| | | ASL4 | G | south + west | ✓ | | |
| | Bedroom | ASB1 | G | east | ✓ | ✓ | ✓ |
| | | ASB2 | G | | ✓ | ✓ | |
| | | ASB3 | 1 | | ✓ | ✓ | ✓ |
| | | ASB4 | 1 | | ✓ | ✓ | |
| | | ASB5 | G | | ✓ | | |
| | Outdoor | AS-outdoor | outdoor | | ✓ | ✓ | |
| VI | Office | VIO1 | G | internal | ✓ | ✓ | ✓ |
| | Lounge/ dining room | VIL1 | 1 | north-east | ✓ | ✓ | ✓ |
| | | VIL2 | 2 | | ✓ | ✓ | |
| | Bedroom | VIB1 | 1 | | ✓ | ✓ | ✓ |
| | | VIB2 | 4 | south-west | ✓ | ✓ | ✓ |
| | Outdoor | VI-outdoor | outdoor | | ✓ | ✓ | |

### 3.2. Overheating metrics

Analysis of the data collected included testing for the prevalence of overheating using *static* and *dynamic* (adaptive) criteria, defined in Table 4. In the static definition of overheating, 'living areas' were taken to be offices and lounge/dining rooms. Occupied hours were defined as 09:00-18:00 (offices) and 08:00-21:00 (lounge/dining rooms). 'Bedrooms' in residential dwellings would generally not be occupied during the day. However, in care homes, some residents were bedbound and others chose to stay in their bedrooms throughout the day, effectively using them as a ‘living area’. Therefore for the analysis, bedrooms temperatures were divided into ‘day’ (07:00 – 22:00) and ‘night’ (22:00 – 07:00).

Table 4 Criteria for assessing overheating using static and dynamic criteria.

| | Overheating criterion | Definition |
|---|---|---|
| **Static** | CIBSE Guide A | 1% or more of occupied hours over 28°C in living areas.<br>1% or more of occupied hours over 26°C in bedrooms. |
| | Heatwave plan for England | A cool room/area within the building to be available where temperatures are kept below 26°C.<br>Excess deaths may become apparent at 24.5°C and higher. |
| **Dynamic (Adaptive)** | CIBSE Guide A | Threshold comfort temperature:<br>$T_{threshold} = 0.33(T_{outdoor}) + 21.8°C$ |
| | - Criterion 1 | Temperatures are at least 1°C above the threshold comfort temperature for ≥ 3% of occupied hours. |
| | - Criterion 2 | Daily weighted exceedance ($W_e$) ≥ 6.<br>$W_e = S(DT \times H_{DT})$<br>*where DT is the temperature difference above $T_{threshold}$ and $H_{DT}$ is the number of hours spent at DT* |
| | - Criterion 3 | Maximum indoor temperature is 4°C or more above $T_{threshold}$. |
| | Dynamic overheating is deemed to have occurred if any two of these three criteria have been fulfilled. | |

### 3.3. Thermal comfort surveys

Thermal comfort surveys were conducted up to three times a day on multiple days throughout the summer period, with a focus on days when outdoor temperatures were forecast to be warmer (Figure 1).

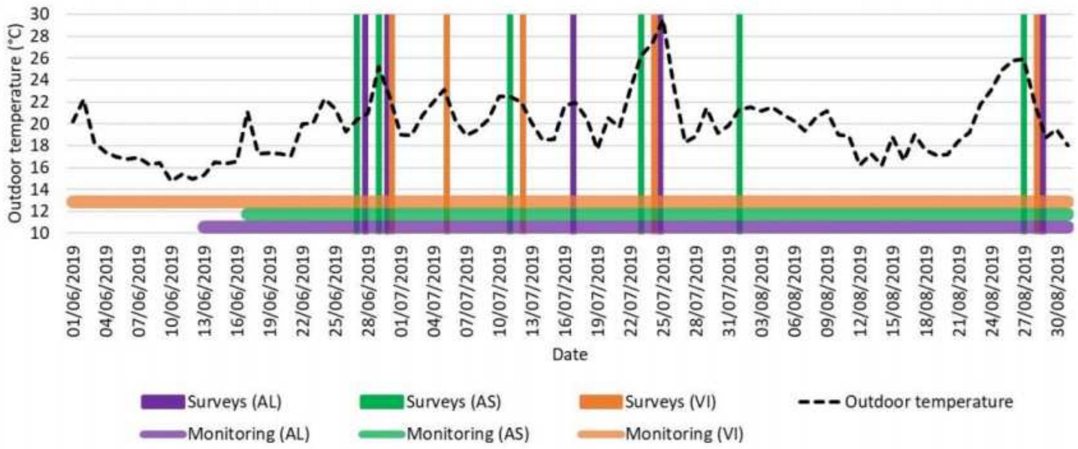



Figure 1 Daily outdoor temperatures (averaged across the three case study care homes, with indoor environmental monitoring periods and dates when surveys were conducted also shown.

A total of 477 surveys were conducted over the summer period, 53% with staff and 47% with residents (Table 5). It was necessary to be selective with residents who participated in the survey since many residents had a degree of dementia and/or communication difficulties that meant they were either unable to understand the questions or unable to provide appropriate responses. Their responses would have introduced randomness into the dataset, so it was necessary to exclude them from the thermal comfort surveys.

Table 5 Survey counts (staff and residents) in the care homes.

| Care home | AL | AS | VI | Total |
|---|---|---|---|---|
| **Staff** | 86 | 90 | 76 | **252** |
| **Residents** | 91 | 65 | 69 | **225** |
| **Total** | **177** | **155** | **145** | **477** |
| **No. of days surveys conducted** | *5* | *6* | *5* | *16* |

The surveys were designed to be brief, gathering thermal sensation and thermal preference votes from the respondents along with contextual information (Table 6). As the surveys were conducted, concurrent local environmental conditions were recorded using hand-held monitoring devices (Extec HT200 and ATP hotwire anemometer), allowing cross-relation of these subjective and objective datasets.

Table 6 Summary of data gathered from surveys.

| Measure | Response / data gathered |
|---|---|
| Thermal sensation: "At present I feel…" | Responses on a 7-point scale: cold / cool / slightly cool / neutral / slightly warm / warm / hot |
| Thermal preference: "I would prefer to be…" | Responses on a 5-point scale: much warmer / a bit warmer / no change / a bit cooler / much cooler |
| Clothing: "I am currently wearing…" | To indicate level of clothing insulation, 16 options including short sleeve shirt/blouse, trousers/long skirt, dress, tights, shoes, slippers |
| Activity: "In the last 15 minutes I have been" | To indicate active or passive behaviour, 7 options including sitting, standing, walking, laying down |
| Controls: "Where I am there is…" | Interviewer observed local controls including state of doors/windows, curtains/blinds, air conditioning, fans, lights |
| Contextual information | Date, time, location (floor/room), role (staff/resident) |
| Concurrent climate measurements | Air temperature, black globe temperature, relative humidity, air speed |

### 3.4. Overview of case study care homes

The key characteristics of the three care homes (AL, AS and VI) are shown in Table 7. All three homes catered residents over 65, many of whom were suffering from a range of dementia-related issues. Care home VI had a small number of younger residents (18-65 years old) who had various learning disabilities and mental health issues. Care homes AS and AL were similar in size, whereas care home VI had almost three times as many rooms.

Table 7 Key characteristics of the three case study care homes.

| Care home AL | Care home AS | Care home VI |
|---|---|---|
| **Location:** East London<br>**Built:** 1950's (purpose built)<br>**Type:** Nursing (local authority)<br>**No. of storeys:** 3<br>**No. of rooms:** 43<br>**Age of occupants:** 65+ | **Location:** West London<br>**Built:** 1980's (purpose built)<br>**Type:** Nursing (privately owned)<br>**No. of storeys:** 3<br>**No. of rooms:** 40 | **Location:** London NW10<br>**Built:** 2013 (purpose-built)<br>**Type:** Nursing (privately owned)<br>**No. of storeys:** 5<br>**No. of rooms:** 110<br>**Age of occupants:** Mainly 65+, |

| | | |
|---|---|---|
| **Care provided:** Includes dementia, Alzheimer's, old age<br>**CQC rating:** Good | **Age of occupants:** 65+<br>**Care provided:** Includes dementia, old age, nursing and palliative care<br>**CQC rating:** Good | with some 18+ residents with acute needs.<br>**Care provided:** Includes nursing, dementia, learning disabilities<br>**CQC rating:** Good |

## 4. Findings

### 4.1. Temperature monitoring

Temperatures in the care homes were consistently in the high-20's (°C) throughout the monitored period (June-August 2019) averaging 25.8°C between 8am and 8pm. In areas occupied by residents (lounges, dining rooms, bedrooms), indoor temperatures often exceeded 30°C and rarely fell below 23°C. The daily average indoor temperature profiles for the three care homes (Figure 2) show similar overall trends in relation to the outdoor temperatures. In care home AL, average lounge temperatures were higher than average bedroom temperatures. The ground floor offices were 1-2°C cooler than the lounges and bedrooms. In care home AS, the average office temperatures were significantly higher than lounges or bedrooms, skewed by the temperatures in the second floor staff room ALO3, located next to the laundry and boiler rooms, which reached temperatures of almost 40°C. The care staff was aware that this room was the hottest room in the building, and therefore rarely used it, preferring to spend their breaks in the dining rooms when residents were not eating. The ground floor office in care home VI was around 3°C cooler than the monitored lounges and bedrooms. This office was an internal room (i.e. with no windows, doors or walls to the outside) and thus much less affected by outdoor temperatures. In all three care homes, indoor temperatures spiked significantly during the two periods of particularly hot weather around 21st July 2019 and 25th August 2019, exacerbated by high overnight temperatures which prevented the buildings from purging their daytime heat gains.

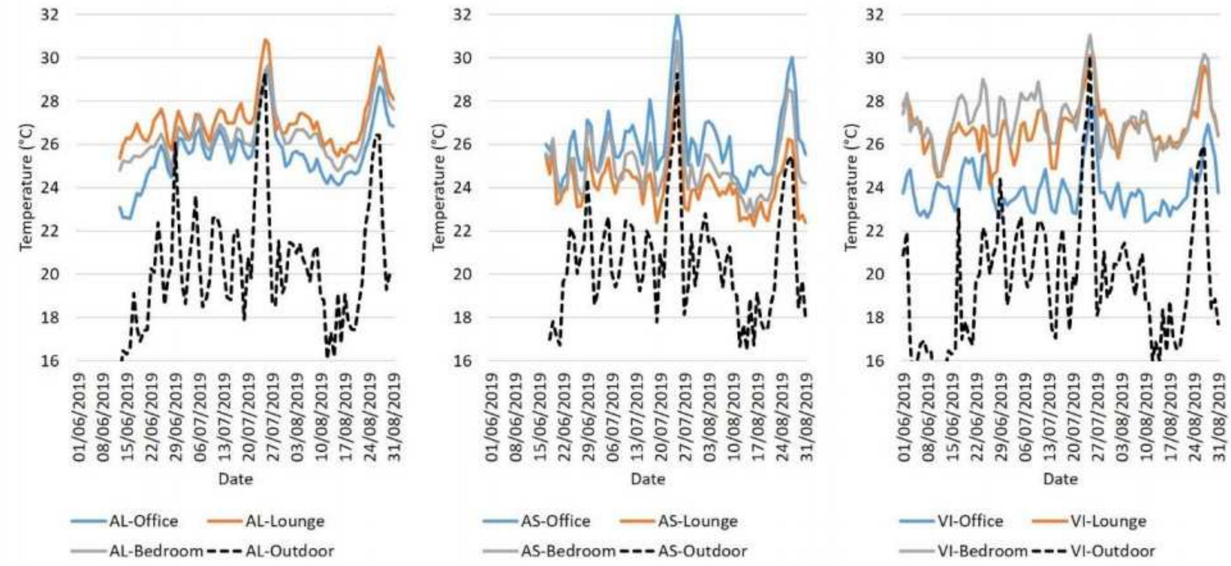



Figure 2 Daily average temperatures in case study care homes AL (left), AS (middle) and VI (right).

Descriptive statistics for the three care homes are shown in Table 8, 9 and 10 by bedrooms, lounges and offices. For bedrooms, results cover all hours of the day; for the lounge/dining rooms and offices they cover occupied hours (08:00-21:00 and 09:00-18:00 respectively). It is found that for the monitored period (June to August 2019), mean and median indoor temperatures are above 24$^o$C in all the spaces across the three care homes, with maximum indoor temperatures around 30$^o$C or above. In case study AL, the ground-floor lounge ALL1 was found to be around 1°C cooler than the two first floor lounges, partly due to its north and west facades allowing less solar gain than the east and south facades of the other lounges, and partly because it had a door to the garden area which could be opened to allow cross-ventilation when required. This implies the effect of orientation and cross-ventilation on indoor temperatures. On the other hand in case study AS, the two east-facing lounges, ASL2 and ASL3 (which had heavy occupancy throughout the day) were significantly warmer than west-facing dining rooms ASL1 and ASL4 (which had intermittent occupancy during meal times).

Table 8 Descriptive statistics for indoor temperatures in case study AL.

| | **Bedroom** | | | | | **Lounge/dining room** | | | **Office** | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **ALB1** | **ALB2** | **ALB3** | **ALB4** | **ALB6** | **ALL1** | **ALL2** | **ALL3** | **ALO1** | **ALO2** |
| **N** | 25648 | 25639 | 25639 | 4096 | 8192 | 13875 | 8604 | 4426 | 9630 | 3076 |
| **Mean** | 25.96 | 26.82 | 26.73 | 26.58 | 26.20 | 26.50 | 27.59 | 27.72 | 25.80 | 25.96 |
| **Median** | 25.80 | 26.68 | 26.55 | 26.67 | 25.83 | 26.33 | 27.36 | 27.62 | 25.65 | 25.83 |
| **Min** | 20.65 | 21.01 | 20.85 | 23.11 | 23.02 | 20.77 | 21.23 | 25.05 | 20.96 | 24.14 |
| **Max** | 29.97 | 31.26 | 31.21 | 30.30 | 31.83 | 32.11 | 32.26 | 32.11 | 31.88 | 29.70 |

Table 9 Descriptive statistics for indoor temperatures in case study AS.

| | **Bedroom** | | | | | **Lounge/dining room** | | | | **Office** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **ASB1** | **ASB2** | **ASB3** | **ASB4** | **ASB5** | **ASL1** | **ASL2** | **ASL3** | **ASL4** | **ALO1** | **ALO2** | **ALO3** |
| **N** | 25077 | 25074 | 25066 | 25068 | 7562 | 13575 | 13580 | 4087 | 2219 | 2835 | 9400 | 9410 |
| **Mean** | 24.70 | 24.12 | 26.06 | 25.17 | 24.81 | 23.69 | 25.15 | 26.05 | 21.32 | 24.77 | 25.14 | 27.28 |
| **Median** | 24.49 | 23.89 | 25.77 | 24.90 | 24.53 | 23.48 | 25.00 | 25.94 | 21.13 | 24.69 | 24.97 | 26.77 |
| **Min** | 20.56 | 18.77 | 22.40 | 21.49 | 21.66 | 18.94 | 18.51 | 22.00 | 13.99 | 21.94 | 22.61 | 20.25 |
| **Max** | 32.70 | 33.74 | 34.34 | 33.79 | 30.53 | 31.70 | 32.29 | 30.44 | 28.69 | 31.88 | 30.40 | 39.92 |

Table 10 Descriptive statistics for indoor temperatures in case study VI.

| | **Bedroom** | | **Lounge/dining room** | | **Office** |
|---|---|---|---|---|---|
| | **VIB1** | **VIB2** | **VIL1** | **VIL2** | **VIO1** |
| **N** | 26495 | 26352 | 14352 | 14352 | 9857 |
| **Mean** | 26.92 | 27.42 | 26.48 | 27.38 | 24.17 |
| **Median** | 26.75 | 27.31 | 26.46 | 27.46 | 23.96 |
| **Min** | 20.58 | 22.78 | 20.01 | 22.30 | 21.66 |
| **Max** | 31.47 | 32.49 | 31.42 | 32.06 | 30.17 |

The distribution of monitored indoor temperatures in the three care homes are presented in 3, grouped by room type. The indoor temperature distributions in the bedrooms and lounges of case study AL had similar profiles, with slightly lower office temperatures. In case study AS, bedroom temperatures were slightly higher than lounge temperatures on average, while case study VI experienced the greatest difference in temperature distributions between staff-occupied offices and staff/resident occupied lounges and bedrooms, with office temperatures lower than lounges and bedrooms.

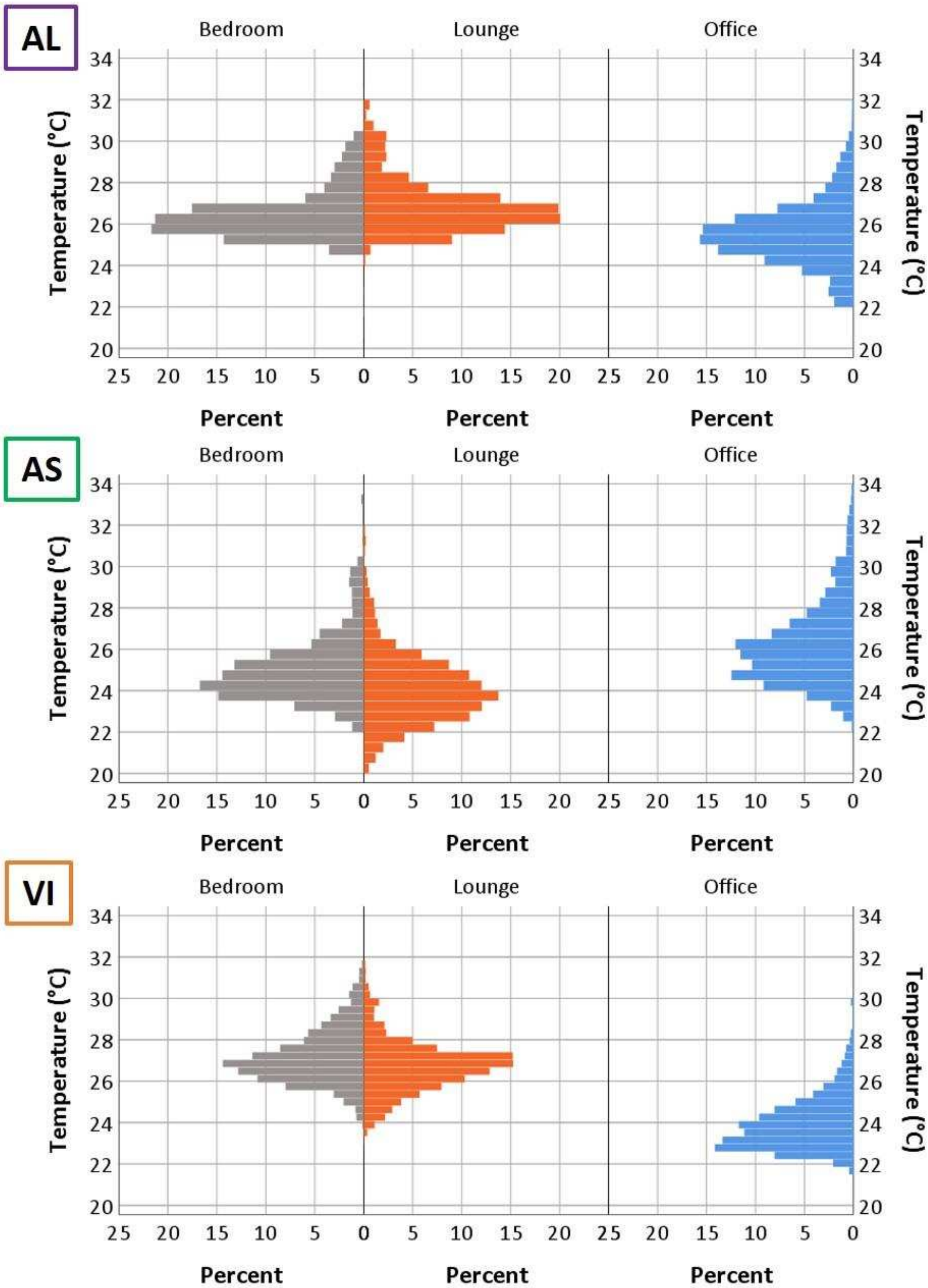



Figure 3 Distribution of indoor temperatures in bedrooms, lounges and offices in case study care homes AL (top), AS (middle) and VI (bottom).

To further investigate indoor temperature in the care homes during a particularly hot week (22nd to 28th July 2019), diurnal profiles for each of the care homes are generated in 4. During this week, overnight outdoor temperatures rarely fell below 20°C, thus preventing night-time purging of heat from the buildings. AL and VI experienced average temperatures of 28-30°C, with little diurnal variation in any of the monitored rooms (other than the office of VI). Case study AS had more diurnal temperature ranges of around 4°C in the lounges, 2°C in the bedrooms and 3°C in the offices. Mobile air-conditioning units deployed in the lounges during this period helped to limit peak temperatures, while the east and west-facing orientations of lounges meant more significant differences in solar gain during the mornings and afternoons.

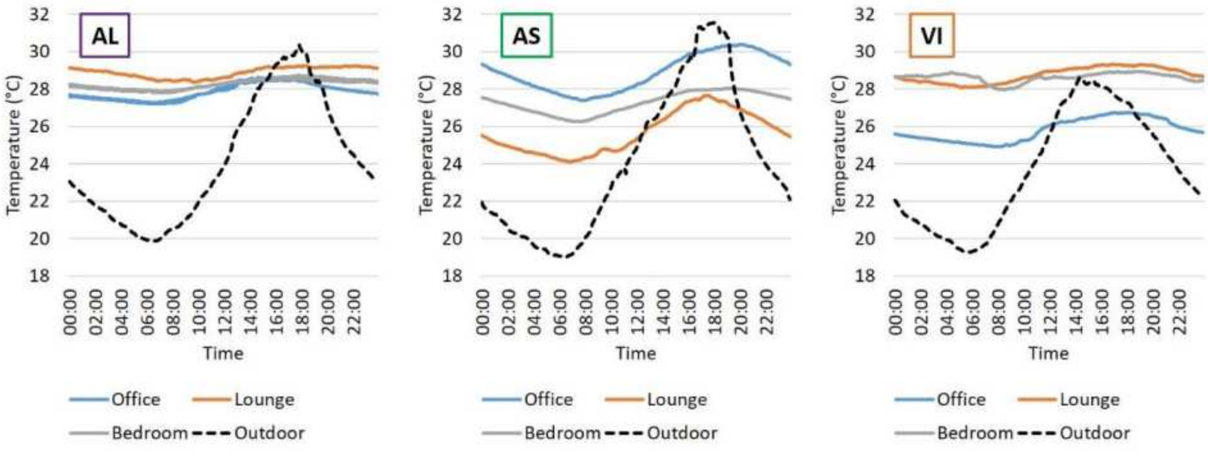


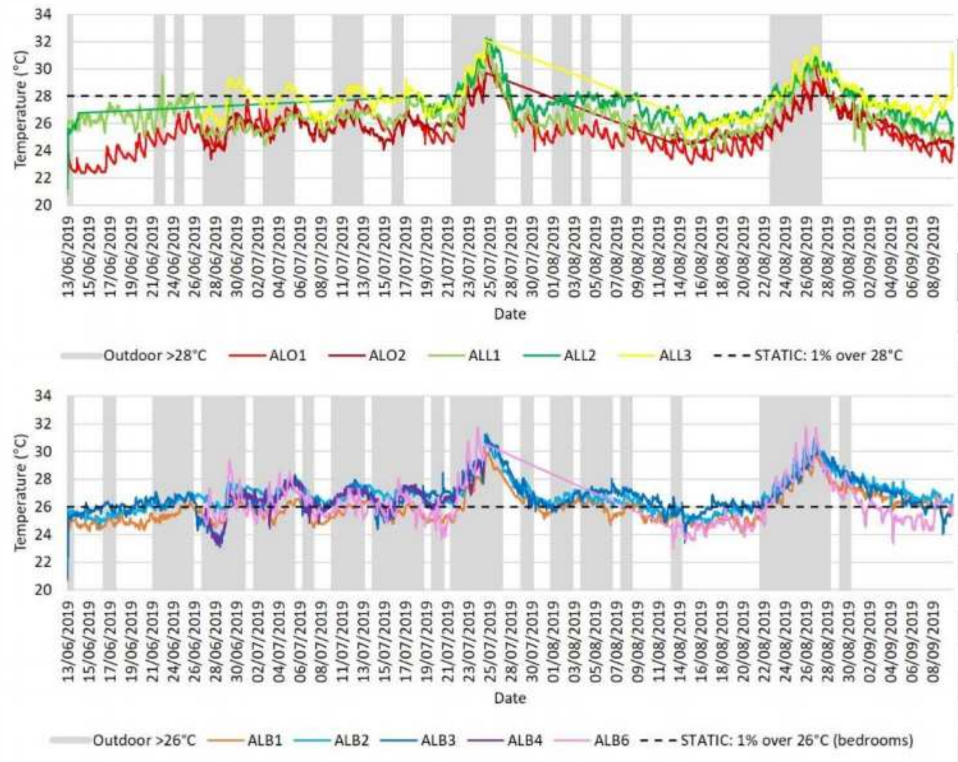

Figure 4 Diurnal temperature profiles averaged over a hot week (22-28 July 2019) in case study care homes AL (left), AL (middle) and VI (right).

Public Health England's Heatwave Plan for England recommends that for care homes, a cool room/area be available for staff and residents to relocate to, where temperatures are kept below 26°C. Interestingly none of the monitored lounges or dining rooms in the case study care homes managed this, with temperatures exceeding 26°C for up to 92% of occupied hours. The Heatwave Plan for England also states that excess deaths may become apparent at temperatures over 24.5°C, which obviously occur for an even higher percentage of occupied hours in the case study care homes. The prevalence of summertime overheating was further confirmed by the analysis below.

**4.2. Overheating analysis**

Using CIBSE Guide A's *static overheating* criteria, almost all of the monitored spaces across the three care homes were found to meet the overheating criteria (exception being the ground floor manager's office ASO1). Temperatures in the monitored rooms are presented along with the static overheating thresholds in Figure and Figure . The grey bars highlight the periods when outdoor temperatures exceeded the threshold overheating temperatures (28°C for offices and lounges, 26°C for bedrooms). Tables to the right of the figures show the percentage of hours that rooms exceeded the thresholds.

In AL, the offices exceeded 28°C for less than 8% of occupied hours and the lounges for between 10 and 35% of occupied hours. By comparison, monitored bedrooms exceeded the 26°C threshold for up to 78% of the day and 77% of the night. In AS, the staff room (ASO3) exceeded 28°C for a third of occupied hours and lounges for between 1 and 7% of occupied hours. AS bedrooms exceeded 26°C for between 10 and 43% of hours. VI's office only exceeded 28°C for 1.5% of occupied hours. There was a significant contrast between the 1st floor lounge VIL1 (benefitting from two large doors which could be opened onto the garden area) and 2nd floor lounge VIL2, which exceeded 28°C for 10% and 29% of occupied hours respectively.

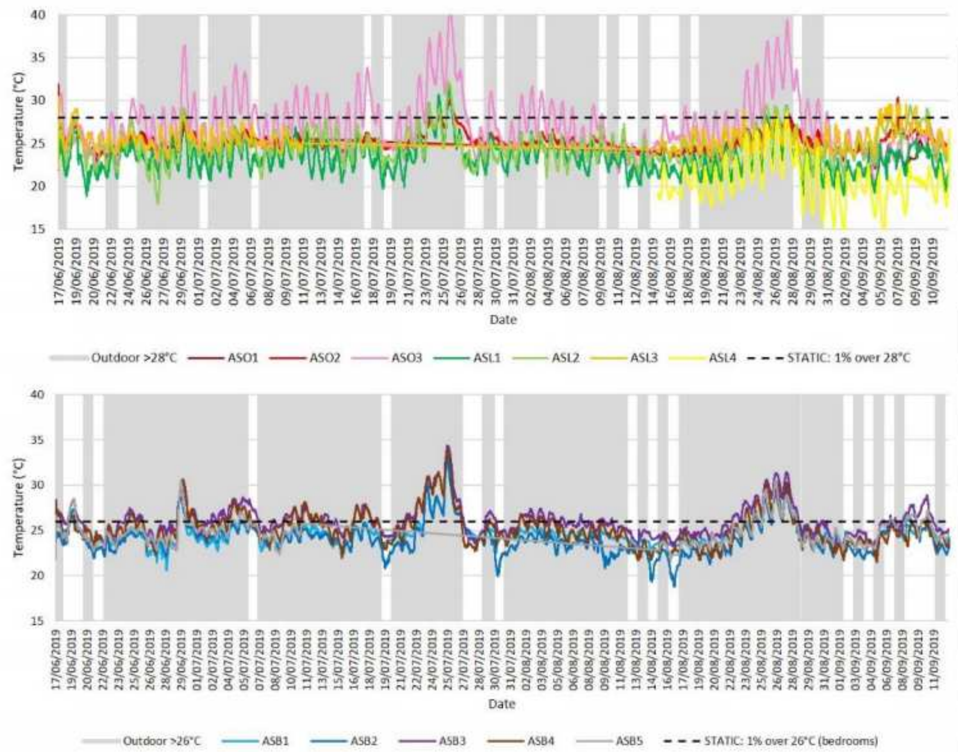



CIBSE Guide A

| Location | Condition | % of time over 28°C |
|---|---|---|
| ALO1 | Occupied | 7.5 |
| ALO2 | | 7.1 |
| ALL1 | | 10.5 |
| ALL2 | | 30.5 |
| ALL3 | | 35.0 |

| Location | Condition | % of time over 26°C |
|---|---|---|
| ALB1 | All hours | 42.1 |
| ALB2 | | 76.8 |
| ALB3 | | 76.4 |
| ALB4 | | 78.1 |
| ALB6 | | 46.2 |
| ALB1 | Day | 43.1 |
| ALB2 | | 78.1 |
| ALB3 | | 77.0 |
| ALB4 | | 78.8 |
| ALB6 | | 44.4 |
| ALB1 | Night | 40.5 |
| ALB2 | | 74.8 |
| ALB3 | | 75.3 |
| ALB4 | | 76.8 |
| ALB6 | | 49.2 |

Figure 5 Case study AL: Temperatures in monitored rooms showing static overheating thresholds for lounges and offices (top) and bedrooms (bottom), with percentage of time thresholds were exceeded also shown.

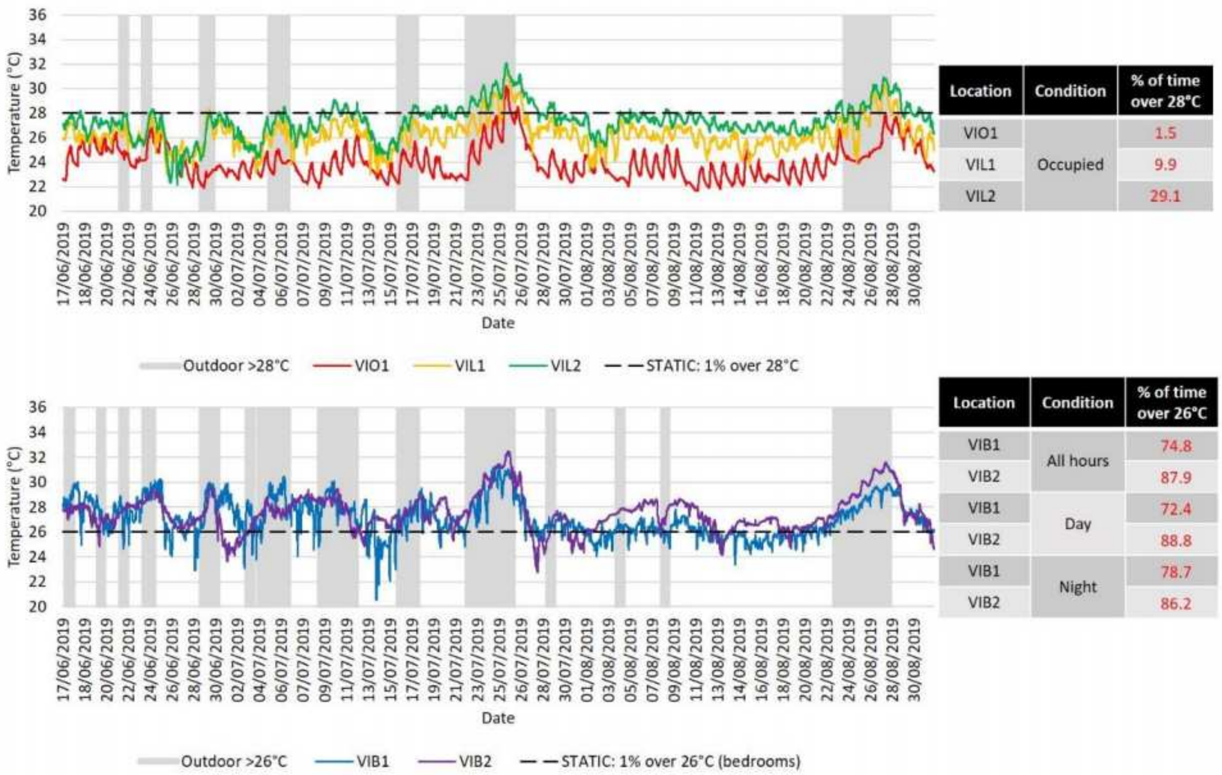



CIBSE Guide A

| Location | Condition | % of time over 28°C |
|---|---|---|
| ASO1 | Occupied | 0.5 |
| ASO2 | | 1.7 |
| ASO3 | | 33.4 |
| ASL1 | | 3.4 |
| ASL2 | | 6.5 |
| ASL3 | | 6.3 |
| ASL4 | | 1.2 |

| Location | Condition | % of time over 26°C |
|---|---|---|
| ASB1 | All hours | 10.9 |
| ASB2 | | 11.1 |
| ASB3 | | 42.8 |
| ASB4 | | 25.9 |
| ASB5 | | 17.8 |
| ASB1 | Day | 11.6 |
| ASB2 | | 11.9 |
| ASB3 | | 42.9 |
| ASB4 | | 25.7 |
| ASB5 | | 18.9 |
| ASB1 | Night | 9.9 |
| ASB2 | | 9.8 |
| ASB3 | | 42.6 |
| ASB4 | | 26.2 |
| ASB5 | | 16.0 |

Figure 6 Case study AS: Temperatures in monitored rooms showing static overheating thresholds for lounges and offices (top) and bedrooms (bottom), with percentage of time thresholds were exceeded also shown.




| Location | Condition | % of time over 28°C |
|---|---|---|
| VIO1 | Occupied | 1.5 |
| VIL1 | | 9.9 |
| VIL2 | | 29.1 |

| Location | Condition | % of time over 26°C |
|---|---|---|
| VIB1 | All hours | 74.8 |
| VIB2 | | 87.9 |
| VIB1 | Day | 72.4 |
| VIB2 | | 88.8 |
| VIB1 | Night | 78.7 |
| VIB2 | | 86.2 |

Figure 7 Case study VI: Temperatures in monitored rooms showing static overheating thresholds for lounges and offices (top) and bedrooms (bottom), with percentage of time thresholds were exceeded also shown.

*Dynamic overheating criteria* (Table 4) take account of how high outdoor temperatures can mitigate the effects of high indoor temperatures. Overheating is deemed to have occurred if any two of these three criteria have been fulfilled. As presented in Table 11, only a few monitored spaces (highlighted cells in orange) across the case study care homes experienced overheating. While in AL, one lounge and one bedroom were found to overheat, in AS, one office and one lounge were overheated. In VI, both bedrooms were overheated. These rooms had orientations mostly towards east, west and north-east.

When analysed by overheating criteria, it was found that in AL, two lounges and one bedroom fulfilled criterion 1 (at least 3% of occupied hours at least 1°C above the threshold comfort temperature), one lounge and one bedroom met two out of three criteria and were deemed to be overheated. In AS, one office (second-floor staffroom described before) and one lounge, but none of the monitored bedrooms, fulfilled criterion 1. In VI, both monitored bedrooms fulfilled criterion 1, with a much higher proportion of occupied hours exceeding 1°C over threshold comfort temperature than any other monitored room other than ASO3.

Criterion 2 (daily weighted exceedance of at least six hours per day) was fulfilled by 16 of the 27 monitored spaces, including six of the seven monitored spaces that fulfilled criterion 1: two lounges and three bedrooms in AL; two offices, two lounges and three bedrooms in AS; and both lounges and both bedrooms in VI. Interestingly, only two monitored spaces, both in AS, fulfilled criterion 3 (maximum indoor temperature more than 4°C above threshold comfort temperature), indicating that although temperatures in the monitored spaces were exceeding threshold comfort temperatures, the duration of overheating was more of an issue than brief periods of extremely high temperatures.

Table 11 Dynamic overheating analysis in monitored rooms across the three care homes. Highlighted cells indicate where overheating criteria were met (units given below).

| AL | | | | AS | | | | VI | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Crit 1** | **Crit 2** | **Crit 3** | | **Crit 1** | **Crit 2** | **Crit 3** | | **Crit 1** | **Crit 2** | **Crit 3** |
| **ALO1** | 0.09 | 0 | | **ASO1** | 0.04 | 0 | | **VIO1** | 0.0 | 0 | |
| **ALO2** | 0.00 | 0 | | **ASO2** | 0.43 | 1 | | **VIL1** | 1.2 | 5 | |
| **ALL1** | 0.65 | 1 | | **ASO3** | 8.41 | 8 | 8.70°C | **VIL2** | 2.3 | 7 | |
| **ALL2** | 4.77 | 4 | | **ASL1** | 0.00 | 0 | | **VIB1** | 6.9 | 44 | |
| **ALL3** | 3.57 | 0 | | **ASL2** | 1.20 | 2 | | **VIB2** | 8.8 | 50 | |
| **ALB1** | 0.30 | 3 | | **ASL3** | 3.26 | 1 | 4.09°C | | | | |
| **ALB2** | 2.94 | 11 | | **ASL4** | 0.00 | 0 | | | | | |
| **ALB3** | 3.38 | 11 | | **ASB1** | 0.00 | 0 | | | | | |
| **ALB4** | 0.00 | 0 | | **ASB2** | 0.07 | 1 | | | | | |
| **ALB6** | 0.49 | 0 | | **ASB3** | 2.69 | 10 | | | | | |
| | | | | **ASB4** | 0.69 | 3 | | | | | |
| | | | | **ASB5** | 0.84 | 0 | | | | | |

Units: Criterion 1 - % of occupied hours; Criterion 2 – No. of days when daily weighted exceedance was greater than 6; Criterion 3 – maximum indoor temperature if more than 4°C over threshold comfort temp.

### 4.3. Thermal sensation and thermal preference

The thermal comfort surveys were conducted over five days in AL and VI and six days in AS. The trends in responses were similar in all three care homes, with the most significant differences seen between residents and staff. The results presented therefore represent the combined responses from all three care homes.

Only 6% of resident responses and 3% of staff responses were on the 'cool' end of the thermal sensation vote (Figure 8, left). Half of resident responses were 'neutral' compared to less than a third of staff responses. More than one-in-three staff responses were 'hot' as compared to fewer than one-in-seven resident responses. The responses to thermal preference showed similar trends (Figure , right). Only 5% of resident responses and 1% of staff responses expressed a desire to be warmer. Two-thirds of residents' responses were for 'no change' in their thermal conditions, compared to one-third of staff responses. A third of staff responses wanted to be 'much cooler' compared to fewer than one-in-eight resident responses.

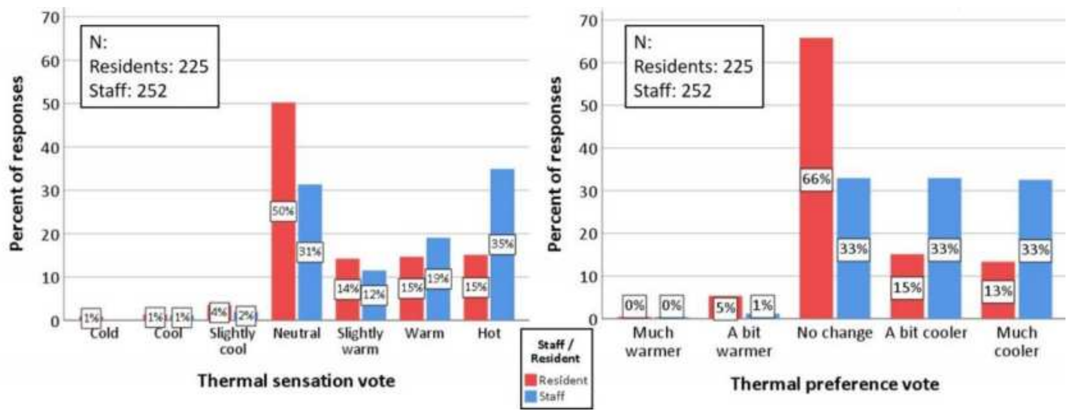
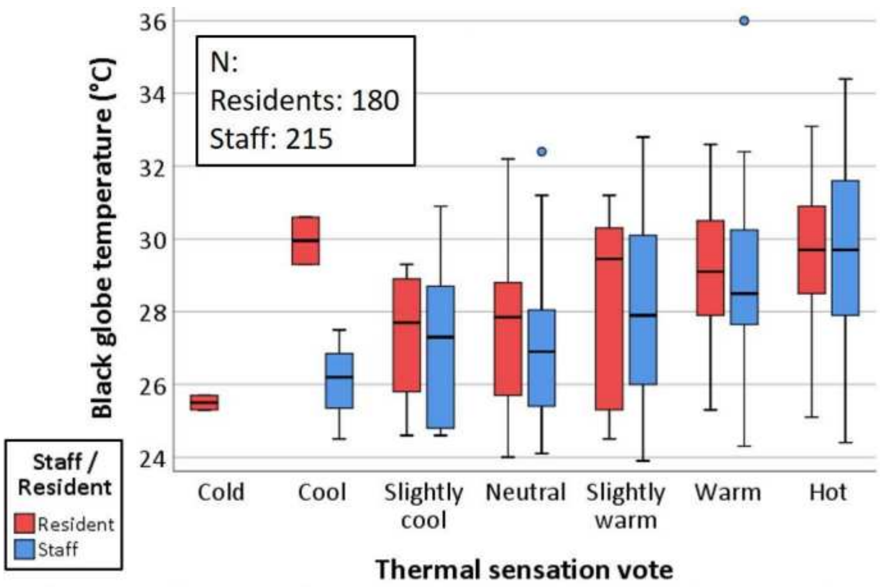


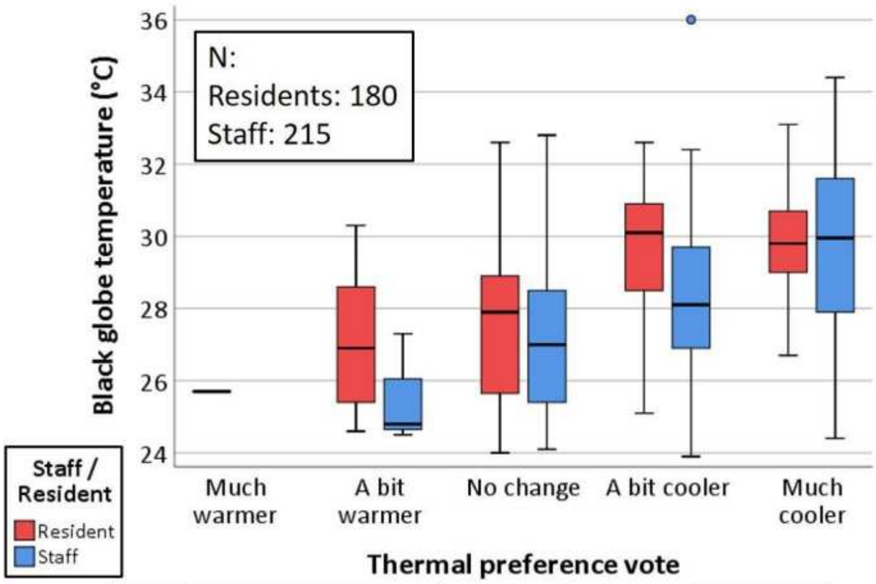

Figure 8 Distribution of responses for thermal sensation (left) and thermal preference (right) for all three case study care homes, grouped by resident/staff.

The majority of surveys conducted also had concurrent localised conditions recorded. No significant trends or correlations were found between survey responses and either RH or air speed (although it is worth noting that unless a respondent was in the direct path of a fan, the measured air movement was extremely low). Boxplots were used to show the distribution of black globe temperatures (a measure of the radiant heat transfer from the human body) recorded for different thermal sensation and thermal preference votes from residents and staff (Figure 9).

The mean temperature that residents considered 'neutral' was 1°C warmer than the temperature considered 'neutral' by staff. Indeed, resident's 'neutral' temperature was considered by staff to be 'slightly warm'. Interestingly, the mean temperature for 'hot' responses was the same for both residents and staff. Regarding thermal preference, the mean 'no change' temperature was 0.9°C warmer for residents than staff, and the mean 'a bit cooler' temperature was 2°C warmer for residents than staff. These results indicate that residents had a significantly higher tolerance of warmer temperatures than the staff. However the extreme 'much cooler' temperature was almost the same for residents and staff (29.8°C and 30.0°C respectively).




| | Cold | | Cool | | Slightly cool | | Neutral | | Slightly warm | | Warm | | Hot | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Res' | Sta' | Res' | Sta' | Res' | Sta' | Res' | Sta' | Res' | Sta' | Res' | Sta' | Res' | Sta' |
| N | 2 | 0 | 2 | 3 | 7 | 5 | 106 | 75 | 10 | 21 | 21 | 36 | 32 | 75 |
| Med. | 25.5 | - | 30.0 | 26.2 | 27.7 | 27.3 | 27.9 | 26.9 | 29.5 | 27.9 | 29.1 | 28.5 | 29.7 | 29.7 |




| | Much warmer | | A bit warmer | | No change | | A bit cooler | | Much cooler | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Res' | Sta' | Res' | Sta' | Res' | Sta' | Res' | Sta' | Res' | Sta' |
| N | 1 | 0 | 8 | 3 | 123 | 73 | 22 | 67 | 26 | 72 |
| Med. | 25.7 | - | 26.9 | 24.8 | 27.9 | 27.0 | 30.1 | 28.1 | 29.8 | 30.0 |

Figure 9 Boxplots showing distribution of black globe temperatures recorded concurrently with thermal sensation votes (top) and thermal preference votes (bottom), grouped by residents and staff, with statistic.

Converting the thermal sensation votes and thermal preference votes into numerical values allowed trend lines to be plotted against concurrent black globe temperatures (Figure 10). The Pearson correlations were found to be similar for staff and residents for both thermal sensation vote vs. black globe temperature and thermal preference vote vs. black globe temperature (between 0.41 and 0.45), suggesting that the extent of influence that indoor temperature had on thermal sensation and thermal preference was similar for both residents and staff.

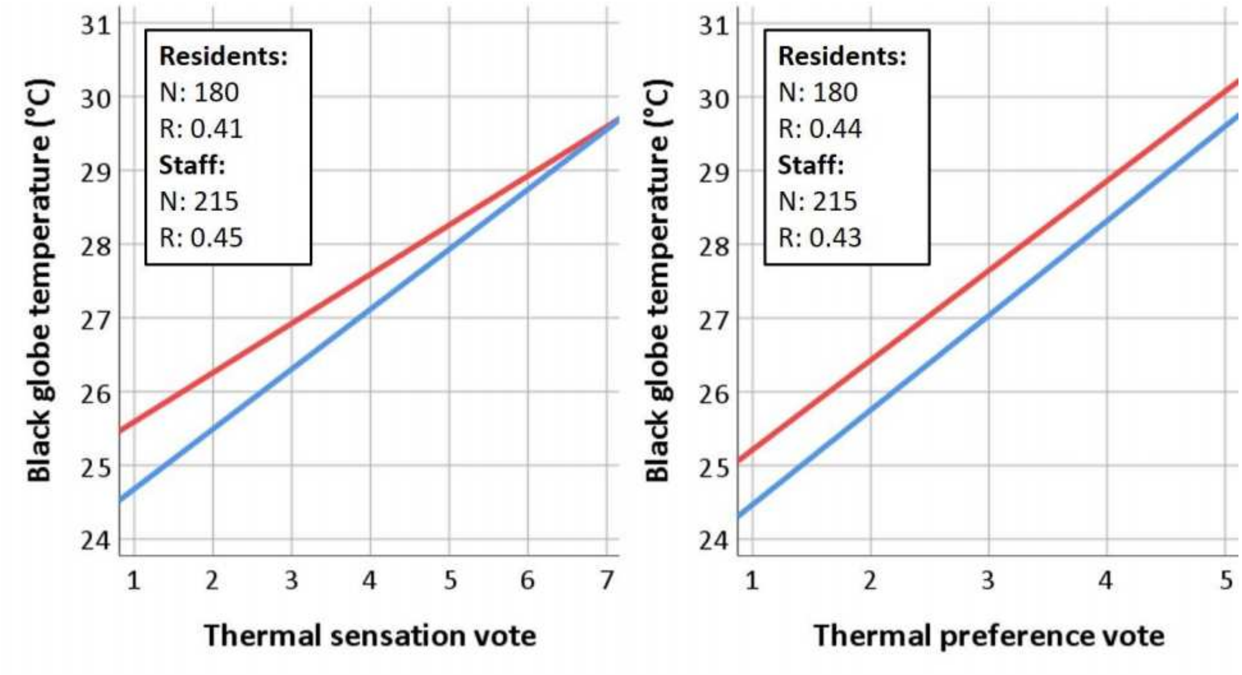



Figure 10 Trend lines showing the relationship between thermal sensation votes (left) and thermal preference votes (right) with concurrent black globe temperatures for residents and staff, with Pearson correlations (R) also shown.

The levels of clothing insulation and controls (see Table 6) did not show any statistically significant relationship with thermal sensation or thermal preference votes. As expected, activity in the 15 minutes prior to the survey was predominantly 'passive' (sitting, laying down, occasionally slow walking) for residents, but staff reported being more 'active'. The differences in thermal sensation and thermal preference votes for residents and staff who had been active, passive or a combination of both in the 15 minutes prior to responding are shown in figure 11, where the y-axis represents the percentage of responses within each group (active, mixed and passive).

The 8% of resident responses and 62% of staff responses where respondents had been active prior to the survey were more likely to express thermal sensation towards the 'hot' end of the scale and thermal preference towards the 'cooler' end of the scale than those who had been passive. The difference between 'active' and 'passive' was much more evident in the residents than the staff. By assigning a numerical value to both the activity responses (from (1) 'laying down' to (5) 'walking indoors/outdoors') and thermal sensation/preference votes, it was possible to conduct a Spearman's Rho correlation analysis to evaluate the strength of this relationship. For residents, the correlations with 'activity' were 0.17 and 0.14 for thermal sensation and thermal preference respectively. For staff, the correlations with 'activity' were 0.14 and 0.15 for thermal sensation and thermal preference respectively (all statistically significant at the 0.05 level). Although these relationships were statistically significant, they were much less strong than the relationship between black globe temperatures and thermal sensation/preference.

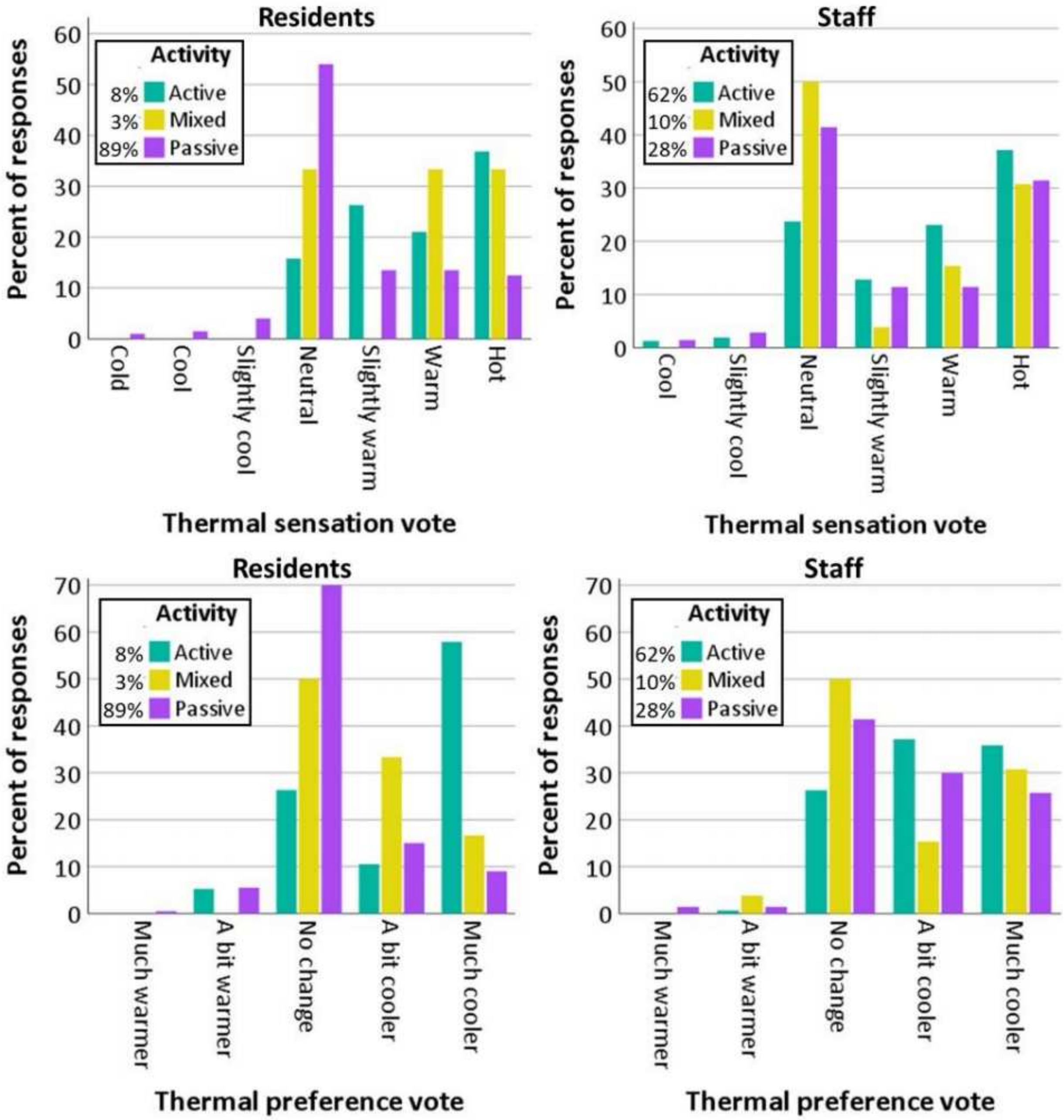



Figure 11 Distribution of responses for thermal sensation (top) and thermal preference (bottom) for residents (left) and staff (right), grouped according to their activity in the 15 minutes prior to responding. Percent of responses (y-axis) represents percentage of group responses.

## 5. Discussion

The three case study care homes showed similar trends, both in their measured indoor environmental temperature, as well as in the responses to thermal sensation and thermal preference from residents and staff. Indoor temperatures in the monitored spaces were high, exceeding static overheating thresholds in 26 out of the 27 monitored rooms, and dynamic overheating thresholds in 16 rooms. Analysis found that overnight, indoor temperatures often remained high, particularly during hot periods when overnight outdoor temperatures remained high. In the communal lounges and dining rooms, and in staff offices, unoccupied overnight hours would have been ideal for temperatures to be able to fall to ambient outdoor levels. However, this often did not happen. This was due to windows needing to be closed overnight for security, particularly in ground floor rooms, or because the rooms were internal – i.e. they had no windows/doors/walls connecting them to the outdoors.

Overheating analysis suggested that the issues were more to do with extended periods of time when temperatures were slightly above the overheating thresholds, rather than short periods of time when temperatures were very high. Staff offices tended to be cooler than spaces occupied by residents (with the notable exception of ASO3, which staff described as 'unbearable' during much of the summer and consequently did not use it on their break times as intended). All of the lounges/dining rooms were 'statically' overheating, but only 1 of the 9 were 'dynamically' overheating.

To counteract the high lounge temperatures, some had mobile fans or air conditioning units brought in during the summer months, with mixed results. The fans created air movement, which was generally pleasing to those within range. The air conditioning (AC) units provided some cooling. However, as they were mobile units, they provided a stream of cooled air at floor level (in contrast to permanent units often located in the ceiling). Residents in the way of this would often complain of the cold draught, and also about the units' noise. Thus the AC units were limited in what they could achieve.

While all of the monitored bedrooms were 'statically' overheating, only 3 out of 12 met two out of the three 'dynamic' overheating criteria. Staff would often ensure that bedroom doors and windows remained open to allow some cross-ventilation. However, this was always at the discretion of the residents, some of whom would insist on their windows in particular remaining closed. Safety regulation meant that windows could only open a maximum of 10cm, so even when open, cross ventilation was limited. Some residents chose to have their curtains closed to prevent direct solar gain or glare. During the summer period, small fans were installed in the bedrooms of VI, providing some air movement and proving popular with the majority of residents.

The survey responses revealed a striking difference between how residents and staff perceived their thermal sensation and thermal preference. The mean neutral temperature (thermal sensation 'neutral', thermal preference 'no change') was around 1°C warmer for residents than for staff, and for thermal sensation on the 'warm' end of the scale and thermal preference on the 'cooler' end of the scale, between 0.6 and 2.0°C warmer for residents than for staff. Members of staff were much more likely to feel the environment to be warm/hot and want it to be cooler, partly due to the fact that they were more physically active, attending to the needs of the predominantly passive residents.

Analysis found Spearman's Rho correlations between thermal sensation/preference and activity to be much smaller than between thermal sensation/preference and measured temperatures for both residents and staff. Staff duties (including helping residents to dress and undress, get into and out of bed or chairs, as well as cleaning and serving meals) were often physically demanding. Although they were able to drink to help alleviate the effects of the heat, their uniforms limited how much they could adjust their clothing comfort levels. Staff often commented that although they would encourage residents to drink more during the hot weather and dress more lightly, many residents would want to stick to the same habits and routines regardless of the weather.

## 6. Conclusion

This study has investigated empirically the indoor temperatures over the summer of 2019, in three purpose-built nursing care homes located across London. Through surveys, the research has also investigated for the first time, the response to thermal sensation and thermal preference from residents and staff occupying the case study care home settings. All three care homes were found to experience overheating (both static and dynamic) in the majority of monitored rooms, particularly lounges and bedrooms. However, there was a significant disparity between how residents and members of staff perceived the same environmental conditions: residents were much more content with warmer conditions than the staff caring for them.

Care homes are hybrid buildings, serving both as living spaces for the residents (the majority of whom lead passive, sedentary lives) and as offices and workspaces for the staff members (whose work is often physically demanding). In addition, the residents are inherently much older and have more acute medical needs than the staff. The dichotomy between these two groups of people occupying the same spaces makes providing comfortable environments challenging, particularly during periods of hot weather.  This raises the question of whether current definitions for overheating are appropriate for care home settings or whether they need tweaking for these bespoke buildings.

As a consequence of the findings presented here, it is evident that building design of care homes should be carefully considered, thinking beyond the obvious needs of keeping occupants warm during the cold winter months, to keeping them comfortable during the hot summer months. This could be through passive design features such as shading (with trees or breeze soleil), cross-ventilation (with careful consideration as to how window openings could facilitate this whilst conforming to safety standards which limit how much they can open), or evaporative cooling using water features in garden areas. The deployment of (ceiling or wall mounted) fans could help to augment the effectiveness of cross-ventilation strategies, although there are constraints on how fans are used due to regulations aimed at reducing the risk of spreading infections. For existing care homes retrofitting external shading and evaporative cooling strategies could be relatively low cost and, since, they are essentially external changes, cause relatively low disruption to residents in their implementation. Retrofitting air conditioning would be expensive and disruptive, and residents may not accept it.

Further to building-related measures, changes to staff and patient routines could be considered. Staff often complained that they were limited in how much they could adapt what they were wearing, both due to uniform policies and health and safety constraints (no open-toed sandals, for example). Research could investigate how different clothing options could help alleviate staff discomfort during hot weather. Providing staff with 'cool rooms' and designing shift patterns to allow regular visits to these locations to cool down may also help staff cope. However, neither of these solutions deal with the issue of residents overheating (whether they feel it or not). Overnight, bedrooms often had windows and doors closed. Allowing, where possible and with occupants' consent, windows to remain open overnight would allow more nocturnal purging of heat. In conclusion, satisfying the comfort needs of residents and staff remains a challenge, but could be achieved through better management of the indoor environment, if those responsible have the knowledge and resources available.

## 7. Acknowledgements

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# Development of an integrated data acquisition system for thermal comfort studies of older people

**Veronica Soebarto[1], Terence Williamson[1], Helen Bennetts[1], Larissa Arakawa Martins[1], Dino Pisaniello[2], Alana Hansen[2], Renuka Visvanathan[3], Andrew Carre[4]**

[1] School of Architecture and Built Environment, The University of Adelaide, Adelaide, Australia;
[2] School of Public Health, The University of Adelaide, Adelaide, Australia;
[3] Adelaide Medical School, The University of Adelaide, Adelaide, Australia;
[4] School of Property, Construction and Project Management, RMIT University, Melbourne, Australia

**Abstract:** Extreme weather conditions have profound negative impacts on health and well-being. Among those who are impacted the most are older people, or those who are 65 years and over. This paper presents a study to understand the thermal conditions in the homes of older South Australians as well as the occupant's thermal comfort, responses and well-being. The study is critical as 95% of older Australians prefer to age-in-place, or live as long as possible in their own home. The paper focuses on the method and tool to capture this information using a robust indoor environmental monitoring system, integrated with an occupant survey system based on an 'older people-friendly' electronic tablet that allowed the participants to reflect on their "right here right now" experience over summer, autumn and winter seasons in 2019. The development of this integrated system is discussed in detail, while a number of examples of the data collected during the summer and winter periods are presented, including indoor temperatures, thermal sensation votes, clothing behaviours, perception of indoor quality, and self-reported health/well-being. Lessons learned from the study are also reported.

**Keywords:** Thermal comfort study, older people, monitoring

## 1. Introduction

In the last few decades, studies have demonstrated the relationships between temperature, particularly outdoor temperatures, health and wellbeing, mortality and morbidity. Mortality and morbidity rates tend to increase at extreme temperatures, either low or high, and decrease at moderate temperatures (Barnett et al, 2012; Gasparrini et al, 2015). Among those vulnerable to heat or cold are older people, or those aged 60 or 65 years and over. As we age, we experience physiological changes, such as reduced vascular reactivity, lower metabolic rate and reduced muscle strength, all of which can affect our thermal sensitivity and regulation (Blatteis, 2012). A number of age-related medical conditions, such as cardiovascular disease, respiratory disease and diabetes mellitus are exacerbated by hot environments (Ishigami et al, 2008). These conditions decrease the body's ability to adapt to changes in environmental conditions (Lomax and Schonbaum, 1998). Likewise, cold winter periods are linked to excess mortality and morbidity due to cardiovascular disease and respiratory illness (Baker-Blocker, 1982; Conlon et al, 2011; Ryti et al, 2016). Geographic location and city size have also been found to contribute to cold weather vulnerability. Cardiovascular-cause mortality has been found to be higher in smaller, rural communities than in larger metropolitan areas (Gomez-Acebo et al, 2010). It was argued that denser, more populated urban environment retain more heat, which may buffer people's exposure to cold winter temperatures (Wu et al, 2011). On the other hand this heat island affect, increases the vulnerability of those living in highly urbanized cities in hot climates.

Most of these studies, however, focus on the relationship between outdoor ambient temperatures and health. With the increasing proportion of older people from the overall population worldwide, and the fact that the vast majority of older people want to 'age-in-place', or live in their own home for as long as possible, it is as important to investigate the relationship between indoor environment and older people's health and well-being. The understanding of this relationship will inform relevant stakeholders in the housing sector and assist with the development of policies and regulation as well as design approaches and construction techniques that will ensure a quality living environment for older people.

Studies about the relationships between the living environment and older occupants have emerged in the past decade particularly in countries where there is an increase in the proportion of older people from the general population (e.g. Hwang and Chen, 2010; Jiao et al, 2017; Wang et al, 2018). Nevertheless, such research is scarce in Australia, one of the nations with an increasing population of older people. The study reported in this paper aims to advance our knowledge of optimal housing for older people in Australia in order to support them to live independently. The study was conducted in South Australia, focusing on three climatic zones: warm temperate (*Csa*) of an urban metropolitan area, cool temperate (*Csb*) found in regions with higher altitudes as well as in a coastal area, and hot arid (*BSk*) consisting of very low density regional towns.

As the first step, a general survey of 250 randomly selected older people was conducted in the second quarter of 2018 to investigate whether there were associations between climatic conditions, housing types and constructions, heating and cooling behaviours and the participants' health and well-being (Soebarto et al, 2019). Additionally, to obtain insights about the strategies to achieve thermal comfort undertaken by older people as well as existing problems related to planning and house design, a series of focus group discussions were held in a number of locations in the three climate zones during the third quarter of 2018 (van Hoof et al, 2019).

Finally, to gain further understanding of the actual living conditions of older people and the relationships between indoor environment, particularly temperature, humidity, air movement and quality, and occupant's perceived health and well-being, indoor environment monitoring and occupant surveys were conducted in 57 homes involving 71 older occupants. The study was conducted from the third week of January to the end of October in 2019, covering a period of summer, autumn and winter. The participants were recruited from those who participated in the initial survey and focus group discussions as well as from publicity in various media outlets. Human ethics approval to conduct the indoor environment monitoring and occupant survey was received from the Human Research Ethics Committee at The University of Adelaide, approval number H-2018-042.

This paper focuses on the methodology and tools developed to conduct the monitoring and occupant survey, while the results of the study are reported in another paper (Williamson et al, 2020). Note that in addition to conducting the long-term monitoring and occupant survey, the researchers gathered information about the participants (e.g. age, income and education levels, general health and quality of life, strategies for cooling, heating and ventilation) and about their house (e.g. type - separate house, detached, apartment-construction, heating and cooling devices, and energy use records). These data are necessary to interpret the monitored indoor environmental data and the occupant's survey responses.

## 2. Overview of data acquisition and survey tool developments

There is a long tradition of field studies of thermal comfort in actual buildings that combine indoor environmental quality monitoring and thermal comfort surveys (for an overview see Mishra and Ramgopal, 2013; Rupp et al, 2015). Researchers have conducted such studies to investigate whether the indoor environment in an existing building is acceptable (see for example Mumovic et al, 2009; Huizenga et al, 2006), to compare satisfaction with different control systems e.g. fully air conditioned, mixed-mode, or natural ventilation (de Dear et al, 1991; Andreasi et al, 2010; Rupp et al, 2015); to look at thermal comfort in particular building types such as offices (Rijal et al, 2017), health and aged care buildings (Tartarini et al, 2016) and educational buildings (de Dear et al, 2015), as well as to investigate the influence on thermal comfort of personal characteristics of the occupants such as age or gender (Del Ferraro et al, 2015; Maykot et al. 2018).

For thermal comfort studies, the indoor environmental parameters collected are, at least, dry bulb and globe temperatures, relative humidity and air velocity. Depending on the purpose of the study, other environmental parameters affecting indoor air quality may also be measured and recorded: $CO_2$ and VOC levels (for indoor air quality), illumination levels (for visual quality), and noise level (for aural quality). These parameters may be measured at a particular point in time (when an occupant survey is being administered) or are continuously recorded, normally every 15-30 minutes (ASHRAE 2017), for a certain period. The BOSSA Nova IEQ cart is an example of such data acquisition system (Candido et al, 2013).

To understand the conditions in homes at different times in a year, studies of the indoor environment are usually conducted over a relatively long period, between 3 to 12 months. Ideally the data acquisition devices should be small, unobtrusive and battery-powered to ensure that they do not interfere with the occupants' regular activities and do not contribute to the occupants' electricity usage (for example, Soebarto and Bennetts, 2014; Parkinson et al, 2015; Daniel et al, 2017). Figure 1 shows an example of such device.

Figure 1. Small and unobtrusive data acquisition device (Daniel et al 2017)

Alongside the collection of indoor environmental data, occupants are often asked to respond to an indoor environmental survey throughout the data collection period. Many studies use paper-based survey forms (for example Indraganti and Rao, 2010; Takasu et al, 2017) while others use an online survey on computers or smart phones (for example de Dear et al, 2018).

The challenge of such data acquisition and survey methods is that both types of data collected (i.e. the indoor environmental parameters and the occupant's survey responses) have to be merged manually by the researcher in order to analyse the relationships between the survey responses and the various parameters at the time the occupant responded to the survey. Using paper-based surveys also poses an additional challenge as it relies on the researcher's diligence in transferring the information into a readable format for further analysis. The survey participants may also accidently, or intentionally, skip some questions, thus resulting in incomplete survey responses.

An early attempt to streamline thermal comfort data collection and analysis, and to ensure that all survey questions were answered, was built, tested and deployed in 1986 by researchers at The University of Adelaide in South Australia. The Comfort Vote Logger (CVL) was a self-contained, compact and easy-to-use device to record indoor environmental parameters and occupant responses (Williamson et al, 1995). While the device was recording the environmental parameters, the user entered relevant responses, such as their individual identification (up to 4 users), thermal sensation (on a 7-point scale), clothing level (three options), activity level (three options) and heating/cooling operation as well as air movement (three options). See Figure 2. The device not only automatically recorded dry bulb temperature and humidity at hourly intervals but also recorded when the occupants entered their responses. The data were stored in a removable ‘Memory Module’ containing two battery backed RAM chips capable of storing up to 2046 complete time-stamped voting records. A big disadvantage of this device, however, was that it required a 240Volt connection and it required the researcher to retrieve the data by physically removing the memory module. Nevertheless, over a number of years of operation, around 40,000 individual voting records were recorded in cities and towns throughout Australia (Williamson et al, 1991).

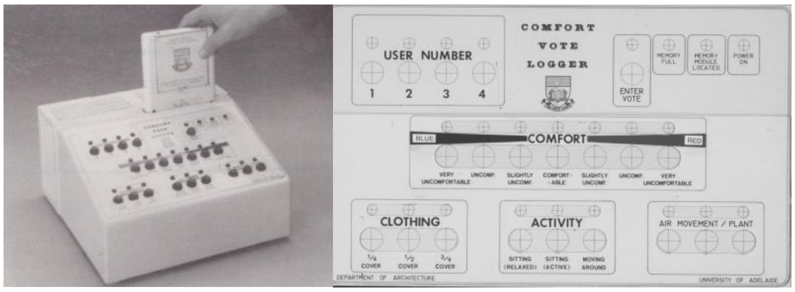



Figure 2. Comfort Vote Logger developed in 1986

An advancement of the CVL is a much smaller indoor environmental quality logger developed by Carre and Williamson (2018). The logger continuously records environmental parameters that affect thermal comfort as well as visual, aural and olfactory comfort. It also provides an interface for the occupant to respond to relevant survey questions in the form of a small (100 mm x 100 mm) touch screen (Figure 3). This logger is low cost and based upon the Arduino microcontroller platform (Arduino, 2016). Using the built-in 3G cellular modem, data collected are automatically sent to the Cloud daily, thus, unlike the CVL, it does not require the researcher to be physically with the logger in order to retrieve the data.

Figure 3. Indoor environmental quality logger (Carre and Williamson 2018)

## 3. Development of a new integrated data acquisition system for studies of older people

While the indoor environmental quality logger developed by Carre and Williamson (2018) is robust, remotely accessible, and small enough to not interfere with occupants' activities, it is not practical for use by older participants, ironically due to its small size. Some older people have weakening eyesight while others may experience muscle and joint problems in their hands, making it difficult for them to read the text on a small screen or to respond to the survey questions by touching a small screen.

For older people, a much larger tablet with larger font size is required. Nevertheless, the new system must meet the same requirements: (1) robust, (2) unobtrusive, (3) not rely on the occupant's electricity (and internet connection), and (4) user-friendly. The new indoor environment survey tablet and data acquisition system are described below.

### 3.1. Indoor environment survey tablet

The indoor environment survey tablet was intended for the participants to complete regular comfort surveys electronically - once a day whenever possible, or at least two times a week - about their perceptions, preference, response and satisfaction particularly on the thermal conditions inside their dwelling but also on other indoor environmental factors such as air quality and air movement. Note that assessing the visual and aural parameters and satisfaction was outside the scope of the study.

Based on the four principles mentioned above and the need for a larger user interface, an electronic tablet with a 7" touch screen (*Nextion* by *Itead*) was used. Each tablet was secured in a sturdy custom-made laser-cut acrylic enclosure. A strong handle was then screwed into one end of the enclosure so that the participant could easily lift it up or carry it to different rooms. A single button was added to 'wake up' the tablet (Figure 4). The tablet is powered by a 20,000 mAh power bank (*Xiaomi*), giving a theoretical battery life of 6 months, and controlled by an *Arduino* development board (*Seeeduino Stalker* V3.1), which incorporates a Real Time Clock (RTC). All of these are connected by a printed circuit board (PCB) which was custom fabricated for this purpose.

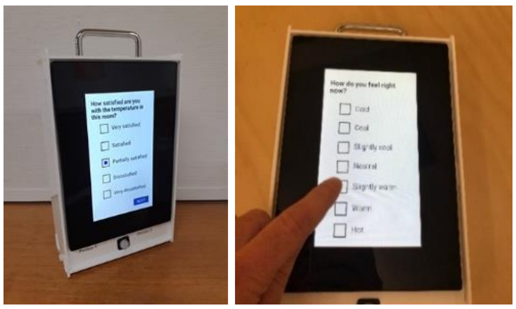


Figure 4. The new indoor environment survey tablet

To commence a survey, the participant presses the button below the screen to 'wake up' the tablet and start the survey. The next question will appear after the participant touches 'Next' on the screen. Shortly after the completion of the survey, the screen switches off and the survey responses are automatically transmitted wirelessly to the logger (see below), where they are time-stamp recorded along with the environmental measures taken within five minutes of the survey response.

The first question is intended for the participant to identify who she or he is (Person 1/Person 2), in case there are two participants in a household (if there is one person per household, she or he will be advised to press 'Person 1'). The next question is to indicate which room she or he is in (Living room/Bedroom). The following questions cover the conditions about the participants (such as their activity and clothing) and their environment as well as their perceptions, sensations and preferences. The questions are either multiple-choice questions (e.g. Are windows in this room: all closed, some closed/open, all open), on 5 to 7-point scale (e.g. Do you feel: cold, cool, slightly cool, neutral, slightly warm, warm, hot), or requiring yes/no answers (e.g. The heater in this room is: on, off). Each question requires only one answer.

Both the text and appearance of the questions on the tablet were discussed and tested in two focus group discussions with older participants. In general, the participants indicated that all the questions were understandable; however, the main criticism was of the original appearance of the tablet: it had white text on a black screen, similar to the screen on the indoor environmental quality logger developed by Carre and Williamson (2018). While Carre and Williamson's respondents had no issue with the tablet appearance, as the majority were younger adults, the older participants found it particularly difficult to read white text on a black screen. Also, initially some graphics and colours were used to represent the answers. There were, for example, pictures of people wearing different types of clothing accompanying the answers for a question on clothing, and colours were used to accompany the answers for thermal sensation questions (from dark blue to represent 'cold' to dark red to represent 'hot'). Very quickly, such representations were criticized by the older participants, stating that they were unnecessary.

Based on all the feedback, the survey questions and the screen interface were modified and then presented to a third focus group. This group found all the questions and interface to be very clear, thus the screen design was then finalized. A summary of the questionnaire and options for the answers is presented in Table 1. Note that there is only one question presented at a time and the participant needs to touch the Next "button" to go to the next question, until the end of the survey. Therefore, no question can be skipped because the next question will not appear until the participant answers the question. A user manual was also created to provide explanations about each question and the answers.

### 3.2. Indoor environmental conditions logger

The indoor environment conditions logger consists of a CCS811 sensor which measures air temperature, relative humidity (RH), CO2 and VOC levels, a Maxim DS18B20 temperature sensor mounted in a matt-black 38mm table tennis ball to measure globe temperature and a ModernDevice Wind Sensor RevC mounted on the logger box. All instruments are polled at 30-minute intervals and when a participant completes a comfort survey. The data are then stored locally on a Secure Digital (SD) card of 8 GB capacity as a text file. An *XBee* (Digi) radio is incorporated in the logger and this allows communication with the survey tablet. The logger is also equipped with a 3G cellular modem, which allows the data, containing time-stamped participant surveys and logger measurements, to be transmitted to an external FTP (File Transfer Protocol) website once per day.

The logger architecture is based on the *Atmega* 328 microprocessor (Amtel Systems Corporation) and employs an *Arduino* derived development board (*Seeeduino Stalker* V3.1) with a Real Time Clock (RTC) which is battery backed in case of loss of power, similar to the survey tablet. Likewise, the logger uses a Printed Circuit Board (PCB) connections to manage the power supply for the logger, provided by a 20,000 mAh *Xiaomi* power bank. Firmware, written using the Arduino Integrated Development Environment (IDE) in a version of C++, controls the core functions of the logger and survey tablet. Similar to the survey tablet, the logger is then placed in a sturdy enclosure (Figure 5).

Table 1. Summary of indoor environmental survey questionnaire

| Type | Questions | Choices for answers |
|---|---|---|
| Identification | Person No: | Person 1, Person 2 |
| | Which room are you in? | Living room, Bedroom |
| Thermal comfort related questions | How are you currently dressed? | Very light, Light, Moderate, Heavy, Very heavy |
| | Describe your activity in the last 15 minutes in this space: | Very relaxed, Relaxed, Light, Moderate, Active |
| | How do you feel right now? | Cold, Cool, Slightly cool, Neutral, Slightly warm, Warm, Hot |
| | Would you prefer to be… | Cooler, No change, Warmer |
| | How satisfied are you with the temperature in this room? | Very satisfied, Satisfied, Partially satisfied, Dissatisfied, Very dissatisfied |
| Heating, cooling, ventilation related questions | The air conditioner in the room is… | On, Off |
| | A heater in this room is … | On, Off |
| | A fan in this room is … | On, Off |
| | Curtains / blinds in this room are… | All open, Some open/closed, All closed |
| | In this room, windows and door(s) to outside are: | All open, Some open/closed, All closed |
| | In this room, door(s) to other room(s) are: | All open, Some open/closed, All closed |
| Air quality related questions | Do you think the air in this room is… | Stuffy, OK, Draughty |
| | Do you feel that the air quality in this room is: | Very good, Good, OK, Poor, Very poor |
| Health/well-being related questions | How would you describe your health and well-being at the moment? | Very good, Good, Reasonable, Poor, Very poor |
| | The conditions in this room influence my health and well-being: | Definitely yes, Probably yes, Yes, Unsure, Probably not, Definitely not |

Figure 5. The indoor environment data logger (left); with the survey tablet (right)

### 3.3. Calibration and testing

The temperature, humidity and $CO_2$ sensors were tested against a calibrated HOBO® MX $CO_2$ Logger (MX1102) while the wind sensor/anemometer was tested against a TSI 8475 Air Velocity omnidirectional probe to develop a calibration curve Voltage versus Air Speed (m/sec). During the deployment it became obvious that the anemometer results were temperature sensitive. A series of laboratory tests confirmed this suspicion and a software compensation methodology was developed based on the device voltage measurement that was recorded at each logger output. Subsequent testing with a number of wind sensors against the TSI 8475 confirmed the accuracy of this conversion.

At the completion of monitoring, all sensors were again tested and compared with the HOBO® MX $CO_2$ Logger (MX1102) along with an Assmann Aspirated Psychrometer measuring dry and wet bulb temperature (from which RH was calculated), in a controlled environment during a period of 24 hours. All environmental loggers showed little measurement drift during their deployment and presented +/- 0.5 degrees Celsius accuracy for temperature and +/- 5% accuracy for relative humidity.

## 4. Operation and communication

Once a day during the research period, each logger transmitted a data file containing time stamped indoor environmental measurements and survey data to a FTP website. The file was stored in a directory linked to the logger's unique telephone number which related to the 3G modem and SIM card installed in the logger. Researchers were able to access daily data files on the FTP site, which are named based on the date when they were created by the logger.

The communication between each logger and survey tablet pair was tested prior to installing them in a participant's home. Additionally, as each logger transmitted a file once per day, the researchers were able to identify if a logger stopped working or if there was an issue with the survey tablet, and could take corrective actions immediately. The rigid structure of the logger file structure also facilitates the aggregation of files for analysis purposes. Files can be quickly downloaded and aggregated using simple batch scripts for more detailed analysis.

One limitation of the newly developed system is the battery life. At the time of the development, the only battery that was able to power the logger with its various sensors as well as the survey tablet, and was within the budget of the project, had 6 months of battery life. This meant that just before the end of the first six months of the monitoring study, the researchers had to go back to each of the houses to replace the batteries. While replacing the batteries did not result in any data losses, this process added some operational cost to the project. However, returning to the participants' homes also allowed the researchers to have further conversations with the participants, which provided additional insights into their behaviours, health and well-being during the study.

## 5. Sample results

Software scripts have been prepared to automatically: (1) collate all the daily indoor environmental parameters from each house as well as from all houses, and (2) collate the survey responses as well as indoor environmental parameters from each house as well as all houses. Up to the end of October 2019, in total there were 10,788 responses from the occupant survey. This means, **on average**, during the 8.5 months of study, each person responded 154 times, or about 3 to 4 times a week, which was more than the minimum that was expected (twice a week). However, upon a closer inspection of the data, we found that 3 people responded less than 30 times while a few others responded twice a day for the entire study period. Such information will be useful in interpreting the collated results, but also indicated the need to carefully look at individual responses.

Figure 6 is an example of the raw data from one house. It shows the date and time when the indoor environmental parameters were measured, followed by the data (e.g. dry bulb temperature, relative humidity, globe temperature, air velocity, $CO_2$ level). The row with the time of 06:08:27 indicates the data from the survey tablet with the responses to the survey questions presented in Table 1. Note that the options for the answers that appeared in text on the survey tablet were replaced by numbers. For example, a very light clothing is indicated by "1" whereas a very heavy clothing is indicated by "5".

```
HH Creat:2019-03-29 00:00:20
HH LogID:N047
HH ACal:0016
2019-03-29 00:00:20,M,22.41,0.00,61.83,22.43,0.09,720,0,400,0,0,0,0
2019-03-29 00:30:20,M,22.44,0.00,61.83,22.43,0.08,659,0,407,1,0,0,0
2019-03-29 01:00:20,M,22.45,0.00,60.63,22.50,0.08,672,0,400,0,0,0,0
2019-03-29 01:30:20,M,22.45,0.00,60.43,22.50,0.08,681,0,403,0,0,0,0
2019-03-29 02:00:20,M,22.42,0.00,58.13,22.43,0.08,668,0,400,0,0,0,0
2019-03-29 02:30:21,M,22.36,0.00,55.36,22.43,0.120,758,0,405,0,0,0,0
2019-03-29 03:00:20,M,22.41,0.00,55.34,22.37,0.08,662,0,408,1,0,0,0
2019-03-29 03:30:20,M,22.35,0.00,54.76,22.31,0.08,656,0,403,0,0,0,0
2019-03-29 04:00:20,M,22.23,0.00,53.57,22.18,0.08,684,0,406,0,0,0,0
2019-03-29 04:30:21,M,22.21,0.00,52.86,22.18,0.08,681,0,413,1,0,0,0
2019-03-29 05:00:20,M,22.13,0.00,53.69,22.18,0.08,688,0,413,1,0,0,0
2019-03-29 05:30:20,M,22.16,0.00,51.97,22.18,0.08,681,0,406,0,0,0,0
2019-03-29 06:00:20,M,22.11,0.00,49.99,22.18,0.09,707,0,402,0,0,0,0
2019-03-29 06:08:27,S,0,1,1,3,4,4,2,2,2,2,2,1,3,1,2,3,3,5,0,0,0
2019-03-29 06:10:20,M,22.09,0.00,49.79,22.12,0.09,729,0,400,0,0,0,0
2019-03-29 06:30:20,M,22.13,0.00,49.59,22.06,0.08,688,0,409,1,0,0,0
2019-03-29 07:00:21,M,22.09,0.00,49.59,22.00,0.09,694,0,406,0,0,0,0
```

Participant
responding to survey

Figure 6. Example of raw data of indoor environmental parameters and survey response

Once the indoor monitoring data and occupant survey responses from the same house have been collated and/or the data from all houses are put together, it is possible to conduct various analyses to respond to the research questions to achieve the research aim, i.e. to understand actual living conditions of older people and the relationships between various indoor environmental condition parameters and occupant's perceived health and wellbeing. Some of the data are presented below, while detailed analyses from the study are presented in another paper (Williamson et al, 2020).

### 5.1. Indoor temperatures and thermal sensation votes

Figure 7 shows the range of indoor temperature in every hour of the day when the participants responded to the survey during summer and winter months. The data show that the range of indoor temperatures during the summer months was wider than during winter and that many of the participants let the indoor temperatures rise above 25 °C and even above 30 °C. This confirms the responses from the occupant survey which indicated that 83% of the time when they voted 'slightly warm' to 'hot', the air-conditioner was not being used (either because of choice or because they did not own a cooling system), despite the fact that 61% of those who voted 'slightly warm' to 'hot' preferred to be cooler.

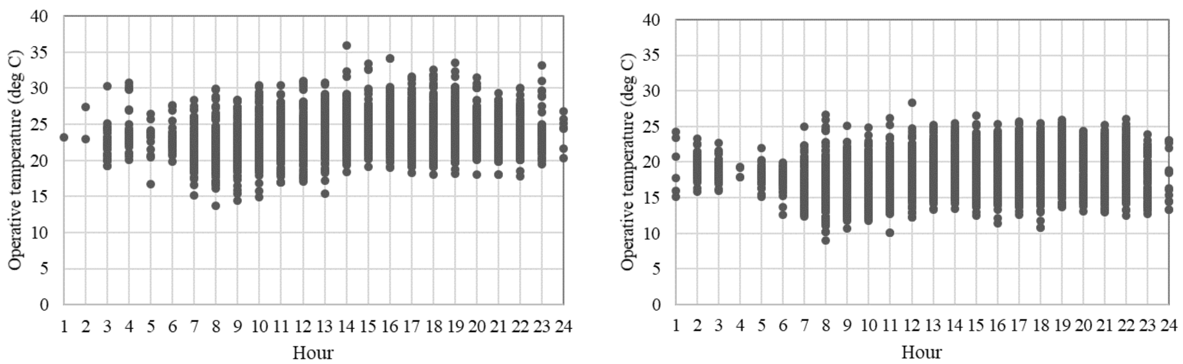



Figure 7. Hourly indoor operative temperature range when participants responded to the survey in summer (left) and winter (right)

Interestingly, the data also indicated that during the monitoring period, there was always at least one person responding to the survey even in the early hours of the day and that the participants routinely responded to the survey at more or less the same time of the day (Figure 8). In both summer and winter, most responses occurred late in the afternoon as well as in late morning.

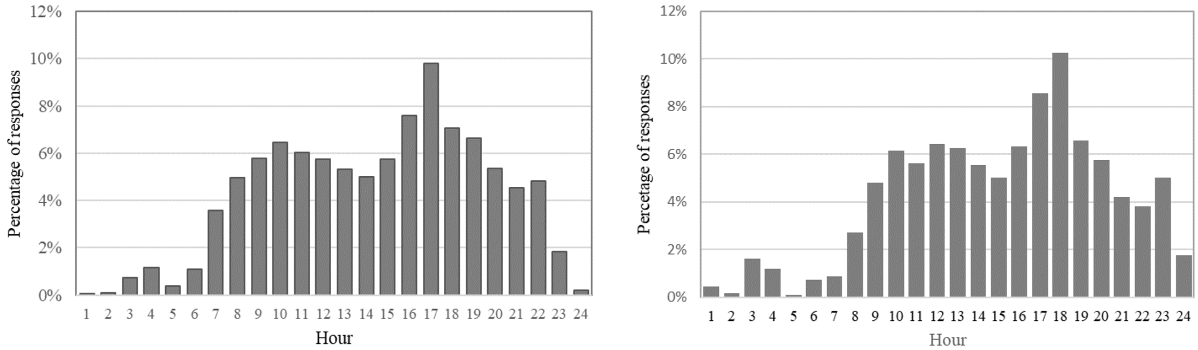



Figure 8. Percentage of responses every hour throughout summer (left) and winter (right)

Figure 9 shows the frequency of each thermal sensation vote during summer and winter months. The results show that overall the participants perceived their dwelling (living room and main bedroom) to be 'neutral' for around 50% of the time, followed by 'slightly cool' (between 22% during summer and 27% during winter), and slightly warm (14% during summer and 9% during winter). Interestingly during summer, 'cool' votes were accounted for 10% of the time whereas during winter there were only 7% of the time that the participants voted to be 'cool'. The data showed that, when the participants responded to the survey during winter months, 30% of the time the heater was in use and this may explain the lower percentage of 'cool' responses during winter, whereas, during summer, the participants indicated that no heater was in use despite the fact that the indoor temperatures in some houses were below 18 °C, as indicated in Figure 7 above.

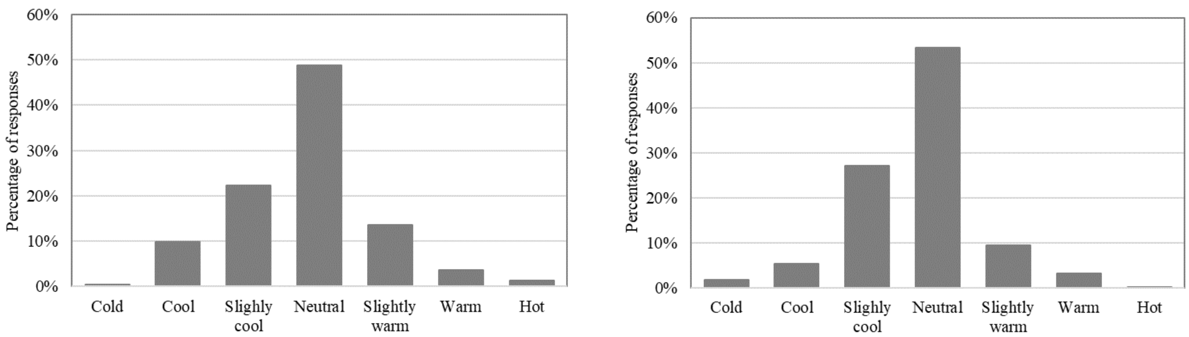



Figure 9. Thermal sensation votes during summer (left) and winter (right) months

Figures 10 presents the indoor operative temperatures and thermal sensation votes during summer and winter months, while Figure 11 illustrates the average thermal sensation vote calculated for every 0.5K of indoor operative temperature with a regression model fitted using weights according to the number of votes in each temperature bin, indicating neutral temperature of 25.4 °C in summer and 23.8 °C in winter.

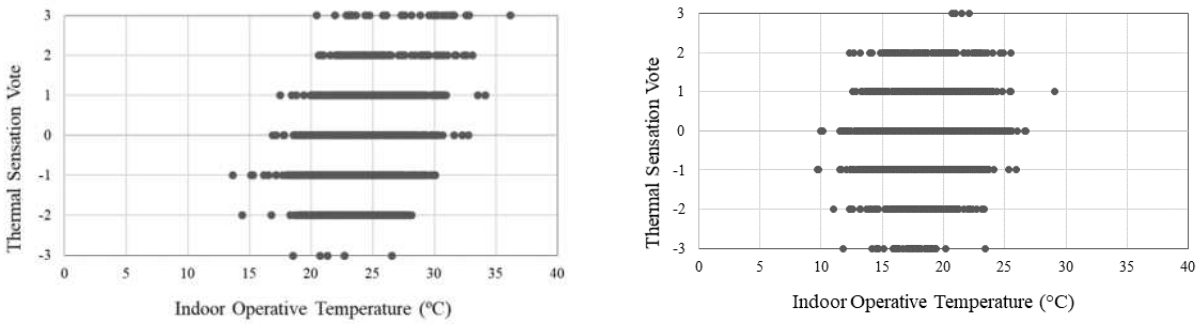



Figure 10. Thermal sensation votes vs indoor operative temperatures during summer (left) and winter (right) months

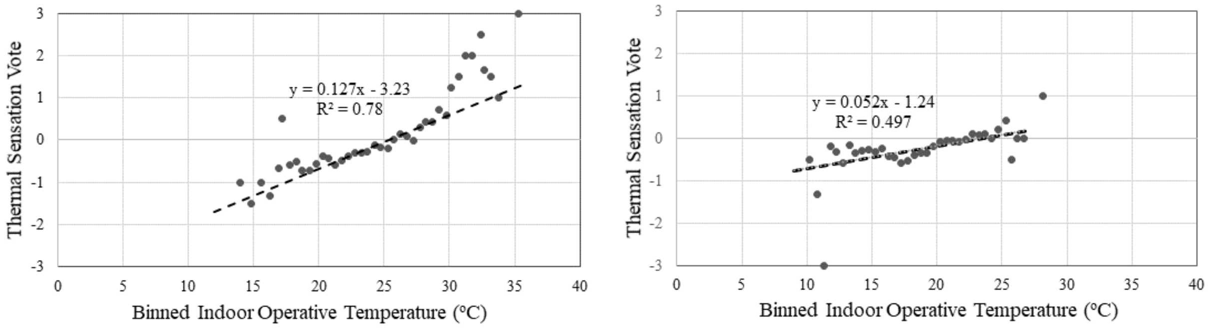



Figure 11. Average thermal sensation vote vs binned indoor operative temperature during summer (left) and winter (right) months.

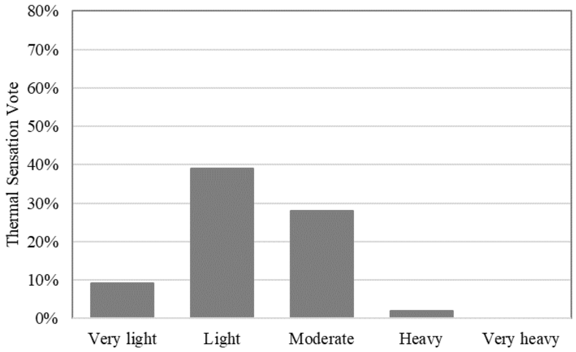
## 5.2. Clothing

During summer months, the majority of participants indicated wearing 'light' clothing, followed by 'moderate' and 'very light' clothing, whereas during winter months the majority wore 'moderate' clothing, followed by 'heavy' clothing, as shown in Figure 12. Clothing seems to be an important strategy for them to stay cool in summer or warm in winter, instead of using the cooling or heating system.

Table 2 presents examples of clothing types for each clothing level used in the study (this information was part of the instruction manual given to the participants). It is however interesting to see that there were a few responses indicating that they were wearing 'light' clothing during winter months. Upon a closer investigation, these occurred when the participants had just done an activity (such as vigorous housework or an exercise), or when the heater was on.

Table 2. Examples of clothing types for each clothing category

| Clothing category | Examples |
|---|---|
| Very light<br>(approx. 0.2 clo) | • underwear with sleeveless, lightweight pyjamas<br>• underwear or bathers and lightweight sarong<br>• underwear and t-shirt or light-weight sleeveless top and shorts or light skirt with no shoes or sandals. |
| Light<br>(approx. 0.45 clo) | • underwear with short-sleeved pyjamas<br>• underwear and shorts or skirt with lightweight short-sleeved top and sandals |
| Moderate<br>(approx. 0.7 clo) | • long-sleeved pyjamas with dressing gown and slippers<br>• underwear and skirt, dress or trousers with long-sleeve shirt, sleeveless vest or light pullover and shoes and socks |
| Heavy<br>(approx. 0.95 clo) | • as 'moderate' plus a sweater or jacket |
| Very heavy<br>(approx. 1.2 clo) | • as 'moderate' but thick trousers or thick skirt and tights, thick pullover and sleeveless vest or jacket |



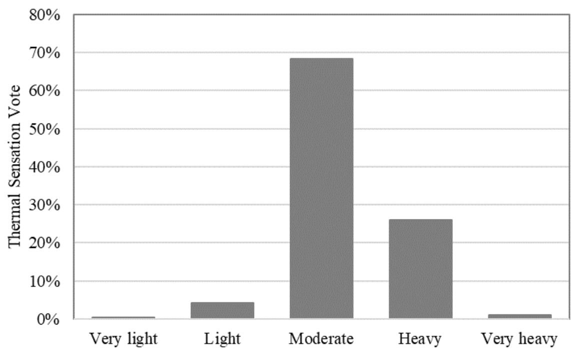
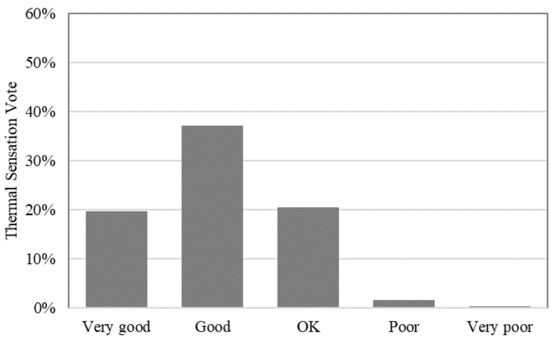




Figure 12. Participants' clothing levels during summer (left) and winter (right) months.

### 5.3. Air quality and health

The data show a higher percentage of responses during winter months indicating a good indoor air quality compared to during summer months (Figure 13). This also corresponds to a higher percentage of responses in winter indicating good health and well-being compared to summer (Figure 14). The difference in the perception of air quality and health between the two seasons was found to be statistically significant ($p$ = 0.038 and $p$ = 0.000, respectively).

Thermal sensation votes were also found to significantly correlate with the perception of good health and well-being ($p$ = 0.000), but interestingly the perception of poor health mostly correlated with a 'cool' thermal sensation. So even though overall the participants felt that both the indoor air quality and their health and well-being were better during winter months, they felt their health worsened when experiencing 'cool' instead 'warm' sensations. This may be related to the fact that, overall, the homes of these older participants tend to be on the cold spectrum, with minimum indoor temperature during winter found to be less than 5 °C in one of the houses. For this house, however, no survey response was given at the time to confirm how the occupants actually felt in such thermal environment.



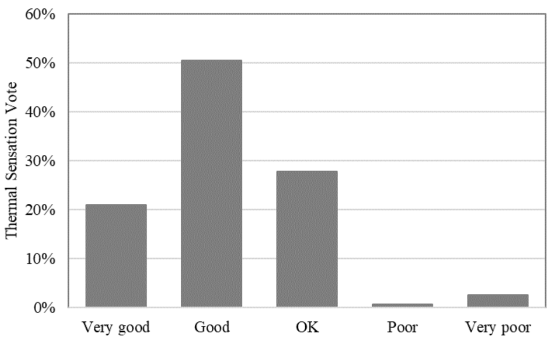
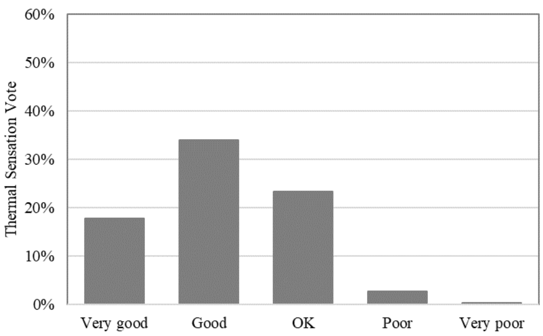




Figure 13. Perceptions of indoor air quality during summer (left) and winter (right) months.



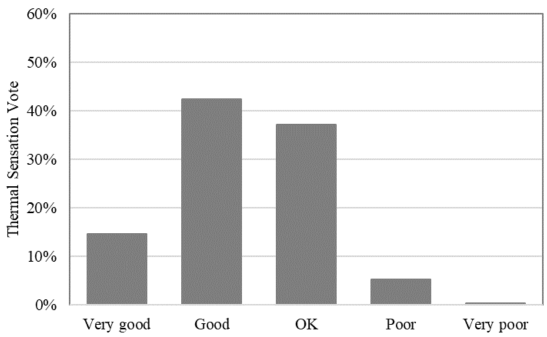




Figure 14. Perceptions of their health and well-being during summer (left) and winter (right) months.

## 6. Lessons learned

### 6.1. Data acquisition and occupant survey tool

Each set of data logger and survey tablet costs no more than $800 (in Australian dollars) while subscription to the FTP server cost no more than $120 per month for the entire 57 loggers. In other words, for the whole 8.5 months of study, it cost less than $850 to build and operate one set of data logger and survey tablet. Despite this relatively low budget, the system is able to collect very rich data providing insights into the indoor environmental conditions of a sample of older people in South Australia as well as the behaviours of these people in responding to their indoor environmental conditions. The only issue with this relatively low cost system was the limited life of the batteries that were used in the system, which required additional costs of travel to each of the participant's homes to replace the batteries at around 6 months after the start of the study.

While remote, portable and affordable indoor environmental monitoring systems have been developed by others, at the time this paper was written, we had not found any existing system that was able to combine the indoor environmental parameters being monitored and the participants' responses. All other existing systems required the data from the two systems or devices to be combined manually post the monitoring or after the participants completed the survey. While a script can be written to combine the data to ensure that the time at which the survey responses were given closely matched the time at which the environmental parameters were being measured and recorded, there can still be a discrepancy between the time stamps of the two systems. On the contrary, in this study, this discrepancy will not happen because the two systems communicate with each other in real time and the environmental parameters around the time the participants provided their survey responses were automatically recorded. This minimizes the risk of having unsynchronized indoor environmental data and survey responses, thus guaranteeing the accurate evaluation of "right here right now" indoor environmental quality.

### 6.2. Participant feedback

Some participants recommended that at the end of each survey, they should be able to review their responses before they touched the "End" button. A number of respondents also said that they would like a 'Back' button.

We sent all participants the summary of their responses (as a plot of indoor temperature and thermal sensation votes) as well as an example of the outdoor and indoor temperature plots every three months, as shown in Figure 15. Keeping the participants informed was an important aspect of the research. Not all the participants could understand the summary but everyone appreciated getting some data about their house and their responses as an indication of the information that was being generated by their 'button-pushing'.

The study also identified two issues that need to be considered for future research into indoor environmental conditions and survey of older people. First, although we have endeavoured to use large font size for the survey tablet, some participants, particularly those who had hand movement problems, found using the tablet challenging. Second, some participants raised their concerns over the use of electronic devices and a wireless connection in their house, as they were worried about the impact for the radiation of such devices on their health. Despite the fact that the impact of the devices used in the study on health would be no more than the impact of electronic devices found in the participants' homes, such as a television, a computer screen or a radio, such concern needs to be taken into account.

Nevertheless, the majority of the participants reported that the data logger and survey tablet placed in their living room had become a point of interest and discussion by anyone visiting their house. For many, responding to the survey had become a daily routine, and they said they would “miss them” when we had to retrieve the logger and tablet from their house at the end of the study.

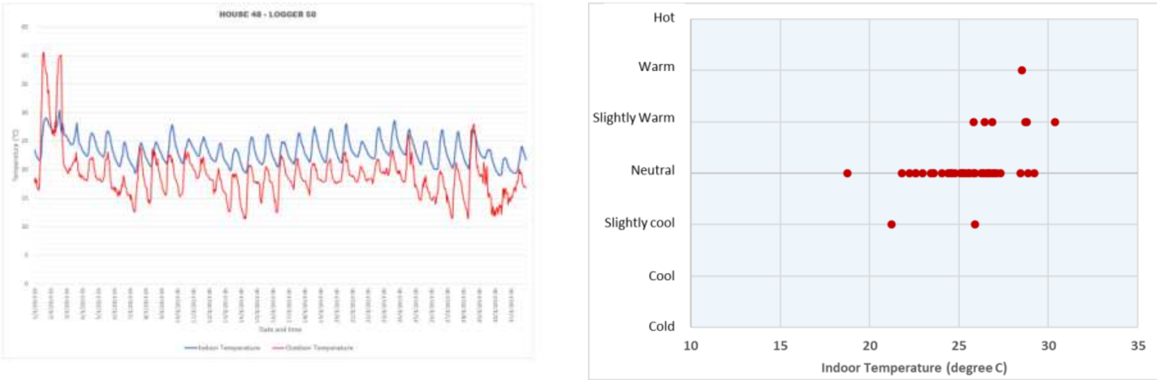



Figure 15. Example of data summary sent to each participant: (1) indoor-outdoor temperature (left) and (2) indoor temperature vs thermal sensation votes (right)

## 6. Summary

We have adopted a robust, unobtrusive and independent system to continuously monitor indoor environmental parameters and record occupant responses to an indoor environment survey. While the study focused on older people, the system can be applied to any other indoor environmental studies with other groups of subjects. The system is capable of recording a vast amount of data with a relatively low cost for what it can do. While the system suffered from a limited battery life, which prohibits the use of such system for a study longer than 6 months without having to go back to replace the battery, it has proven to be an advancement of previous types of data acquisition system and survey tools for studies on indoor environmental conditions and their relationships with occupant behaviours and perceptions.

## 7. Acknowledgements

The research has been funded by the Australian Research Council through the Discovery Project scheme, Project number ARC DP180102019. The researchers wish to acknowledge the participants in the research. The contribution by our Partner Investigator, Professor Joost van Hoof from The Hague University of Applied Sciences, and Chief Investigator Jian Zuo, is greatly appreciated.

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# Thermal Comfort, well-being and health of older residents in South Australia

**Terence Williamson[1], Veronica Soebarto[1], Helen Bennetts[1], Larissa Arakawa Martins[1], Dino Pisaniello[2]**

[1] School of Architecture and Built Environment, The University of Adelaide, Adelaide, Australia;
[2] School of Public Health, The University of Adelaide, Adelaide, Australia

**Abstract:** This paper will report findings of a research project aimed at investigating the actual thermal environment of the housing of older occupants (aged over 65) in South Australia together with their thermal preferences and behaviours during hot and cold weather and relationships to their well-being and health. Information was collected with an innovative data acquisition system (reported elsewhere). The research covered three climate zones and extended over a 9-month period. The study involved a total of 71 participants in 57 houses. More than 10,000 comfort/well-being questionnaire responses were collected together with more than 1,000,000 records of indoor environmental conditions. Relationships between thermal sensation and self-reported well-being/health as it is influenced by indoor environmental conditions will be detailed as will the various adaptive strategies the occupants employ to maintain their preferred conditions. The circumstances found acceptable will be compared with present Standard recommendations.

**Keywords:** Thermal comfort, ageing, health, well-being

## 1. Introduction

At the First Windsor conference *Standards for Thermal Comfort* back in 1994, Michael Humphreys presented a seminal paper entitled “Thermal Comfort Temperatures and the Habits of Hobbits” (Humphries, 1995). In this paper he set out a field study process by which we could discover the comfort temperatures and conditions most favoured by Hobbits and by comparison the human occupants of buildings. These recommendations, as we know, have led to the development of the Adaptive Thermal Comfort approach, now accepted in Standards around the world. There was nothing in Humphreys’s paper to suggest that the Hobbits being observed were anything except healthy young adults.

Inevitably however, even for Hobbits, age catches up with them and as Bilbo Baggins in Tolkien’s The Hobbit laments, “I am old, Gandalf. I don't look it, but I am beginning to feel it in my heart of hearts. Well-preserved indeed! ……… That can't be right. I need a change, or something.” He goes on to wish that he could just, “… sit at home in my nice hole by the fire, with the kettle just beginning to sing!”. Just like Bilbo Baggins, the vast majority of older Australians want to live independently and comfortably in their own home for as long as possible.

This paper reports on findings of a research project involving a field study aimed at investigating the actual thermal environment of the housing of older occupants (aged 65 and over) in South Australia together with their thermal preferences and behaviours during hot and cold weather and relationships to their health and well-being. Overall, the project involves several phases that include an extensive telephone survey of around 250 participants, 7 focus group discussions with 49 participants and detailed monitoring of a selection of houses. Human ethics approval to conduct the indoor environment monitoring was received from the Human Research Ethics Committee at The University of Adelaide, approval number H-2018-042.

When interviewed during the early stages of the project, participants said they feel both the cold and the heat much more than when they were younger, and that getting older had affected their perception of the thermal environment (van Hoof, et al. 2019) One participant in a focus group meeting said "*As I've aged, I fear the cold and I feel the cold more than when I was younger. The heat doesn't affect me as much, I haven't noticed suffering from heat, but I do know that as I've become older, I suffer more from the cold weather."* On the other hand, another stated, "*When it's hot I can't take the heat and I feel so cold nowadays so I definitely feel a big change."* Other participants indicated that ageing had affected their activity levels and mobility and this had implications for their thermal comfort, "*I think that in many cases we're not as active as we used to be so we're not warming ourselves up but we've also got a lot more time to think about it rather than when we had a job.".* They were also aware that their health can be affected by changing thermal conditions, with arthritis being a common complaint. "*Sometimes my arthritis tells me there's going to be bad weather ….. when I get more arthritis that really affects me because I get frustrated; I can't do things that I want to do*." They were often concerned about the costs associated with heating and cooling a house*. "….. because we all live on our own it's easier for us to make do rather than have to pay extreme electrical costs of running anything, heating or cooling. Like I said, my throw rug only costs me 4 cents an hour to run".* Even so*, "I'm still scared of how much it's going to cost me because we're on a pension*".

Questions that flow from these new circumstances of ageing include, "Do these changes of habit and circumstance signal a change in preferences that needs to be accounted for in an adaptive comfort model?" and "To what extent are thermal conditions and health and well-being interrelated"?

The paper will explore these issues. It will describe the thermal conditions found in a sample of houses and examine some of the adaptive strategies employed by the participants to maintain their preferred conditions, as well as relationships between thermal sensation and self-reported well-being/health as it is influenced by indoor environmental conditions. The acceptable thermal conditions are compared with present Standard recommendations. Another paper to be presented at the conference examines findings that relate to the effects of personal characteristics on comfort and wellbeing (Arakawa-Martins, 2020).

## 2. Study setting

The State of South Australia (SA) is located in central southern Australia and has a population of approximately 1.7 million, most of whom (77%) live in the State's capital city of Adelaide. In general, South Australia experiences warm to hot summers (December to February) and relatively mild winters (June to August). For energy-efficient building design the National Construction Code identifies three climate zones in the State - (1) semi-arid, (2) warm temperate, and (3) mild temperate, specified as climate zones 4, 5 and 6. These are similar to the *BSk, Csa*, and *Csb* zones in the Köppen-Geiger climate classification system (BOM, 2014) and these classifications are used in this paper.

This study focused on regions in each climate zone with relatively high concentrations of older people. Therefore, the semi-arid climate region (*BSk*) was represented by three towns known in SA as the "Iron Triangle" (townships of Port Augusta, Whyalla and Port Pirie) in the mid north of SA. The warm temperate climate region (*Csa*) was represented by the Greater

Metropolitan Adelaide region, while the mild temperate climate region (*Csb*) was represented by the southern coastal area in the Fleurieu Peninsula and parts of the Hills area east of metropolitan Adelaide. Figure 1 shows the three regions for the study.

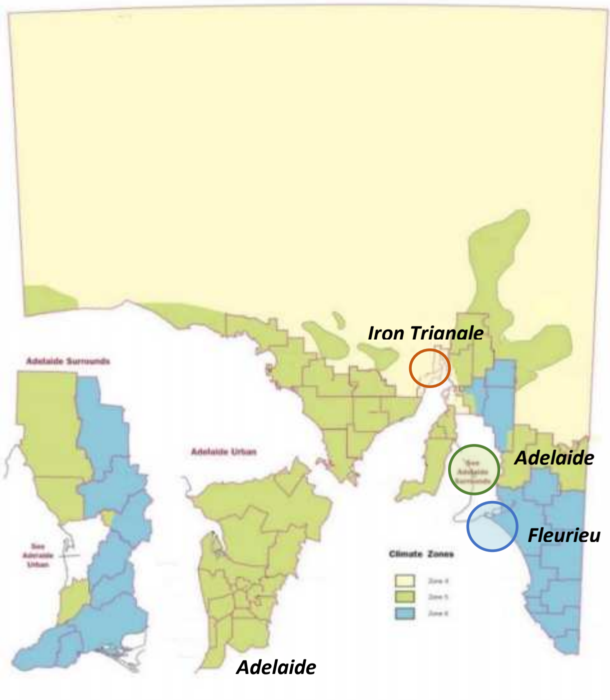



Figure 1. Climate zones in South Australia and the three study regions
Source: Adapted from Australian Building Codes Board, National Construction Code
(Zone 4 = *BSk*; Zone 5 = *Csa*; Zone 6 = *Csb*)

Figure 2 shows comparisons of the monthly mean maximum and minimum temperatures at meteorological monitoring stations in these climate zones: Whyalla (representing *BSk*), Kent Town (*Csa*) and Victor Harbor (*Csb*).

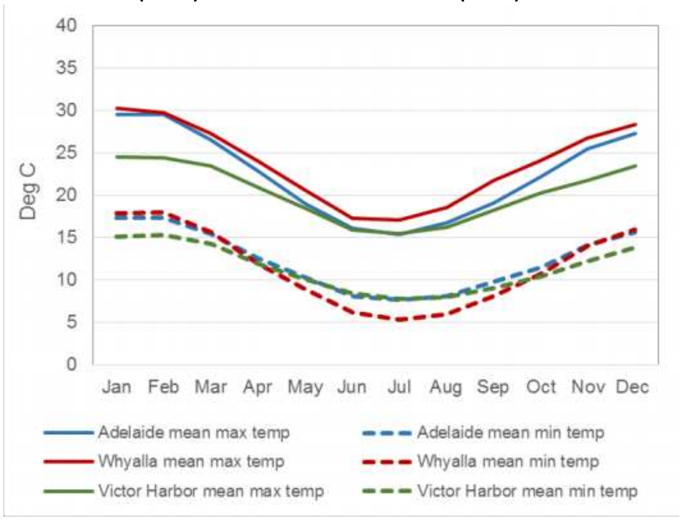



Figure 2. Monthly mean maximum and minimum temperatures in Whyalla (*BSk*), Kent Town (*Csa*) and Victor Harbor (*Csb*)
Source: Compiled based on data from Australian Government Bureau of Meteorology

### 2.1 Participants and houses

Householders who agreed to take part in the monitoring exercise were self-selected from the initial phases of the research project, the telephone survey and the focus group discussions as well as from publicity in various media outlets (Soebarto, et al., 2019). One criterion for participation was an agreement not be absent for a period in excess of 6 weeks during the monitoring period.

A total of 57 houses, consisting of 71 participants were involved in the exercise over approximately 9 months from January to October 2019. This period covered summer and winter months, as well as autumn and part of spring. About 67% of the participants were female and 33% male. Their ages ranged from 65 years with 10% over 85 years.

Figure 3 shows some examples of the houses monitored and Figure 4 gives a breakdown of the types of houses. Overall 23% of the houses were located in a retirement village setting.

Figure 3: A sample of typical houses included in the monitoring program

The houses were mostly typical of the construction types in South Australia: external walls of cavity brick or brick veneer construction and roofs of corrugated steel sheeting or concrete tiles. The older houses had suspended timber floors while newer houses had concrete slab-on-ground construction. The approximate floor area of the separate and semi-detached houses taken together was 156 sq.m., smaller than the average floor size of Australian homes which is 186.3 sq.m. All houses had heaters and all but two houses had air-conditioners (coolers) in at least one room of the house, generally the living area; however, for majority of the time the houses were operated as free-running (FR), that is, without heating and cooling.

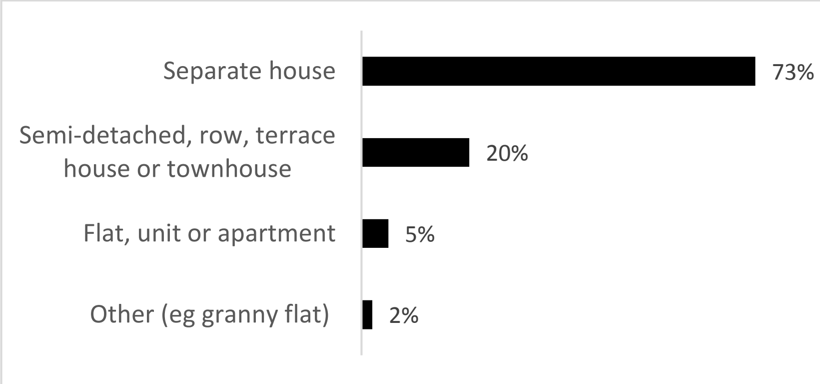



Figure 4: Types of houses monitored

## 3. Monitoring

Information was collected with an innovative data acquisition system which is described elsewhere (Soebarto et al., 2020). The logger recording environmental conditions every 30 minutes was placed in the main living room of the house, but the portable Tablet allowed the participant to record their responses (referred to as a vote) in the living room or the bedroom. A HOBO® U12-013 data logger was placed in the main bedroom of each house to measure temperature and humidity. Files of hourly weather data from eight Bureau of Meteorology stations were obtained with the station closest to each house identified.

The monitoring included houses in the three climate zones and during the 9-month period more than 10,000 comfort/well-being questionnaire votes were collected together with more than 1,000,000 records of indoor environmental conditions.

Participants were asked to vote regularly, if possible, once per day. Some were more diligent in their voting than others, with on average each participant recording around 150 votes. In general participants did notify the researchers prior to periods of absence.

Daily data text files of the recordings together with the vote information were downloaded via the 3G network and regularly inspected by a researcher to identify any anomalies or problems. If a suspected issue was identified, arrangements were made to visit the house and rectify the problem. For example, in some tablets the battery became dislodged causing the screen to not work. The repair involved adding a piece of plastic foam to support the battery and took about 5 minutes.

A computer script was developed to assemble all the data from the loggers, HOBOs® and BOM weather files for analysis. Comfort indices such as Predicted Mean Vote (PMV) and Standard Effective Temperature (SET*) were also calculated and added to the compiled data files. A total of 10787 completed votes were received during the monitoring period. A number of votes were considered as outliers (e.g. PMV outside the range ±4) and were disregarded for analysis.

### 3.1 Internal temperatures

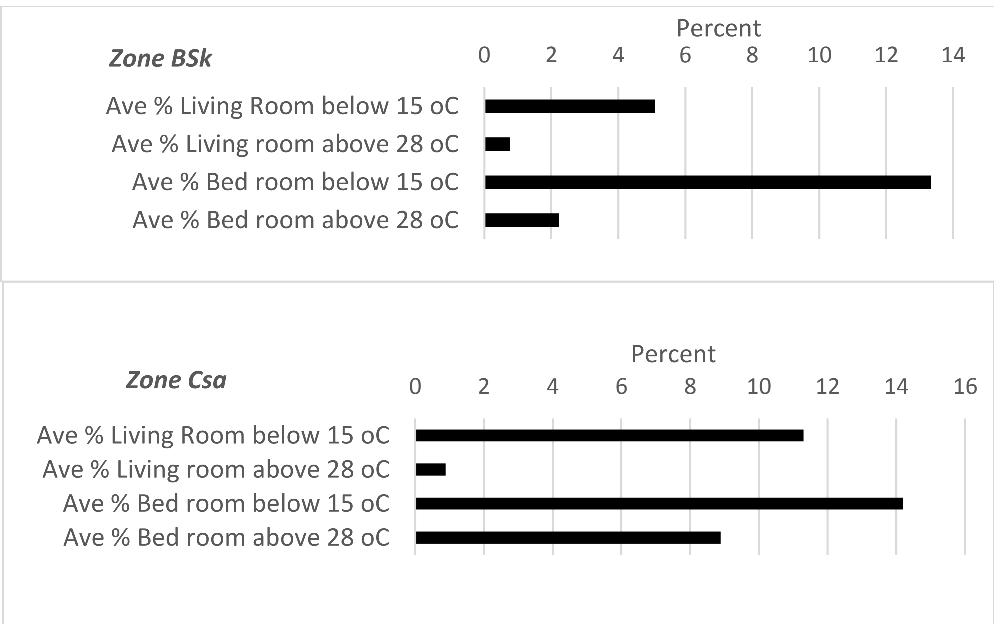
The weather in South Australia is generally described as Mediterranean with hot dry summers and cool mild wet winters. Table 1 shows the cooling degree hours (base 28 $^{o}$C) and heating degree hours (base 15 $^{o}$C) derived from the Bureau of Meteorology (BOM) hourly temperatures for the 10 months (Jan – Oct) of the monitoring period in 2019. While, as seen in Figure 1, the State is divided into several climate zones, Table 1 shows there is considerable variation within a zone. While there may be short periods of extreme heat, in general as the Table shows, in all zones the climate is heating dominated. This is mirrored in the temperatures recorded in the houses.

Temperatures in the living room and main bedroom of houses showed considerable variation. This reflects not only the external weather, but factors such as the occupants' behaviour, their use of heating and cooling appliances, as well as aspects of the house design that influence the thermal environment.

Table 1: Heating and Cooling Degree hours for Bureau of Meteorology stations relevant to the locations of the participants' homes

| Location | Köppen Classification Climate Zone | Cooling degree hours – base 28 °C | Heating degree hours – based 15 °C |
|---|---|---|---|
| Whyalla – Iron Triangle | *BSk* | 2605 | 13697 |
| Port Pirie – Iron Triangle | *BSk* | 4124 | 14810 |
| Adelaide – West Tce | *Csa* | 2492 | 12008 |
| Adelaide – Kent Town | *Csa* | 3003 | 13025 |
| Adelaide – Airport | *Csa* | 1608 | 12318 |
| Noarlunga | *Csa* | 1950 | 14957 |
| Edinburgh Airport | *Csa* | 3147 | 14857 |
| Parafield Airport | *Csa* | 3257 | 15009 |
| Hindmarsh Island – Fleurieu | *Csb* | 1018 | 12394 |
| Mount Lofty – Hills | *Csb* | 819 | 32191 |

Figure 5 shows the percentage of all hours for houses in each climate zone when the dry bulb temperature was below 15 °C and above 28 °C in living rooms and bedrooms. A perhaps surprising observation is the time when both living rooms and bedrooms are below 15 °C. While this Figure shows the average, a number of houses in Zones *Csa* and *Csb* recorded temperatures in the living room and the bedroom below 15 °C for more than 30% of hours even if in all cases heating was available.



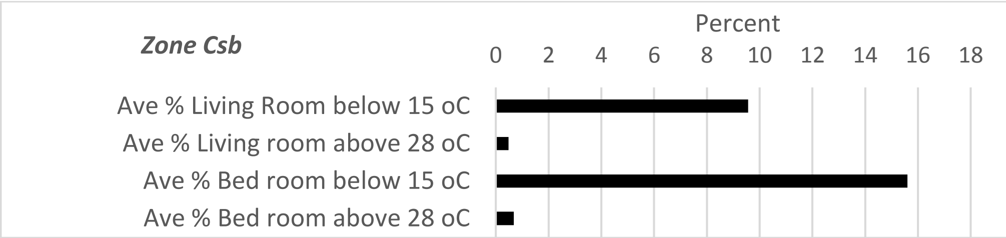



Figure 5: Percentage of hours below 15 °C and above 28 °C in living rooms and bedrooms.

The relatively low percent of time above 28 °C is indicative of several factors; the fairly mild temperatures during most of the monitoring period, house construction that ameliorates temperature extremes, and adaptive behaviours, for example, applying shading devices and finally the use of air-conditioning (cooling).

### 3.2 Occupant behaviours

The survey Tablet sought responses to 17 questions concerning the indoor conditions, perceptions and preferences that participants were asked to complete. These are shown in Table 2. The following section presents a summary of the results in the three climate zones to some of the questions.

Table 2. Summary of indoor environmental survey questionnaire

| Type | Questions | Choices for answers |
|---|---|---|
| Identification | Person No: | Person 1, Person 2 |
| | Which room are you in? | Living room, Bedroom |
| Thermal comfort related questions | How are you currently dressed? | Very light, Light, Moderate, Heavy, Very heavy |
| | Describe your activity in the last 15 minutes in this space: | Very relaxed, relaxed, light, moderate, active |
| | How do you feel right now? | Cold, Cool, Slightly cool, Neutral, Slightly warm, Warm, Hot |
| | Would you prefer to be… | Cooler, No change, Warmer |
| | How satisfied are you with the temperature in this room? | Very satisfied, Satisfied, Partially satisfied, Dissatisfied, Very dissatisfied |
| Heating, cooling, ventilation related questions | The air conditioner in the room is… | On, Off |
| | A heater in this room is … | On, Off |
| | A fan in this room is … | On, Off |
| | Curtains / blinds in this room are… | All open, Some open/closed, All closed |
| | In this room, windows and door(s) to outside are: | All open, Some open/closed, All closed |
| | In this room, door(s) to other room(s) are: | All open, Some open/closed, All closed |
| Air quality related questions | Do you think the air in this room is… | Stuffy, OK, Draughty |
| | Do you feel that the air quality in this room is: | Very good, Good, OK, Poor, Very poor |
| Health/well-being related questions | How would you describe your health and well-being at the moment? | Very good, Good, Reasonable, Poor, Very poor |
| | The conditions in this room influence my health and well-being: | Definitely yes, Probably yes, Unsure, Probably not, Definitely not |

#### 3.2.1 Use of heaters and coolers

Unlike houses in other countries, very few houses in South Australia have central heating and cooling systems. Heating was supplied in the houses by a number of means that ranged from ducted systems to portable electric radiators and blower heaters. Heating in bedrooms was generally with a portable device and generally used for only a few hours in the evening. Cooling was achieved mainly with split systems, that is, an external compressor coupled to an indoor fan coil unit. Tables 3 and 4 show for each climate zone the percent of time heating and air-conditioning (cooling) were reported to be operating at the time of a vote. In climate zone *BSk* the heating was reported to be on 22.3% during a vote and cooling 15.3% of the time. The participants in climate zone *Csb*, in theory the coldest, reported the lowest use of heaters when they voted at 14.1% of times. On the other hand, they recorded the air-conditioner (AC) operating 12.6% of the time. Taking all Zones together the proportion of ACs operating at the time of a vote increased with increasing external temperature. At 28 $^{o}$C, 28% of respondents indicated that the AC was On. This increased to 58% once the external temperature increased to 38 $^{o}$C.

Table 3: Percent of time heating On/Off during voting and corresponding TSV

| **TSV** | **Climate *BSk*** | | **Climate *Csa*** | | **Climate *Csb*** | |
|---|---|---|---|---|---|---|
| Heater | % Off | % On | % Off | % On | % Off | % On |
| Cold | 0.2% | 2.4% | 1.2% | 0.6% | 0.9% | 2.6% |
| Cool | 10.2% | 0.0% | 6.8% | 1.7% | 6.4% | 7.4% |
| Slightly cool | 17.8% | 10.2% | 27.1% | 17.8% | 25.6% | 25.1% |
| Neutral | 53.3% | 23.6% | 52.1% | 58.4% | 54.4% | 49.9% |
| Slightly warm | 12.6% | 25.2% | 10.0% | 14.0% | 9.9% | 11.5% |
| Warm | 4.3% | 38.6% | 2.2% | 7.4% | 2.4% | 3.5% |
| Hot | 1.6% | 0.0% | 0.7% | 0.1% | 0.4% | 0.0% |
| Overall TOTAL % | 77.7% | 22.3% | 81.0% | 19.0% | 85.9% | 14.1% |

Table 4: Percent of time cooling (AC) On/Off during voting and corresponding TSV

| **TSV** | **Climate *BSk*** | | **Climate *Csa*** | | **Climate *Csb*** | |
|---|---|---|---|---|---|---|
| Cooler | % Off | % On | % Off | % On | % Off | % On |
| Cold | 0.2% | 3.4% | 1.2% | 0.5% | 0.9% | 2.5% |
| Cool | 7.2% | 11.5% | 5.2% | 11.3% | 6.6% | 5.6% |
| Slightly cool | 16.4% | 14.9% | 25.8% | 21.3% | 26.1% | 21.6% |
| Neutral | 46.0% | 50.6% | 54.6% | 42.0% | 54.0% | 52.1% |
| Slightly warm | 15.9% | 12.6% | 9.7% | 20.2% | 9.4% | 15.7% |
| Warm | 13.3% | 4.6% | 3.2% | 2.9% | 2.6% | 2.5% |
| Hot | 1.0% | 2.3% | 0.4% | 1.8% | 0.4% | 0.0% |
| Overall TOTAL % | 84.7% | 15.3% | 89.7% | 10.3% | 87.4% | 12.6% |

Examination of Tables 3 and 4 reveals some interesting aspects regarding heating and cooling responses. An analysis of the figures in Table 3 shows that when heaters were reported as on, compared to the off state, the participants reported thermal sensation votes (TSVs) that increased towards warmer conditions. This is much as expected. However, an examination of Table 4 shows that, compared with the off state, only in climate Zone *BSk*, did the participants indicate TSVs tending towards cooler conditions when the AC was on. In the other two Zones the participants reported generally warmer TSVs with the AC on. This apparent anomaly will require further investigation.

### 3.2.2 Clothing

The clothing levels reported by the participants in the 3 zones is shown in Figure 6. On balance the climate zones show similar results. The somewhat greater variation of clothing levels in climate Zone *BSk*, with more "very light" and "heavy", is likely due to the greater variability of the weather in that region. The slightly higher level of "moderate" clothing reported in Zone *Csb* is in line with the hot/warm and cold/cool weather that can be implied from Table 1. Otherwise there appears to be little difference in clothing worn in the three climate zones. Typical "moderate" clothing would be trousers and a long sleeve shirt or a knee-length skirt, a long sleeve shirt and pantyhose.

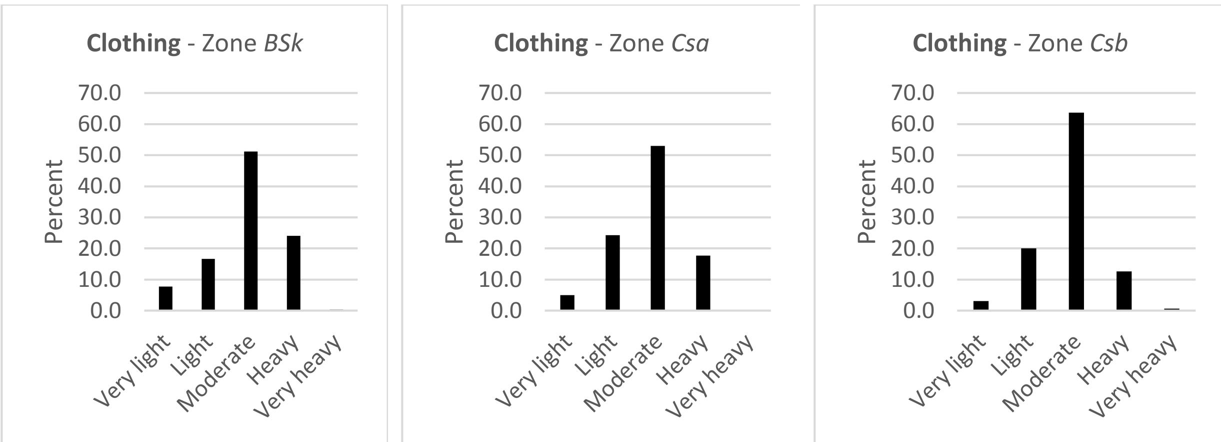



Figure 6: Clothing levels reported by participants in three climate zones

Taking all climate zones together, Figure 7 shows that the participants adjusted their clothing level in relation to the internal operative temperature (binned at 0.5K intervals). The weighted regression line shows clearly that as the temperature increased lighter clothing was employed. The slope of the line indicates that this is a main adaptive strategy.

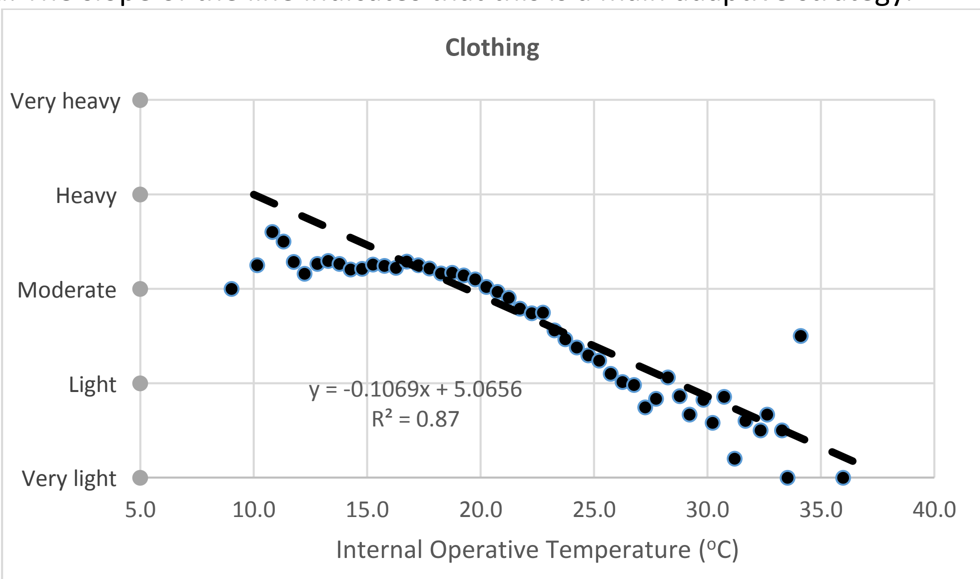


Figure 7: Internal operative temperature (°C) versus clothing levels reported by participants all climate zones

### 3.2.3 Activity

The activity levels reported by the participants are shown in Figure 8. In all climate zones around 80% of the time the participants reported being "very relaxed", "relaxed" or "light" (perhaps waiting for their kettle to boil?). In zone *BSk*, the higher percent reported as "relaxed" is probably a reflection the smaller number of votes and the health conditions of the participants. For further analysis each reported activity is associated with a Met level. For example, "Light" is designated as Met 1.5 and "Active" as Met 2.0.

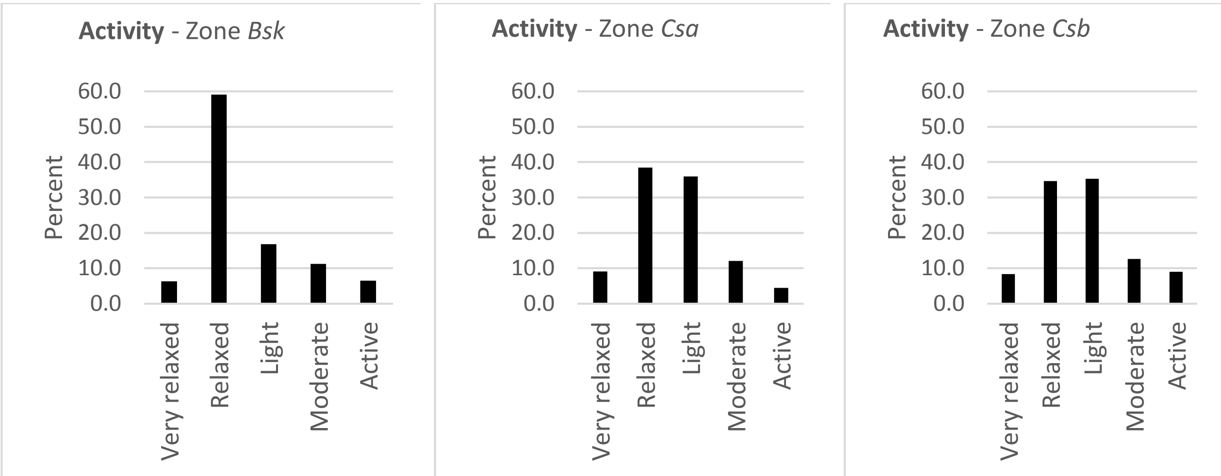



Figure 8: Activity levels reported by participants in three climate zones
Note: Zone BSk – N=570, Zone Csa – N=4261, Zone Csb – N=5965

For all zones combined, Figure 9 shows that activity reduces as the internal operative temperature increases. That is, the participants tend to slow down as reported in the interviews. The increases in activity when the temperature is below 15 °C could be interpreted as efforts to keep warm.

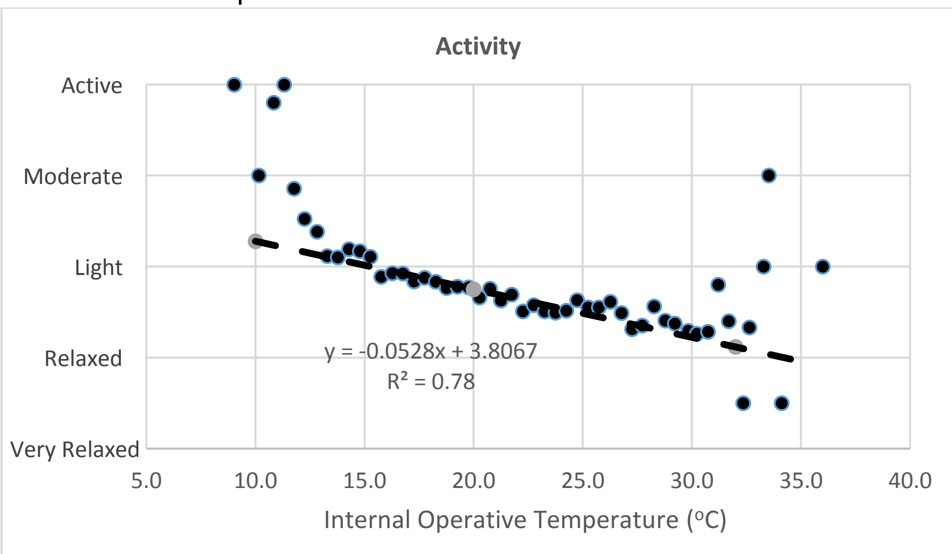



Figure 9: Internal operative temperature (°C) versus activity level reported by participants all climate zones

## 4. Thermal sensation and preference

Figure 10 shows the frequency of responses recorded for the question "How do you feel right now?" over the whole monitoring period - the thermal sensation vote (TSV). For climates *Csa* and *Csb* the balance of votes was slightly on the cool/cold side, while for zone *BSk* the balance was about equal.

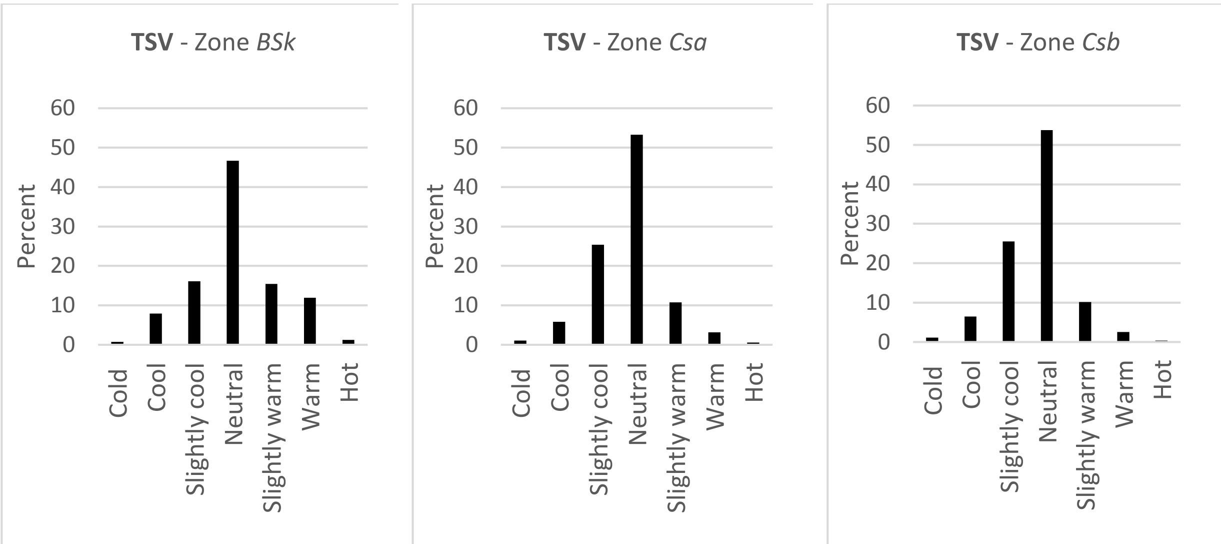



Figure 10: Frequency of thermal sensation votes (TSV) by participants climate zones

A crosstabulation of TSV and responses to the question "How would you prefer to be?" (Preference) is shown in Table 5 for all votes

Table 5: Crosstabulation TSV and Preference - N=10787

| | Cooler | No change | Warmer | TOTAL |
|---|---|---|---|---|
| Cold | | 0.0% | 1.1% | 1.1% |
| Cool | 0.1% | 2.5% | 3.7% | 6.3% |
| Slightly cool | 0.1% | 13.4% | 11.4% | 25.0% |
| Neutral | 0.5% | 51.2% | 1.6% | 53.2% |
| Slightly warm | 2.8% | 7.5% | 0.5% | 10.7% |
| Warm | 1.2% | 2.0% | 0.1% | 3.3% |
| Hot | 0.5% | 0.0% | | 0.5% |
| TOTAL | 5.1% | 76.5% | 18.4% | 100.0% |

Each climate zone showed similar results. Of significance is that around 77% of the time the participants had a preference for "No change" and more than 25% of these votes corresponded to a TSV other than neutral with a significant preference (13.4%) expressing the preference for the sensation of "Slightly cool". Back in 1994, Williamson, et al., (1995) suggested *"… the notion that neutral or preferred temperatures are equivalent must be questioned. The preference for, or acceptance of, non-neutral thermal conditions is an important fact which should be considered when assessing design options*". This recommendation has not changed.

### 4.1 Thermal sensitivity

The thermal sensitivity of occupants in the three climate zones was assessed by plotting the internal operative temperature against their TSVs. The regression coefficient or gradient of these plots is interpreted as being inversely related to the occupant's thermal adaptability, the greater the slope the more sensitive (or less accepting) are they to temperature changes. A slope of 0.13/K was reported by de Dear et al. (2018) in their study of houses in Sydney and Wollongong. Daniel et al. (2019) reported a slope of 0.11/K for a cohort of occupants monitored during cold weather in Adelaide, SA. Williamson and Daniel (2018) showed a regression coefficient of 0.31/K for a recent cohort in naturally ventilated houses in Darwin, NT.

Figure 11 shows the weighted regression lines for internal temperatures binned at 0.5K for zone *Csa*.

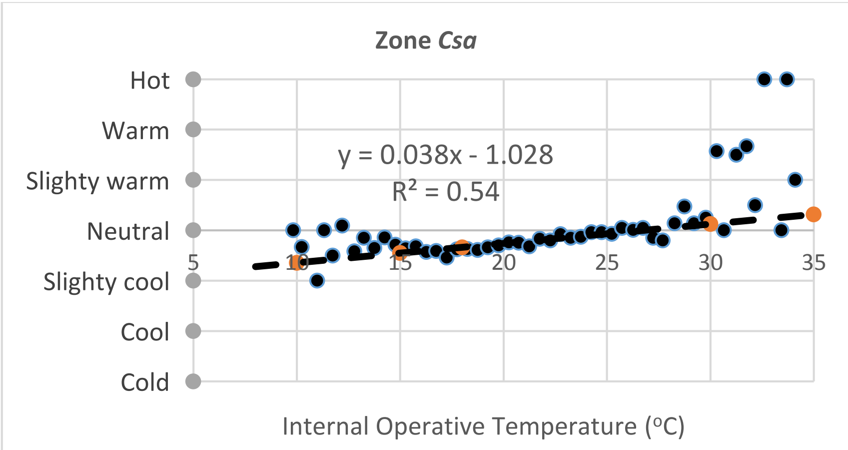



Figure 11: Thermal sensation votes (TSV) versus Internal operative temperature binned at 0.5K intervals

Similar plots for the other climate zones give, for *Csb* a slope of 0.12/K, and for BSk a slope of 0.076/K. A t-test analysis applied to each pair of slopes indicates that these slopes are significantly different- *Csa/Csb* ($t=9.14$, $p<0.05$), *Csa/BSk* ($t=3.36$, $p<0.05$) & *Csb/BSk* ($t=3.35$, $p<0.05$). Comparing with other studies this cohort of older residents would seem far less sensitive to temperature variations compared with a more general cohort.

### 4.2 Thermal satisfaction

One survey question "How satisfied are you with the temperature in this room?" sought to elicit a response regarding the point-in-time overall approval of the thermal conditions. The results for each zone are shown in Figure 12.

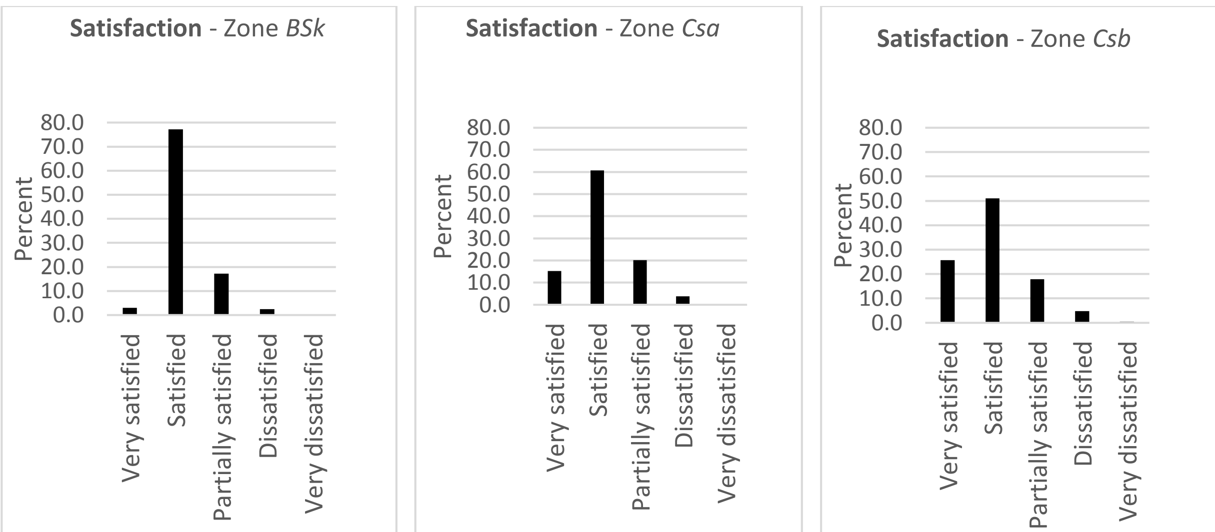



Figure 12: How satisfied are you with the temperature in this room?

Overall, the participants reported “Very satisfied or “Satisfied” on 78% of occasions. Only in Zone *Csb* were the votes “Very dissatisfied” and “Dissatisfied” greater than 5%. Overwhelmingly the participants were satisfied with their thermal environment.

## 5. Health and well-being

As described above the participants in this project were generally aware that thermal conditions could affect their health and well-being. Two questions of the survey were designed to explore this issue – “…. describe your health and well-being at the moment?” and “… the conditions in this room influence my health and well-being?”. The crosstabulation of results is shown in Table 6.

Table 6: Cross tabulation of influence of conditions in the room on present health/well-being

| | | Definitely yes | Probably yes | Unsure | Probably not | Definitely not | TOTAL |
|---|---|---|---|---|---|---|---|
| Present Health | Very good | 5.9% | 8.4% | 0.3% | 3.7% | 0.5% | 18.8% |
| | Good | 13.2% | 19.2% | 3.7% | 5.4% | 0.3% | 41.8% |
| | Reasonable | 2.7% | 15.5% | 4.8% | 6.6% | 5.0% | 34.6% |
| | Poor | 0.3% | 1.6% | 0.5% | 1.3% | 0.6% | 4.3% |
| | Very poor | 0.1% | 0.0% | 0.0% | 0.1% | 0.3% | 0.5% |
| | TOTAL | 22.2% | 44.7% | 9.4% | 17.0% | 6.7% | 100.0% |

About two-thirds of responses reported “Definitely yes” or “Probably yes” that the thermal conditions in the room influenced their health and/or well-being. On about 61% of occasions the participants indicated that their health was “Very good” or “Good” with a further 35% suggesting “Reasonable”. An understanding of these results becomes clearer with a plot of health/well-being against internal operative temperature as shown in Figure 12. The influence of temperature is more pronounced (presumably adversely) below about 15 °C and above about 28 °C.

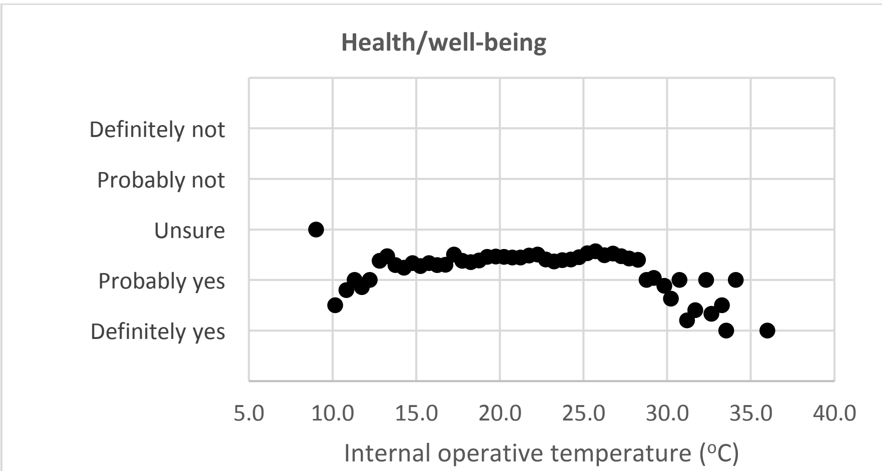



Figure 13: Specified participant health/well-being versus Internal operative temperature
N = 10787

## 6. External versus indoor acceptable temperature

The operational utility of the adaptive comfort concept in Standards such as ASHRAE 55 and EN 15251 show a relationship between the external running mean prevailing temperature and the indoor neutral or acceptable temperature. Williamson and Daniel (2019) have recently proposed an adaptive comfort model based on a large database assembled for temperate regions of Australia and computed by a Modified Griffiths technique,

- $T_{comf} = 15.9+0.26T_{pma(out)}$

Using the same method, the present data produces a relationship between the prevailing mean outdoor temperature (alpha = 0.6) and indoor acceptable temperature as shown in Equation 1 ($R^2$=0.62)

$$T_{comf} = 16.3+0.29T_{pma(out)} \qquad \text{Eq (1)}$$

Figure 14 shows for comparison these models as well as the ASHRAE 55 Standard model neutral temperature - $T_{comf} = 17.8+0.31T_{pma(out)}$. The present model indicates that the older participants of this study prefer slightly higher temperatures compared to the general population in the temperate regions of Australia. The Figure also illustrates that using the ASHRAE 55 model for housing in Australia is inappropriate

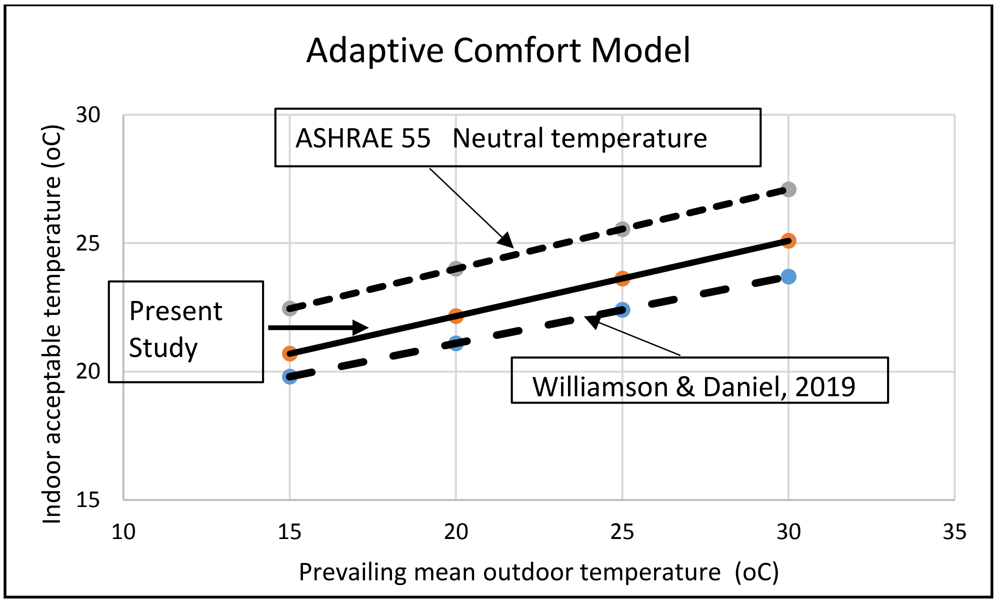



Figure 14: Adaptive comfort models, Prevailing mean outdoor temperature versus Indoor acceptable temperature.

## 7. Conclusion

This paper reports on part of a study involving older South Australians aimed at better understanding the relationship between external weather, aspects of the built form of the dwelling, the occupants' thermal comfort and energy use. The overall aim is to investigate strategies and develop guidelines for improving the thermal environment so that as people age, they may remain in their own house with conditions that do not adversely affect either their health or well-being.

The mass of data collected during the field study phase shows that the older cohort of South Australians who participated in this study were less sensitive to temperature variations compared to the general population in Australia reported in other studies. They appeared to be adept at employing adaptive strategies, for example, altering their clothing and activity as a function of temperature as well as the judicious use of heating and /or cooling. In general, the participants operated their house in free-running mode, with on average heating or cooling employed for around 33% of the time a vote was recorded. On the whole, they expressed satisfaction with the thermal environment in their house even in conditions that might normally be considered beyond Standard comfort limits.

As Bills (2018) reported from study of a small sample of the older population in SA cold/cool conditions were accepted or tolerated and even preferred and that this situation was associated with an increase in reported health symptoms. The current study has confirmed the prevalence of indoor temperatures below those conventionally considered as comfortable. In particular, in each of the three climate zones, measurements showed significant portions of time when the temperature, particularly in bedrooms, was below 15 $^{o}$C. This is an issue that future guidelines should address. Periods of hot weather were found to be less an issue because of adaptive measures adopted by the participants together with the use of air-conditioning used to alleviate the extremes of temperature.

An acceptable temperatures adaptive model developed from the data collected in this study could be used as first cut assessment of the acceptability (or otherwise) of existing and new housing where people (or Hobbits) may wish to sit and age in their hole.

## 8. Acknowledgements

The authors would like to thank all participants involved in this project. Without their enthusiasm over the long period of monitoring this study would not have been possible. This study is supported by the Australian Research Council (ARC DP180102019) and the Faculty of Professions Divisional Scholarship from The University of Adelaide, Australia.

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# Individualising thermal comfort models for older people: the effects of personal characteristics on comfort and wellbeing

**Larissa Arakawa Martins[1], Terence Williamson[1], Helen Bennetts[1], Jian Zuo[1], Renuka Visvanathan[2], Alana Hansen[3], Dino Pisaniello[3], Joost van Hoof[4] and Veronica Soebarto[1]**

[1] School of Architecture and Built Environment, The University of Adelaide, Adelaide, South Australia, Australia, larissa.arakawamartins@adelaide.edu.au;
[2] Adelaide Medical School, The University of Adelaide, Adelaide, South Australia, Australia;
[3] School of Public Health, The University of Adelaide, Adelaide, Australia;
[4] Faculty of Social Work & Education, The Hague University of Applied Science, The Hague, The Netherlands.

**Abstract:** As people age, physiological changes affect their thermal perception, sensitivity and regulation. The ability to respond effectively to temperature fluctuations is compromised with physiological ageing, upsetting the homeostatic balance of health in some. As a result, older people can become vulnerable at extremes of thermal conditions in their environment. With population ageing worldwide, it is an imperative that there is a better understanding of older people's thermal needs and preferences so that their comfort and wellbeing in their living environment can be optimised and healthy ageing achieved. However, the complex changes affecting the physiological layers of the individual during the ageing process, although largely inevitable, cannot be considered linear. They can happen in different stages, speeds and intensities throughout the ageing process, resulting in an older population with a great level of heterogeneity and risk. Therefore, predicting older people's thermal requirements in an accurate way requires an in-depth investigation of their individual intrinsic differences. This paper discusses an exploratory study that collected data from 71 participants, aged 65 or above, from 57 households in South Australia, over a period of 9 months in 2019. The paper includes a preliminary evaluation of the effects of individual intrinsic characteristics such as sex, body composition, frailty and other factors, on thermal comfort. It is expected that understanding older people's thermal comfort from the lens of these diversity-causing parameters could lead to the development of individualised thermal comfort models that fully capture the heterogeneity observed and respond directly to older people's needs in an effective way.

**Keywords:** thermal comfort, older people, body composition, frailty, personal comfort models

## 1. Introduction

### 1.1. Overview on ageing and thermal comfort

As people age, unavoidable physiological changes such as structural skin modification and metabolic alterations affect their thermal perception, sensitivity and regulation (Blatteis, 2012; Dufour and Candas, 2007). Overall, physical ageing is commonly associated with a significant compromise of the efficiency of thermal defence mechanisms and the ability to respond effectively to temperature fluctuations, upsetting the homeostatic balance of health in some. As thermoregulation plays a vital part in human survival, older people[1] can become vulnerable at temperature extremes in their environment, therefore demanding special attention to their thermal needs and preferences (Shibasaki et al., 2013).

[1] Although the United Nations define older people as aged 60 years old or over, in Australia the term is used to define people aged 65 years old or over. This paper defines older people as aged 65 years old or over.

This is particularly important because it is hypothesised that extreme weather events may increase not only in number, but also in intensity and overall duration (Intergovernmental Panel on Climate Change, 2014; World Health Organization, 2004). Based on comprehensive research that analysed a wide body of observations and modelling studies of the world climate systems as well as the plausibility of future projections across all commonly used scenarios, the highly detailed report from the Intergovernmental Panel on Climate Change (2013) points to the increase in the number of warm days and nights on the global scale and to the increase of the frequency of heat waves in large parts of Europe, Asia and Oceania.

Australia is reported as one of the world's regions that is particularly susceptible to heat waves and drought conditions according to the last five-year period report from the World Metereological Organization (2016). In the summers of 2012/2013 and 2013/2014, the country experienced records for persistent heat in many cities, including the four consecutive days above 41 °C in Melbourne, Victoria. Likewise, Adelaide, in South Australia, records regular heatwaves and extreme heat events during which total ambulance call-outs and total mortality tend to escalate (Faunt et al., 1995; Nitschke et al., 2011). In addition, as Åström et al. (2011) highlighted, it is alarmingly likely that the dramatic impacts of extreme events on population's health will be even greater than seen previously.

As lowered heat tolerance can make older people more vulnerable to heatwaves (Hansen et al., 2011; Stafoggia et al., 2006), understanding older people's thermal needs and preferences to improve the thermal conditions of their environment becomes essential.

Many international studies have addressed thermal adaptation for the ageing population (Jiao et al., 2017; Taylor et al., 1995; van Hoof and Hensen, 2006; van Hoof et al., 2017; Yang et al., 2016). However, in Australia, the subject has only emerged in the past few years. While consistent progress has been made from diverse perspectives, many specific topics would still benefit from further investigation: the geographical differences in older people's thermal perception, the effects of mild thermal disturbances on older adults' health and smart home technologies for enhancing thermal comfort are some of the research topics that could still be expanded (van Hoof et al., 2017).

Furthermore, while some thermal comfort studies conclude that there is no difference between older adults compared to younger adults regarding thermal comfort (Fanger, 1970), more recent research has shown considerable differences in older people's preferences (Jiao et al., 2017; Schellen, 2012; Schellen et al., 2010; Taylor et al., 1995; Tsuzuki and Ohfuku, 2002). Although inconclusive, the distinction between how older adults seem to perceive thermal comfort when compared to the young populations could be caused by a combination of both physical ageing and relevant behavioural differences (van Hoof et al., 2017).

Interestingly, the differences relating to thermal comfort and perception are present not only between older and younger cohorts, but also between individuals in the older group (Peng, 2010; Wong et al., 2009). For this reason, understanding diversity in older age also becomes crucial in order to predict older people's needs and requirements in an accurate way.

### 1.1. Drivers of diversity in older age

The ageing process is deeply influenced by complex biological and physiological changes in an individual. However, most of the time these changes are independent from chronological age - the total number of years a person has lived -, and, although largely inevitable, they cannot be considered linear. These changes can happen in different stages and with different speeds and intensities throughout older age. For this reason, it is very common to observe older people with the exact same chronological age having completely different functional capabilities. This means that, while some older people with a certain chronological age may be frail or lack the capacity to meet their basic needs and undertake basic activities, other older people with the same chronological age may retain full physical and mental functioning, not requiring any external support (World Health Organization, 2015).

The diversity in older age happens firstly because the mechanisms of ageing are extremely random. Secondly, it is believed that environmental and behavioural elements also play a relevant part in the trajectories of ageing. According to the World Health Organization's report entitled 'World Report on Ageing and Health', older people's heterogeneity goes beyond genetic inheritance or the deliberate choices made during their lives. Both physical and social environments that people inhabit can affect health directly and indirectly (World Health Organization, 2015).

The Report also explains that healthy ageing can only be reached when older people are able to achieve the things that they have reason to value. In order to do so, functional ability is essential. However, functional ability depends on the intrinsic capacity of each individual and the multiple interactions between this individual and the diverse environmental characteristics he/she is exposed to. Therefore, whether or not older people can experience healthy ageing will be determined not only by their individual capacity but also by the interactions with the environments they are surrounded by at a certain point in time.

In its conclusion, the Report emphasises the need to better understand the diverse needs of older populations in order to develop relevant policy that fosters healthy ageing. Among the different ways to achieve this better understanding, person-centred approaches are strategies that could be applied by the WHO for health and long-term care settings. This new approach could result in a real paradigm shift in the way global health services are managed and provided, delivering health services that respond directly to people's needs and preferences, in a safe and effective way.

Looking from the same perspective, the field of thermal comfort is also experiencing the same paradigm shift. Most studies on thermal comfort that focus on the population level, on averaged responses from a group of people and on one-size-fits-all centralised thermal management, are being called into question by much more individualised and occupant-centric alternatives (Kim et al., 2018). This indicates that diversity in preferences, perceptions are beginning to be taken into account in these studies, and that occupants whose comfort perception generally deviates from averaged populations means are finally being regarded as relevant. In this context, since older people's individual differences are wide, much could be profited by investigating their environmental comfort from the same occupant-centric approach.

### 1.2. Individual differences in human thermal comfort

Explaining diversity in perceived thermal comfort has been an interest of many studies for decades. The fact that subjects might perceive and respond completely differently when exposed to the exact same thermal environment indicates that other factors and stressors than the environmental parameters should also be considered when designing or managing the built environment (Wang et al., 2018). These factors can range from psychological, physiological and personal characteristics to the social and environmental contexts of each individual (Bluyssen, 2019).

However, international standards still adopt aggregate modelling approaches, such as the Predicted Mean Vote (PMV) model (Fanger, 1970) and the adaptive model (de Dear and Brager, 1998; Nicol and Humphreys, 1973), as the bases for the thermal requirements for human occupancy in the built environment. As aggregate models, they are only able to explain human thermal sensation on a population or group level, mainly based on physical parameters and behavioural factors (operative temperature, relative humidity, air speed, clothing and activity levels). This implies that assessing design options is often based on complying with an averaged thermal comfort zone, disregarding those occupants whose comfort perception deviates from the population mean because of their intrinsic characteristics.

Providing environments that thermally satisfy all occupants means truly capturing the diversity observed between them. For this reason, quantifying the effects of individual factors on perceived thermal comfort and incorporating these on the existing comfort models have become increasingly important, especially considering the health and energy related benefits of doing so (Schweiker et al., 2018).

Among the factors that might lead to the individual differences in thermal comfort, some have been considered especially relevant in the field. The potentially diversity-causing parameters identified in most studies include age, sex, body composition (for instance, body fat, basal metabolic rate), chronic diseases, physical disabilities, fitness and temperature, seasonal, and climatic zone acclimation and habituation (Bluyssen, 2019; Schweiker et al., 2018; Wang et al., 2018; Zhang et al., 2001). Although between-subject differences – or inter-individual differences – such as body composition and climatic habituation seem to be considered important factors explaining the diversity in human thermal comfort response and perception, age and sex still show inconsistent conclusions in terms of their effects on comfort (Schweiker et al., 2018; Wang et al., 2018).

## 2. Objectives

Considering all the above, the objective of this paper is to evaluate the effects of individual intrinsic characteristics on older people's perception and response to thermal environments. Furthermore, this paper also aims to look at the combined effects of these individual parameters, attempting a better understanding of the interactions between them.

It is expected that understanding older people's thermal comfort from the lens of these diversity-causing parameters could lead to the development of individualised thermal comfort models that fully capture the heterogeneity observed and respond directly to older people's needs in an effective way.

## 3. Study design and data collection

To achieve the before mentioned goals, this study collected data from 71 participants (23 males and 48 females) from 57 households located in South Australia. The participants were drawn from the first two stages of the research project 'Improving the thermal environment of housing for older Australians' (Soebarto et al., 2019a; van Hoof et al., 2019) and through press releases in various media formats. All participants were aged 65 years or above and living independently. Their dwellings are located in hot dry (BSk), warm temperate (Csa) and cool temperate (Csb) climate zones, according to the Köppen–Geiger climate classification system. The data were collected during a period of 9 months in 2019, covering both hot and cold seasons, which provided the range of variations in environmental conditions necessary for a comprehensive analysis.

The data collection process involved visiting each house to apply a short questionnaire, conduct an open-ended interview about the house details and install indoor environment data loggers in the house's main living room and main bedroom. A thermal comfort survey tablet was also installed to be used by the participants to answer a survey about their thermal environment and their preferences and sensations.

All data collection tools (such as questionnaire, interview, loggers) were designed to cover a wide range of variables and factors known in the architecture science, medicine and public health fields of study to influence and affect thermal comfort, sensation and preference. In addition, the results from the previous phase of this research project, which gathered data via seven focus group sessions with 49 older South Australians (van Hoof et al., 2019) also contributed to highlight less quantifiable aspects of older people's thermal perception and response, which are often overlooked in comfort studies (for instance, personal beliefs and experiences). Unique factors such as use of outdoor spaces, self-rated health, habituation to climatic zones, which are also often ignored in thermal comfort studies or extremely hard to obtain, were included in the study as well.

The questionnaire covered participant's personal data (such as sex, age, level of education, general health status, frailty score, use of outdoor spaces, etc.) and their general behaviour towards thermal comfort. It was conducted using a paper-based form, taking from 10 to 40 minutes to complete. The questionnaire also included a body composition assessment, using a Tanita Inner Scan RD-953 scale (Tanita Corporation, 2016; Volgyi et al., 2008). The equipment's measurements are based on the principles of bioelectrical impedance to calculate a number of body variables (for instance, body water, fat, bone, muscle percentages, etc.).

An open-ended interview gathered information about the participant's house and took from 10 to 40 minutes depending on the size of the house, complexity of systems and level of details shared by the participants.

The indoor environment data logger contained sensors that measured air temperature, globe temperature, air speed, relative humidity, CO2 and Volatile Organic Compounds (VOC). The logger coordinates measurements from the sensors, undertaken at 30-minute intervals and when a participant completes a comfort survey. The logger was self-contained and did not require connection to the dwelling's electricity or Internet systems. The data were automatically sent to a web-based server and could be accessed remotely (Soebarto et al., 2019b).

The thermal comfort survey tablet was intended to allow participants to complete comfort surveys electronically, once a day or at least once a week - about their clothing, activity, thermal sensations (TSV) and preferences, window and door operations, as well as heating, cooling and fan operations. The survey also included questions about the participant's perceptions of the indoor environment quality as well as their self-reported health and wellbeing status at that particular point in time. Each survey took no more than a few minutes to complete. The tablet was self-contained and did not require connection to the dwelling's electricity and Internet systems (Soebarto et al., 2019b).

Up to the end the monitoring period, 10,787 votes were recorded from the occupant survey.

Table 1 shows the individual parameters analysed in this paper and the range of possible categories for each one. They are: sex, age, personal weather preference, habituation to climatic zones, frequent use of outdoor spaces, body composition variables, presence of chronic diseases or frequent symptoms, frailty and self-rated health.

Table 1 - Individual parameters analysed in this study

| **Individual parameters** | **Categories (code)** |
|---|---|
| Sex | Male (1)<br>Female (2) |
| Age | 65 to 69 years old (1)<br>70 to 74 years old (2)<br>75 to 79 years old (3)<br>80 to 84 years old (4)<br>85 or more years old (5) |
| Personal weather preference | Generally prefers hot weather (1)<br>Generally prefers cold weather (2)<br>Does not like either hot or cold weather (3)<br>Has no preference, likes both weathers (4) |
| Habituation to climatic zones [a] | Csa (warm temperate) (1)<br>Csb (cool temperate) (2)<br>BSk (hot-dry) (3) |
| Frequent use of outdoor spaces | No (0)<br>Yes (1) |
| Body Composition<br>Height (cm)<br>Weight (kg)<br>Body Mass Index - BMI (kg/m$^2$)<br>Body Fat (%)<br>Muscle Mass [b] (kg)<br>Physique Rating [c] (between 1-9)<br>Bone Mass (kg)<br>Visceral Fat rate [d] (between 1-59)<br>Basal Metabolic Rate - BMR (kcal)<br>Total Body Water (%) | <br>Numerical variables |
| Chronic diseases or frequent symptoms<br>Asthma<br>Respiratory illnesses<br>Heart diseases<br>Renal condition<br>Dehydration or heat stroke<br>High Blood Pressure<br>Allergy | <br>No (0)<br>Yes (1) |
| Frailty [e] | Not frail (1)<br>Apparent vulnerability (2)<br>Mild frailty (3)<br>Moderate frailty (4)<br>Severe frailty (5) |
| Self-rated health when voting | Very good (1)<br>Good (2)<br>Reasonable (3)<br>Poor (4)<br>Very poor (5) |

[a] Habituation to climatic zones was considered when participants lived in the location for more than 5 years.
[b] Sum of skeletal muscle, smooth muscle and water in muscle.
[c] Calculated according to the ratio between fat and muscle.

[d] Calculated according to the amount of fat that is in the internal abdominal cavity, surrounding the vital organs in the abdominal area.
[e] Assessed according to the Modified Reported Edmonton Scale (MRES) (Rose et al., 2018).

## 4. Preliminary results

The analysis presented in this paper involved statistically regressing the occupant's thermal sensation votes (TSV, on a 7-point scale, from hot (+3), warm (+2), slightly warm (+1), neutral (0) to slightly cool (-1), cool (-2) and cold (-3)) against each of the personal individual parameters, first individually and then combined in a stepwise linear regression. All regressions were weighted according to the number of votes each participant recorded, so that personal parameters could be equally counterbalanced. The results of each individual linear regression and statistical significance are shown in Table 2.

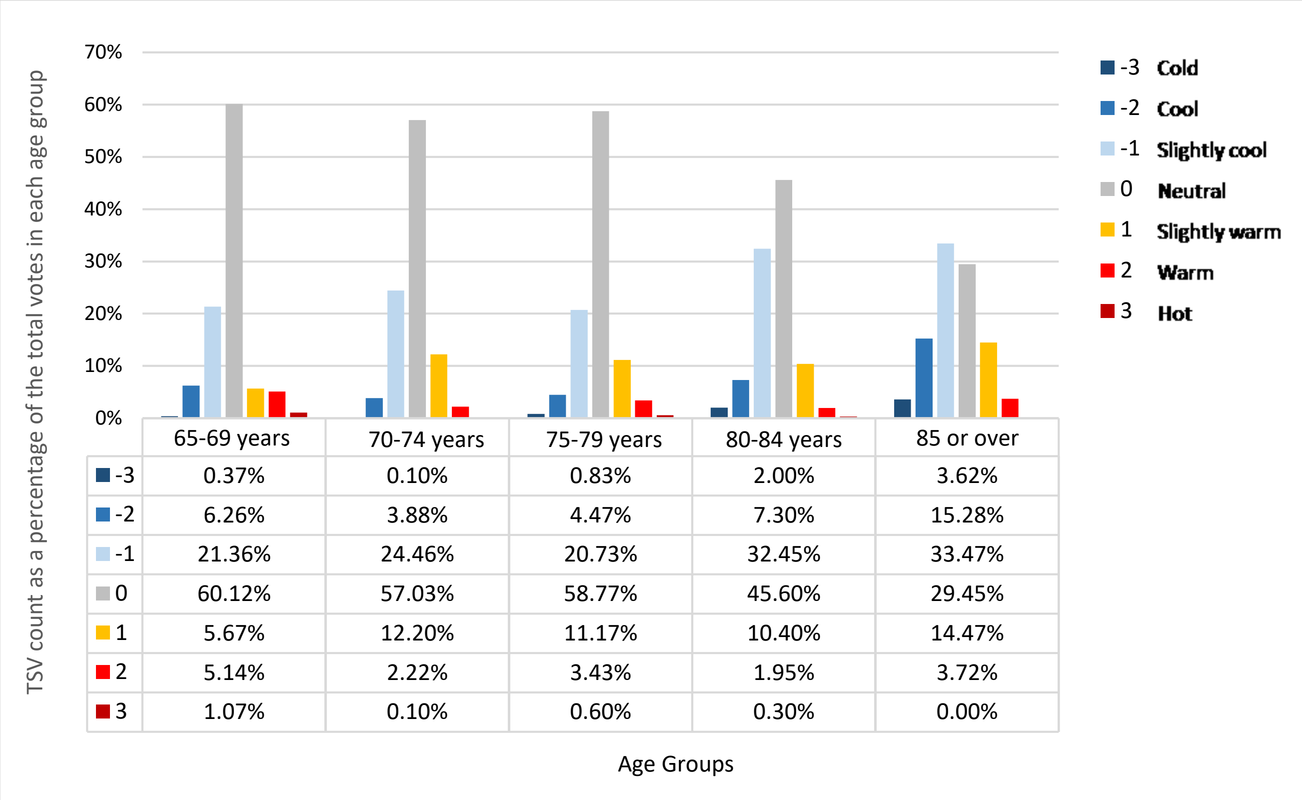
Table 2 – Results (p-value and regression coefficient B) of individual linear regression for each individual parameter

| Individual Characteristics | p-value [a] | B (95% Confidence Interval for B) |
|---|---|---|
| Sex | **0.000** | 0.089 (0.052 / 0.125) |
| Age | **0.000** | -0.120 (-0.135 / -0.104) |
| Self-rated health when voting | **0.000** | -0.044 (-0.067 / -0.022) |
| Habituation to Climate Zone | **0.046** | 0.028 (0.000 / 0.055) |
| Personal Weather Preference | **0.000** | 0.050 (0.034 / 0.066) |
| Frequent use of outdoor spaces | **0.000** | 0.120 (0.081 / 0.159) |
| Frailty Score | **0.000** | -0.080 (-0.104 / -0.055) |
| Height | **0.002** | -0.003 (-0.005 / -0.001) |
| Weight | 0.354 | 0.001 (-0.001 / 0.002) |
| BMI (Body Mass Index) | **0.004** | 0.004 (0.001 / 0.008) |
| Body Fat Percentage | 0.131 | 0.002 (0.000 / 0.004) |
| Muscle Mass | 0.345 | 0.001 (-0.001 / 0.0036) |
| Bone Mass | 0.278 | 0.024 (-0.020 / 0.068) |
| Body Water Percentage | **0.000** | -0.011 (-0.014 / -0.008) |
| BMR (Basal Metabolic Rate) | 0.212 | 0.00004 (0.000 / 0.000) |
| Physique Rating | **0.000** | 0.041 (0.026 / 0.056) |
| Visceral Fat Rate | **0.016** | -0.002 (-0.004 / 0.000) |
| Asthma | **0.000** | 0.204 (0.144 / 0.264) |
| Respiratory Illnesses | **0.000** | -0.239 (-0.304 / -0.174) |
| Heart Disease | 0.117 | 0.042 (0-0.011 /0.095) |
| Renal Disease | **0.000** | -0.261 (-0.344 / -0.178) |
| High Blood Pressure | **0.000** | -0.085 (-0.120 / -0.050) |
| Allergies | **0.016** | -0.051 (-0.092 / -0.009) |
| Dehydration | **0.000** | -0.584 (-0.684 / -0.484) |

[a] Note: p-value highlighted in bold indicates statistically significant ($p<0.05$).

Sex was found to be a statistically significant predictor of thermal sensation (p=0.000) for the older population analysed in this study. Interestingly, the neutral temperature (when TSV = 0) for males was 25.1 °C, while for females, it was almost 2 K lower, 23.6 °C. Likewise, the preferred temperature (when participants report wanting 'no change' on a 3-point preference scale from 'warmer', to 'no change, to 'cooler') was also 1.4 K higher for males than for females (24.2 °C for men vs. 22.8 °C for women).

Age was also a significant predictor of thermal sensation between the five age groups analysed in this study (p=0.000). The data collected shows, as seen in Figure 1, that the older groups (for instance, more than 85 years, group 5) tend to feel sensations other than neutral more frequently than the younger groups (for instance, 65-69 year old, group 1), which might indicate a decrease in thermal adaptability with age.




| | 65-69 years | 70-74 years | 75-79 years | 80-84 years | 85 or over |
|---|---|---|---|---|---|
| -3 | 0.37% | 0.10% | 0.83% | 2.00% | 3.62% |
| -2 | 6.26% | 3.88% | 4.47% | 7.30% | 15.28% |
| -1 | 21.36% | 24.46% | 20.73% | 32.45% | 33.47% |
| 0 | 60.12% | 57.03% | 58.77% | 45.60% | 29.45% |
| 1 | 5.67% | 12.20% | 11.17% | 10.40% | 14.47% |
| 2 | 5.14% | 2.22% | 3.43% | 1.95% | 3.72% |
| 3 | 1.07% | 0.10% | 0.60% | 0.30% | 0.00% |

Figure 1 - TSV count as a percentage of the total votes in each age group

The same level of statistical significance (p=0.000) and negative correlation is present between self-rated health and thermal sensation and the frailty score and thermal sensation. This indicates that the poorer the participants reported their health, and/or the frailer the participant was scored, the more frequently they felt colder in terms of thermal sensation. Figure 2 shows the TSV count as a percentage of total votes for each health group.

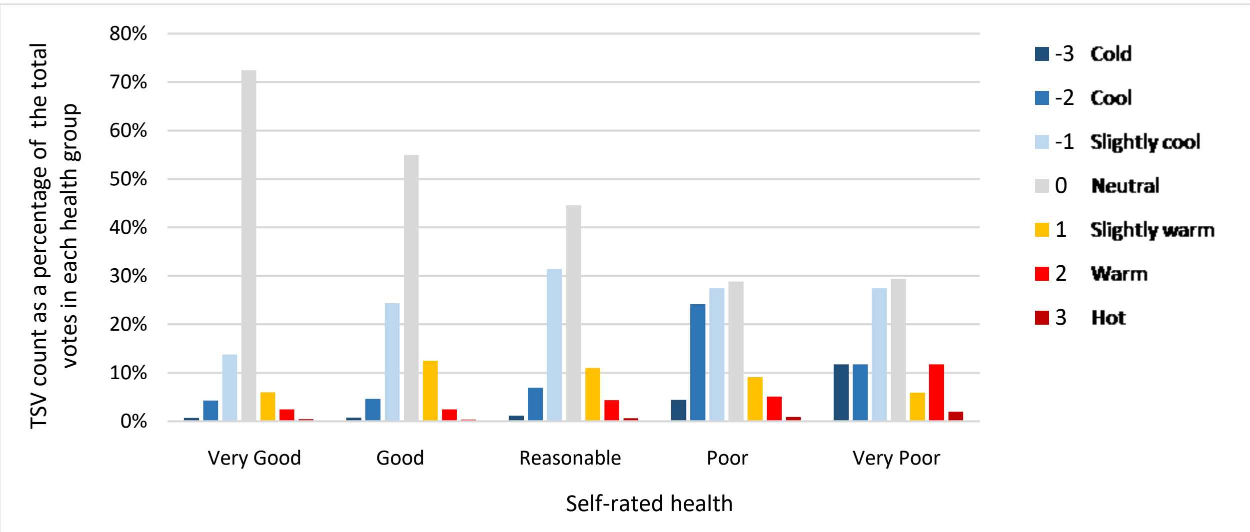



Figure 2 - TSV count as a percentage of the total votes in each health group

Participant's personal weather preferences also proved to be a significant predictor of thermal sensation for the older cohort (p=0.000). As shown in Figure 3, participants that reported preferring hot weather tended to feel colder more frequently than participants that reported preferring cold weather. In addition, those who reported having no preference between cold and hot weather, were also the ones that felt neutral more frequently.

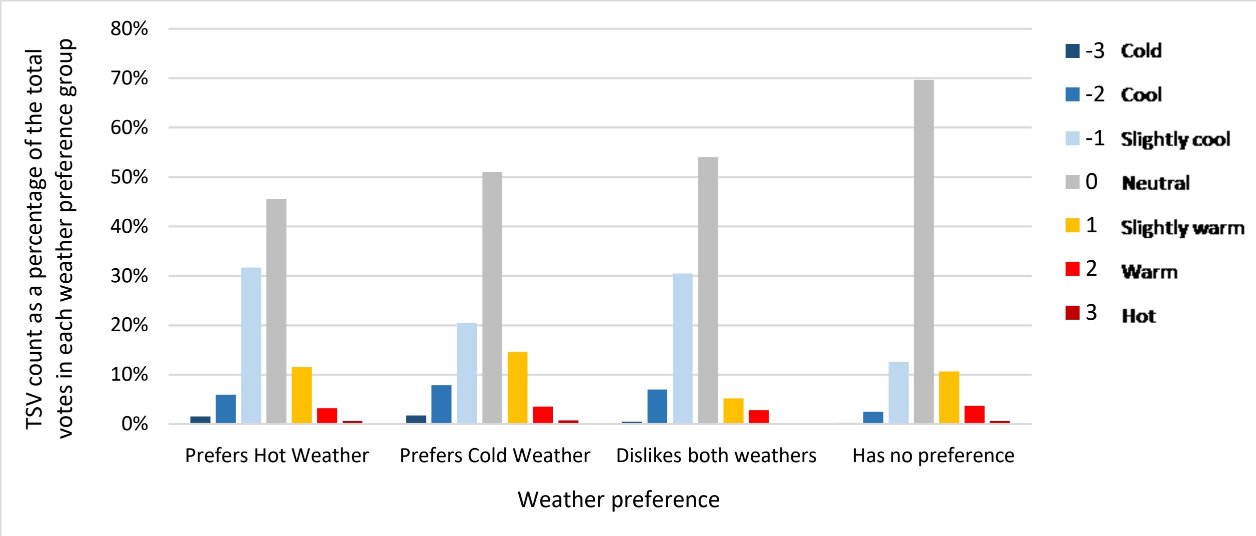



Figure 3 - TSV count as a percentage of the total votes in each weather preference group

Likewise, the frequent use of outdoor spaces proved to be statistically significant as a parameter to predict thermal sensation (p=0.000). Those who reported a frequent use of outdoor spaces tended to feel warmer more frequently. The frequent use of outdoor spaces might be directly linked to an increase in the participants' metabolic rates, which directly affects human thermoregulation. In addition, the use of outdoor areas might indicate more direct interactions with extremes in temperatures, which might again influence thermal perception and sensitivity when indoors.

The participants' habituation to climatic zones has a poorer statistical significance as a predictor of thermal sensation (p=0.046). In addition, the neutral temperature for participants living in the cool temperate zones (Csb) was 23.7 °C – approximately 2.3 °C lower than the neutral temperature for the participants living in the warm temperate zones (Csa) –, which might indicate considerable temperature acclimation in each of the groups because of longer exposures to specific climates. However, the neutral temperature for the participants living in the hot-dry zone (BSk) was 20.4 °C – almost 6 K lower than participants living in the warm temperate zones (Csa). This could indicate either that other factors might be influencing these participants' thermal sensations (for instance, personal preference for colder weather or more frequent use of air-conditioning, shown in the data) or that the reduced data size for this specific climate zone might be a limitation for the analysis.

Regarding body composition, in this study, half of the parameters analysed proved to be significant predictors of thermal sensation for the older population studied (p<0.05). However, weight, body fat percentage, muscle mass, bone mass and basal metabolic rate (BMR) were not statistically significant to explain thermal sensation (p>0.05). Interestingly, these are the individual parameters most commonly found as significant predictors of thermal sensation in many thermal comfort studies for younger populations (Schweiker et al., 2018; Wang et al., 2018). However, both BMI (Body Mass Index) and Physique Rate, which are calculated according to the height and weight ratio (BMI) and the fat and muscle ratio (Physique Rating), can still be considerable important for the prediction of thermal sensation.

Regarding the presence of chronic diseases or frequent symptoms, asthma, respiratory illnesses, renal diseases, dehydration, high blood pressure and allergies can all be considered as important factors affecting thermal sensation ($p=0.000$). The only chronic disease that was reported by the participants and was not considered statically significant as a predictor of thermal sensation was heart disease ($p>0.05$).

Finally, the combined effects of the different individual parameters was analysed through a stepwise linear regression. After all variables that indicated multi-collinearity were excluded from the model (Variance Inflation Factor VIF > 10), the final result indicated the following individual parameters as the main predictors of thermal sensation for the older population: age, sex, frequent use of outdoors, self-rated health, habituation to climate zone, height, body water percentage, physique, bone mass, asthma, high blood pressure, dehydration and respiratory illness. Table 3 shows the results for each of the parameters of the final combined model.

Table 3 - Results (p-value and regression coefficient B) of stepwise linear regression for combined individual parameters

| **Individual Characteristics** | **p-value** | **B (95% Confidence Interval for B)** |
|---|---|---|
| Age | 0.000 | -0.121 (-0.144 / -0.099) |
| Asthma | 0.000 | 0.416 (0.338 / 0.4931) |
| Body Water Percentage | 0.000 | -0.031 (-0.037 / -0.0239) |
| Height | 0.000 | 0.011 (0.006 / 0.0146) |
| High Blood Pressure | 0.000 | -0.112 (-0.153 / -0.0701) |
| Dehydration | 0.000 | -0.419 (-0.533 / -0.3035) |
| Frequent use of outdoors spaces | 0.000 | 0.138 (0.087 / 0.1882) |
| Respiratory Illness | 0.000 | -0.230 (-0.3 / -0.1591) |
| Physique Rating | 0.000 | 0.056 (0.037 / 0.0749) |
| Sex | 0.000 | -0.274 (-0.4 / -0.1482) |
| Habituation to Climate Zone | 0.001 | 0.057 (0.023 / 0.0904) |
| Self-rated health when voting | 0.001 | 0.044 (0.018 / 0.0695) |
| Bone Mass | 0.015 | -0.147 (-0.266 / -0.0281) |

Adding the standard physical parameters (operative temperature, relative humidity, air speed, clothing level and activity levels) to this regression model results in a final model that can explain up to 20% of the variance in the data for this population ($R^2$ of 0.2). Although relatively low, this is a relevant improvement from using only the physical parameters or only the personal individual factors as independent variables to predict thermal sensation.

## 5. Next steps

Although largely inevitable, the complex changes affecting the physiological layers of the individual during the ageing process can happen in different stages, speeds and intensities. This not only results in an older population with a great level of heterogeneity, but also a great level of risk.

Therefore, since older people's individual differences are wide, considering them as a uniform population in terms of thermal perception could result in leaving a significant number of older occupants in thermal discomfort. Depriving older people of living environments that meet their thermal comfort preferences could, in turn, affect their health and wellbeing to different extents, depending on both their physiological capacity for acclimatisation during long exposures to low or high temperatures and their capacity to bear the costs of constant reliance on heating and cooling (Soebarto et al., 2019c).

Thus, it becomes essential to better understand older people’s thermal differences so that comfort and wellbeing in their living environment can be optimised and healthy ageing achieved.

Through understanding older people’s thermal comfort from the lens of their diversity-causing parameters this paper advocates a more holistic approach to thermal comfort modelling, considering not only physical parameters as predictors of thermal perception and sensation, but also the psychological, physiological, personal, social and environmental contexts of each individual. In addition, this paper shows that intrinsic variables related to health and well-being, such as body composition parameters, presence of chronical diseases, self-rated health status and frailty score, can positively contribute to a more comprehensive and accurate approach for predicting thermal comfort for an older person.

With a better understanding of the drivers of diversity in older age, individualising thermal comfort models for this cohort becomes a natural next step. Recent years have shown an increasing number of studies aimed at the development of different forms of individualised comfort models as a response to the traditional approach to thermal comfort research (Kim et al., 2018). Called personal comfort models, the new approach was created to overcome most of the restrictions that the PMV and adaptive models present. Instead of an average response from a large population, these personalised models are designed to predict individuals’ thermal comfort responses. Besides taking the individual person as the unit of analysis, personal comfort models are also able to incorporate new relevant input variables (e.g. age, health status, body composition) other than the pre-defined physical factors and can use direct feedback from inhabitants to calibrate, adapt and train themselves.

This explains an important paradigm shift observed in the field today, from centralised and fixed-set-point management, to individualised, occupant-centric and data-driven thermal conditioning management in the built environment. By addressing the issue of individual differences in an innovative way, empowered by the rapid technology development, this approach provides relevant comfort and energy related benefits and it may be a relevant option to capture and absorb individual diversity and increase user acceptability.

As part of this research project, a preliminary development of personal comfort models for older people – using machine learning algorithms – already shows that, on average, the individualised models improved the predictions of their thermal sensation by 48% when compared to the performance of individually applying traditional PMV models (Arakawa Martins et al., 2019). Studies of personal comfort models that focus solely on older people are still rare in the literature. Nonetheless, considering the personal comfort models’ ability to absorb people’s diversity and susceptibility to environmental conditions, they are very appropriate for the effective prediction of older people’s diverse thermal preferences. This could be one more step towards decreasing thermally related vulnerability, enhancing wellbeing and potentially promoting energy efficiency through better indoor comfort management for older people’s dwellings.

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# Evaluation of thermal comfort in elderly care centres (ECC)

**Nuria Forcada[1] and Blanca Tejedor[2]**

[1] Department of Project and Construction Engineering (DPCE), Group of Construction Research and Innovation (GRIC), Universitat Politècnica de Catalunya (UPC), Colom, 11, Ed. TR5, 08222 Terrassa, Barcelona, Spain. E-mail: nuria.forcada@upc.edu
[1] Department of Project and Construction Engineering (DPCE), Group of Construction Research and Innovation (GRIC), Universitat Politècnica de Catalunya (UPC), Colom, 11, Ed. TR5, 08222 Terrassa, Barcelona, Spain. E-mail: blanca.tejedor@upc.edu

**Abstract:** The demand for elderly care centres (ECCs) is increasing as the population ages. This paper presents a field investigation on the thermal comfort of elderly in ECC and compares the outputs of existing thermal comfort standards with perceived thermal comfort of the elderly occupants of the building. Indoor and outdoor conditions were measured along the year and in different zones of an ECC (bedrooms, living rooms and dining rooms). A questionnaire survey to the residents was used to gather the occupants' thermal satisfaction. The findings indicate that standards based on adaptive models to evaluate the thermal comfort in elderly people are more precise than those based on the predicted mean vote (PMV). Results also highlight that this group prefers higher temperatures than the rest of the population. The findings also suggest that the time of the day and if the space is air conditioned do also influence thermal comfort in ECCs. These results can help standardise thermal comfort of elderly people.

**Keywords:** thermal comfort, elderly people, elderly care centres (ECC), PMV, adaptive thermal comfort model.

## 1. Introduction

According to United Nations estimates, the total number of people aged 65 years and older was 506 million in 2008, and is anticipated to double to 1.3 billion by 2040, which will be 14 percent of the total global population (2015). By 2050, Europe will be the world's oldest region, with its elderly population increasing more than fivefold from 40 million to 219 million (Bentayeb et al., 2013). This trend explains the increasing demand for long-term care services (Damiani et al., 2009) such as elderly care centres (ECCs). Furthermore, considering that persons who are 65 years or older often spend a considerable portion of their lives indoors, the energy consumption of maintaining the indoor conditions of these centres is high (Mendes et al., 2015). Clearly, the thermal comfort of these centres cannot be ignored (Raymann and Van Someren, 2008).

The thermal environment can be described as the characteristics of the environment that affect heat exchange between the human body and the environment (Ashrae 2013). There has been extensive modelling and standardisation of thermal comfort, which both depend on physical and physiological parameters (Taleghani et al 2013).

In general, the elderly population has an average thermal comfort that is different from the general population (Hwang and Chen, 2010; Schellen et al., 2010; deGroot and Kenney, 2007; Hoof and Hensen, 2006) because their energy expenditure decreases (Antunes et al., 2005). Furthermore, indoor environmental conditions vary in space and time. Therefore, the specific features of comfort within different spaces and the well-being of older people living in ECC should be analysed. This paper is based on a literature review and quantitative and qualitative research and analyses thermal comfort needs in ECC. The aim of the study was to: 1) compare the output of existing thermal comfort standards using the monitored data in different zones (bedrooms, living rooms and dining rooms) in ECCs. 2) compare these results with the perceived thermal comfort of the elderly occupants of the building. 3) analyse the validity of existing standards to evaluate the thermal comfort of elders, and 4) study variability among different spaces and time slots within ECCs (bedrooms, living rooms and dining rooms),

## 2. Thermal comfort in ECCs

Thermal comfort in living environments is very important not only for health but also for the well-being (Kameni et al., 2014).

Thermal comfort is affected by clothing, activity, age, health status, sex and adaptation to the climate and local environment of the individual and the household (Vandentorren et al., 2006; World Health Organisation, 1984). However, levels of older people's comfort are an important part of a holistic view of well-being.

### 2.1. Evaluation of thermal comfort

When discussing thermal comfort, there are two main models that can be used: the predicted mean vote (PMV) model and the adaptive model. The most commonly used model for evaluating general or whole body thermal comfort is the PMV model by Fanger (1973). PMV is expressed on the Ashrae 7-point scale of thermal sensation (cold, cool, slightly cool, neutral, slightly warm, warm, hot). The outcome of the model is a hypothetical thermal sensation vote for an average person: i.e., the mean response of many people with equal clothing and activity levels, who are exposed to identical, uniform environmental conditions. Ashrae (2013) defines thermal sensation as a conscious feeling, which requires subjective evaluation. The PMV model is adopted by the international standards ISO 7730 (2005), Ashrae Standard 55 (2013) and EN 15251 (2007). These standards aim to specify conditions that provide comfort to most healthy building occupants. EN 15251 (2007) mentions that for spaces occupied by very sensitive and fragile people, PMV should be kept between -0.2 and +0.2 on the Ashrae 7-point scale of thermal sensation. EN 15251 (2007) includes 3 categories (I, II and III) and indicates that the most restrictive category should be adopted for elderly occupants, while Ashrae Standard 55 (2013) presents only 2 ranges (80% or 90% of satisfied people) and no specific indication for the elderly.

Another method to evaluate thermal comfort is the adaptive model, which is based on the idea that outdoor climate influences indoor comfort because humans can adapt to temperatures at different times of the year. Ashrae Standard 55 (2013) and EN 15251 (2007) include models of adaptive thermal comfort. The use of an adaptive comfort model considers people's tendency to adapt to fluctuating environmental conditions (Nicol et al., 2012). Adaptation can be physiological, psychological or behavioural, so a wider range of thermal comfortable conditions and a closer relationship with the external climatic environment can be obtained. The adaptive hypothesis predicts that contextual factors, such as having access to environmental controls, plays a role. This model assumes that occupants are sedentary, with metabolic rates of 1-1.3 met, and a prevailing mean temperature between 10°C and 33.5°C.

The Ashrae adaptive standard only applies to buildings with no mechanical cooling installed, while EN15251 can be applied to mixed-mode buildings provided the system is not running.

### 2.2. Characteristics of older adults living in ECC

The abovementioned standards mainly focus on office situations, which tend to be populated by people roughly aged between 20 and 65 years old. Most of the people in ECCs are aged 65 and over.

Although Ashrae suggested that the thermal sensation of old people and younger adults does not differ, and that the effects of sex and age is due to activity and clothing, several studies have indicated that the optimal thermal sensation of older people differs from that of younger adults (Schellen et al., 2010; Hwang and Chen, 2010; DeGroot, 2007; Hoof, 2006) and the two populations' sensitivity to hot and cold environments may vary. The process of biological ageing may affect the perception of thermal comfort because of a decrease in the ability to regulate body temperature with age. On average, older adults require higher ambient temperatures (Hong et al., 2015; Tweed et al., 2015; Hwang and Chen, 2010; Schellen et al., 2010; van Hoof et al., 2010).

Given the rapid increase in aging population in recent years, attention is now focused on thermal comfort in the design and planning of environments for the elderly (Yang et al., 2016; Walker et al., 2016; Alves et al., 2016; Hong et al., 2015; Tweed et al., 2015; Mendes et al., 2013; Mendes et al., 2015; Hwang and Chen, 2010; Schellen et al., 2010; Hoof et al., 2010).

Some studies focused on older citizens' comfort in housing (Miller et al. 2017, Jiao et al. 2017). However, the special characteristics of EECs where residents do not control thermal parameters and air conditioning systems can help analysing the validity of existing standards and more accurate and objective results can be extracted.

## 3. Method

Indoor occupants' thermal sensation is primarily influenced by the indoor climatic parameters present in the environment and by the behaviour of occupants to adapt to changes.

In this study, the measurements of indoor and outdoor climatic parameters of different zones within an ECC and the subjective questionnaire assessing the elderly people's thermal sensations were conducted simultaneously. Results were contrasted to existing thermal comfort levels to analyse the validity of current standards to evaluate the thermal comfort of elderly people.

### 3.1. Physical measurements

To determine thermal comfort based on the different standards, metabolic activity and clothing insulation were estimated with the assistance of ECCs staff and caregivers. Then, the indoor and outdoor air temperature, the mean radiant temperature and the air speed were also measured. The measurements were made in the places where the occupants were expected to spend time. For this study, temperature and humidity sensors together with globe thermometers were placed in different ECC areas (2 in the dining rooms, 2 in the living rooms and 2 in the bedrooms). Measuring equipment was placed according to ISO 7726 (2002). Physical measurements were collected from April 2013 to March 2014, so that the effect of different seasons could be analysed. In this study, the cooling season ran from June to August 2013, the heating season from December 2013 to February 2014, and midseason from April to May and September to November of 2013 and March of 2014.

These data were used to evaluate the thermal comfort by using the international current standards ISO 7730 (2005), Ashrae Standard 55 (2013) and EN 15251 (2007) and compare and analyse the comfort zones in existing regulations.

The comfort results from using existing regulations were then compared to residents' satisfaction using a questionnaire survey.

### 3.2. Questionnaire Survey

A survey to assess thermal environmental conditions was developed considering the special characteristics of elderly people (defined as people aged 65 and over). Caregivers administered the survey to selected ECCs occupants in winter (21st of February) and in summer (15th of July) at 11:00. Questionnaire survey results were contrasted to thermal comfort results obtained from the standards to evaluate the suitability of existing standards for older adults.

Thermal satisfaction is complex and subjective to the occupants (Kameni et al., 2014).

In the specific case study, occupants are older adults who in some cases might have some cognitive problems or mental deterioration. Therefore, a questionnaire survey was designed to get the most precise and objective thermal satisfaction from older adults. ECCs staff and caregivers suggested that using the Ashrae 7-point scale of thermal sensation (cold, cool, slightly cool, neutral, slightly warm, warm, hot) with older adults would bring confusions to the residents. In fact, a test was done with 5 of the residents and they could not distinguish among cold, cool and slightly cool and also among hot, warm and slightly warm. A new qualitative method was designed. The initial option was to show images of the thermal sensation such as a person in the desert sweating (hot), in the beach (warm) or just in summer (slightly warm) so as to distinguish among the different thermal sensations for heat. Symbols, draws and judgments were also used in other research approaches for kindergardens (Fabbri 2013). However, images didn't improve the determination of the thermal sensation of residents. They did only perceived when a room was cool or warm but not the different levels of cold of hot. Finally, the questionnaire was formulated to compare the comfort among zones (bedroom, living room, dining room) and time slots (morning, afternoon, evening). To increase the accuracy of the results, the same aspect was evaluated using several types of questions (for example, respondents were asked to determine the warmest area, and later in the survey to determine the hottest area). The test was successful and results were coherent with what was expected although no quantitative values where obtained to contrast to the calculated PMV from the standards. Then, a qualitative analysis to compare the questionnaire results and the analysis of the measured comfort parameters using the existing standards was carried out.

The survey consisted of three parts. The first included questions about the respondent (age, room number, sex, if he/she is heat sensitive or cold sensitive) and general thermal sensation. The second part included questions about thermal sensations (see Appendix 1). The questions were organised to determine thermal comfort during the day and in the various ECC areas.

Firstly, respondents were asked to determine the time of day (morning, afternoon or evening) when the ECC is cooler, the time of the day when the ECC is warmer, and the time of day when they feel most comfortable. Then respondents were asked to determine which space in the ECC (bedroom, dining room, living room, other) was cooler, which space was warmer, and where they feel most comfortable. The occupants were also allowed to explain their dissatisfaction by answering an open-ended question.

The survey was distributed to all residents who had sufficient physical and mental skills to complete it (48 residents both in summer and winter).

## 4. Building characteristics

The analysed ECC is called Sanitas Mayores Les Corts and is in Barcelona. Barcelona has a humid subtropical climate with mild winters and hot, humid summers. Sanitas Mayores Les Corts consists of two separate buildings with separate entrances that are connected internally on the ground floor. In the middle of the block is a garden for residents. The plot has a total area of 10,780m2: 6.869m2 corresponds to the Evarist building, 2.797m2 to the Caballero building, and 1114 m2 to the garden. Figure 1 shows an aerial view of the ECC.

Figure 1. Sanitas Mayores Les Corts

The Evarist building has six floors of rooms and Caballero has two. On the ground floor, there are shared areas such as cafeterias, multipurpose rooms and waiting rooms, as well as the administrative area. This ECC can accommodate 278 residents.

The main facade of the Evarist building is oriented northwest. The other façade faces southeast, so the rooms are designed to take advantage of the sun all day in the winter, and from morning until noon in the summer. The main facade of the Caballero building is also oriented southeast, but this building is lower.

Both buildings were built with the same construction materials. The structure is made from reinforced concrete and reticular slabs. The roof is flat, with extruded polystyrene insulation and a waterproofing asphalt polymer, finished with a layer of gravel. The exterior walls are ceramic perforated brick, coated with a monolayer coating. The interior dividing walls are plasterboard. The pavements of most areas (halls, corridors, rooms, control rooms, etc.) are made from compact marble, while bathrooms are made from stoneware non-slip flooring.

Sanitas Mayores Les Corts has two independent HVAC systems, one for each building. Both are air-water systems including one chiller, one boiler, an air handling unit (AHU) with heat recovery and several fan coils in the rooms. This is a two-tube system and includes thermostats in each zone, to adjust the set point temperature by 1ºC.

### 4.1. Residents' daily activities

Residents wake up between 8:00 and 8:30. They have a shower and go the dining room for breakfast. At 9:00 several activities are scheduled. Some residents just rest in the lounge while others enrol for these activities. Lunch is at 13:00. After lunch, some residents rest in their rooms while others rest in the living room. The afternoon programme starts at 17:00, and at 19:30 residents have dinner. At 21:00 they go to bed.

### 4.2. Operation of the ECC

In the winter, fan coil units are programmed to work from 7:00 to 11:00, during which time residents wake up and shower. In autumn and spring, fan coil units are scheduled to work from 7:30 to 10:30, and in summer from 8:00 to 10:00.

Then, at 16:00-17:00 (depending on the season) fan coil units are turned on again until 21:00, when residents go to sleep. Fan coils in the dining room and living room have the same schedule.

Although there is an AHU for each building, natural ventilation is found to be enough. Once the residents have left their rooms (8:30), cleaning staff open the windows and tidy up. This process lasts 10 minutes approximately. When residents are in the living room, the dining room is also ventilated.

## 5. Results

### 5.1. Monitored data results

Thermal comfort depends on the indoor and outdoor air temperature and relative humidity, the mean radiant temperature and the air speed.

Thermal comfort also depends on individual parameters such as the degree of activity and the level of clothing. In each area (bedroom, living room and dining room), residents carry out different activities throughout the day (in the morning and evening residents get dressed in the bedrooms, at midday they eat in the dining room, during the day and afternoon they read, play or rest in the living room, etc.). Therefore, the activity factor and the level of clothing was estimated with the support of the care givers and based on these conditions.

Thermal comfort is also influenced by variability during the day and over time in crowding or under-occupancy (Ormandy and Ezratty, 2012). For our study, only occupied times of the day in the different areas were analysed, and there was no variability in occupation. Residents always have the same routine every day and in all seasons. The same is true of weekdays and weekends. The special characteristics of an ECC where there is no unusual behaviour or improvisation make it easy to evaluate. Fluctuations in exterior conditions and the residents' routine led to the following hourly analysis: night: from 22:00 to 7:00; early morning: from 7:00 to 9:00; morning: from 9:00 to 13:00; midday: from 13:00 to 16:00; afternoon: from 16:00 to 20:00; evening: from 20:00 to 22:00.

Although thermal comfort also depends on health status and sex (Mendes et al., 2015), the proportion of men and women in ECC is generally similar. In the analysed ECC, residents do not have major diseases and can move around by themselves or in wheelchairs.

Based on ECC staff and caregivers, the following clothing characteristics (Clo) and degree of activity (Met) were selected for the areas and periods. Tables 1, 2 and 3 present this information, the interior and exterior conditions, and the fulfilment of ISO 7730 (2005), Ashrae Standard 55 (2013) and EN 15251 (2007).

Exterior conditions were typical from a Mediterranean country with mild winters and hot, humid summers.

At night exterior temperatures in winter are around 11ºC, in summer 24ºC and midseason from 15 to 20ºC, while relative humidity ranges from 67 and 75%RH along the year. At midday is when major differences among seasons exist. In winter, exterior temperature is around 15ºC, in summer 30ºC and in midseason from 22 to 23ºC.

**Bedrooms**

Table 1 presents activity levels, clothing level, exterior conditions, interior conditions and thermal evaluation based on the standards for the different seasons and time slots for the bedrooms. At night, residents are sleeping, in the morning (from 7:00 to 9:00) they are changing, at midday they are resting and in the evening (from 20:00 to 22:00) they get undressed to go to bed.

Table 1. Bedroom data and thermal comfort analysis

| | Activity (Met) | Level of clothing (Clo) | T ext (ºC) | H ext (%) | T int (ºC) | H int (%) | Mean radiant T (ºC) | PMV | | Sensation (Ashare) | | PMV (EN-15251) | PPD (%)EN-15251 | Cat EN 15251 | Status Class I EN- |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Winter** | | | | | | | | | | | | | | | |
| Night | 0.8 | 0.96 | 11.1 | 67 | 24.2 | 39.6 | 24.2 | * | | | C | -0.88 | 21 | IV | C |
| Early morning | 1.2 | 0.57 | 12.5 | 64 | 24.5 | 41.3 | 24.5 | 0.01 | 5 | N | B | 0.01 | 5 | I | C |
| Midday | 0.8 | 0.96 | 15.2 | 55 | 25.1 | 37.5 | 25.3 | * | | | C | -0.55 | 11 | III | C |
| Evening | 1.2 | 0.57 | 12.1 | 66 | 24.2 | 38.7 | 24.2 | -0.09 | 5 | N | C | -0.09 | 5 | I | C |
| **Spring** | | | | | | | | | | | | | | | |
| Night | 0.8 | 0.75 | 15.7 | 70 | 25.8 | 44.7 | 25.8 | * | | | C | -0.64 | 14 | III | C |
| Early morning | 1.2 | 0.57 | 17.1 | 66 | 26 | 45.5 | 26 | 0.46 | 9 | N | A | 0.46 | 9 | II | C |
| Midday | 0.8 | 0.75 | 22.1 | 50.9 | 25.9 | 41.9 | 26.2 | * | | | C | -0.57 | 12 | III | C |
| Evening | 1.2 | 0.57 | 17.8 | 66.4 | 26 | 43.5 | 26 | 0.45 | 9 | N | A | 0.45 | 9 | II | C |
| **Summer** | | | | | | | | | | | | | | | |
| Night | 0.8 | 1 | 23.5 | 73.1 | 26.3 | 64 | 26.3 | * | | | B | 0.2 | 6 | II | C |
| Early morning | 1.2 | 0.57 | 25.8 | 65 | 25.8 | 63.7 | 25.9 | 0.55 | 11 | S.W. | A | 0.55 | 11 | III | C |
| Midday | 0.8 | 1 | 30.1 | 53 | 25.8 | 60.3 | 26.3 | * | | | B | 0.06 | 5 | I | T.C. |
| Evening | 1.2 | 0.57 | 24.8 | 70 | 26 | 63.7 | 26 | 0.6 | 12 | S.W | B | 0.6 | 12 | III | C |
| **Autumn** | | | | | | | | | | | | | | | |
| Night | 0.8 | 0.75 | 19.2 | 75 | 25.9 | 57.8 | 25.9 | * | | | B | -0.46 | 9 | II | C |
| Early morning | 1.2 | 0.57 | 21.5 | 70 | 25.7 | 57.4 | 25.7 | 0.46 | 9 | N | A | 0.46 | 9 | II | C |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Midday | 0.8 | 0.75 | 23.2 | 62 | 26.3 | 52.8 | 26.6 | * | | | B | -0.29 | 7 | II | C |
| Evening | 1.2 | 0.57 | 19.8 | 74 | 26 | 55.9 | 26 | 0.54 | 11 | S.W. | A | 0.54 | 11 | III | C |

* Metabolic rates below 1.0 are not covered by ASHRAE Standard 55-2013.
N: Neutral, S.W.: Slightly warm, C: Comfortable, T.W: Too warm, T.C: Too cool.

The activity level is different when residents are sleeping, dressing or undressing and just resting. The level of clothing does also differ for the different seasons.

At night, interior conditions in the bedrooms are very variable. In winter 24.2ºC and 39.6%HR while in summer 26.3ºC and 64%HR. Relative humidity is much higher in summer than in winter provoking a hotter thermal sensation.

In the midday, interior temperatures in bedrooms are kept quite constant (around 25 and 26ºC) but relative humidity is still very different (in winter 37.5%HR and in summer 60.3%HR).

**Living rooms**

Table 2 presents activity levels, clothing level, exterior conditions, interior conditions and the thermal evaluation based on the standards for the different seasons and time slots for the living rooms. During the morning (from 9:00 to 13:00) and the afternoon (from 16:00 to 20:00) residents spend the time resting, playing or reading in the living room.

Table 2. Living room data and thermal comfort analysis

| | Activity (Met) | Level of clothing (Clo) | T ext (ºC) | H ext (%) | T int (ºC) | H int (%) | Mean radiant T (ºC) | PMV | | Sensation (Ashare) | | PMV (EN-15251) | PPD (%)EN-15251 | Cat EN-15251 | Status Class I EN-15251 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Winter** | | | | | | | | | | | | | | | |
| Morning | 1 | 1.01 | 14.6 | 57.4 | 24.5 | 39.4 | 24.5 | 0,26 | 6 | N | B | 0,26 | 6 | II | C |
| Afternoon | 1 | 1.01 | 13.6 | 61.6 | 25.1 | 40.3 | 25.1 | 0,43 | 9 | N | B | 0,43 | 9 | II | C |
| **Spring** | | | | | | | | | | | | | | | |
| Morning | 1 | 0.74 | 21.4 | 53.5 | 25.8 | 45.7 | 25.8 | 0,31 | 7 | N | B | 0,31 | 7 | II | C |
| Afternoon | 1 | 0.74 | 19.1 | 60.1 | 26.6 | 45.7 | 26.6 | 0,56 | 12 | S.W. | C | 0,56 | 12 | III | C |
| **Summer** | | | | | | | | | | | | | | | |
| Morning | 1 | 0.61 | 29.7 | 55.5 | 25.5 | 62.8 | 25.6 | 0,14 | 5 | N | A | 0,14 | 5 | I | T.C |
| Afternoon | 1 | 0.61 | 27.1 | 62.2 | 25.5 | 63 | 25.7 | 0,16 | 6 | N | B | 0,16 | 6 | I | T.C |
| **Autumn** | | | | | | | | | | | | | | | |
| Morning | 1 | 0.74 | 22.7 | 63.1 | 24.4 | 59.4 | 24.4 | -0,02 | 5 | N | A | -0,02 | 5 | I | C |
| Afternoon | 1 | 0.74 | 21.2 | 69.7 | 24.7 | 61.1 | 24.7 | 0,09 | 5 | N | A | 0,09 | 5 | I | C |

* Metabolic rates below 1.0 are not covered by ASHRAE Standard 55-2013.
N: Neutral, S.W.: Slightly warm, C: Comfortable, T.W: Too warm, T.C: Too cool.

The activity level is the same in the morning and in the afternoon. Only, the level of clothing varies in the different seasons.

Interior conditions in the living room do only vary 1ºC from winter and summer but relative humidity differs more than 20% (relative humidity in winter is around 40%HR while in summer around 63%HR). However, interior conditions in the morning and in the afternoon are nearly the same.

## Dining rooms

Table 3 presents activity levels, clothing level, exterior conditions, interior conditions and the thermal evaluation based on the different standards for the various seasons and time slots for the dining rooms. The time slots in which residents are in the dining room are early morning (from 7:00 to 9:00), midday (from 13:00 to 16:00) and evening (from 20:00 to 22:00).

Table 3. Dining room data and thermal comfort analysis

| | Activity (Met) | Level of clothing (Clo) | T ext (ºC) | H ext (%) | T int (ºC) | H int (%) | Mean radiant T (ºC) | PMV | | Sensation (Ashare) | | PMV (EN-15251) | PPD (%)EN-15251 | Cat EN-15251 | Status Class EN-15251 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Winter** | | | | | | | | | | | | | | | |
| Early Morning | 1 | 1.01 | 12.5 | 64 | 24 | 35.4 | 24 | 0.1 | 5 | N | A | 0.1 | 5 | I | C |
| Midday | 1 | 1.01 | 15.2 | 55 | 24.4 | 37.6 | 24.4 | 0.22 | 6 | N | B | 0.22 | 6 | II | C |
| Evening | 1 | 1.01 | 12.1 | 66 | 23.1 | 38.8 | 23.1 | -0.12 | 5 | N | A | -0.12 | 5 | I | C |
| **Spring** | | | | | | | | | | | | | | | |
| Early Morning | 1 | 0.74 | 17.1 | 66 | 24.7 | 44.4 | 24.7 | -0.05 | 5 | N | A | -0.05 | 5 | I | C |
| Midday | 1 | 0.74 | 22.1 | 50.9 | 25.8 | 44 | 26 | 0.32 | 7 | N | B | 0.32 | 7 | II | C |
| Evening | 1 | 0.74 | 17.8 | 66.4 | 25.1 | 44.9 | 25.1 | 0.08 | 5 | | A | 0.08 | 5 | I | C |
| **Summer** | | | | | | | | | | | | | | | |
| Early Morning | 1 | 0.61 | 25.8 | 65 | 25.8 | 60.9 | 25.8 | 0.21 | 6 | N | B | 0.21 | 6 | II | C |
| Midday | 1 | 0.61 | 30.1 | 53 | 26 | 60.9 | 26.3 | 0.33 | 7 | N | B | 0.33 | 7 | II | T.C |
| Evening | 1 | 0.61 | 24.8 | 70 | 26 | 63.4 | 26 | 0.31 | 7 | N | B | 0.31 | 7 | II | C |
| **Autumn** | | | | | | | | | | | | | | | |
| Early Morning | 1 | 0.74 | 21.5 | 70 | 23.6 | 57.4 | 23.6 | -0.29 | 7 | N | B | -0.29 | 7 | II | T.C |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Midday | 1 | 0.74 | 23.2 | 62 | 23.9 | 55.9 | 24.1 | -0.18 | 6 | N | B | -0.18 | 6 I | T.C |
| Evening | 1 | 0.74 | 19.8 | 74 | 23.8 | 58.3 | 23.8 | -0.22 | 6 | N | B | -0.22 | 6 II | C |

* Metabolic rates below 1.0 are not covered by ASHRAE Standard 55-2013.
N: Neutral, S.W.: Slightly warm, C: Comfortable, T.W: Too warm, T.C: Too cool.

The activity level is the same in all time slots but the level of clothing varies in the different seasons.

The temperature of the dining room in winter is around 24ºC and the relative humidity 37%. Summer temperatures and relative humidity are higher (around 26ºC and 61%HR). Midseason temperatures are similar to winter but with higher relative humidity.

### 5.2. Questionnaire results

Fifty-eight per cent of the respondents considered themselves to be neither heat nor cold sensitive. Twenty-seven percent considered themselves to be cold sensitive, while only 15% thought they were heat sensitive.

For the summer period, most respondents did not consider any time of day (53%) or any space in the ECC (57%) to be cooler. However, 24% of the respondents found the bedrooms to be the coolest space in summer. Regarding the sensation of warmth, almost all the respondents (47%) considered the afternoon to be the warmest time of the day, but no difference was perceived among spaces. The time of day when the ECC was considered most comfortable was the afternoon (45%), while 52% of the respondents considered there was no difference between spaces. Twenty-five percent considered the living room to be the most comfortable area. The warmest period of the day was considered the afternoon, and it was also stated to be the most comfortable time. These results reinforce the idea that old people would rather be hot than cold.

For the winter period, no respondents considered the afternoon the coldest time of day, while the morning and the evening were both considered to have the same cooling sensation. A total of 55% of respondents considered that there was no difference between spaces in terms of cooling sensation, followed by 27% of respondents who considered the bedroom to be the coolest area. The warmest time of the day was stated to be the afternoon (50%), although 42% of respondents considered that there was no difference. The dining room (42%) and living room (42%) were equally considered to be the warmest space in winter. Finally, respondents also considered that the afternoon was the most comfortable time of day (42%), followed by the evening (25%). A total of 33% of respondents considered there was no difference between areas regarding thermal comfort, but 25% of respondents believed that the living room was the most comfortable. These results also confirm that in cool periods (winter), the warmer spaces were believed to be the most comfortable.

The main finding is that both for summer and winter, the afternoon was the warmest time of day and the most comfortable. Respondents preferred higher temperatures in summer and winter.

Regarding the open-ended question, respondents mentioned that when the heating is on they feel dryness that causes breathing problems, and mouth dryness which is uncomfortable. However, ECC staff mentioned that humidity cannot be very high, because it can cause various respiratory allergies. Microorganisms that reproduce on wet surfaces (such as mites) also particularly affect people with chronic respiratory diseases (e.g., asthma). Humidity also acutely affects the symptoms of rheumatism and other bone diseases (e.g., arthritis).

## 6. Analysis of results

Questionnaire survey results were contrasted to thermal comfort results obtained from the standards to evaluate the suitability of existing standards for older adults. Although the results of the questionnaire survey were qualitative conclusions and comparisons could be drawn.

In bedrooms, for winter mornings and evenings when the temperature is around 24.5ºC and humidity around 41%RH and residents are getting dressed or undressed, all standards consider the bedroom to be within the comfort conditions or slightly warm.

Based on the EN15251 (2007) categories, in the bedrooms nearly all time slots and seasons met the comfort conditions for Category I, which is used for spaces occupied by very sensitive, fragile people.

Surprisingly, in the summer, when interior temperatures vary from 25ºC to 26ºC in bedrooms and Ashrae Sandard 55 (2013) considers the environment to be slightly warm (both in the morning and in the evening), with a PMV index of 0.6 (slightly warm) and 12% PPD, the results of the survey revealed that 24% of residents considered the bedrooms to be the coolest space. This suggests that, special comfort analysis and comfort thermal levels should be defined for these areas of the building.

On summer mornings, the adaptive standard considers the bedrooms to be too cool. This result corresponds with residents' feelings: they considered the bedrooms the coolest place in summer.

At night, Asharae 55 (2013) is not applicable, but the PMV in winter for the bedrooms (EN 15251 [2007]) was -0.88 with 21% of PPD not meeting old people's required comfort levels. At night, summer and autumn obtained 6% and 9% of PPD. However, the adaptive analysis for the night revealed a comfortable environment that met status class I for old people. The only residents' input for the night was that nobody complained about thermal comfort at this time.

Although residents consider the bedrooms to be the coolest space in summer, for them the most comfortable area is the living room in the afternoon, with 25.5ºC and 63%HR. However, it was slightly too warm according to the PMV method and slightly higher than defined by Spanish regulation (23-25ºC, 45-60%RH). Morning conditions (temperature and humidity) during summer do not vary from afternoon conditions. Then, solar radiation and natural lighting might be the main cause of their varying perceptions. Living rooms have high window façades to let the sun into the spaces. Outdoor conditions, which are normally better during the afternoon, directly affect the comfort sensation, although temperature and humidity are very similar. The fact that residents consider the living room to be the most comfortable place during the afternoon might also be because it is the zone where they spend much of their time and elder adults are not used to changes.

In winter, residents consider the warmest and most comfortable place to be the living room in the afternoon (25.1ºC, 40.3%HR), rather than in the morning (24.5ºC, 39.4%HR). These results also confirm that for cool periods (winter) the warmer spaces are considered the most comfortable (Hoof and Hensen, 2006; Hwang and Chen, 2010; Mendes et al., 2015).

Although PMV methods did not find any differences in comfort from morning to afternoon in the living room in winter, both temperatures are outside of Spanish Royal Decree 1027 (2007) levels of thermal comfort, but within humidity levels (20-23ºC, 40-50% RH).

According to ISO 7730 (2005) and EN 15251 (2007), the recommended level of thermal comfort for the elderly is not achieved in winter or spring. Both standards consider these conditions to be acceptable only for a normal level of expectation; not for a high level of expectation.

The temperatures in the living room were also within comfortable conditions according to Class I acceptability limits on the Adaptive EN 15251 (2007), except in the summer when they were too cool, mainly because of extreme exterior conditions (29.7ºC and 55.5% of RH in the morning and 27.1ºC and 62.2% of RH in the afternoon). These results contrast with residents' sensations, as they did not consider any time of day (53%) or any space in the ECC (57%) to be cooler.

The dining room was also considered to be the warmest place but also the most comfortable together with the living room, according to residents, although they did not meet the expected limits for ISO 7730 (2005) and EN 15251 (2007). The results for the dining room show that the PMV index (Asharae 55 [2013]) in all seasons ranges from -0.12 to 0.33 (neutral) while interior conditions in summer were around 26ºC.

The temperature of the dining room in winter ranges from 23.1 to 24.6 (higher than the comfort temperatures defined by Spanish regulation RITE (2007) [20-23ºC]) and humidity from 35.4% to 38.8% (lower than the range of comfort humidity defined by this regulation [40-50%]). However, conditions in winter were considered comfortable and within the high comfort levels of the different standards.

With the Asharae 55 (2013) PMV method, the sensation in the summer and autumn in the early morning, midday and evening in the dining room was comfortable, but the interior conditions did not meet the expected limits for ISO 7730 (2005) and EN 15251 (2007) for elderly people.

Furthermore, in summer, the temperature of the dining room was about 26.3ºC (higher than the comfort temperatures defined by Spanish regulation RD 1027 [2007] [23-25ºC]) and humidity 60.1% (a bit higher than defined by this regulation [45-60%]).

For the dining room, the adaptive EN 15251 (2007) results for the autumn revealed that the temperature was too cool for elderly people. These results contrast with residents' sensations: they did not consider any time of day (53%) or any space in the ECC (57%) to be cooler. These results suggest that the adaptive method might not be useful for ECC. Residents do not normally leave the building, are not allowed to adapt the conditions by controlling air conditioning, opening windows, etc., so exterior conditions might not influence their comfort.

## 7. Discussion

The analysis of the results suggest that the standards' comfort zones may be not warm enough for older adults, who reported an optimum temperature above 25ºC in all seasons. These results found significant differences between room and season for air temperature. Respondents felt more comfortable and satisfied during the cooling season than during the other seasons, due to their general preference for a high indoor temperature, in agreement with the results of Mendes et al. (2015).

Based on the results of this analysis, adaptive models to evaluate thermal comfort are more precise for older adults than those based on PMV and PPD. Exterior temperatures are determinant for the interior comfort. However, for midseason, the thermal sensation using the PMV and PPD comfort models in spring and autumn in all zones of the ECC was found to be neutral. Spring and autumn is half of the year in Mediterranean countries. During this period, exterior conditions are mild so interior comfort can be obtained without running the air conditioning. The comfort results during periods when no air conditioning is used leads us to conclude that general standards can be used for midseason. However, a thermal satisfaction analysis during these seasons should be carried out to support this conclusion.

These conditions should be contrasted with workplace regulations. Elderly cohabit with ECC staff and caregivers. The regulations determine temperature limits depending on the activity in the workplace. For example, in Spain, Royal Decree 486 (1997) on workplaces determined temperature limits of about 14-25ºC for light work and 17-27ºC for sedentary work. Depending on the area of the ECC and the activity of the caregivers, thermal limits should be balanced between those defined by the elderly thermal comfort and those acceptable for the workers' activity.

## 8. Conclusions

The aim of the paper was to compare and contrast the validity of existing standards to evaluate thermal comfort of older adults.

It highlighted the differences in thermal sensation between older people and the rest of the population, and the need for specific comfort regulations for older adults. In general, PMV/PPD comfort standards do not currently apply to the older population. They only determine higher restricted limits of PPD, instead of determining the conditions that affect thermal comfort. The results of this study highlighted that adaptive thermal comfort models are more accurate than PMV/PPD for older adults.

This study has developed a new questionnaire to evaluate thermal comfort for older adults. Comparing the thermal comfort among different zones allow getting the thermal comfort from the same respondents in the same time. Although being a qualitative method conclusions and comparisons could be drawn. However, this study should be enlarged to other ECCs and including a bigger sample size.

From the analysis, the comfort sensation in different zones (bedroom, living room and dining room) was found to be constant, due to the residents' routine. However, although with the same indoor conditions, level of activity and clothing, residents found the afternoon in the living room in summer more comfortable than the morning. The only parameter found to be different was the outdoor temperature (29,7ºC for the morning and 27,1ºC for the afternoon). Therefore, adaptive comfort models that are based on the exterior temperatures might be more precise than those based on static information.

This study makes a significant contribution to the continuing development and refinement of comfort standards that acknowledge the links between thermal characteristics for old people and their impact on comfort.

The fact that old people prefer higher temperatures in both winter and summer can be used by facility managers to adjust temperature set points. The results can be used for future design and refurbishment of ECCs and have the potential to be used for improving national and international standards.

Analysis of ECCs such as the one presented in the paper are objective enough to be used in other type of buildings for old people such as houses, elderly day care centres, senior community centres, retirement villages, etc.

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## Appendix A: COMFORT QUESTIONNAIRE

**Section A: respondent's details**

**1.** You are…

- ☐ Sensitive to cold
- ☐ Sensitive to heat
- ☐ Neither of the above

**2.** What would you like the temperature of the ECC to be like?

- ☐ Higher
- ☐ Lower
- ☐ The same as it is

**Section B: Thermal sensation**

**3.** When do you feel that the ECC is coolest?

- ☐ In the morning
- ☐ In the afternoon
- ☐ In the evening

**4.** Where do you feel that the ECC is coolest?

- ☐ Room
- ☐ Living room
- ☐ Dining room
- ☐ Another zone

**5.** When do you feel that the ECC is warmest?

- ☐ In the morning
- ☐ In the afternoon
- ☐ In the evening

**6.** Where do you feel that the ECC is warmest?

- ☐ Room
- ☐ Living room
- ☐ Dining room
- ☐ Another zone

**7.** When do you feel more thermally comfortable?

- ☐ In the morning
- ☐ In the afternoon
- ☐ In the evening

**8.** Where do you feel more thermally comfortable?

- ☐ Room
- ☐ Living room
- ☐ Dining room
- ☐ Another zone

# What about children? Implications from their subjective perception and the risk of overheating in schools

**Marije te Kulve[1,3], Runa T. Hellwig[2], Froukje van Dijken[1], Atze Boerstra[1*],**

[1] bba indoor environmental consultancy, The Hague, The Netherlands
[2] Department of Architecture, Design and Media Technology at Aalborg University, Denmark
[3] Human-Technology Interaction, School of Innovation Sciences, Eindhoven University of Technology, Eindhoven, the Netherlands

* corresponding author, email: ab-bba@binnenmilieu.nl

**Abstract:**
During field surveys carried out by the authors, it was noticed that thermal perception voting of children is not in line with the expected thermal perceptions according to comfort models. Literature indicates that temperature may well be perceived differently by children, as compared to adults. At moderate temperatures, surveyed children seem to experience warmer thermal sensations than expected from the PMV-model. However, at elevated temperatures, children appeared to perceive environments as less warm than predicted by the model. Operative Temperature requirements for buildings (as mentioned in standards like EN 16798-1 and EN-ISO 7730) that are used primarily by children, most importantly schools, may therefore not provide adequate comfort for them. Does this mean that lowered temperature limits for environments where children are the main users should be used? Does this imply that mechanical cooling systems or intelligent passive cooling solutions should become 'obligatory' in school buildings where they can be afforded? Given the consequences of active school building cooling on energy use, it is therefore important to have a good understanding of this apparent discrepancy between how thermal comfort is perceived by adults and children. It is proposed in the paper that the thermal perception of children, and the consequences on the temperature requirements for schools is a subject that needs greater research, understanding and discussion.

**Keywords:** Thermal comfort, children, perception, physiology, questionnaires.

## 1. Introduction

Thermal comfort studies increasingly focus on the variations in thermal sensation between individuals. Physiological, psychological and behavioural factors affect thermal perception and contribute to this inter- and intra- individual variation. Recently, Schweiker et al. (2018) reviewed those aspects that have been demonstrated to be drivers for such differences in thermal perception. Physiological factors such as body composition, metabolic rate and adaptation, and psychological aspects such as perceived control have been proven to affect the thermal perception (Schweiker et al, 2018; Boerstra, 2016, Bischof et al. 2007). However, in that review of Schweiker et al. (2018), the demographic characteristics sex and age, which are known to be factors affecting physiological differences, gave no clear drivers for differences in thermal perception. Though the review drew mainly from studies on the relevant effect of older age ranges. Bischof et al. (2007) found that young aged (<30) and females are more likely to report thermal discomfort or thermal dissatisfaction compared to other age groups and males, whereas thermal sensation is not affected by age or sex. In the few studies on the effects as perceived by younger people (<18 years old), these reported that children appeared to prefer lower temperatures compared to adults (Rupp et al, 2015).

This conclusion is in line with the observations of the authors in the field, who noticed that the thermal sensations of children in schools is often higher ("warmer") than expected, based on the in-situ measured temperature compared to predictions derived from the PVM and the adaptive model.

In the review of Rupp et al. (2015), a distinction is made between different age groups of children. For children aged between 4-6 years old (kindergarten), only few studies have been carried out. These studies confirm that the thermal sensation vote of children is usually higher than compared to the predicted mean vote as defined in e.g. EN-ISO 7730. (e.g. Fabbri, 2013 and Yun et al, 2014).

There are more studies available that were carried out with children aged 7 years and older. Of these, several indicated that children preferred lower operative temperatures than expected from the PMV and the Adaptive Model (e.g. Mors et al, 2011 and Teli et al, 2012). In line with these observations, a field study among Australian school children (at primary and high schools, aged 10-18) showed that the neutral temperature of children was around 22.5°C, which is below the prediction of the PMV model in a warm environment (de Dear et al, 2015). The study also demonstrated that the relation between the AMV of children and the PMV depends on the operative temperature. Below 25-26°C the AMV of children was higher (warmer) than the predicted by the PMV model. However, the votes matched the PMV-model predictions, when the indoor temperature was between 25-27°C. Above 27°C, the thermal sensation votes of the children were lower (cooler) than what is expected by the PMV-model (de Dear et al, 2015). More recently, an analysis of a two databases of primary and secondary Australian school children was performed by Kim and de Dear. They showed that the preferred temperatures of school children were 1-2°C lower than the neutrality predicted for adults using the adaptive model (Kim and de Dear, 2018). Finally, an overview of 50 years of thermal comfort research in classrooms by Singh et al (2019), concluded that for all stages in education, students report feeling comfortable on the cooler side of thermal sensation.

All in all, (though this overview is not complete) the tendency is clear that children rate the thermal environment differently compared to the above mentioned comfort models. Most studies show that thermal sensation in children seems to be warmer than opposed to adults under the same conditions. Although for higher ambient temperatures, this may not be the case: the study of de Dear et al (2015) showed that the AMV of children is lower (cooler) than the predicted by the PMV model for temperatures >26-27°C. It appears obvious that temperature guidelines for buildings where children are the main occupants (e.g. school and daycare centers), are fitted to their needs. Especially for babies and young children that are recognised as a vulnerable section of the population in case of a heat wave (e.g. German Guideline on heatwave plan development on a regional level BMUB 2017). But do these observations mean that temperature limits in schools should be lowered? And does this imply that mechanical cooling systems or intelligent passive cooling solutions should become 'obligatory' in schools that can afford them? What would be the consequences of cooling school buildings on energy use? In a warming world, with regard to their adaptability, would it be a supportive approach to offer cooler environments for children? We think it is important to have a good understanding of this apparent discrepancy between the reported thermal perception of adults and children. This study was undertaken to explore the potential causes for these differences in thermal perception, and in it the impact of metabolism, subjective evaluation and behavioural changes on children's thermal evaluation of the environment, and influences on children's adaptability are discussed.

## 2. Metabolic rate of children

The PMV-model uses standardised values of metabolism to consider different metabolic activity in the thermal sensation, but not individual metabolic rates. The definition of the MET unit is based on an "average" male person of 40 years old (Byrne et al, 2005). Likely the metabolic rate that is used as input for the PMV model, is not representative of children's metabolisms. Havenith evaluated metabolic rates and clothing insulation of school children aged between 9 – 18 during different lessons (theory, practical and physical lessons). The metabolic rates (W/m$^2$) of children were lower than of adults during similar activities (Havenith, 2007). It was suggested that this, especially for younger children, in part can be attributed to their smaller volume to surface ratio. Meaning that their heat loss is relatively high. This observation is opposed to the lower neutral temperatures of children reported in the studies cited above.

However, the actual activity levels during the day will have an important influence on the discrepancy in thermal perception. Children are likely to be more physically active during the day than an average office worker e.g. they are physically active during breaks, and some lessons like gym, and are likely to have an increased metabolism when they get back in class and sitting behind their desk. A Norwegian study monitored the activity levels of preschool children (age 3 or 4) and observed that sedentary behaviour during the entire day was observed between 2.7 to 6.5 hours per day (Andersen et al., 2017). Thereby showing that young children are generally more active than adult office workers. Also for older children (aged 10-18) activity levels appear to be generally higher than office workers. In a field study of de Dear et al. (2015), the average metabolic rate was 1.5 MET, as obtained from a questionnaire with choices between sitting 1.2 MET and active 1.5 MET.

Finally, differences in thermophysiology during exercise are observed among children. Younger children (age 9) have higher skin temperatures during the same exercise than older children (age 13) (Havenith et al., 2019). These higher skin temperatures were accompanied by a lower sweat rate, resulting in less cooling, although it was demonstrated that the younger children have a higher skin blood flow in the forearm as compared to older children. Also the larger surface to volume ratio of children improves dry heat loss. So heat loss strategies differ between children and adults, but do not necessarily put them at a higher risk in higher ambient temperature, not being extreme temperatures (Falk and Dotan, 2008).

From a physiological perspective, part of the reason why children generally prefer lower ambient temperatures, has been shown to possibly be that they are generally more physically active as compared to adults.

## 3. Subjective evaluation of children

Another explanation for the discrepancy between the thermal sensation of children and adults could be related to the way thermal comfort is investigated, especially the use of different questionnaires for each group, and a further reason that could contribute to deviations in thermal evaluation, may result from differences in interpretation of the thermal sensation scales. Is a child able to respond in a subtle way to a question on a 7-point scale such as the standard ASHRAE thermal comfort scale? Or will children tend to vote more in the extremes than adults? A slightly elevated temperature could trigger an adult to vote ‘slightly warm’ while a 10-year-old child in the same situation may jump directly from a score ‘neutral’ to ‘hot’.

A recent study amongst university students from different age groups in a temperate climate supports this theory. Young adults, university undergraduate students in their first semester (naïve in terms of building physics and indoor climate) appear to evaluate the importance of indoor environmental aspects in a more pronounced (extreme) way than older students. From this study, it seems that the undergraduate student’s indoor environmental concept is divided in two categories: *important* factors (odours, lighting, sound, temperature, ventilation) and *non-important* factors (humidity, air movement). Students on the master’s level, who learnt already something about indoor climate, and young adults (<31) working in office environments, reported in a more nuanced manner: their evaluation consisted of a more differentiated picture on the importance of indoor environmental parameters (Hellwig, 2017).

It was observed in the data of the ProKlimA study (Bischof et al. 2003) that in general young people (<31 years) report more extreme responses (warmer, less satisfied, less comfortable etc.) than older people on issues of indoor environmental quality (Hellwig, 2005). The hypothesis proposed to explain these outcomes is that young people tend to report in an exaggerated way, rather than reporting in a balanced or differentiated way because they have not yet collected many individual experiences with indoor environments, they may simply reflect the social norms about the indoor climate because they in fact simply adapt to those conditions they normally occupy, within limits.

Additionally, it can be discussed that if the “neutral” is the desired thermal sensation for school children. From the analyses of the Australian studies, it was observed that school children prefer a thermal sensation that was slightly cooler than neutral (Kim and de Dear, 2018). In their study, this effect is explained as a seasonal effect where students prefer ‘a cooler than neutral sensation in a hot and humid climate and a ‘warmer than neutral’ sensation in a cool climate. However, subjective votes reported in de Dear et al. (2015) from Australian school children show no extreme voting, instead subjective vote of “slightly warm” at about 27°C to “slightly warm” to “warm” at about 29°C.

Finally, contextual factors can affect thermal perception. In adults, it has been demonstrated that there is a relationship between thermal perception, humidity and perceived indoor air quality (Toftum 2002). Therefore, thermal perception in schools, may be influenced by suboptimal indoor air quality (often a problem in schools due to high occupancy levels). For the contextual factors, it would be interesting to compare thermal perception of teachers and students.

## 4. Clothing behaviour of children

With an increasing age, around secondary school, children become better in making adjustment to restore thermal comfort such as changing clothing level. The ability to make these changes are important to obtain thermal comfort, especially in naturally ventilated buildings (Singh et al., 2019). Depending on the country and school protocols, children have freedom in choosing their clothing insulation. In the field study of de Dear (2015), the average clothing insulation was 0.45 clo, where the indoor temperature was between 18-31°C. This indicates that children can wear shorts and t-shirt to remain thermally comfortable at higher ambient temperatures.

Young children, especially, are more dependent on their care givers to make behavioural changes, or changes in their environments. However, to make adequate changes from the perspective of a child, it is important that the care giver can estimate the thermal state of children. In a study among 6 day-care centres in the Netherlands, thermal sensation from the care givers, the thermal sensations of the children estimated by the care givers and skin temperatures of both care givers and children were monitored. The results show that the skin temperatures, and thermal sensations, of the care givers were correlated. But for the children, there was no significant relation between the skin temperatures of children and their thermal sensations, as estimated by the care givers (Folkerts et al, 2019). These results indicate that it is hard for care givers to adequately estimate thermal sensation of children. The dependency of children on their clothing insulation, may negatively affect their thermal comfort. Also, wearing inflexible school uniform reduces the behavioural adaptability of children in schools.

## 5. Adaptability of children

The questions raised at the beginning of this paper, whether active cooling of classrooms would be an appropriate answer to the subjective voting of children needs to be discussed very seriously. As known from the adaptive thermal comfort approach, humans adapt to their prevailing indoor environmental conditions (Humphreys, 1976, de Dear and Brager 1998). Active cooling in schools would cause the children to adapt to the narrower temperature band and the lower temperature level. In a warming world, this would likely reduce their acclimatisation level. Non-exposure to warmth remove the stimulus to acclimatise to warm weather, which would diminish the children's adaptability in the long term (Hellwig, 2018). Also cardiovascular health may benefit from exposure to temperature that are just outside the thermoneutral zone (van Marken Lichtenbelt et al. 2017).

A higher impact resulting from climate change is expected for non-acclimatised people, compared to those who are already acclimatised to local climates (Boeckmann & Rohn, 2014). In Australia, a modelled study has shown that a reduced number of days for undertaking outdoor activities are possible for non-acclimatised people in the future, compared with those estimated for the acclimatised population (Maloney & Forbes 2011). Even exposure to mild heat, results in an increased resilience to heat (Pallubinsky et al, 2017). Special guidance for teachers, and parents, on how to support the children in warm periods could be a good solution, changing lesson schedules, encouraging the children to drink more, shifting more exhausting activities to cooler periods etc., and also making "dealing with warmth" a topic of the education.

Field studies confirm that a diverse thermal exposure in classrooms positively accounts for a greater degree in thermal adaptability, for instance children in naturally ventilated classrooms were less sensitive to temperature changes than those in air-conditioned classrooms (de Dear et al, 2015). The range of acceptable temperatures for school children was even estimated to be wider than that of adults (Kim and de Dear, 2018). Seasonal adaptation may also explain why, for high indoor temperatures, thermal sensation of children was lower than expected from the PMV model. All in all, this confirms that it makes sense to expose school children to certain range of indoor temperatures. Keeping in mind that, especially for lower temperatures, thermal sensations of children are generally warmer.

### 6. Practical implication in schools

This overview paper has shown that there are wide range of factors that may relate to the differences in the thermal perception of adults and children. The personal factors that are most commonly used to estimate thermal sensation, such as clothing level and metabolic rate, differ between children and adults, and between an office and a school environment. Moreover, methods of evaluating the thermal responses of children may result in different scores being attributes to the same thermal state, because children may either not understand the question asked, or tend to vote in a less differentiated manner. All together it is not surprising that most field studies observe that different thermal perceptions are experienced by children and adults in similar thermal conditions.

Rather than simply report thermal perceptions of children, organisations should consider the effect of temperature on learning performance when formulating temperature guidelines for school buildings. In accordance with the outcomes from reported studies on thermal preferences in temperatures ranging from 20°C - 30°C, Danish students were shown to perform best under a lower ambient temperature (Wargocki et al, 2019). They found an effect on thermal perception and student performance of increased speeds (1-2% per 1 K), but not on the error rate in students work. The actual span of temperatures affecting children's performance, is probably related to the thermal environment, both indoors and outdoors, to which they have become adapted to (de Dear et al, 2015). A literature overview in de Dear et al (2015) on school children performance also summarised findings on decreased speed of performance in warmer environments, but they reported also that the number of errors in school tests did not tend to increase with elevated temperatures. It can be asked whether it poses a problem if the actual time of a year that such results are reported for are considered. Moreover, it is uncertain whether results from laboratory tests are representative of the effect of temperature on the education of children (Humphreys et al, 2016). Nonetheless, extremely high, or low, temperatures in the classrooms should be avoided.

All in all, the reported thermal perception of children, combined with the higher levels of physical activity in schools of the children, as well as of the teachers, who generally are standing and walking considerably more often than an average office-worker, advocate in favour of lower temperature limits in schools, or more use of the cooling effects of useful opening windows in classrooms. Moreover, due to high occupancy there is an increased risk for overheating, especially if ventilation rates are low, as in areas without opening windows, openable to instantly increase airflow when needed. A sensible starting point in the design of educational facilities, especially primary, schools in moderate climates, is to assume that with rising global temperatures overheating is increasing, and increasingly will become a greater problem compared, than the heating to alleviate cold weather. Therefore extra effort needs to be expended in the appropriate passive design of our school buildings (improved opening windows, solar shading devices, better use of building mass and summer night cooling, etc) and enhance their performance, in relation to warm weather, under every day operation (Hellwig, 2016). High ventilation rates are necessary at times to achieve this in warm and hot periods. Provision of enhance air flow should be designed carefully to prevent draught (especially in cold, windy weather). The correct design and detailing of the building envelope, and its systems, is fundamental to the avoidance of a poor and unpleasant thermal environment in educational buildings.

Although still some effort is put in identifying and explaining learning performance decreases in children due to “non-optimised” conditions, it is questioned whether active cooling would be the right answer to negate this. Logically this will depend on the climate. Also taken into consideration is the fact that artificially lower temperatures potentially also lowers the adaptability of children to higher temperatures. Of course, the currently endemic systematic overheating experienced in schools, particularly modern schools, resulting from the inappropriate design, operation or construction of systems and buildings should be corrected wherever possible, not least because they can considerably extend the overheating periods experienced. Furthermore, peak cooling will increasingly have to be used to avoid extreme indoor temperatures during summer, while maintaining adaptive capacity to higher ambient temperatures, and avoid extensive energy use for cooling. Passive ways of reducing the peak cooling load through timetabling, shifting teaching to cooler times of the day, and moving the locations of teaching activities from the hotter to the cooler parts of the building using thermally landscaped teaching schedules may also prove effective in reducing the effort of cooling for educational facilities.

## 7. Conclusion

In conclusion, this review highlights the need for temperature guidelines for schools to pay attention to the thermal perceptions of children, that has been shown to differ quite considerably , than reported by adults at the same temperatures. For moderate temperatures (<25°C), study results are quite consistent showing that children perceive the environment as being warmer than do adults. Above these ambient temperatures, the adaptation opportunities available to children, and their level of existing adaptation, potentially plays a large role in which temperatures are perceived as being too warm. In defining appropriate temperature guidelines for schools, a better understanding is needed as to why such differences in perception exist, how it affects learning performance of pupils and students, and to what extent are children safely adapt to the ambient temperatures.

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# Welcome to the School of Heat: Assessing heat-perception in schools through participative research and emotional design as drivers for sustainable and healthy approaches in non-adult population

**Samuel Dominguez[1], Teresa Cuerdo[2], Jesica Fernandez-Agüera[1], and Miguel Angel Campano[1]**

[1] Universidad de Sevilla, Escuela Técnica Superior de Arquitectura, Spain, sdomin@us.es, jfernandezaguera@us.es, mcampano@us.es;
[2] Instituto de Ciencias de la Construccion Eduardo Torroja, Spain, teresacuerdo@ietcc.csic.es

**Abstract:** Students are exposed during long time to habitually poor environments in schools, and given that their vulnerability and social function makes them a priority, many previous research related Indoor Environment Quality (air-contamination and thermal environment) with students-performance and cognitive processes.
Most of these approaches focus on cold-period, but Climate Change processes are lengthening the warm-season, particularly in southern Europe, where overheating episodes have evolved from incidental towards a usual risk.
Users often have restricted resources to apply adaptive-strategies, such as modifying clothing, attitude and position, as well as denning the natural-ventilation —traditional in these buildings— limited by outdoor noise, pollution and others.
The efforts of the authorities have mainly been directed towards a timely mitigation, usually circumstantial, and not toward resilience of these facilities, often advising resignation as an answer, thus the "school of heat" concept.
Within this study, research participatory-action techniques have been developed, involving schoolchild in the definition of their perceived environment as an empowerment tool, enhancing the evolution of the user role from passive receptor to active drivers.
The work identifies the greatest strengths proposed by users, using the environmental, psychological and health impact of school users to generate potential tools for the improvement of the spaces.

**Keywords:** Schools, heat-perception, user's perception, qualitative technique

## 1. Introduction

Human beings depend on energy for almost all of their daily activities. Energy is not only required to cover basal needs, but also those which allow them to remain comfortable to face climate dynamic variations outdoors (Lusinga and de Groot, 2019), even more for vulnerable population, as children (UNICEF, 2019). These variations have been altered by anthropogenic activity, boosting extreme weather conditions related to Climate Change, or more complex effects, as the called Urban Heat Island (Sánchez-Guevara *et al.*, 2019). This effect also impacts on indoor air quality, resulting in discomfort and even affecting health (Ballester et al., 2006; Linares and Díaz Jiménez, 2008; Ortiz *et al.*, 2017), especially in risk groups, such as elderly (Jimenez *et al.*, 2011), children (Linares and Díaz, 2009) and births (Arroyo *et al.*, 2016), but also with a significant incidence in the active population (Díaz et al., 2006).

Among the most studied buildings in the field of comfort, schools represent a relevant group. One of the main reasons is the exposure of children, spending long time under indoor environmental conditions. These children are considered risk population, and there are also other considerations, such as social or vulnerability aspects (UNICEF, 2015), which can influence, so investigating in this regard has become a global priority, as a development objective sustainable by 2030 (UNICEF, 2019).

Comfort studies in schools are progressed in last fifty years (Singh *et al.*, 2019). Recently, many of the studies in educational buildings include more innovative methods: student performances, cognitive processes, or disruptive and engaging techniques, such as storytelling (Ebersbach and Brandenburger, 2020), gamification (Konis *et al.*, 2020), or adaptation and comparison among more traditional ones, as Post-Occupancy Evaluation (Martinez-Molina *et al.*, 2017; Merabtine *et al.*, 2018; Rodriguez, Coronado and Medina, 2019). Qualitative techniques are sometimes included as part of mixed methods, such as open-ended interviews (Nakanishi, 2020). Techniques to evaluate subjective aspects of users' perception on comfort are developed (Wang *et al.*, 2019), but often are misnamed as "qualitative" (Cuerdo, 2017; *Papaz*oglou *et al.*, 2019; Shahzad *et al.*, 2019).

Internal comfort in schools results a wide-spread research topic, however there are still some gaps that could be studied in greater depth and solved.

There are many comfort studies in schools that develop research focused on cold season, since it occupies the most of the school period, sometimes also including midseason (Campano *et al.*, 2019). But climate change is effectively lengthening the warm season, especially in areas of Southern Europe, where episodes of overheating affect the performance of daily tasks inside these buildings.

Despite some research literature have not taken into account children to express how they feel or perceive emotions when they interact with their built environment (Fusco et al., 2012), recent studies have been demonstrated that non-adult population is able to offer interesting insights to researchers.

Fostering participative research with engaging techniques allows children motivation and broad-mindedness. The power of these techniques in sustainability, Indoor Environmental Quality or users' comfort in schools may not only make students aware, but also move their knowledge to homes and share it with families (Tucker and Izadpanahi, 2017).

## 2. Objectives

The main objective in this study consists of knowing the perception of comfort in classrooms by secondary school children (12-16 years), using participatory techniques.

Moreover, the specific goals are:

- Characterise the user's perception about what they understand as comfort, related to their stay in the classroom, more specifically during warm season.

- Establish a participatory, mixed method, where subjective and objective aspects can contribute to build a coherent discourse on the perception of comfort in the classroom, taking into account the active participation of the user.

- Create a critical awareness about the importance of environmental comfort in classrooms, where their users participate actively, acquiring knowledge that allows them to communicate their shortcomings and propose solutions to mitigate them.

## 3. Methodology

This study presents a participative research on heat perception, using the emotional design as a driver through a mixed approach to classroom users (students).

The qualitative-exploratory and participatory part of the study is carried out using two techniques: emotional drawings, and group debate around them. Through the drawings, students visually express their understanding of indoor comfort in the school (Buyssen et al., 2020). This technique also allows them to graphically communicate which elements provide comfort, and which contribute to its lack.

Then, they develop their group discourse on the level of comfort perception inside the classroom. The drawings previously selected can act as triggers to elicit deliberation. Students build a consensus on what they understand by thermal and environmental comfort in the classroom, what aspects affect positively and negatively, and what proposing solutions to achieve it. Finally, two questionnaires complete the whole students' evaluation, one based on the user perception of how they feel indoors (aligned with ISO 7730), and the second one about classroom features that may affect comfort and health in the classroom, under their point of view (Bluyssen et al., 2018).

In parallel, indoor environment parameters, such as air temperature and relative humidity, are monitored with portable sensors during working sessions with children. Data monitoring allows assessing the adaptation degree of the method to the specific characteristics of the proposed study-case.

### 3.1. Case study

The evaluation of this methodology was carried out in a Secondary School in Seville (Spain). 32 students were part of this study, aged between 12 and 14. According to literature, this range of age is more appropriate to express descriptions and relationships between students and built environment (Fusco et al., 2012).

The study period was between 2$^{nd}$ and 11$^{th}$ October 2019. The monitoring of indoor environmental parameters (temperature, relative humidity) is carried out simultaneously with the reflection-by-drawing exercise and the completion of questionnaires by the students. For the field measurements, a portable device was arranged in each class during the whole class time for every session and classroom. Despite the date, and as an evidence of the climate-change ravages, the range of outdoor temperatures corresponds to the summer period, recording outdoor maximum temperature of 33.4 oC and minimum temperature of 20.4 oC, in order to know the comfort perception in the classrooms taking into account the warm season. The stablished schedule for students' evaluations was set between 08:00 and 14:30 hours, since children complete their activities during the class time. The indoor environmental conditions in classrooms in terms of support for HVAC equipment were freely evolving.

To carry out the exercise in each classroom, four sessions are needed, taking three consecutive classes in the same week and lasting as much as 1 hour per session. The facilitator-researcher led these sessions. During this time, the tasks to complete were the following:

1) Shallow presentation of the activity, emotional drawing by the students, coding of the drawings;

2) First group-debate after drawing selection by the facilitator;

3) Keywords categorization, jotted down by the facilitator from the students' consensus and questionnaires;

4) thinking about possible solutions to settle what they considered negative for comfort.

### 3.2. Qualitative technique: drawings.

Currently, drawing is a tool with unquestionable scientific-rigor. It is used in medical tests, in Pediatrics and Psychology for instance, and its validation is based on evidence, recognized as an emotional driver to know and evaluate children behaviour, even for the detection and monitoring of emotional, cognitive or behavioral disorders (Chollat *et al.*, 2019). Despite images in general are considered qualitative data (Cuerdo, 2017; Cuerdo-Vilches and Navas-Martín, 2020), there are quantitative tests able to assess children drawings (Galli *et al.*, 2019).

Drawings are also used as part of mixed methods, as well as triangulated with other evaluation techniques that support or refute the results, often applied in child population (Buyssen et al., 2020). Well-known and validated drawing tests are Draw-a-man Test (DAMT) (Chollat *et al.*, 2019), Family Drawing, linked to Attachment Theory (Pace, Guerriero and Zavattini, 2020) or Kinetic Family Drawing (Kim and Suh, 2013), validated with others, such as problem behaviour tests, to predict and mediate internal childhood behaviour problems (Kim and Suh, 2013). Researchers often compare with questionnaires and objective visual indicators and given insights on familiar relationships, following the art-based phenomenological analytic approach (Zaidman-Zait, Yechezkiely and Regev, 2020). Other research applies creative techniques as writing and storytelling to work psychological disorders (Altay, Kilicarslan-Toruner and Sari, 2017).

### 3.3. Questionnaires

Two questionnaires were given to students, with scaled answers for a better understanding and evaluation on their part, as well as to collect aggregated data.
Firstly, they were asked to fill in the questionnaire on user comfort perception, aligned with ISO 7730, with questions about comfort perception, which included environmental issues such as classroom location, lighting perception (Lourenço, Pinheiro and Heitor, 2019), indoor air quality and possible inconveniences linked to the pupil's position in the classroom.

Secondly, the facilitator distributed to the students the questionnaire on what conditions influence their comfort in the classroom. It also contained scaled-answers and included a wide variety of issues that potentially could affect to the environmental conditions of the classroom, as well as to their hypothetical improvement according to the students' own perspective.

### 3.4. Group Debate

The facilitator selected among all the drawings collected, those that could represent the most of the pupils, or which provoke more interesting questions, so that the debate flowed easily and effectively. The facilitator asked the creators to explain what they have drawn in order to better understand what they want to reflect, after a discussion starts.

## 4. Results

### 4.1. Drawings

In the first session, students had to make a drawing that showed elements or factors that represented the discomfort in the classrooms. This explanation was just orientative, trying not to skew their own perceptions about the existing problems and their way of showing them with images. A code instead of the name was provided to each survey, in order to they could be expressed more freely. For this studiy, spontaneous or freely expressed answers could give much more valuable data than pre-defined answers, even if it is harder to quantify.

In this case study, 20% of the students did not know what to draw about the classroom, and 5% wrote a small opinion instead of drawing. 50% of the drawings included an air conditioner and the student's position in the classroom. 45% of the students drew windows, being one of the most significant elements because the sun's rays enter through the them, even drew the views in front of windows. Many of the drawings included the blackboard, although in the debate it was said that it was a component to be placed in the classroom. Other drawings included water, doors, airflow, clothes, and hairstyles.

Figure 1. Emotional drawings performed by students

### 4.2. Questionnaires

The surveys distributed included 3 fundamental questions. Scale/rank questions (from 0 to 5 ) were used to ask respondents to rate items in order of importance or preference, where 0 meaned that the element had no influence and 5 that it was very influential:

- First question: "What elements have influence in establishing whether the classroom is comfortable?"
  50% of students voted that the most relevant elements were noise, heat, smell and the number of students in the classroom. The elements voted like less important were wall color, roof color, floor material and windows views (Table 1).
- Second question: "What elements are able to influence a good temperature?"
  The most voted elements were to have air conditioning and that the air conditioning was on. Other factors voted like important were the number of students and the movement of the air in the classroom. Other elements were considered like a medium importance, including elements that were of little importance in comfort such as wall color, roof color, floor material and windows views (Table 2).
- Third question: "What elements would you change for get a better temperature in the classroom?"
  The answers were similar to the question 2, given that the most important elements were related to air conditioning. Other additional factors were the distance to the window and the existence of air flow/breeze (Table 3).

Table 1. Response rate about factors that influence comfort in the classroom

| | Important (%) | Medium (%) | Not important (%) |
|---|---|---|---|
| Chair comfort | 35 | 29 | 36 |
| Table distribution | 29 | 18 | 53 |
| Classroom lights | 33 | 20 | 47 |
| Classroom size | 43 | 22 | 35 |
| Classroom noise | 56 | 14 | 30 |
| Classroom heat | 59 | 19 | 22 |
| How illuminated is the classroom | 45 | 21 | 34 |
| Wall color | 16 | 18 | 66 |
| Roof color | 14 | 11 | 75 |
| Floor material | 8 | 13 | 79 |
| Window views | 22 | 12 | 67 |
| Number of students | 53 | 8 | 39 |
| Classroom smell | 55 | 15 | 30 |

Table 2. Response rate about factors that influence the temperature in the classroom

| | Important (%) | Medium (%) | Not important(%) |
|---|---|---|---|
| Chair comfort | 25 | 57 | 18 |
| Table distribution | 18 | 73 | 8 |
| Classroom lights | 32 | 49 | 19 |
| Classroom size | 33 | 56 | 11 |
| Classroom noise | 32 | 51 | 17 |
| How illuminated is the classroom | 33 | 57 | 10 |
| Wall color | 8 | 73 | 18 |
| Roof color | 7 | 83 | 10 |
| Floor material | 3 | 86 | 11 |
| Window views | 19 | 71 | 10 |
| Number of students | 47 | 37 | 16 |
| There is an air conditioning | 72 | 26 | 3 |
| Air conditioning is on | 59 | 35 | 5 |
| Distance to the window | 37 | 48 | 15 |
| Distance to the door | 22 | 61 | 18 |
| Light that enters through the window | 41 | 50 | 9 |
| Air movement | 49 | 44 | 7 |
| Window opening | 38 | 42 | 20 |
| Opening of the blind | 39 | 45 | 16 |
| Projector power on | 14 | 79 | 7 |
| My activity: thinking… | 18 | 64 | 18 |

Table 3. Response rate about factors should be changed to improve the temperature in the classroom

| | Important (%) | Medium (%) | Not important (%) |
|---|---|---|---|
| Chair comfort | 41 | 47 | 12 |
| Table layout | 31 | 57 | 12 |
| Classroom lights | 29 | 56 | 15 |
| Classroom size | 35 | 56 | 10 |
| Classroom noise | 40 | 49 | 11 |
| Classroom heat | 64 | 27 | 9 |
| How illuminated is the classroom | 34 | 56 | 10 |
| Wall color | 15 | 72 | 13 |
| Roof color | 13 | 83 | 4 |
| Soil type | 6 | 87 | 7 |
| Window views | 25 | 72 | 3 |
| The number of classmates in the classroom | 38 | 49 | 13 |
| Let there be air conditioning | 57 | 37 | 6 |
| That the air conditioner is on | 55 | 38 | 6 |
| The distance to the window | 30 | 53 | 17 |
| The distance to the door | 26 | 66 | 9 |
| The light that enters through the window | 26 | 59 | 15 |
| The air current that reaches me | 45 | 34 | 21 |
| That the window is open | 38 | 43 | 19 |
| That the blind is lowered | 31 | 61 | 7 |

### 4.3. Group Debate

In session 2, the facilitator asked the creators to explain what they had drawn in order to better understand what they wanted to show, after other students expressed their opinions about those drawings. Table 4 shows the most repeated words in the group debate about the question “What do you see here?”.

Table 4. Frequency of words in the group debate

| Letter | Question | Concept more repeated | Number |
|---|---|---|---|
| S | What do you **see** here?  | Sun | 30 |
| | | Window | 26 |
| | | Wall | 18 |
| | | People | 15 |
| | | Light | 12 |
| | | Digital Blackboard | 11 |



In session 4, it was proposed to think about possible solutions to improve the thermal comfort. The windows were proposed to be changed, using improvements such as corbels, sunshades, or curtains. Larger trees could be planted in the playground to provide shade and a cooler environment. It was also necessary to include some element that moved the air, or open the windows when there were windy conditions outside.

Many students said that it was important the kind of clothes they wore, although sometimes this measure was insufficient to achieve well-being conditions indoor. Other measures were to turn off the light, install fans of hand-fans, drink water or even change the hairstyle.

In addition, students performed claims such as “overheating due to excessive solar radiation through the windows” or that “with such heat can not think”, even that “they get very distracted during the day to try to find solutions to have less heat”

Having to engineer "homemade" mechanisms to acclimatize or seek comfort often resulted in wasted time, according to the testimonies of the participants, as using the notebooks as fans or got wet in the playground so as not to pass heat when they entered the classroom.

## 5. Conclusions

A present qualitative environmental assessment analysis has been applied on a case of study, helping students to think about the environment that surrounds them in order to take into account parameters that they did not know before or did not think they could influence. In the successive sessions, the followed metodology helped them become more interested in the tasks they performed and in the answers given by their peers.

In this way, the questionnaires distributed encouraged them to think about parameters that could influence on the assessment of the classroom temperature and have helped them to look for possible solutions to the problem posed. The solutions that students gave, which covered a wide range of issues, also served to address the heat adaptation concern and even to raise awareness about energy savings.

Although the results provided by the assessment of just 33 participants can not be extrapolated, this study can be used as a first approximation that shows that this methodology is valid, requiring more research in this regard.

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# Thermal comfort assessment in university classrooms in the tropics.

**Gabriel Guevara**[1], **Guillermo Soriano**[2] **and Isabel Mino-Rodriguez**[3]

[1] Facultad de Ingenieria Mecanica y Ciencias de la Produccion, Escuela Superior Politecnica del Litoral ESPOL, Guayaquil, Ecuador.

[2] Centro de Energías Renovables y Alternativas, CERA, Escuela Superior Politecnica del Litoral ESPOL, Guayaquil, Ecuador.

[3] Institute for Environmental Design and Engineering, University College London, London, United Kingdom

**Abstract**: Thermal comfort is a paramount objective in university classrooms when the aim is to maximize learning and productivity performance. The challenge to achieve thermal comfort in classrooms in the tropics is even greater due to the extreme weather conditions and the elevated internal and external heat gains. This study is based on thermal comfort responses from 415 questionnaires collected from December 2017 to January 2018 at three geographic regions in Ecuador. The study aims to compare real thermal sensation and predicted models. Several uninsulated free-running and air-conditioned classrooms were considered as part of the sample. The cities and tropical climates analyzed were Guayaquil (Aw), Quito (Cfb) and Tena (Af). Despite the differences in weather, the building design and properties in terms of materials are very similar. PMV and adaptive methods were used for comparison to actual votes through linear regression analysis. The comfort temperature calculated with Griffiths method showed that the mean operative temperature is not different from TSV neutral temperature, a difference of 1.1K 0.4K and 0K for Guayaquil, Tena and Quito were found. In conclusion, higher levels of comfort are observed in free-running classrooms in Quito regardless of the lower air temperature.

**Keywords:** thermal comfort; tropics; free-running; neutral temperature.

## 1. Introduction

Two important aspects are usually considered in these types of thermal comfort studies, health, and energy saving. In terms of energy savings, the correct indoor temperature setting for both hot and cold regions influence in the use of energy in buildings [17]. The effects of a thermal environment in the classroom, in which the sensation is not pleasant are already known. From the difficulty to concentrate, learn memory, think until complete a test [23]. It was found that at different levels of temperature the students' performance is affected depending on the task [23]. In college, it is common for students to enter and exit after a new class begins. Singh M. discussed the fact that the students in the first minutes have a thermal transient condition, because of that the feeling of the previous environment greatly affects the thermal comfort and preference of the students [22] especially when the outdoor temperature is considered as hot or cold.

The intention of this study is to examine the application of thermal comfort standards in the climatic and behavior conditions in Ecuador. To do so, it will compare subject sensation votes with comfort models from international standards as ASHRAE 55 and EN 15251, calculating PMV in air-conditioned classroom and the adaptive model for free-running mode. Identify any differences between the thermal comfort range indicated by occupants in Guayaquil, Quito and Tena with other cities under the same climate zone. The use of the Griffiths equation to calculate the comfort temperature is useful to have another neutral temperature reference, especially when the sample is small.

### 1.1 Review of literature

Studies of thermal comfort in university classrooms have been registered since 2004 by Krüger and Zanninb [14] in natural ventilated classroom. Countries such as Taiwan, China, Japan, Italy, United Kingdom, and USA are the countries where more studies have been carried out. The PMV-PPD and the adaptive model are used simultaneously by researchers [16] [15] [26] [5] with more emphasis on adaptive methodology to evaluate classrooms that operate with natural ventilation or a combination of natural and mechanical when the objective is to reduce the use of energy dedicated to heating or cooling systems.

The field study conducted by Cheng et al [3] in classrooms, dormitories and outdoor spaces of universities in Taiwan showed an operative temperature of thermal neutrality in dormitories fell at 25.4°C. Results estimated that students in Taiwan prefer a cooler than the neutral thermal condition in dormitories and classrooms. Linear regression of operative temperature and thermal sensation for mechanical (TSV = 0.345 Top - 8.8; R=0.91) and Natural ventilation (TSV = 0.338 Top – 8.4; R=0.97) indicate students' thermal sensitivity are similar in dormitories of natural ventilation and air-conditioning. Zaki et al [27] investigated the comfort temperature and adaptive behavior of university students in Malaysia and Japan in mechanical cooling and free-running operative mode. In Japan, the mean comfort operative temperature in free-running mode was 25.1°C, while in Malaysia was 25.6°C. For mechanical cooling operation inside classrooms, the mean comfort operative temperature was 26.2°C in Japan and 25.6°C for Malaysia. One of the main conclusions in this study was the validity of applying thermal comfort standards in hot-humid climates. Wang H. [24] conduct an experimental study that looks for a barometric effect in human thermal comfort at three different altitudes (0 m, 1300m and 2300m) simulated by a decompression chamber. The results showed that as the altitude increases the average thermal sensation decreases and the subjects become more sensitive to air currents so they would prefer low air velocities. Natarajan et al [16] conducted a field study in an office building located in Bogota which has a highland climate. The study aimed to compare subjective votes with the predicted model of thermal comfort standards concluding that the predicted results were in agreement with the subject responds in air-conditioned office but not in natural ventilation spaces.

Air-conditioned classrooms in a hot and humid climate were used for field experiments by Fang et al [6] in Hong Kong. Result in neutral and preferred temperature were 24.14°C and 24.58°C respectively and the comfort range (+0.5<PMV<+0.5) was between 21.56 °C and 26.75 °C. In most air-conditioned classrooms, subjects indicate a preference for a slightly cool environment independent of the climate zone in which they are located [22], also many studies agree that people in the tropics are adapted to warm environments and are more sensitive to the cold. The comfort temperatures and preferences found in studies are used to develop comfort equations that can estimate the indoor temperature of the classrooms for each climate zone. It becomes difficult to find similarities in the results when the weather conditions and the mode of operation are not the same.

## 2. Methodology

### 2.1. Climatic condition

The thermal comfort study was focused on university's classrooms. In Quito the survey was conducted at the Escuela Politecnica Nacional (EPN), which is located on the south-west of the city, during the wet season in December 2017 to January 2018. Quito's climate is classified as subtropical highland (Cfb); based on the Köppen world climate classification of Kottek et al [13]. The annual average temperature is 15.6°C and presents two main seasons: dry (June - September) and the wet (October - May) and high levels of solar radiation due to the elevation (2800 m). In Guayaquil, the field study was chosen at Escuela Superior Politecnica del Litoral (ESPOL), located on the west side of the city during the wet season in January 2018. Guayaquil climate is classified as Equatorial savannah with dry winter (Aw), mean outside temperatures of 28°C, heavy rain from January to April and from June to November is excepted precipitation below 60 mm. The last location where the study took place was in Tena at IKIAM university, during the wet season in January 2018. The tropical rainforest (Af) is the classification due to the constant rainfall throughout the year, for that reason, a dry season is not very defined. The outdoor temperature oscillates between 18°C and 36°C and the average annual temperature is 23°C.

### 2.2 Classroom condition

Seven classrooms of the faculty of chemical and mechanical engineering at EPN were surveyed. Those classrooms operate under free-running conditions during the whole year. In Guayaquil, seven classrooms of mechanical engineering (ESPOL) were selected for the study. The lecture rooms had central air conditioning, and windows cannot be open. The day of the survey application had normal outdoor conditions, warm and humid. The five classrooms used in the faculty of natural science at Amazon Regional University (IKIAM) in Tena were a one-story building and had air conditioning and operable windows. The day of the survey application had normal outdoor conditions, warm and humid.

### 2.3 Data collection

The study includes two activities, obtaining the environmental measurements and conducting a survey with a set of questions to collect the reactions and opinions of university students in lecture hours. It was a requirement that students did not know human thermal comfort and each respondent could only participate once [21].

#### 2.3.1. Thermal comfort survey

Data analyzed for this study correspond to the current thermal state and background of the cross-national dataset (Schweiker et al, 2019). The questionnaire contained a fixed scale to indicate the thermal states. The thermal sensation and preference were evaluated with a 7-point scale ending with the choices "Cold" and "Hot", "much cooler" and "much warmer" respectably. A 4-point scale for acceptance for and a 5-point scale for satisfaction. The survey was conducted when participants had been seated for at least 30 minutes and the Spanish version of the questionnaire was used

(b) (c)

**Figure 1. Students filling questionnaire during lecture hours. Free running (a) EPN at Quito; Air conditioner (b) Guayaquil and (c) Tena**

**Table 1. Thermal comfort scales**

| Thermal sensation | | Thermal comfort | | Thermal preference | | Thermal acceptability | |
|---|---|---|---|---|---|---|---|
| Scale number | Verbal anchor | Scale number | Verbal anchor | Scale number | Verbal anchor | Scale number | Verbal anchor |
| -3 | Cold | 1 | Comfort | 1 | Much cooler | 1 | Clearly accep. |
| -2 | Cool | 2 | Slightly uncomfort | 2 | Cooler | 2 | Just accep. |
| -1 | Slightly cool | 3 | Uncomfortable | 3 | Slightly cooler | 3 | Just unaccep. |
| 0 | Neutral | 4 | Very Uncomfortable | 4 | No change | 4 | Clearly unaccep. |
| 1 | Slightly warm | 5 | Extremely Uncomfortable | 5 | Slightly warmer | | |
| 2 | Warm | | | 6 | Warmer | | |
| 3 | Hot | | | 7 | Much warmer | | |

### 2.3.2. Thermal environment parameters

While the subjects filled up the questionnaire, the indoor environmental parameters were measured. Physical parameters were measured close to the subjects, but with enough distance to not interfere with them. The indoor air temperature ($T_a$), relative humidity (RH) and air velocity ($V_a$) were measured using the Heat stress monitor (QUESTemp° 36) which complies with the ISO 7726 accuracy ranges. The mean radiant temperature ($T_{mr}$) was calculated using the guidelines outlined in the ASHRAE fundamentals handbook, estimated from the globe temperature ($T_g$), which was measured using a 150 mm (6 in) diameter black globe thermometer; technical specification can be found on table 2. For the free-running case, the average outdoor temperature was collected from a local weather station. Simultaneous measurements of the indoor climatic parameter were taken by a heat stress monitor positioned in the middle of the classroom at a height of 0.6 m above the floor, which represents the middle height of the occupant at the seated level.

**Table 2. Specification of measurement equipment**

| Instrument | Parameter | Description | Range | Resolution |
|---|---|---|---|---|
| QUESTemp 36 and air-probe | Dry bulb temperature (Ta) | The dry bulb thermometer (right position) measures the ambient air temperature, shite plates surround the sensor to shield it from radiant heat. | 0 - 120°C | 0.1°C |
| | Globe temperature (Tg) | An approximation of the radiant heat exposure on an individual is measured by a 6-inch (15.24 cm) blackened cooper sphere mounted on the equipment case. | 0- 120C | 0.1°C |
| | Relative humidity (RH) | Relative humidity sensor is incorporated in the sensor case, slots allows air to circulate. | 20 - 95% | 1% |
| | Indoor air movement (Va) | Omni-directional anemometer sensor that measures air flow and is mounted behind the sensor case. | 0 - 20 m/s | 0.1m/s |
| Testo 835-H1 | Surface temperature (IR) | Infrared thermometer, noncontact temperature and moisture measurements. | -30 to 600°C | 0.1°C |
| Testo 435 and multifunction probe | Pressure (Pa) | A multi-functional measurement instrument | 0 - 2000 hPa | 0.1 hPa |

$t_a$: indoor air temperature; $t_g$: globe temperature; $t_r$: mean radiant temperature; $t_{op}$: operative temperature; RH: indoor relative humidity; $V_a$: air movement.

## 3 Result and discussion

A total of 415 valid questionnaires were completed, 142 from Quito, 183 from Guayaquil and 90 from Tena. Because all respondents were performing sedentary activity such as reading and writing, the metabolic rate was taken as 1.2 met, in accordance with ASHRAE 55 Standard 55 [1]. The cloth insulation in Guayaquil and Tena is lower than Quito basically because of the warm outdoor environment. For the tropical rainforest students, the garment used was long pants, T-shirt and casual shoes. In highland climate, the garments are the same but thicker and also using a sweater or jacket. The average thermal insulation value for the highland climate was estimated from the ISO 9920 standard [12] as 0.85 cl, for the tropical rainforest and hot-humid climate as 0.50 cl. The details of the garments are in table 5.

### 3.2 Outdoor environmental condition

The outdoor relative humidity in EPN classrooms surroundings (Quito) varies greatly. The values range from 41% to 62%. The average outdoor temperature is 18°C, with 15°C and 20°C being the lowest and highest recorded. In the outdoor environment near the ESPOL classrooms (Guayaquil) the environment due to the season was slightly humid with an average of 75% relative humidity and a mean temperature of 27.5°C. In IKIAM (Tena) the average humidity was 88%, with 83 and 96 being the lowest and highest values recorded. The outdoor temperature was 23.1°C with ranges from 22.1°C to 24.5°C.

**Table 3. Summary of mean outdoor conditions**

| University | Region | Air temperature [°C] | | | Relative humidity [%] | | |
|---|---|---|---|---|---|---|---|
| | | Mean | Lower | Higher | Mean | Lower | Higher |
| EPN | Quito | 18 | 15 | 20 | 48 | 41 | 64 |
| ESPOL | Guayaquil | 27.5 | 26.9 | 30.6 | 74 | 64 | 82 |
| IKIAM | Tena | 23,1 | 21.1 | 24.5 | 88 | 83 | 96 |

### 3.3 Indoor environment measurement

The classrooms at EPN were on free-running mode, keeping doors and windows closed. The indoor air temperature remained higher than the outside temperature, with a mean temperature of 21.4°C partially due to the heat input of the people. The air velocity remained less than 0.2 m/s in the classrooms except for ECEPN04 and ECEPN06 where they had windows and doors open respectively. At ESPOL(Guayaquil) classrooms the highest temperature recorded was 26°C in ECESP03, except for that, the temperature variation in other classrooms was 1.4 degrees. In IKIAM (Tena) the average temperature was 24°C, with the ECIKI04 classroom being an exception because despite operating the air conditioning the windows were opened. Also, the wind speed was greater than 0.2 m /s for the same reason.

**Table 4. Physical parameters**

| | Classroom Code | N | Windows/ door | Operation mode | $t_a$ [°C] | $t_g$ [°C] | $t_r$ [°C] | $t_{op}$ [°C] | $V_a$ [m/s] | rh [%] |
|---|---|---|---|---|---|---|---|---|---|---|
| Quito | ECEPN01 | 22 | CW-CD | FR | 22.4 | 21.6 | 21.1 | 21.8 | 0.1 | 42.0 |
| | ECEPN02 | 24 | CW-CD | | 18.8 | 19.2 | 19.4 | 19.1 | 0.1 | 53.0 |
| | ECEPN03 | 19 | CW-CD | | 23.0 | 23.1 | 23.2 | 23.1 | 0.2 | 52.0 |
| | ECEPN04 | 20 | WO-CD | | 20.6 | 20.7 | 20.8 | 20.7 | 0.4 | 54.0 |
| | ECEPN05 | 22 | CW-CD | | 21.6 | 21.9 | 22.2 | 21.8 | 0.2 | 61.0 |
| | ECEPN06 | 27 | WO-CD | | 20.0 | 22.5 | 25.4 | 22.2 | 0.3 | 51.0 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | ECEPN07 | 8 | CW-CD | | 23.2 | 23.3 | 23.4 | 23.3 | 0.2 | 45.0 |
| Guayaquil | ECESP01 | 14 | CW-CD | AC | 21.4 | 21.9 | 22.2 | 21.8 | 0.1 | 44.0 |
| | ECESP02 | 39 | WC-DO | | 24.1 | 24.6 | 25.0 | 24.5 | 0.2 | 52.0 |
| | ECESP03 | 22 | CW-CD | | 26.0 | 26.4 | 26.6 | 26.3 | 0.1 | 61.0 |
| | ECESP04 | 32 | CW-CD | | 21.4 | 21.7 | 21.9 | 21.6 | 0.1 | 37.0 |
| | ECESP05 | 25 | WO-CD | | 23.8 | 24.1 | 24.4 | 24.0 | 0.2 | 51.0 |
| | ECESP06 | 31 | CW-CD | | 21.0 | 21.7 | 22.4 | 21.6 | 0.3 | 37.0 |
| | ECESP07 | 21 | CW-CD | | 24.2 | 24.3 | 24.4 | 24.3 | 0.2 | 48.0 |
| Tena | ECIKI01 | 19 | CW-CD | | 21.8 | 22.9 | 23.8 | 22.6 | 0.2 | 57.0 |
| | ECIKI02 | 18 | CW-CD | | 23.1 | 24.2 | 24.9 | 24.0 | 0.1 | 52.0 |
| | ECIKI03 | 22 | CW-CD | | 24.6 | 24.9 | 25.1 | 24.8 | 0.1 | 78.0 |
| | ECIKI04 | 14 | WO-DO | | 27.2 | 27.9 | 28.6 | 27.8 | 0.3 | 65.0 |
| | ECIKI05 | 12 | CW-CD | | 23.4 | 23.9 | 24.3 | 23.8 | 0.2 | 46.0 |

$t_a$: indoor air temperature; $t_g$: globe temperature; $t_r$: mean radiant temperature; $t_{op}$: operative temperature; RH: indoor relative humidity; $V_a$: air movement. FR: free-running; AC: air conditioner; N: sample size. CW: closed window; WO: window open; DC: door closed; OD: door open

**Table 5. Thermal insulation garments, extracted from ASHRAE**

| | Garment | Value [clo] |
|---|---|---|
| Guayaquil - Tena | Underpants, shirt with short sleeve, light trousers, light socks and shoes | 0.50 |
| Quito | Underpants, shirt, trousers, jacket, socks and shoes | 0.85 |

Extracted form table A1 insulation value of typical clothing ensembles; Clo: insulation unit

### 3.4 Subjective thermal responses

#### 3.4.1 Thermal sensation, thermal preference, thermal acceptance

According to the votes at EPN classrooms, the mean thermal comfort vote in the seven classrooms is neutral (-0,05), indicating their state between comfortable and slightly comfortable, recalling the mean temperature for this set of classrooms was 21.4°C. For the classroom ECEPN05 presents a mean vote closer to slightly comfortable despite having an air temperature close to the average (21.6°C); This is because the relative humidity (61%) at that time was higher among all the others. The mean preference vote was "no changes", the only one making a notable difference was the ECEPN06 classroom indicating slightly cold because most of them were inclined to a warm thermal sensation in the classroom. The students responded in general that the environment was only acceptable.

The resulting votes at ESPOL classrooms were slightly cool (-1.05) as a mean vote for thermal sensation, it's seen that in ECESP03 is the only classroom in Guayaquil that expressed a neutral thermal sensation. The mean thermal comfort vote was between comfortable and slightly comfortable (1.57) with an air temperature of 23,1°C among the seven classrooms. The votes for preferences were in accordance with the air temperature, ECESP04 and ECESP06 declared slightly warm in a 21,0°C and 21,4°C respectively. ECESP02, ECESP03, ECESP05 and ECESP07 prefer a slightly cooler space in which the mean temperature in those four classrooms were 24.5°C. The acceptance mean vote of the thermal condition in classroom "was just acceptable".

In Tena, the thermal sensation was within -0.5 to 0.5 in ECIKI03 and ECIKI04 where the air temperature is higher (24.6°C; 27.2°C). In others classroom the thermal sensation is slightly cool mainly because the temperature is 2 or 3 degrees lower. Five classrooms vote for a slightly comfort state, accepting their thermal condition and preference was to not make changes.

**Table 6. Mean values of subjective votes**

| | Classroom code | $t_{op}$ [°C] | TSV (S.D.) | TCV (S.D.) | TPV (S.D.) | TAV (S.D.) | N |
|---|---|---|---|---|---|---|---|
| Quito | ECEPN01 | 21,8 | -0.3 (1.2) | 1.5 (0.5) | 4.1 (1) | 2.1 (0.5) | 22 |
| | ECEPN02 | 19,1 | -0.7 (0.5) | 1.4 (0.5) | 4.4 (1) | 1.8(0.4) | 24 |
| | ECEPN03 | 23,1 | 0.3 (1.1) | 1.6 (0.6) | 3.8 (1.1) | 2 (0.3) | 19 |
| | ECEPN04 | 20,7 | -0.3 (0.9) | 1.4 (0.7) | 4.2 (0.7) | 1.9 (0.4) | 20 |
| | ECEPN05 | 21,8 | -0.3 (0.9) | 1.7 (1) | 3.8 (1.1) | 1.9 (0.4) | 22 |
| | ECEPN06 | 22,2 | 0.4 (0.8) | 1.4 (0.6) | 3.4 (0.8) | 2 (0.6) | 27 |
| | ECEPN07 | 23,3 | 0.6 (0.9) | 1.5 (0.5) | 3.1 (0.6) | 2 (0) | 8 |
| Guayaquil | ECESP01 | 21,8 | -1.5 (0.9) | 1.4 (0.5) | 4.1 (0.7) | 1.9 (0.5) | 14 |
| | ECESP02 | 24,5 | -0.8 (0.5) | 1.2 (0.4) | 3.5 (0.6) | 1.7 (0.5) | 39 |
| | ECESP03 | 26,3 | 0 (0.8) | 1.5 (0.8) | 2.9 (0.9) | 2.0 (0.4) | 22 |
| | ECESP04 | 21,6 | -1.8 (0.9) | 2.1 (0.5) | 4.7 (0.8) | 2.5 (0.7) | 32 |
| | ECESP05 | 24,0 | -1.0 (0.8 | 1.6 (0.5) | 3.6 (1.0) | 1.9 (0.3) | 25 |
| | ECESP06 | 21,6 | -1.8 (2.2) | 1.9 (0.9) | 4.6 (0.7) | 2.1 (0.5) | 31 |
| | ECESP07 | 24,3 | -0.4 (0.7) | 1.3 (0.4) | 2.9 (0.7) | 2.0 (0.4) | 21 |
| Tena | ECIKI01 | 22,6 | -1.5 (0.9) | 2.0 (0.7) | 4.4 (1.0) | 2.3 (0.6) | 19 |
| | ECIKI02 | 24,0 | -1.6 (0.6) | 1.5 (0.5) | 4.3 (1.2) | 2.2 (0.6) | 18 |
| | ECIKI03 | 24,8 | -0.2 (0.6) | 1.5 (0.5) | 3.8 (1.0) | 1.9 (0.4) | 22 |
| | ECIKI04 | 27,8 | 0.3 (1.1) | 1.6 (0.6) | 3.8 (1.1) | 2.0 (0.3) | 14 |
| | ECIKI05 | 23,8, | -1.6 (0.8) | 1.9 (0.8) | 4.6 (0.8) | 2.0 (0.6) | 12 |

$t_{op}$: operative temperature; TSV: thermal sensation vote; TCV: thermal comfort vote; TPV: thermal preference vote; TAV: thermal acceptance vote; (S.D.): standard deviation; N: sample size.

### 3.4.2 Comparison with standards

From the guidelines of F. Nicol in the analysis result of a field study [17], a linear regression of thermal sensation votes and the indoor operative temperature is made to determinate the temperature which has a neutral vote as well the range of temperature where the votes are within -0,5 <TSV< 0,5. The PMV was calculated from ASHRAE 55 for each classroom in air conditioner mode based on the physical measured and personal variables. Then for the free-running spaces, the adaptive model from EN 15251 and ASHRAE 55 were used.

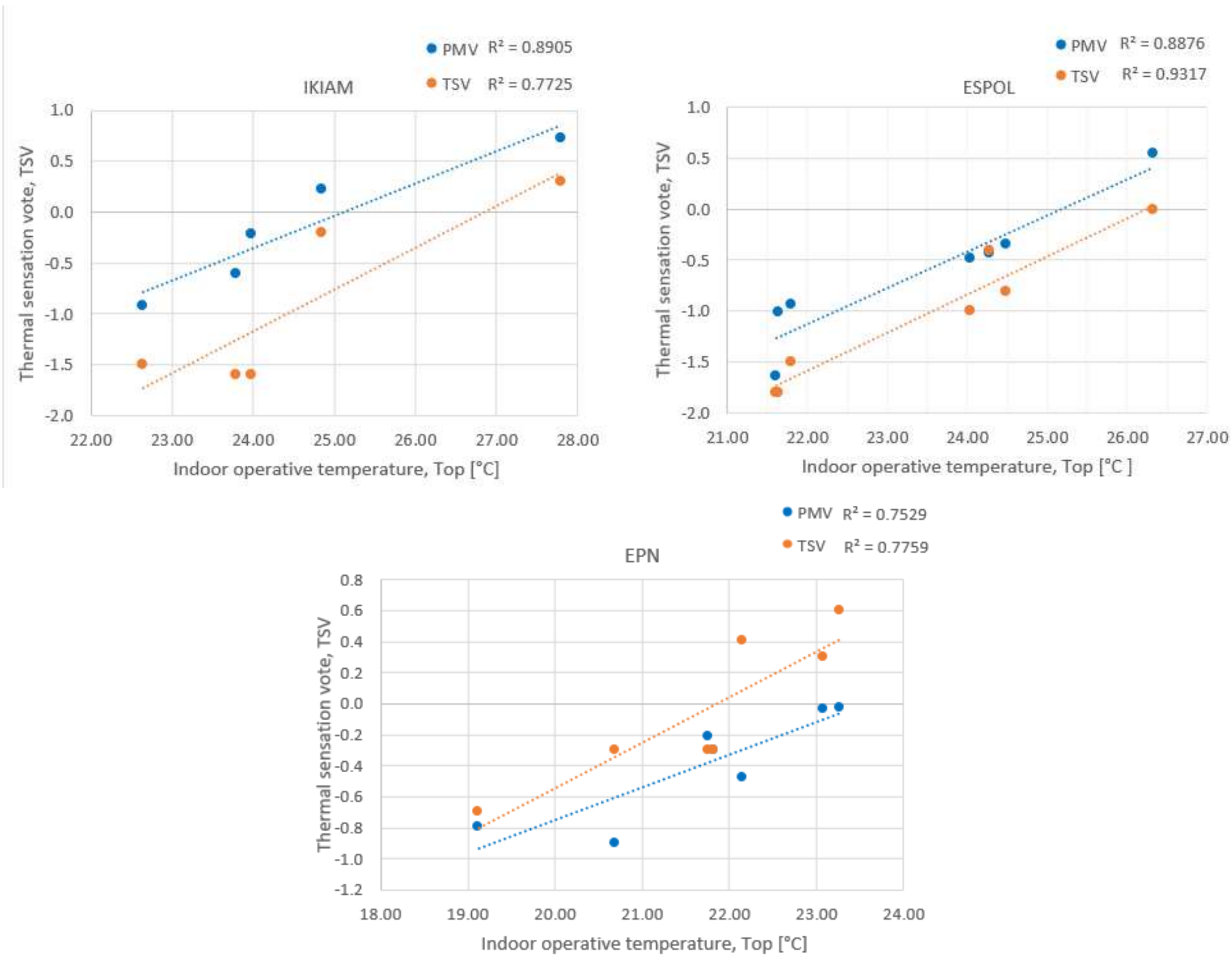


**Figure 2. Linear regression, TSV and PMV (vs.) operative temperature**

**Table 7. Summary of regression equation in air conditioner mode**

| University | City | Equation | *R* |
|---|---|---|---|
| ESPOL | Guayaquil | $TSV = 0,3718T_{op} - 9.7616$ | 0,96 |
| | | $PMV = 0,3536T_{op} - 8.8999$ | 0,94 |
| IKIAM | Tena | $TSV = 0,4082T_{op} - 10,963$ | 0,87 |
| | | $PMV = 0,3173T_{op} - 7.9654$ | 0,94 |
| EPN | Quito | $TSV = 0.2933T_{op} - 6.4074$ | 0,88 |
| | | $PMV = 0,2109T_{op} - 4.9702$ | 0,86 |

PMV: Predicted mean vote; TSV: Thermal sensation vote; $t_{op}$: operative temperature; R: Correlation coefficient

At ESPOL classroom, the neutral operative temperature (when the mean vote is zero) is calculated from both regression equations in table 7 resulting in 25.0°C for PMV and 26.3°C for TSV. For Operative temperature neutrality, PMV underestimates the observed neutrality by 1,3K. The 90% and 80% of thermal acceptance is between -0.5 to 0.5 and -1 to 1 respectively on the ASHRAE seven-point scale; using both regression equation, the thermal acceptability range manifested in the survey (TSV) is between 24.9°C-27.6°C and 23.6°C-28.9°C for the 90% and 80%. For the predicted thermal acceptability range is 23.6°C-26.4°C and 22.2°C-27.8°C. It's to be expected that the predictive operative temperature range would be narrower compared to the actual mean votes due to the personal sensation of each person. Recalling the thermal comfort and preference scales and considering the long-time living in hot-dry climate, students indicate warmer preference when the indoor operative temperature is below 21.8°C, and a cooler preference above 24.0°C.

At IKIAM classrooms the neutral operative temperature calculated was 26.9°C for TSV and 25.1°C for PMV. In this case 1.8 K more than the predicted value; the thermal acceptability range manifested in the survey was between 25.6°C-28.1°C and 24.4°C-29.3°C for the 90% and 80% and for the predicted thermal acceptability, the range was 23.5°C-26.7°C and 22.0°C-28.3°C. As expected for a hot climate, the thermal sensation rage is wider than the predicted. A student in rainforest climate reaches a comfort state even in warmer conditions. The cooler preference is notable above 25°C, and warmer preference below 24°C. That said, the PMV neutral temperature would make more sense than TSV.

Already knowing that PMV is mostly used for air-conditioned spaces, the comparison was made even though. The neutral operative temperature calculated for EPN classroom was 21.8°C for TSV and 23.5°C for PMV. The highland students reach neutral sensation 1.7°K less than expected from the model. Thermal sensation range manifested in the survey was between 20.1°C-23.5°C and 18.4°C-25.2°C for 90% and 80%. For the predicted thermal acceptability range was 21.2°C-25.9°C and 18.8°C-28.3°C. Only for temperatures below 21°C the PMV and TSV match above that temperature. Subjects indicate more sensitivity to warm temperatures and PMV could not predict their sensation.

**Table 8. Summary of thermal comfort ranges from real and predicted votes**

| University | City | Operation Mode | Neutral temperature *, [°C] | | PMV | | TSV | |
|---|---|---|---|---|---|---|---|---|
| | | | PMV | TSV | (90%) | (80%) | (90%) | (80%) |
| ESPOL | Guayaquil | AC | 26.3 | 25.0 | 23.6°C-26.4°C | 22.2°C-27.8°C | 24.9°C-27.6°C | 23.6°C-28.9° |
| IKIAM | Tena | | 25.1 | 26.9 | 23,5°C -26-7°C | 22,0°C -28,3°C | 25.6°C-28.1°C | 24.4°C-29.3°C |
| EPN | Quito | FR | 23.5 | 21,8 | 21.2°C-25.9°C | 18.8°C-28.3°C | 20.1°C-23.5°C | 18.4°C-25.2°C |

Neutral temperature*: Calculated by linear regression, TSV and PMV vs operative temperature,

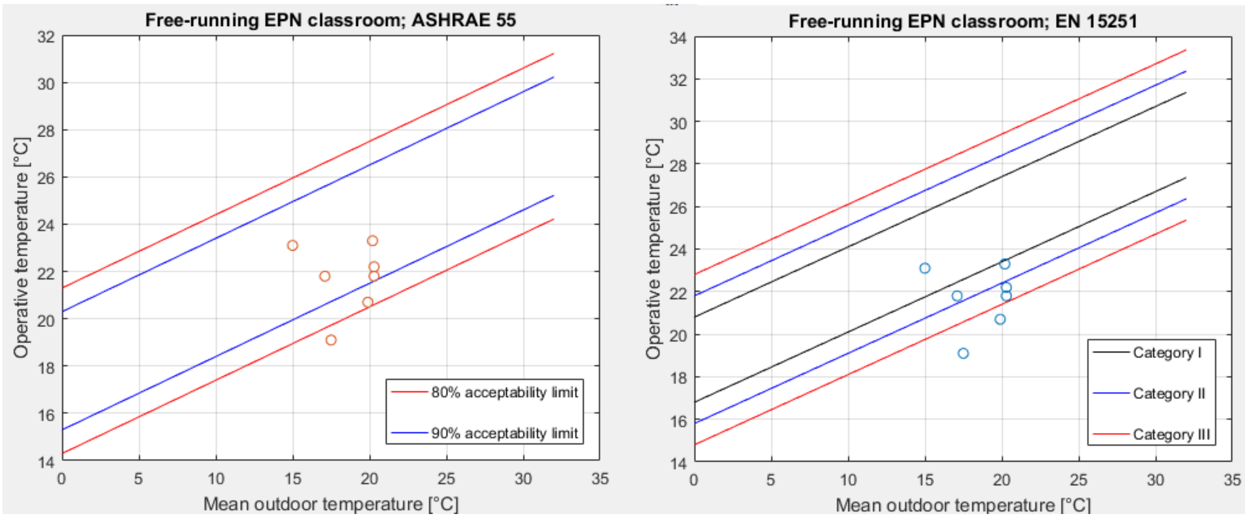


**Figure 3. Relative thermal sensation response at EPN**

In EPN classrooms (Quito), it's very common to close doors and windows to keep a warmer environment. According to the ASHRAE adaptive method, ECUEPN02 classroom is out of range. The students indicated a slightly cold sensation in the environment, that is the reason why they prefer a change to slightly warm (4.4). ECUEPN04 is a classroom that is within 80% acceptance since the classroom ambient temperature is only 0.8K below average (21.4°C). Five classrooms are in the 90% acceptance range in which match with student acceptance and indicate that they would not make changes or prefer a slightly warm environment. The temperature at which more acceptance is shown was between 21.8°C and 22.5°C.

### 3.5 Comfort Temperature by Griffiths Method

This method is useful for small samples and when the temperature comfort range from linear regression is small [7]. Griffiths assumed that the increase in temperature for each scale point on the comfort scale was effectively 3K for a seven-point scale [17]. The equation used to calculate comfort temperature in the classroom was:

$$T_{conf} = T + (0 - TSV)/a$$

where $T_{conf}$ is the comfort temperature (°C), T is the indoor air temperature (°C) or globe temperature (°C) and a is the regression coefficient. The method was used in many works [8] [9] [20] [27] with three different regression coefficients (0.25, 0.33, 0,50) indicating that 0.50 had a better result. Nicol and Humphreys [18] found that the actual value of the constant must be more than 0.40.

**Table 9. Summary of mean comfort temperature by different regression coefficient**

| Mode | University | Region | Regression coefficient | N | Mean Comfort temperature [°C] | S.D. |
|---|---|---|---|---|---|---|
| FR | EPN | Quito | 0.25 | 147 | 21.87 | 0.93 |
| | | | 0.33 | 147 | 21.83 | 0.70 |
| | | | 0.50 | 147 | 21.79 | 0.74 |
| AC | ESPOL | Guayaquil | 0.25 | 184 | 27.05 | 2.31 |
| | | | 0.33 | 184 | 26.18 | 1.4 |
| | | | 0.50 | 184 | 25.25 | 0.63 |
| AC | IKIAM | Tena | 0.25 | 85 | 28.29 | 2.12 |
| | | | 0.33 | 85 | 27.39 | 1.39 |
| | | | 0.55 | 85 | 26.45 | 0.93 |

FR: free running; AC: air conditioner; N: sample size S.D.: standard deviation

The calculated comfort temperature using 0.5 as the regression coefficient is very similar to the neutral temperatures calculated from the linear regression with the students' thermal sensation votes. In ESPOL and IKIAM classrooms, there is a temperature difference of 1.1K and 0.4K respectively but using 0.33 as the regression coefficient in Guayaquil the temperature difference is lower (0.1K). At EPN classrooms the comfort temperature was already very close with the lowest regression coefficients (a = 0.22; 0.33).

**Table 10. Summary of mean comfort temperature in different field study**

| Area | Climate classification | Reference | Comfort temperature [°C] | Mode |
|---|---|---|---|---|
| Quito (Ecuador) | Cfb | This study | 21.8 | FR |
| Bogota (Colombia) | Cfb | Natarajan S. et al (2015) | 23.0; 22.6 | NV; AC |
| Hong Kong | Cfa | Fang et al (2018) | 24.1 | AC |
| Guayaquil (Ecuador) | Aw | This study | 25.3 | AC |
| Jos (Nigeria) | Aw | Ogbonna, A. C., & Harris, D. J. (2008) [19] | 26.3 | NV |
| Central area (Taiwan) | Am | Cheng et al (2008) | 25.4; 25.7 | NV; AC |

| | | | | |
|---|---|---|---|---|
| Tena (Ecuador) | Af | This study | 26.5 | AC |
| Kuala Lumpur (Malaysia) | Af | Zaki S.A. et al. (2017) | 26,8; 25.6 | FR; AC |
| (Singapore) | Af | Wong N.H. and Khoo S. S (2003) [25] | 28.3 | NV |

FR: free running; AC: air conditioner; NV: natural ventilation; fa: Humid subtropical climates; Cfb: Subtropical highland climate; Aw: Tropical savanna climate; Af: Tropical rainforest climate; Am: Tropical monsoon climate

When comparing each city analyzed in this study with others that maintain the same type of climate, the following was obtained: in Quito (Cfb) subjects achieve a neutral thermal sensation at a slightly lower temperature than Bogotá (Cfb) [16] taking into account that the operating conditions are different. In Guayaquil (Aw), the neutral temperature is very similar to the classrooms and dormitories of Taiwan central area (Am) [3], and its 1K lower than Jos (Aw) [19] which operated at natural ventilation. In Tena (Aw) it has a higher comfort temperature (26.5°C) than in Kuala Lumpur although they have similar climate and are under mechanical ventilation, in Singapore (Af) the neutral temperature is approximately 2K higher than the previous ones, clearly, in Singapore they have more tolerance to these temperatures (28.3°C).

## 4 Conclusion

The results indicate that the PMV is not able to predict the thermal sensation of students in classrooms with mechanical ventilation in Guayaquil and Tena. The temperature ranges with 80% and 90% acceptance are very similar, but with differences from 0.5k to 1.1k. The PMV in these warm climates estimates a lower percentage of satisfaction compared with declared by the students. In free-running classrooms, the standard EN 15251 adaptive model restricts the conditions of the classrooms to a greater extent than ASHRAE 55, in both methods they coincide in accepting environments in which acceptance is positive and slight thermal preference changes.

The neutral temperatures from TSV in Quito, Guayaquil, and Tena were 21.8°C, 26.3°C and 26.9°C respectively. Compared to others of the same type of climate, they are not so different even though the classrooms operate in different modes. The type of clothing, the long-time under the climatic conditions of the environment and the expectation vary in each place developing an adaptation with the local environment.

It was found by comments in the surveys that students prefer a cold environment than a warm environment regardless of the local region in which the students responded. Of course, the neutral temperature range is different. In the case of cold weather, students have easy actions to maintain a neutral sensation such as increasing their clothes, closing doors and windows and then opening them when air needs to be renewed. In the classrooms of hot climates, the way to stay in a neutral state is through an air-conditioned environment, but by not having control of the air temperature when it is very low, students lose their comfort quickly.

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# The effects of occupants' expectations on thermal comfort under summer conditions

**Romina Rissetto, Marcel Schweiker and Andreas Wagner**

Karlsruhe Institute of Technology, Germany, romina.rissetto@kit.edu

**Abstract:** Climate change has led to higher indoor temperatures and more discomfort hours. This fact has encouraged an extensive assessment of users' thermal comfort in office buildings. However, there is a gap between predicted-actual comfort votes and comfort-related behaviors. One reason could be differences in comfort expectations. This study investigates the impact of users' expectations of indoor climate and behavioural adaptations on their thermal satisfaction in a working environment. We conducted a pilot study in a laboratory setting, where participants experienced moderately high indoor temperatures in two different appointments. A control group received information about an innovative ceiling fan, which after an acclimatization phase all participants could control. Participants' thermal comfort and expectation responses were recorded. Results showed that comfort expectations in the first week were significantly different from those in the second week. Moreover, no significant differences were found in expectations of perceived air quality and between groups with different information provided. Results suggest that a first experience in a certain setting would set occupants' expectations of indoor conditions for a second experience in the same environment. Besides, the implementation of an unknown personalized adaptive strategy fulfilled participants' expectations of indoor conditions.

**Keywords:** comfort expectations, thermal comfort, perceived indoor air quality, adaptive behaviours

## 1. Introduction

In order to reduce the total energy consumption in both commercial and residential buildings, research on the interaction between occupants and building systems has shown high potential to achieve energy improvements. However, a non-occupant-centric design of building systems, could lead to a rebound effect on occupant behavior (Guerra Santin 2013).

In the past two decades, there has been a growing number of studies trying to explain occupant interactions with building systems through the lens of psychological theories (Wilson and Dowlatabadi 2007). Using interdisciplinary research approaches could provide insides into the drivers and decision-making of energy-saving behaviors in buildings without affecting occupant comfort. In other words, energy reduction strategies and comfort standards should consider factors such as occupants' preferences and expectations, personal and social norms, needs and beliefs.

According to Chappells and Shove (2005) there is a trade-off between occupants' thermal comfort, energy efficiency and building management requirements in office buildings. Although the discomfort experienced by the occupants will ultimately impact on their willingness to perform energy-efficient behaviors, there is a performance gap between assumed and actual comfort-related behaviors (Brown and Cole 2009). Auliciems (1981) defines satisfaction with an indoor climate as the result from matching actual thermal conditions in a given context and one's thermal expectations of what the indoor climate should be like in that same context. Therefore, understanding the interaction between thermal expectations and adaptive behaviors seems a possible path to enhance comfort and predict comfort-related behaviors.

In this paper we propose an analysis of occupants' expectations of the indoor climate and its implications on their thermal comfort and behaviors. We focus on the study of influential factors on thermal and behavioral expectations within buildings.

## 2. State-of-the-art and background

In the built environment, several conceptual models have emerged to understand occupant behaviour and comfort by integrating them within psychological frameworks. For instance, D'Oca *et al.* (2017) integrated the MOA model with the DNAs conceptual framework to understand drivers motivating occupants to interact with building control systems. From another perspective, Schweiker and Shukuya (2009) combine findings from the field of neural science and present a sensor-control-action cycle as theoretical basis of occupant-behaviors. However, the inclusion of occupants' expectations in the prediction of thermal comfort and occupant behaviours has not been extensively assessed.

The work of Auliciems (1981) focuses on a "psycho-physiological model", in which thermal expectations of a certain indoor environment affect occupants' thermal satisfaction. According to the model, past thermal experiences and adaptive opportunities of a building are the main factors that shape occupants' expectations. From another perspective, Fanger and Toftum (2002) include occupants' expectations in the assessment of thermal comfort as a factor of dependence on air conditioning systems, based on the thermal sensation votes for specific warm climatic conditions of natural ventilated buildings.

Although the importance of assessing expectations in the built environment has been pointed by several authors (Fountain *et al.* 1996; Brown and Cole 2009; Luo *et al.* 2018), thermal expectations have been directly measured only by Rajkovich and Kwok (2003), and recently by Schweiker *et al.* (2020). The latter found out that there is a significant influence of the level of expectation on thermal comfort, and that indoor temperature, day of experiment and location (field vs laboratory) showed significant influences on thermal expectations.

According to Wigfield and Eccles (2000), individuals' behaviours can be explained by their beliefs about how well they will do on the activity (expectancies) and the extent to which they value it (evaluation). In other words, a person's attitude towards a behaviour and the valence of the attitude, will guide to a certain behaviour. This cognitive process approach is described in the Theory of Planned Behaviour (Ajzen 1991), which incorporates attitudes as a predictor of behaviours, and are consistently found to have greater predictive validity when they are directed towards a specific behaviour – in comparison to general attitudes (Ajzen and Fishbein 2005).

Moreover, it has been suggested that the magnitude of the attitude–behaviour relation may be moderated not by attitude accessibility but by other correlated factors such as amount of knowledge (Ajzen and Fishbein 2005). From the point of view of consumer satisfaction, Anderson (1973) suggests that a more favourable evaluation is obtained when a product is accurately described than when no information is provided. In this respect, Naddeo *et al.* (2015) analysed the positive effect of knowledge and biased information on higher perceived comfort. Similarly, Brown and Cole (2009) analyse the influence of knowledge of building performance on comfort expectations and behaviours.

However, when a new technology is implemented, there is often a gap between what is known and what actually is put in use. To evaluate the acceptance and adoption of a new idea, theories attempt to explain factors affecting whether individuals will adopt an innovation or technology. The diffusion of innovations (Rogers 1983) describes the innovation-decision process as the process in which an individual passes from first knowledge of a technology to form an attitude towards it, then adopt and implement it, and finally confirm the decision. Those innovations have five main attributes that affect individuals' behaviours and explain the rate of innovation adoption: relative advantage, compatibility, complexity, trialability and observability.

## 3. Research framework and hypothesis

The review of the state of the art and theories has shown that the interaction between people's expectations and their perception of comfort and behavioural performance has not been studied in depth in the built environment. In addition, influencing factors of expectations and the way to assess them need further study. Therefore, a study framework of expectations is proposed (Figure 1) from which the following research questions arise:

1. To what extent do comfort expectations (thermal conditions and air quality) affect occupants' comfort evaluation and consequently their perceived comfort?
2. Which factors influence people's indoor climate expectations?
3. To what extent do behavioural expectations affect occupants' performance evaluation and their consequently behaviour?
4. Which factors influence people's behavioural expectations?
5. To what extent do behavioural/performance expectations affect the perceived comfort?

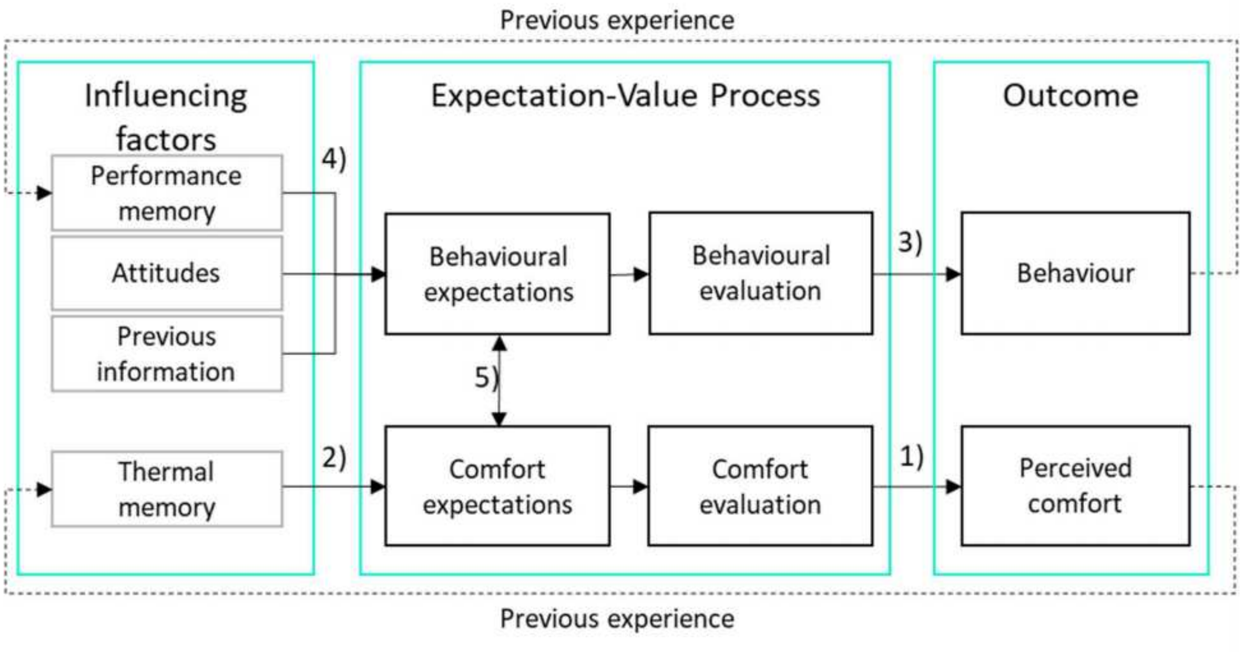


Figure 1: Psychological framework of expectations, comfort and behaviour.

Based on the existing literature and the proposed research framework and questions, the following hypothesis are investigated:

1.
   1.1. Perceived comfort: thermal comfort and perceived air quality will be lower when conditions were not as expected (Schweiker *et al.* 2020).
2.
   2.1. Thermal memory: first experiences in a certain environment will set expectations in a later experience in the same environment (Auliciems 1981).

3.
   3.1. Behaviour: behavioural adaptation will be lower when performance evaluation has a low value and expectations are not met (Wigfield and Eccles 2000).

4.
   4.1. Performance memory: first experiences with a certain behaviour will set expectations in a later performance (Auliciems 1981).
   4.2. Attitudes: positive attitudes towards behavioural performance will positively influence performance evaluation (Ajzen and Fishbein 2005).
   4.3. Previous information: knowledge and previous information will set positive performance expectations and consequently perceived comfort (Naddeo et al. 2015).

5.
   5.1. Behaviour-comfort expectations: negative expectations on the effect of adaptive opportunities on indoor climate conditions (temperature/air quality) will lower comfort expectations and consequently perceived comfort.

In order to avoid misleading interpretations of consumers' satisfaction and evaluation of a certain product (Kokthi and Kelemen-Erdos 2017), we need a common definition of expectations. The following definitions will be used in this paper:

- Predicted expectation: the realistic and anticipated thermal or behavioral experience, i.e. what the user believe will happen, in accordance to the definition from Thompson and Sunol (1995).
- Level of expectancy: congruence between the predicted thermal or behavioral experience, and the actual perceived experience (e.g. "is the temperature as expected?"), in accordance to Schweiker *et al.* (2020).
- Compared expectations: the actual vote of the thermal or behavioral experience in comparison to predicted expectation (e.g. "warmer than expected"). For the thermal assessment, both thermal comfort and sensation will be assessed.

## 4. Methodology: pilot study

In order to first assess the above research questions, a pilot study was conducted as explain below.

### 4.1 Facility and test conditions

The experiment was conducted between August and September 2018 in the climate chamber LOBSTER (Schweiker *et al.* 2014). Two office rooms and an entrance-/control room constitute the facility (Figure 2). Each room has two openable windows and is equipped with an innovative personalized ceiling fan, which has a diameter of 300 mm and is integrated in an acoustical ceiling panel (Figure 3).

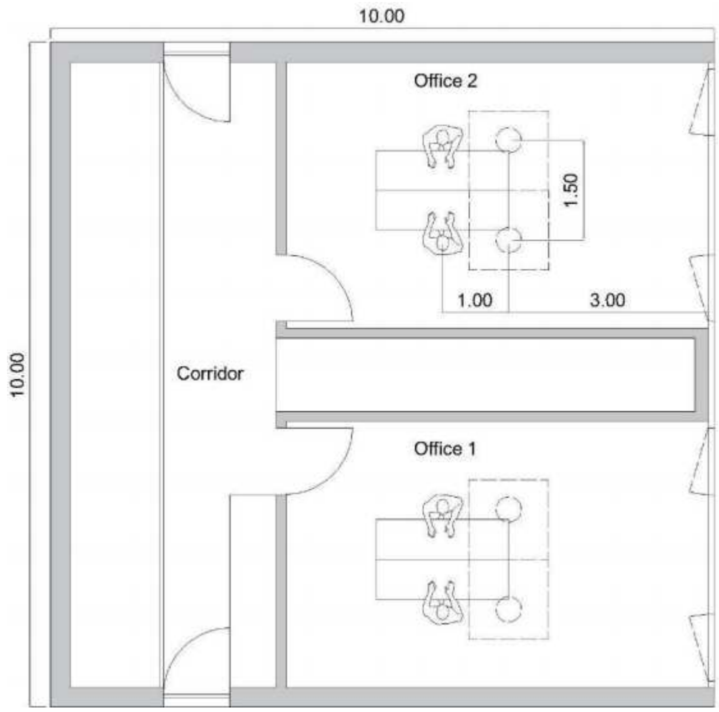


Figure 2: Floor plan and position of participants, ceiling fan and windows

Figure 3: Office room 2

Table 1 presents the room conditions and the correspondent control and experimental groups. Each subject participated twice. The room was set to warm conditions. The first appointment (M1) was set to 28°C / 50% RH, and in the second appointment (M2), only one room was set to 31°C / 50% RH. In the first appointment, half the participants were provided biased information about the personalized ceiling fan, such as benefits (energy efficient, quiet) and characteristics (personal, controllable).

Table 1: Thermal conditions and information groups for first (M1) and second (M2) appointments. Informed group (green); non-informed group (light green); 28°C (purple); 31°C (grey).

| M1 | Day 1 | | Day 2 | | Day 3 | | Day 4 | | Day 5 | | Day 6 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Office | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 |
| Participant | 1, 2 | 3, 4 | 5, 6 | 7, 8 | 9, 10 | 11, 12 | | 13, 14 | | 15, 16 | 17, 18 | |
| M2 | Day 7 | | Day 8 | | Day 9 | | Day 10 | | Day 11 | | Day 12 | |
| Office | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 |
| Participant | 1, 2 | 3, 4 | 5, 6 | 7, 8 | 9, 10 | 11, 12 | | 13, 14 | | 15, 16 | 17 | |

### 4.2 Participants

Eighteen male and female participants between 18-34 years old took part in a half-day experiment for the first test condition, from whom 17 repeated the experiment in the second appointment. Participants had to be German or show proficiency level of the German language, and be non-smokers.

### 4.3 Experimental procedure

The whole experiment lasted 3 hours 30 minutes, from 9 am to 12.30 am.

Figure 4 describes the daily schedule. In the first 10 minutes (T0) we explained the experiment in the front room and we provide a first questionnaire in paper format. Participants were asked about their a) thermal preference and b) their thermal expectations in the experiment room.

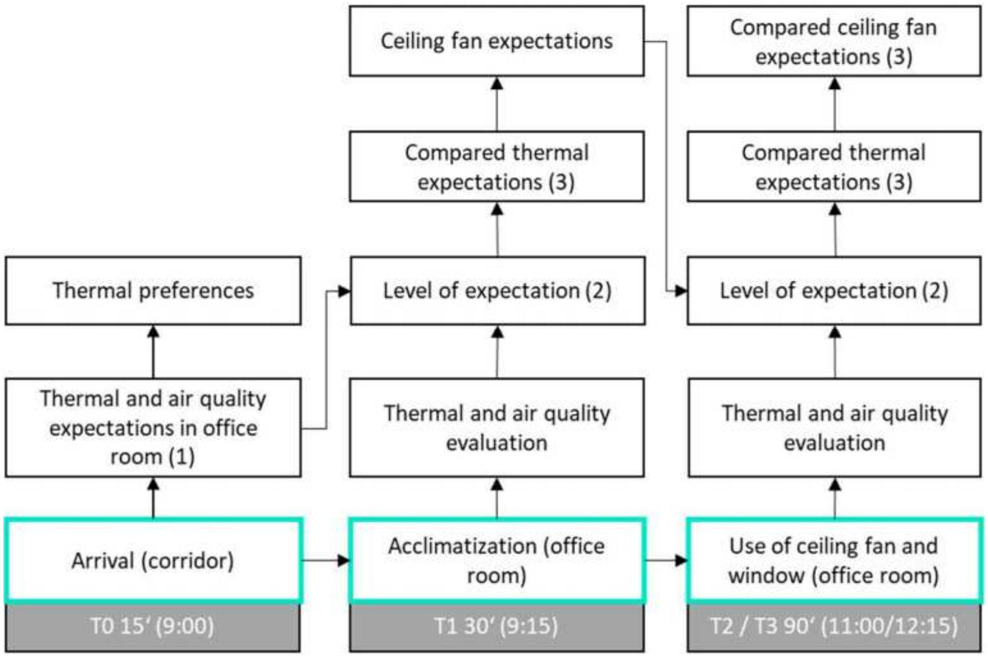


Figure 4: Daily schedule and correspondent questions. In grey: phase duration and start time questionnaire. T0: before entering the experiment room; T1: acclimatization phase; T2: first hour with the possibility of using the ceiling fan/windows; T3: end of experiment.

After entering the room, participants could work on their own tasks with the computers provided. During the first 30 minutes (T1), they adapted to the given warm conditions in the room and filled out the second questionnaire. Participants were asked about a) their actual thermal comfort, sensation, acceptability and preference, and air quality sensation and comfort, b) if the encountered thermal/air quality conditions were as expected, c) their thermal/air quality expectations in comparison to the actual vote, and d) their expectations about general ceiling fans and the personalized ceiling fan from the experiment.

After the acclimatization phase, they had the possibility to turn on the ceiling fan and choose the desired air speed by means of a control dial, and tilt the windows. After 90 minutes (T2) a new questionnaire with the same questions as T1 was provided. The last questionnaire was filled 15 minutes before ending the experiment (T3).

Ceiling fan's expectations were quantified with several items based on Rogers' main attributes of innovations in a 7-point scale ("strongly agree" to "strongly disagree"). Moreover, 5 categories were assessed: expectations of ceiling fans in general, expectations of personalized ceiling fans, compared expectations of personal ceiling fans (only in M2), importance of using ceiling fans and attitudes towards the use of ceiling fans. Thermal and air quality expectations were quantified as follow:

1. Predictive Sensation/Comfort 7-point scale (only in T0): "How do you expect the thermal conditions/air quality in the room?" ["warm/good" to "cold/bad" and "uncomfortable" to "comfortable"].
2. Skip logic question: "Are the encountered thermal conditions/air quality as expected?" ["Yes/No"];
3. Sensation 7-point scale: "If not as expected, how were the thermal conditions/air quality in comparison to the expected?" ["much warmer/much better as expected" to "much cooler/worse as expected"];
4. Comfort 7-point scale: "If not as expected, how do you find the thermal conditions/air quality in comparison to the expected?" ["much more uncomfortable as expected" to "much more comfortable as expected"].

## 5. Results and Discussion

### 5.1. Outdoor temperature

Figure 5 shows the outdoor temperatures from 8 am to 9 am and the running mean outdoor temperature (Trm) for the first (Day 2 to Day 6, Day 9) and second appointment (Day 11 to Day 13, Day 16 to 18). In both weeks, outdoor temperatures fluctuated from 15°C to 23°C from 8 am to 9 am. The Trm did not significantly vary along the experimental days in each appointment, but a decrease can be observed comparing the first and the last days of experiment.

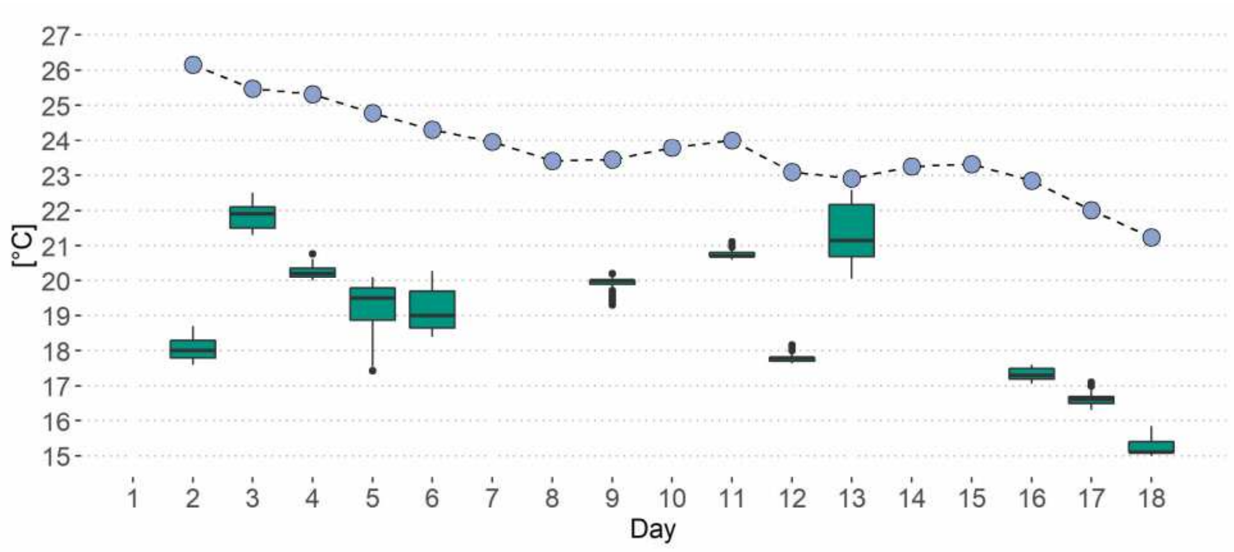


Figure 5: Boxplot of outdoor temperatures for each day of experiment between 8-9:00 am and running mean outdoor temperatures in M1 and M2.

### 5.2. Thermal comfort and perceived air quality

#### 5.2.1. Temperature sessions

Figure 6 presents the distribution of thermal sensation votes in the acclimatization phase (T1) separately for session groups (paired). The group experiencing 28°C in both appointments voted in average "slightly warm" and "warm" with no significant difference (Figure 6 left).

A significant difference in thermal sensation votes was found for the group experiencing 28°C in the first appointment and 31°C in the second appointment (Figure 6 right). They rated thermal conditions as "slightly warm" and "warm" respectively (M1: Mdn = 5; M2: Mdn = 6; $p = .039$; $N = 10$). A significant difference was also found for thermal acceptability and preference votes: the first experience was rated as "slightly acceptable" while the second as "slightly unacceptable" (M1: Mdn = 3; M2: Mdn = 2; $p = .016$; $N = 10$). They would prefer thermal conditions "slightly cooler" and "cooler", for the first and second appointments respectively (M1: Mdn = 3; M2: Mdn = 2; $p = .008$; $N = 10$).

Air quality was perceived as "slightly bad" and "slightly uncomfortable" in the acclimatization phase (T1) in both sessions and no significant difference in perceived sensation between temperature conditions was found.

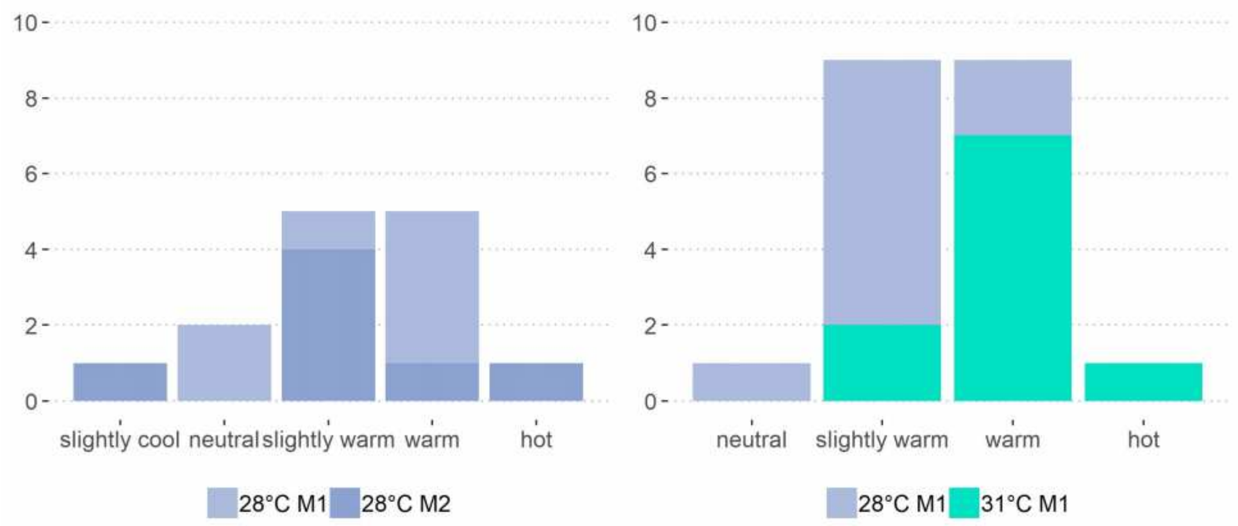


Figure 6: Thermal sensation votes for different session groups in T1. Group experiencing 28°C-28°C for the first and second meeting respectively (left) and group experiencing 28°C-31°C respectively (right).

### 5.2.2. Timing

Figure 7 presents the distribution of thermal sensation votes for the acclimatization phase (T1), the first hour after the acclimatization phase (T2) and after two hours (T3), separately for the first session and the second session at both temperature conditions (28°C and 31°C). While T1 was mostly rated as "slightly warm" and "warm" (31°C), both T2 and T3 were rated as "neutral".

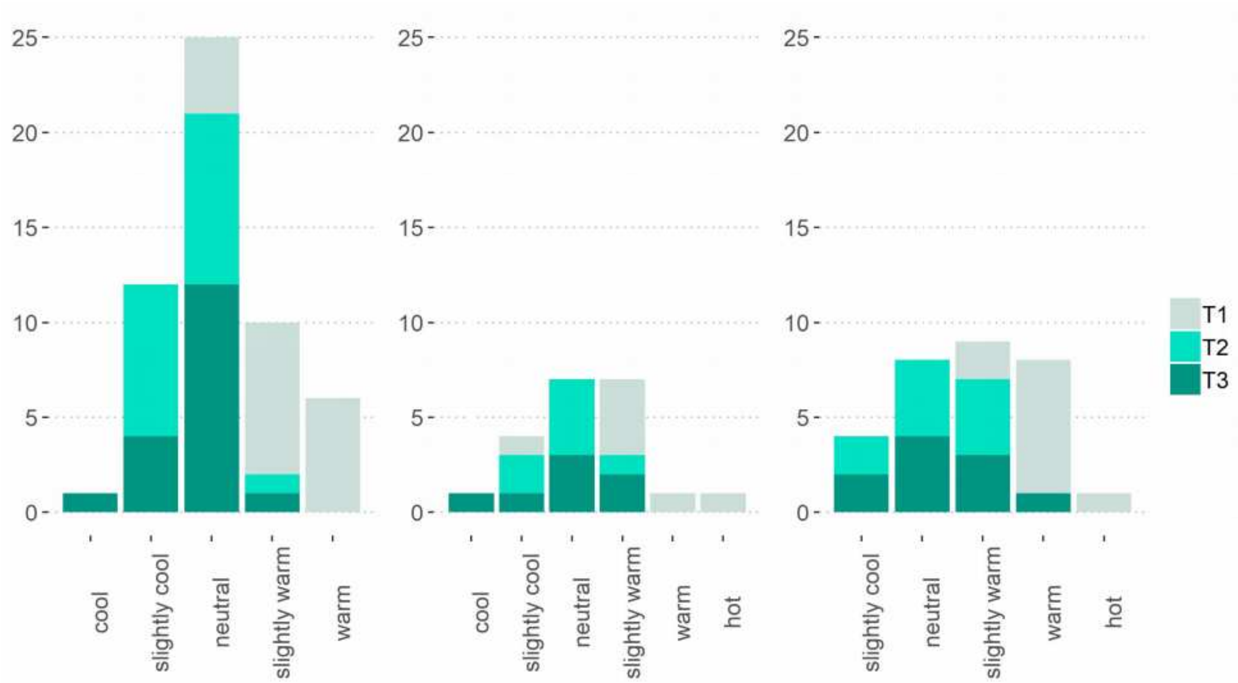


Figure 7: Thermal sensation votes for different times (T1,T2,T3) for the first session (left) and the second session for the 28°C group (middle) and the group with 31°C (right).

Table 2 compares thermal sensation, comfort, acceptability and preference votes in timing for both appointments (M1 and M2). In both sessions, a significant difference for sensation, comfort and acceptability was found between T1 and T2 and T1 and T3, but no difference was found between T2 and T3. In both sessions, a significant difference for thermal preference was found between T0 (Mdn="no change") and T1 (Mdn-28°C= "slightly cooler"; Mdn-31°C="cooler"), T1 and T2 (Mdn= "no change") and T1 and T3 (Mdn= "no change").

Table 2. Friedman test for thermal sensation, comfort, acceptability and preference of perceived thermal conditions. Paired groups correspond to four points in time (T0, T1, T2, T3) in M1 and M2. Significant values (p-values), effect size (r-values) and non-significant results (NS).

| | M1 | | | | M2 | | | |
|---|---|---|---|---|---|---|---|---|
| | T0 –T1 | T1 - T2 | T1 - T3 | T2 - T3 | T0 - T1 | T1 - T2 | T1 - T3 | T2 - T3 |
| Sensation | - | $p_{adj.}$= .000 r = .31 | $p_{adj.}$ = .001 r = .28 | NS | - | $p_{adj.}$ = .001 r = .31 | $p_{adj.}$ = .003 r = .27 | NS |
| Comfort | - | $p_{adj.}$= .018 r = .22 | $p_{adj.}$ = .003 r = .26 | NS | - | $p_{adj.}$ = .000 r = .31 | $p_{adj.}$ = .002 r = .29 | NS |
| Acceptability | - | $p_{adj.}$ = .008 r = .24 | $p_{adj.}$ = .003 r = .26 | NS | - | $p_{adj.}$ = .001 r = .31 | $p_{adj.}$ = .008 r = .25 | NS |
| Preference | $p_{adj.}$ = .000 r = .34 | $p_{adj.}$ = .022 r = .29 | $p_{adj.}$ = .033 r = .28 | NS | $p_{adj.}$ = 001 r = .40 | $p_{adj.}$ = .000 r = .44 | $p_{adj.}$ = 005 r = .36 | NS |

Table 3 presents differences in the perceived air quality sensation and comfort for different points in time for both sessions (M1, M2). Most significant differences were found in the perceived sensation and comfort between T1 (“slightly bad”; “slightly uncomfortable”) and T2 (“slightly good”; “comfortable”) and between T1 and T3 (“good”; “comfortable”).

Table 3. Friedman test for sensation and comfort of perceived air quality. Paired groups correspond to three timings (T1, T2, T3) in M1 and M2. Significant values (p-values), effect size (r-values) and non-significant results (NS).

| | M1 | | | M2 | | |
|---|---|---|---|---|---|---|
| | T1 - T2 | T1 - T3 | T2 - T3 | T1 - T2 | T1 - T3 | T2 - T3 |
| Sensation | **$p_{adj.}$= .006 r = .24** | **$p_{adj.}$ = .011 r = .23** | NS | **$p_{adj.}$ = .024 r = .22** | **$p_{adj.}$ = .001 r = .29** | NS |
| Comfort | **$p_{adj.}$= .037 r = .20** | **$p_{adj.}$ = .037 r = .20** | NS | NS | **$p_{adj.}$ = .001 r = .30** | NS |

### 5.2.3. Previous information

Thermal comfort and perceived air quality was analysed between ‘information’ groups in the first appointment. Although, they rated thermal comfort in the acclimatization phase differently (Mdn= “slightly warm” and “warm”), no significant difference in thermal perception (comfort, sensation, acceptability and preference) and in perception of indoor air quality (comfort and sensation) between groups was found both in the acclimatization phase and along the experiment.

### 5.3. Expectations of indoor climate

Table 4 presents the median votes for expected thermal comfort and sensation before entering the experimental room (predictive expectation), the level of expectancy after entering the room, the actual vote compared to expectations (compared expectation) and the actual vote in the acclimatization phase.

Table 4: Median votes for predictive expectation, level of expectancy, compared expectations and thermal comfort and sensation votes in T0 and T1 for M1 and M2.

| | M1 | | | | M2 | | | |
|---|---|---|---|---|---|---|---|---|
| | T0 | T1 | | | T0 | T1 | | |
| | Predictive | Level | Compared | Vote | Predictive | Level | Compared | Vote |
| | **28** | | | | **31** | | | |
| Sensation | slightly cool | no | slightly warmer | slightly warm | warm | no | warmer | warm |
| Comfort | neutral | | slightly more uncomfort. | slightly uncom fort | slightly comfort. | | slightly more uncomfort . | uncomfort. |
| | **28** | | | | **28** | | | |
| Sensation | slightly cool | no | warmer | warm | warm | yes | as expected | slightly warm |
| Comfort | slightly comfort. | | slightly more uncomfort. | slightly uncom fort. | slightly uncomfort. | | as expected | slightly uncomfort. |

Table 5 presents the median votes for level of expectancy, compared expectation for air quality comfort and sensation and the actual comfort and sensation vote in T1, and level of expectancy for T2 and T3. No significant difference was found in the level of expectancy in the acclimatization phase between temperature groups in the second appointment.

Contrary to previous studies (Zhai *et al.* 2017), sensation and comfort votes for perceived air quality in the acclimatization phase did not significantly differ between temperature setting. Moreover, the level of expectancy did not differ between 28°C and 31°C room settings in the second appointment. These results could suggest that 1) expectations do not have an impact on the perception of air quality at moderately high indoor temperatures, or 2) that expected conditions were within the acceptability range of participants. Further analysis is needed to confirm the proposed observation.

Table 5: Median votes for level of expectancy, compared expectations and comfort and sensation votes for air quality in T1, T2 and T3 for M1 and M2.

| | M1 | | | | | M2 | | |
|---|---|---|---|---|---|---|---|---|
| | T1 | | | T2 | T3 | T1 | T2 | T3 |
| | Level | Compared | Vote | Level | Level | Level | Level | Level |
| | **28** | | | | | **31** | | |
| Sensation | no | slightly worse | slightly bad | yes | yes | yes | yes | yes |
| Comfort | | slightly more uncomfortable | slightly uncomfortable | | | | | |
| | **28** | | | | | **28** | | |
| Sensation | no | slightly worse | slightly bad | yes | yes | yes | yes | yes |
| Comfort | | slightly more uncomfortable | slightly uncomfortable | | | | | |

### 5.3.1. Perceived comfort and sensation

In the first appointment, the encountered thermal conditions were not as expected (Mdn=”no”). The group expecting “slightly comfortable” conditions rated the encountered thermal conditions as “warmer as expected” and the actual vote was “warm”. However, the group expecting “neutral” conditions rated the same thermal conditions as “slightly warmer as expected” and the actual vote was “slightly warm”. With respect to hypothesis 1.1, an effect of expectations can be observed on thermal comfort votes in both groups from the first appointment: under same expected thermal sensation votes but different expected thermal comfort in the acclimatization phase, the group expecting more comfortable conditions had a higher disparity with the encountered conditions (not as expected), resulting in warmer thermal sensation votes. These results suggest the importance of assessing previous and compared expectations in a two-dimensional way, i.e. asking about the intensity of expectations (e.g. "warmer as expected") and affective aspect (e.g. "more comfortable as expected").

### 5.3.2. Thermal memory

In the first appointment, conditions were unknown and expected as "slightly cool" before entering the room (T0). However, in the second appointment conditions were expected to be "warm". A significant difference in the expectancy of sensation in T0 was found between the first session with 28°C, expecting "slightly cool" conditions, and the same group participating the second session with 31°C, expecting "warm" (Paired sample sign test, M1: Mdn = 3; M2: Mdn = 6; p = .039; N = 10). Similarly, a significant difference in the expectancy of comfort in T0 was found between the first session with 28°C, expecting "slightly comfortable" conditions, and the same group participating the second session with 28°C, expecting "slightly uncomfortable" (M1: Mdn = 5; M2: Mdn = 3; p = .016; N = 7).

With respect to hypothesis 2.1, an effect of thermal history on expectations can be observed after repeating the experiment. After experiencing an unknown environment for the first time, participants expected a "slightly cool" and "slightly comfortable" conditioned room. After knowing the environment, participants were expecting the same thermal conditions in the second appointment as the one they experienced in the first appointment ("warm"/"slightly uncomfortable"). These results could suggest that a first experience in a certain indoor environment would set expectations of indoor conditions for a second experience in the same environment, under similar thermal outdoor conditions between appointments. This statement is in line with the model from Auliciems (1981) which includes previous thermal experiences as influencing factors of expectations. Moreover, it is of importance to mention that the preferred indoor conditions in comparison to the outdoor conditions before entering the experimental room was rated as "neutral" for all sessions, meaning that outdoor temperature conditions before entering the climate chamber were within the acceptable thermal conditions, and no effect of outdoor conditions was expected for the sessions. These results support previous work (Schweiker *et al.* 2020) where the outdoor temperature or the outdoor-indoor temperature difference did not have an impact on thermal expectations. Future analyses could focus on the effect of a higher range of outdoor temperatures within thermal expectations.

In the second appointment, although both conditions were expected to be "warm", the session with 28°C expected "slightly uncomfortable" thermal conditions, while the session with 31°C expected "slightly comfortable" thermal conditions (Mann-Whitney-U-Tests, 28°C: N = 7; Mdn = 3; 31°C: N = 10; Mdn = 4.5; U = 17.000; p = .088; r = 0.44). An influence of thermal memory on performance expectations can be observed in group experiencing 31°C in the second appointment, who expected to feel "slightly comfortable" despite the expected warm conditions. These results may suggest that, as the effect of adaptive opportunities (window and ceiling fan) was sufficient to achieve comfortable conditions in a warm environment in the first appointment, participants set their expectations for the second appointment by adjusting the memory related to previous experiences or fulfilled expectations, and consequently minimizing thermal discomfort. These results support the analysis from Luo *et* *al.* (2016), suggesting the implementation of effective adaptive strategies to expand and enhance occupants' comfort range. A potential link between performance expectations and perceived comfort could be proposed according to hypothesis 5.1.

In the second appointment, a significant difference in the expected conditions in T1 was found between the sessions. Participants from the session with 28°C "expected" the encountered thermal conditions, while the session with 31°C did "not expect" them (Mann Whitney-U-Tests; 28°C: N=7, Mdn = 1; 31°C: N=10, Mdn = 0; U = 13.500; p = .033; r = 0.61). This result indicates the influence of significant changes in indoor temperatures on level of expectation of thermal conditions in an already known environment.

### 5.3.3. Timing

Figure 8 presents the distribution of the expected thermal conditions at three times of the half day. A pairwise comparison was conducted (N = 9; p = .017; $\chi^2$ = 10.15) and a significant difference in expected conditions was found in the first session between the acclimatization phase and the first hour of experiment after opening the window ($p_{adj.}$ = .24; r = .22), but no difference at the 5% level was found after using the ceiling fan or at the end of the experiment. Although, no significant difference at the 5% level was found in the second session between points in time, Cochran-Q-test found differences between all T1-pars (N = 11; p = .037; $\chi^2$ = 8.50). As before mentioned, thermal expectations in a warm environment were fulfilled as adaptive behaviors were implemented.


Figure 8: Level of expectancy votes for different times: T1, T2 after using the window, T2 after using the ceiling fan and T3 for M1 and M2.

## 5.4. Behavioural adaptation

The interactions of windows and ceiling fans was recorded by self-reported actions by participants. Figure 9 presents the number of participants who opened the window, used the ceiling fan and performed both actions during the experiment.

In the first appointment, half the participants use the ceiling fan and the other half both the ceiling fan and window. Just one person reported the opening of window as single action. In the second appointment, almost half the participants in the room with 28°C used the ceiling fan as single action while the other half performed both actions. Contrarily, by 31°C almost all participants performed both actions.

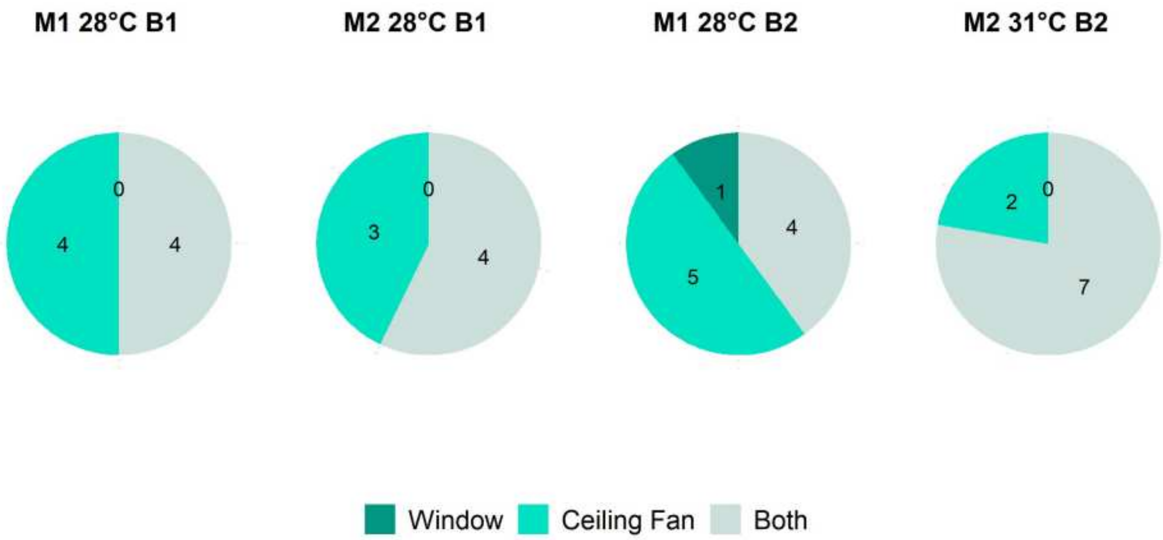


Figure 9: Number of participants who opened the window, turned on the ceiling fan and performed both actions during the day separately for M1 and M2 and temperature settings. B1: office 1; B2: office 2.

### 5.4.1. Performance expectations

The performance expectations of general ceiling fans and of the personal ceiling fan used in this study were analysed. Results from a reliability test and an exploratory factor analysis are shown in Table 6. Reliability test indicates internal consistency for the scale in this specific sample. Although, values lower than 0.7 indicate an unreliable scale, when measuring psychological constructs lower values can be expected due to the diversity of constructs being measured (Field *et al.* 2012). Moreover, as the number of items measuring each construct are within the recommended, a lower threshold can be expected (Hair *et al.* 2014). For this sample, results indicate good reliability of the scales, except for “importance of personalized ceiling fans” and “attitudes towards ceiling fans” in the first appointment.

KMO values indicate the sampling adequacy for each variable in the model and the complete model. As indicated by Field *et al.* (2012), values greater than 0.5 are barely acceptable, and between 0.7 and 0.8 are acceptable. All variables presented in this study present acceptable adequacy.

Table 6: Cronbach α values from reliability test and KMO values from explanatory factor analysis. GFC: general ceiling fans; PCF: personal ceiling fans. In bold: reliable scale and adequate sampling.

| Cronbach α / KMO | M1 | | M2 | |
|---|---|---|---|---|
| | T1 | T2 | T1 | T2 |
| Expectations GCF | **.729 / .617** | **.770 / .692** | **.869 / .705** | **.839 / .748** |
| Expectations PCF I | **.746 / .583** | **.744 / .650** | **.876 / .820** | **.899 / .659** |
| Expectations PCF II | | | **.784 / .698** | **.702 / .624** |
| Importance of PCF | .612 **/ .639** | | **.866 / .711** | |
| Attitudes towards GCF | .651 **/ .540** | | **.910 / .660** | |

Correlations were calculated using Kendall-Tau-b- und Spearman-Rho-Coefficients for correlations between a metric (factors) and ordinal variables. In the acclimatization phase (T1), expectations of personalized ceiling fans are positively correlated to the importance of characteristics and performance of a personalized ceiling fan in both appointments (M1: r=.63, M2: r=.89, p (two-tailed) <.05).

Comparing the acclimatization phase (T1) and after using the ceiling fan (T2), expectations of general ceiling fans in T1 are significantly correlated with the expectations of ceiling fans in T2 (M1: r=.77, M2: r=.81, p (two-tailed) <.05) and the expectations of personalized ceiling fans in T2 (M1: r=.52, M2: r=.83, p (two-tailed) <.05). Similarly, attitudes towards general ceiling fans in T1 are significantly correlated with the expectations of ceiling fans in T2 (M1: r=.52, M2: r=.76, p (two-tailed) <.05).

Only in the second appointment, attitudes towards ceiling fans correlate with expectations of personalized ceiling fans in T2 (r=.74, p (two-tailed) <.01). Moreover, attitudes and expectations of ceiling fans in T1 significantly correlate with the compared expectations of personalized ceiling fans in T2 (Expectations: r= .72, p (two-tailed) <.01; Attitudes: r=.56, p (two-tailed) <.05).

Related to hypothesis 4.1, expectations of ceiling fans in the acclimatization phase correlate with expectations of general fans and personalized ceiling fans after using them, but correlation factors are higher in the second appointment in comparison to the first one. These findings could suggest that 1) expectations were fulfilled when using the ceiling fan in terms of personal control, effectivity and improvement of indoor conditions, and 2) expectations of an unknown technology, in this case an innovative personalized ceiling fan, changed and were more aligned with expectations after a second experience, when compared to the first experience. These suggestions align with the work from Auliciems (1981), suggesting that first experiences with personalized ceiling fan will shape performance expectations for a second experience with the same device.

With respect to the factor analysis results, low KMO values for attitude in the first appointment could indicate unformed attitudes before performing adaptive behaviours, showing low correlation values as well. However, for the second appointment participants could form attitudes towards the use of ceiling fans, which seem to influence performance expectations of general and personal ceiling fans. These results indicate to support hypothesis 4.2 and suggest that attitude towards a specific adaptive behaviour may be shaped and positively influenced after its implementation in a second experience. Furthermore, attitudes and expectations of personalized ceiling fans before its usage correlate with the compared expectations of personalized ceiling fans after using them, showing a positive correlation between the expected performance and expressed attitudes with the fulfilled expectations after using the device. These findings show the effect of attitudes and expectations on performance evaluation, aligned with the work of Ajzen and Fishbein (2005).

Related to hypothesis 4.3, the influence of information on perceived comfort can be discarded for this study, contrary to the work of Anderson (1973) and the study from Naddeo *et al.* (2015). As no significant difference was found between performance expectations of the ceiling fan, the effect of information on the perceived comfort – either thermal or air quality – cannot be assumed. Further analysis should rethink the way previous information was provided and a more specific link between information and its effects on perceived comfort should be proposed.

An effect of expectations on behavioural adaptation (hypothesis 3.1) is suggested by the correlation between expectations and performance importance of a personal ceiling fan for both appointments. This evidence reflects the expectancy-value theory (Wigfield and Eccles 2000), which in this case relates the expectation of using the personalized ceiling fan (likelihood) with the importance assigned to perform certain behaviour (evaluation). Besides, results suggest a methodology to assess performance expectations based on the Theory on Diffusion of Innovation (Rogers 1983) and the Theory of Planned Behaviour (Ajzen 1991) for this specific technology. Further studies may assess the effects of the expectancy-value process on the performance of adaptive behaviours and test the proposed methodology for other adaptive behaviours.

### 5.5. Limitations

Limitations have to be seen in the small sample and limited variance which 1) do not allow a generalization of results and the interpretations of values from the reliability test and factor analysis. Furthermore, the relationship between performance expectations and perceived comfort has not been directly assessed and could be a missing link to fulfil the gap between comfort-related behaviours and actual comfort votes. Finally, other influencing factors could be incorporated in the analysis of expectations.

## 6. Conclusion

This study investigated people's expectations in the built environment, their influencing factors and their impact on perceived comfort and comfort-related behaviours. The following suggestions emerge:

1) a methodology to assess thermal and performance expectations is presented, by directly asking participants about their perceived expectations and the compared expectations. Furthermore, the importance of assessing thermal expectations in a two-dimensional way (comfort and sensation) is stressed.
2) previous experiences in the current environment showed an effect on thermal expectation and performance expectations.
3) attitudes and values towards a certain technology may set performance expectations and impact on behavioural adaptation.
4) biased information given about the performance of an unknown adaptive strategy did not seem to influence later behavioural expectations.

The results suggest that occupants' expectations of indoor conditions may relax in a known environment, but significant changes in indoor temperatures are the most sensitive parameter influencing expectations. Although occupants' expectations range may vary among them, personalized adaptive behaviours tested in this study were effective enough to overcome the disparity in expectancy disconfirmation. Moreover, attitudes and performance expectations of an unknown adaptive behaviour were quickly shaped after a single usage and not by previous knowledge, which may provide guidance to promote high-comfort and energy-efficient adaptive approaches.

## 7. Acknowledgements

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# Evaluation of the comfort attributes and the students' sense of place in the classrooms of the University of Lagos

**Adetokunbo Sangowawa, Andrew Akinnubi and Mike Adebamowo**

Department of Architecture, University of Lagos, Lagos, Nigeria

**Abstract**

Since students spend a greater part of the school day in the classrooms, these spaces should positively impact their comfort, satisfaction, and invariably, their learning experience. The result of the pilot study of the learning environments of the Department of Architecture, University of Lagos is presented. A multi-method approach was adopted that used semi-structured interviews of focus groups of students in the department and the outcome aligned with the parameters of students' satisfaction in previous studies. A questionnaire-based survey was also implemented. Parameters that impacted learning experience included the physical environmental attributes, relational attributes, hostel accommodation and even the availability of electrical power to the classrooms and hostels. The students' comfort and satisfaction are impacted by the IEQ factors, room aesthetics and attachment to place. Using a Kano Model evaluation, majority of the attributes that impacted the student's learning experience were classified in the indifferent category. The explanation for the level of indifference was that the students may have become apathetical. A classroom environment that would be resilient to the current infrastructural and climate issues would need to enhance the attributes that impact the students' comfort and learning experience.

**Key words**: classrooms, comfort, Kano Model, learning experience, sense of place.

## 1. INTRODUCTION

The website of the University of Lagos (Unilag) gives the vision of the Institution as the desire to be "a top-class institution for the pursuit of excellence in knowledge, character and services to humanity". To achieve this, Unilag will "provide a conducive environment for teaching, learning, research and development where staff and students will interact and compete effectively with other counterparts globally" (University of Lagos, 2019). Both the vision and mission statements affirm the importance of the classroom environment in the pursuit of this purpose. The environment must be conducive and should meet the expectation of the students, the teachers and other stakeholders. This is more so as the students spend most of the school days in the classrooms (Choi et al., 2014). It is to be noted that the classroom environment is not only physical, but also social and psychological (Muhammad et al., 2014).

However, there have been financial pressures on Federal Nigeria Universities so much so that physical infrastructures and classroom facilities are in deplorable conditions (Moja, 2000). The poor state of the learning environment has impacted the quality of education (Connor et al., 2005). Consequently, Unilag has not been able to meet its mission of being globally competitive. The Centre for World University Rankings (CWUR) for 2018 – 2019 ranks the University of Ibadan (UI) at #991, the only Nigerian Institution in the list of 1000 schools. Meanwhile, UI is ranked #1 in the nation.

There are many factors that contribute to a satisfactory learning environment. Thus, the issue facing most Higher Education Institutions (HEI) is how best to spend the meagre revenue that accrues to them. How can the HEIs effectively improve the learning environment and experience of the students, thereby achieving their purposes?

### 1.1 Aim and Objectives of study

The aim of the study is the assessment of the physical environment of classrooms in Tertiary Institutions and the students' learning experience, using the University of Lagos as case study. The preliminary study was limited to the Department of Architecture. The objectives of the study include evaluation of the impact of classroom physical environmental parameters on the satisfaction of the students; assessing the importance of attributes that influence the learning experience of the students; the students' sense of place; categorization of the classroom attributes with respect to how they influence the learning experience of the students.

## 2. LITERATURE REVIEW

The Vitruvian attributes of the indoor space are *firmatis* (durability), *utilities* (utility) and *venustatis* (beauty). The durability refers to the perception of safety by the occupants. The attribute of utility is satisfaction with the physical and psychological environmental qualities. Beauty is expected to delight the users and raise the sense of attachment and ownership of space. Many studies, like that of Clements-Croome (2014), have linked the quality of the built environment to the wellbeing of the users. However, an evaluation of the Vitruvian attributes of the indoor space goes beyond the physical architecture.

### 2.1 The Classroom Environment

With regards to higher education institutions (HEI), the classroom environment is physical, social and psychological (Muhammad et al., 2014). The classroom is to satisfy the primary functions of teaching, learning and carrying out research. To effectively do these, the needs and expectations of the users of the classrooms must be met (Sapri et al., 2009)

A primary need and expectation of occupants within an indoor environment is the feeling of comfort and wellbeing. The concept of comfort is subjective and multidisciplinary. Bluyssen (2009) considered comfort from the visual perspective (view, illuminance and reflection); thermal perspective (temperature, humidity, airflow); acoustic perspective (noise, reverberations); air quality (contamination, odour and ventilation). Slater (1985) noted that comfort is the harmony of the physiological, psychological and physical states as pleasantly experienced by the occupant of the space or environment, that is, the occupant is at ease and satisfied with the environment.

Studies have linked the satisfaction of the office worker with their performance and productivity. "A building and its environment can help people produce better work, because they are happier and more satisfied when their minds are concentrated on the job in hand; good building design can help achieve this" (Clements-Croome, 2015 page 173). It is noted that the relative importance of the four factors of IEQ is impacted by location (country), culture and time (Sangowawa et al., 2017). Humphreys (2005) concluded that the overall satisfaction with the office indoor environment does not depend on the individual factors but on the collective whole. Similarly, for the classroom environment the four IEQ parameters of thermal comfort, indoor air quality (IAQ), visual and acoustic comfort have also been linked to student satisfaction and learning experience (Fisk, 2000; Mendell et al., 2002). The linkage between the environmental factors and satisfaction in the classrooms is not limited to IEQ physical factors. Choi et al. (2014) included classroom furniture, aesthetics, classroom layout and technology. "It is important to study the IEQ of classrooms in a comprehensive way that includes all IEQ criteria so that the contribution of each, any, or all criteria can be determined as well as the interaction effect" (Choi et al., 2014 page 4). Barrett et al. (2015) considered the holistic impacts of indoor environment on users and wrote: "Rather than build up from the measurable dimensions of heat, light, sound and air quality, we have taken as a starting point the simple notion that the effect of the built environment on users is experienced via multiple sensory inputs in particular spaces, which are resolved in the users' brains" (page 119).

Based on previous studies, Barrett et al. (2015) proposed three dimensions to structure the factors of the classroom environment which impact the learning ability of the pupils. These are summarised as:

i) Naturalness – light, sound, temperature, air quality and links to nature.
ii) Individualization – ownership, flexibility and connection.
iii) Stimulation – complexity and colour.

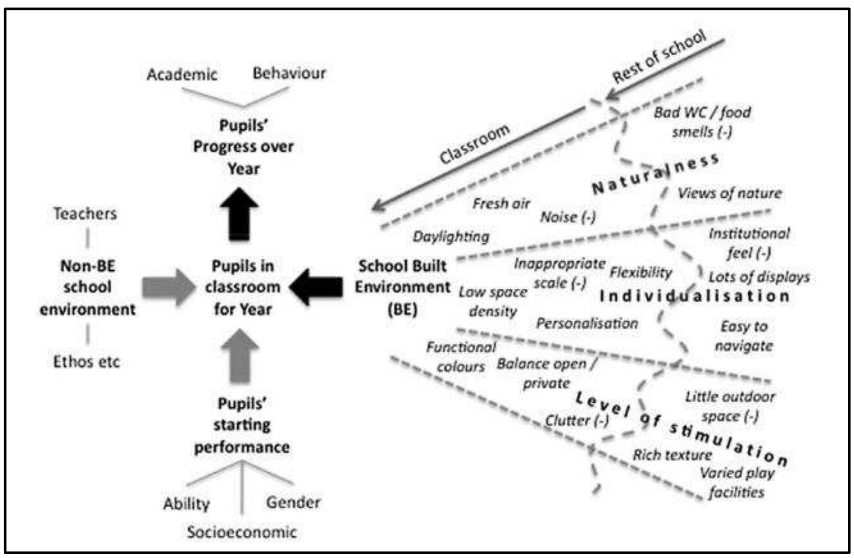


Fig 1 – Overview of the HEAD (holistic evidence and design) research with examples of the Built Environment factors (Barrett et al., 2015)

Seeing the classroom environment more in terms of a social construct, Moos (1979) concluded that both student behaviour and learning are impacted by the social climate of the class. He gave the underpinning three dimensions as: relationship (involvement, cohesiveness, support); system maintenance and change (clarity, control, innovation); personal growth (independence, competition, autonomy). Suffice to say, the three dimensions are themselves affected by the physical environment. In a study of architecture students, Casakin and Davidovitch (2013) described social climate as the ambience that is "a consequence of the interactions between the physical elements of the learning environment, and the interpersonal interactions between students and teachers" (page 862). Seat arrangement and ease of interaction within the classroom are considered as critical factors.

Consistent with the social climate, Yang et al. (2013) configured the classroom environment into three categories: psychological environment (motivation, self-efficacy and achievement); psychosocial environment (belongingness and connection with classmates); physical environment (classroom size, lighting, technology). The physical environment can be further configured into three categories: ambient environment (temperature, acoustics, lighting, air quality); spatial environment (classroom layout, furniture, vision); technology attributes (appropriate hardware, internet availability, ease of software use). The three physical categories are correlated and affect learning experience, student behaviour, satisfaction and performance (Guardino and Fullerton, 2010)

Vosko (1984) noted that the effectiveness of the physical depends on the perceptions of the students. Given the importance of the classroom in the growth and development of the student, it is pertinent to safeguard and improve its attributes (Umar, 2017). Writing conversely with respect to the state of Nigerian public schools, Ezike (2018) noted the "the classrooms are in terrible deplorable conditions, precipitating and provoking an acrid apathy among the students and their teachers, leading to truancy on the part of the learners and skipping of classes by the teachers" (page 65). The resulting underachievement by the students dims hopes and aspirations. The despair is compounded by the financial pressure on the institutions which must find the best use for their meagre income. It is therefore crucial to evaluate the perception of the students and ascertain the importance of the attributes or parameters that impact the learning environment in order to maximise the benefits of spending.

## 2.2 Sense of Place

Cornell (2002 page 41) wrote that "the (classroom) environment should be a place people (students) want to be, not a place they have to be". Sense of place has become an ambiguous term (Cross, 2001) and definitions depend on the academic leaning or intention. In this study, sense of place is taken as a factor that impacts the emotional comfort of an environment (Rogan et al, 2005) and this sense of place is determined by the legibility, perception of and preference for the visual environment and the compatibility of the setting with human purpose (Najafi and Shariff, 2011). Thus, the (classroom) environment is to be distinct or discernable, pleasing and comfortable, functional and/or fulfilling purpose. Shamai et al., (2012) noted that "place" is a combination of the human and physical environment, including attitudes and emotions.

According to Steel (1981), the sense of place is influenced by the physical parameters of size, scale, components, diversity, texture, colour, odour, noise, temperature, lighting, etc. Shamai (1991) claimed that there are three levels to the concept of place: belonging to place; attachment to place; and commitment to (or sacrifice for) place which is the highest level. At the other end is having no sense of place (Najafi and Shariff, 2011) or 'placelessness' (Relph, 1976). Stedman (2002, 2003) asserted that there had to be an overall satisfaction with the place for there to be an attachment to the place. This attachment is strengthened by the physical environment and its characteristics. And in line with Shamai (1991), there can be no commitment to place without an attachment to place.

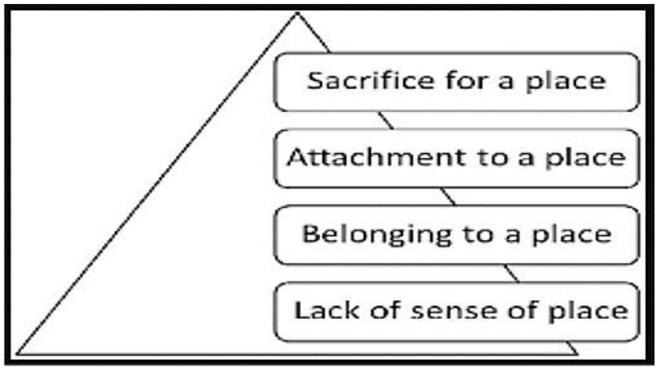

Fig 2 - Scales of Sense of Place (Shamai, 1991)

### 2.3 The Kano Model

The Kano Model is a theory that correlates customer needs or expectations with customer satisfaction (Kano et al., 1984). With regards to the indoor space, it assists in identifying what the occupants need and desire. It is a means of prioritizing attributes. The approach is to classify customer preferences in five categories (Juan et al., 2014) as in figure 3:

- Must-be factors (M) – also referred to as basic or expected factors. While they do not enhance overall satisfaction, their absence or unfulfillment causes dissatisfaction. They are a necessary, but not sufficient, requirement for customer satisfaction (Kim and de Dear, 2012).
- One-dimensional factors (O) – also referred to as proportional or desired factors. The needs, expectations or performance of the factors are directly related to the satisfaction of the customer or client. The better the performance, the greater the satisfaction.
- Attractive factors (A) – also referred to as bonus or delightsome factor. These factors are not expected. When fulfilled, they have a strong impact on satisfaction. Where absent, they do not result in dissatisfaction.
- Indifferent factors (I) – do not have an impact on satisfaction either because the occupants are indifferent or not interested. Satisfaction is not affected by the fulfilment, or not, of expectations.
- Reverse factors (R) - is when a high degree of performance or fulfilment leads to dissatisfaction.
- Questionable factors (Q) – occurs when there is a contradiction in the occupants' assessment, arising from misunderstanding or mistake.

The Kano Model has been adopted and applied in many fields of study. Juan et al. (2014) applied it to intelligent green building study. Kim and de Dear (2012) used it in their study of IEQ and overall workspace satisfaction. Chen et al. (2018) applied the modified model in the correlation between service quality (SERVQUAL) and customer loyalty. The present study uses the model to categorize the different factors of the classroom environment as they impact satisfaction and learning experience.

It is to be noted that the categorization of the Kano Model is dynamic (Matzler et al. 2004) and evolutional (Borgianni, 2016). The categorization is impacted by time, culture and age of customer or occupant (Chen et al., 2018).

Survey questions are posed in a functional and dysfunctional manner, using a 5-point Likert scale. Response to each pair of answers is assessed using the Kano evaluation table

(Berger, 1993) as in table 1 below. The present study uses the expectation and perception pairing.

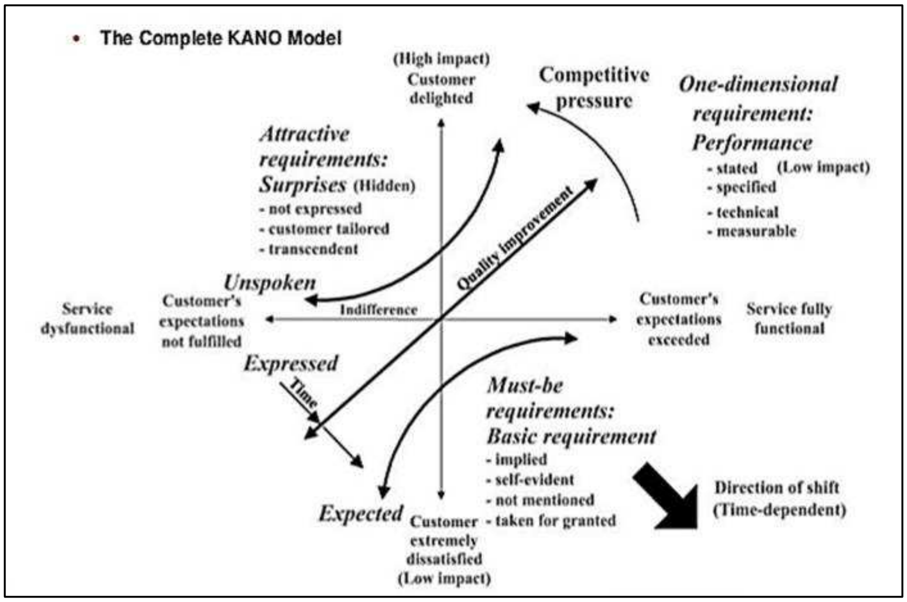


Fig 3 – The complete Kano Model (https://www.slideshare.net/UpendraKartik/kano-analysis-an-executive-summary)

The customer satisfaction coefficient (CSC) is calculated from the evaluation using the following equations:

i. Extent of satisfaction coefficient (SC) = (A+O)/ (A+O+M+I)

ii. Extent of dissatisfaction coefficient (DSC) = - (O+M)/ (A+O+M+I)

Table 1: Kano Evaluation Table

| Customer Requirement | | Dysfunctional | | | | |
|---|---|---|---|---|---|---|
| | | 1 Dislike | 2 Live with | 3 Neutral | 4 Must-be | 5 Like |
| Functional | 1 Dislike | Q | R | R | R | R |
| | 2 Live with | M | I | I | I | R |
| | 3 Neutral | M | I | I | I | R |
| | 4 Must-be | M | I | I | I | R |
| | 5 Like | O | A | A | A | Q |

The references for the letters in table 1 are: A = attractive; O = one-dimensional; M = must-be; Q = questionable; R = reversible; I = indifferent

The impact of the factors on satisfaction or dissatisfaction is greater when the coefficients are closer to 1 or -1. The coefficients can be graphically represented in a customer satisfaction coefficient diagram (Qiting et al., 2011).

The Kano Model has been lauded for being able to determine the product features that maximize the customer satisfaction. It also has its criticism. Matzler (2004) opines that the Kano survey and analysis can be cumbersome. It does not explain behavioural factors, motivation or the drivers of perception (Bhattacharyya and Rahman, 2004). The shortcoming notwithstanding the Kano Model has been widely used in academic and several industries. It has also been adopted in this study to categorize the attributes of the classroom environment as they impact the learning experience.

## 3. RESEARCH METHODS

The research is a case study of the University of Lagos and the initial study is limited to the learning environments of the department of Architecture. The methodology is multi-method.

1. A qualitative survey using semi-structured interviews of focus groups of students.
2. A quantitative survey of undergraduate and postgraduate students using printed and online distribution.

The qualitative survey enquired about factors or parameters that influence the students' perception of satisfaction and learning experience. The quantitative survey instrument is an adaptation of the Sustainable Post-Occupancy Evaluation Survey (B3-SPOES) developed by the research centre of the University of Minnesota. The instrument was adopted to enhance the validity and reliability of the study. It uses a 7-point Likert scale to evaluate students' perception of satisfaction with the thermal, lighting, acoustic, and indoor air quality conditions as well as the aesthetics, furnishing, view, cleanliness and space provision.

The outcome of the qualitative survey indicated that there are more attributes that impacted the learning experience of the students than the environmental factors indicated in the B3-SPOES instruments. These include relationships, hostel accommodation, teaching ability of lectures, availability of electric power, etc. The level of importance/expectation, and the perception of fulfilment/satisfaction of the 28 identified attributes were assessed using a 5-Likert scale evaluation. The attributes were further categorized using the Kano Model.

## 4. MAIN DISCUSSIONS

### 4.1. Students' satisfaction

Figure 4 shows the mean score for the students' perceived satisfaction with the parameters of environmental quality of the classrooms. The highest score, +0.85, for the study is for 'overall lighting'. The lowest score, -1.45, is for 'availability of appropriate and latest accessories and technology'. The students are dissatisfied with more parameters than those they are satisfied with. The overall satisfaction score 'B18' is just +0.03, signifying indifference. Unfortunately, the physical IEQ factors of thermal, acoustic and air quality all have negative scores. The score for thermal comfort is -0.24. In post-survey discussion, the students believe that proper functioning ceiling fans will aid thermal satisfaction. Mini rechargeable personal fans are becoming a feature with the female students.

The factors of aesthetics and personal space also had negative scores. The students' assessment of the classroom environment is rather poor.

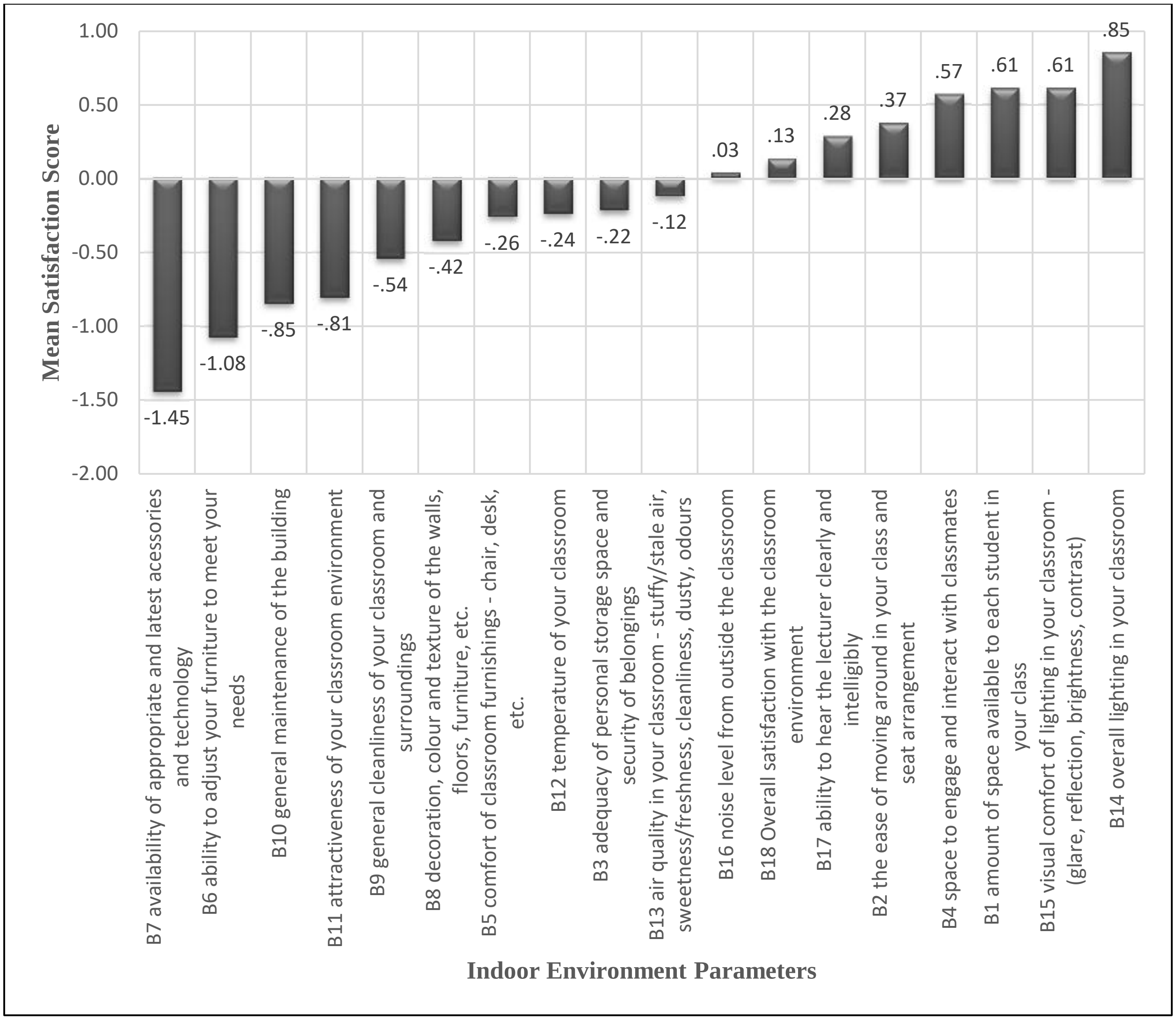


Fig 4 – Scores for satisfaction with physical indoor environmental parameters

## 4.2. Importance of attributes

The students were questioned about how their learning experience is impacted by the classroom environment. Figure 5 presents a poor assessment. Apart from lighting, the student's ability to learn appears to be impeded by the quality of classroom environment. Only the visual environment has a positive score. The thermal and acoustic attributes have the worst scores. However, it is noteworthy that the scores are between -1 and +1. This implies that hindrance to learning is not excessive nor is the enhancement impressive.

From table 2, all the 17 classroom environmental parameters were strongly associated with the overall classroom satisfaction. However, the association of the thermal comfort and the seat arrangement were not statistically significant. The physical environmental parameters had the least strength of associations (Cramer's V). The highest strength was with furniture. The results for the relational parameters align with the studies of Yang et al., (2013) and Chan et al. (2014) for higher education classrooms. Summarily, the perceived satisfaction of the Lagos students is largely negative.

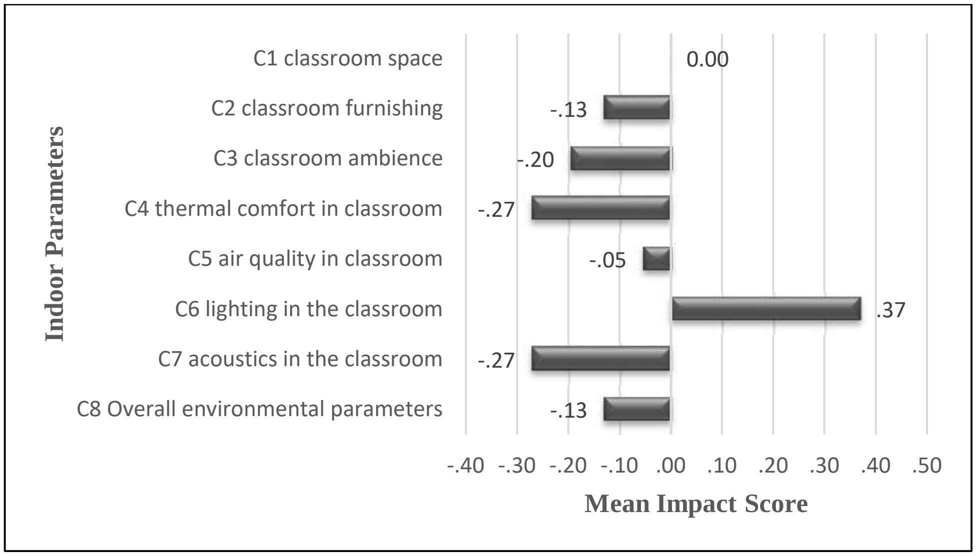


Fig 5 – Scores for impact of physical indoor environmental parameters on learning experience

Table 2: Association between physical indoor parameters and learning experience

| PARAMETER | CHI² SIGNIFICANCE | CRAMER'S V |
|---|---|---|
| B5 classroom furnishings - chair, desk, etc. | .000 | .443 |
| B8 decoration, colour and texture of the walls, floors, furniture, etc. | .000 | .442 |
| B17 ability to hear the lecturer clearly and intelligibly | .000 | .411 |
| B3 adequacy of personal storage space and security of belongings | .000 | .382 |
| B7 availability of appropriate and latest accessories and technology | .001 | .362 |
| B1 amount of space available to each student in your class | .000 | .360 |
| B10 general maintenance of the building | .003 | .346 |
| B11 attractiveness of your classroom environment | .004 | .342 |
| B14 overall lighting in your classroom | .007 | .330 |
| B9 general cleanliness of your classroom and surroundings | .010 | .326 |
| B4 space to engage and interact with classmates | .011 | .325 |
| B13 air quality in your classroom - stuffy/stale air, sweetness/freshness, cleanliness, dusty, odours | .024 | .314 |
| B16 noise level from outside the classroom | .032 | .311 |
| B6 ability to adjust your furniture to meet your needs | .047 | .305 |
| B15 visual comfort of lighting in your classroom - (glare, reflection, brightness, contrast) | .050 | .304 |
| B12 temperature of your classroom | .092 | .294 |
| B2 ease of moving around in your class and seat arrangement | .175 | .282 |

### 4.3. Students' sense of place

The result of the students' perception of sense of place is presented in fig 6. The good score for the place attachment (D4) is in relation to a social factor and not the quality of the space. Satisfaction with the classroom 'place' (D2) and how it serves purpose (D3) have negative scores. Ahn (2017) wrote that students' sense of belonging to university is strongly associated with social capital. Thus, place attachment can be reinforced by social capital or social interactions even though the physical environment is not judged as satisfactory. What the present study has not done is to explore how bad the physical environment must be to negate the effect of a positive social environment, or vice-versa. This can be the subject of future studies.

The students were questioned about their sense of belonging or feelings towards the University of Lagos (Unilag). This question has the highest score of +0.91, expressing the students' pride about attending Unilag. Relating this to Stedman's (2003) proposition presents an anomaly. Since the place satisfaction and place attachment had negative scores, the students are not supposed to have a positive sense of belonging. Post-survey interviews affirmed that the feeling of pride essentially results from the students' assessment that Unilag is the foremost university in the country. It can be inferred that there is pride in being connected to or associated with success or greatness. The question posed by this is whether place attachment can be influenced by place recognition or reputation?

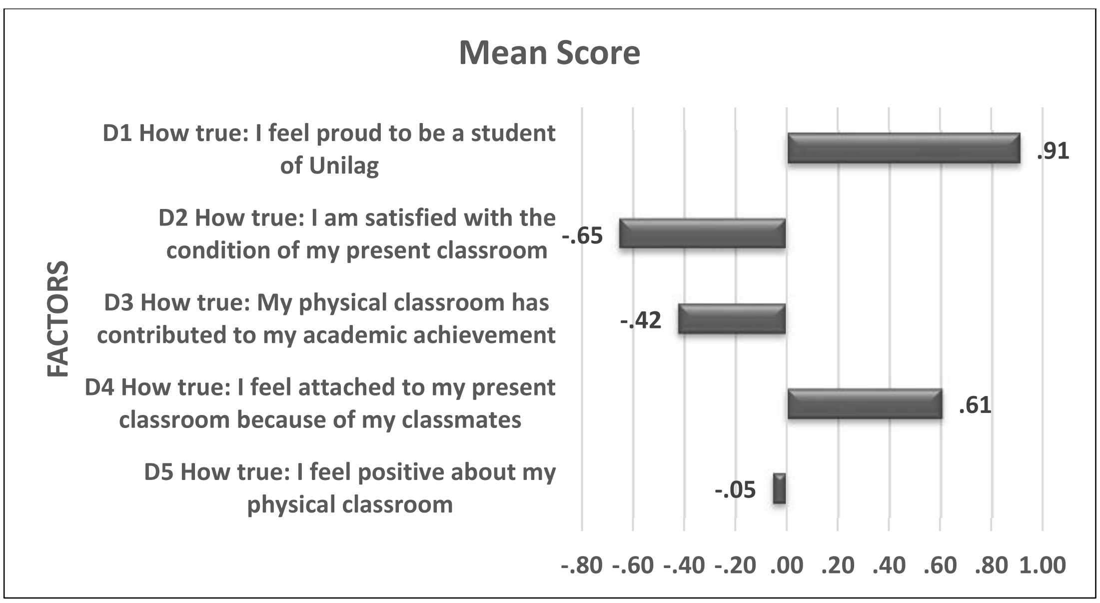


Fig 6 - Scores for sense of place parameters

### 4.4. Categorization of classroom attributes

The Kano Model was used to categorize the attributes. The reliability test gave a Cronbach's alpha of 0.892 and 0.834 for the expectation and perception data respectively. These indicate very good internal consistency for the scales.

The students' expectations for the 28 attributes shown in table 3 are positive with only 'no distraction/disturbance within the classroom' as the only attribute that fell below the indifference mark. In terms of the perception of satisfaction, just over 50% of the attributes register above the indifference mark. The highest expectation is with the availability of power. The highest level of dissatisfaction, that is, the difference between expectation and perception is with 'access to Wi-Fi'.

The Kano Model evaluation is presented in table 3 and graphically in figure 7 below. None of the 28 attributes has a 'must-be' status. Only 'access to Wi-Fi' is in the one-dimensional category, meaning the more of this attribute, the better satisfied the students would be. 'Health/wellbeing', 'comfortable furniture', availability of power' and 'lecturers' ability to teach' are classified as bonus or attractive attributes. Their fulfilment is unexpected, and they strongly impact satisfaction. All the other 24 attributes are classified as being 'indifferent'. Since the outcome of the Kano Model is affected by culture and time, comparison to other studies is to be with care. In the study of students of Ataturk University in Turkey, Bilgili and Unal (2008) found 6 indifferent attributes and 29 one-dimensional attributes.

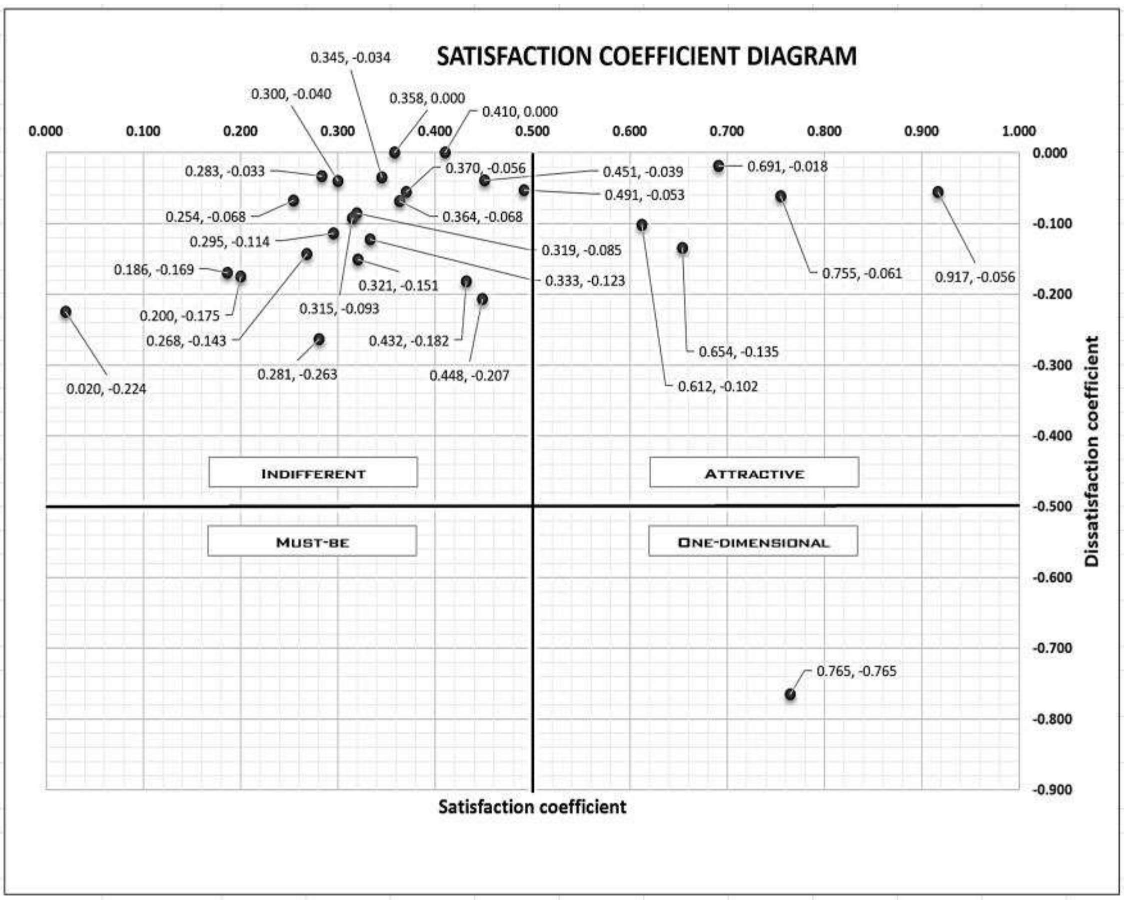


Fig 7 – Customer satisfaction matrix

Table 3: Kano evaluation table

| Parameters | M | O | A | I | R | Q | O+A+M | I+R+Q | category | (A+O)/ (A+O+M+I) | -(O+M)/ (A+O+M+I) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| E1 Access to wi-fi | 7 | 32 | 7 | 5 | 2 | 14 | 46 | 21 | O | 0.765 | -0.765 |
| E2 Health/wellbeing | 0 | 3 | 34 | 12 | 4 | 14 | 37 | 30 | A | 0.755 | -0.061 |
| E3 Air quality - stuffy/stale/odour | 1 | 4 | 26 | 18 | 6 | 12 | 31 | 36 | I | 0.612 | -0.102 |
| E4 Artificial lighting | 0 | 0 | 19 | 34 | 5 | 9 | 19 | 48 | I | 0.358 | 0.000 |
| E5 Cleanliness | 2 | 1 | 27 | 27 | 4 | 6 | 30 | 37 | I | 0.491 | -0.053 |
| E6 Daylight | 0 | 0 | 16 | 23 | 7 | 21 | 16 | 51 | I | 0.410 | 0.000 |
| E7 No distraction-disturbance within classroom | 5 | 2 | 6 | 27 | 15 | 12 | 13 | 54 | I | 0.200 | -0.175 |
| E8 Furniture arrangement | 1 | 1 | 16 | 42 | 3 | 4 | 18 | 49 | I | 0.283 | -0.033 |
| E9 Absence of Glare | 3 | 2 | 11 | 28 | 8 | 15 | 16 | 51 | I | 0.295 | -0.114 |
| E10 Adequate sleep | 4 | 4 | 13 | 32 | 8 | 6 | 21 | 46 | I | 0.321 | -0.151 |
| E11 No overcrowding in classroom | 4 | 4 | 15 | 21 | 12 | 11 | 23 | 44 | I | 0.432 | -0.182 |
| E12 Personal storage space | 3 | 2 | 15 | 34 | 7 | 6 | 20 | 47 | I | 0.315 | -0.093 |
| E13 Audi-visual equipment | 11 | 0 | 1 | 37 | 6 | 2 | 12 | 45 | I | 0.020 | -0.224 |
| E14 Relationship with classmates | 3 | 0 | 16 | 25 | 5 | 18 | 19 | 48 | I | 0.364 | -0.068 |
| E15 Privacy | 6 | 4 | 7 | 42 | 3 | 5 | 17 | 50 | I | 0.186 | -0.169 |
| E16 Refreshments | 8 | 7 | 9 | 33 | 4 | 6 | 24 | 43 | I | 0.281 | -0.263 |
| E17 Relationship outside the class | 2 | 0 | 15 | 33 | 4 | 13 | 17 | 50 | I | 0.300 | -0.040 |
| E18 Hostel accommodation | 6 | 6 | 20 | 26 | 3 | 6 | 32 | 35 | I | 0.448 | -0.207 |
| E19 Comfortable furniture | 2 | 5 | 29 | 16 | 4 | 11 | 36 | 31 | A | 0.654 | -0.135 |
| E20 Satisfaction with Lecturer's ability to teach | 0 | 1 | 37 | 17 | 4 | 8 | 38 | 29 | A | 0.691 | -0.018 |
| E21 Outside view (from the window) | 4 | 0 | 15 | 40 | 6 | 2 | 19 | 48 | I | 0.254 | -0.068 |
| E22 Workload | 5 | 2 | 17 | 33 | 4 | 6 | 24 | 43 | I | 0.333 | -0.123 |
| E23 Classroom aesthetics (wall/floor colour and texture) | 4 | 4 | 11 | 37 | 5 | 6 | 19 | 48 | I | 0.268 | -0.143 |
| E24 No distraction-disturbance from outside classroom | 3 | 1 | 14 | 29 | 10 | 10 | 18 | 49 | I | 0.319 | -0.085 |
| E25 Accessibility to Lecturer by Students | 2 | 0 | 20 | 36 | 0 | 9 | 22 | 45 | I | 0.345 | -0.034 |
| E26 Feeling of safety | 2 | 1 | 19 | 32 | 1 | 12 | 22 | 45 | I | 0.370 | -0.056 |
| E27 Access to literature and course materials | 1 | 1 | 22 | 27 | 1 | 15 | 24 | 43 | I | 0.451 | -0.039 |
| E28 Availability of power (electricity) | 0 | 2 | 31 | 3 | 4 | 27 | 33 | 34 | A | 0.917 | -0.056 |

Category legend: A – attractive; I – indifferent; M – must be; O – one dimensional

Given that most studies in the developed western economies place importance on the physical attributes of the indoor environment – lighting, thermal, acoustics and air quality - the high level of indifference for the Unilag study was further investigated. The Kano Model categorization for the highest ranked attributes in terms of measure of importance (expectation) was checked. How can the students be indifferent to the same factors that had been strongly associated with their learning experience? It is possible to term this as apathetical, that is, an absence of interest or emotion. What could be responsible for this behaviour? Ezike (2018) related the apathy in secondary school students in Nigeria to the deplorable condition of the classrooms. Amadi and Ohaka (2018) discovered that poor infrastructure in Rivers State Universities (in Nigeria) arouses apathy among students and lecturers. The explanation for the present study may be that the students' unfulfilled expectations led to the state of indifference, a feeling of apathy. A further study of the students' perception is recommended to ascertain this apathetic feeling.

## 5. CONCLUSIONS AND RECOMMENDATION

The classroom environment impacts the perceived satisfaction of the student's even though the measure of satisfaction had mixed results. The overall level of satisfaction is about neutral. The classroom environment also impacts the learning experience of the students, but with very poor results. The study showed that, even though the expectations of quality of the classroom attributes are high, the students have a sense of indifference or apathy towards most of the attributes regarding how these impacted the learning experience.

It is recommended that the Institution would need to rehabilitate and upgrade the classroom environments in line with the outcome of this study if the students' satisfaction and enthusiasm for learning are to be enhanced. The attractive parameters like classroom ambience, furniture, audio-visuals, power supply and wi-fi provisions will need to be upgraded at the minimum as these will ensure that Unilag achieves her mission statement.

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# Current research status of thermal comfort of preschool children

**Yao Meng*, Weiming Chen, Bin Cao**

Department of Building Science, Tsinghua University, Beijing, China
Correspondence email：edimengyao@163.com

**Abstract:** The health and growth of preschool children is a very important issue. Because of 3-6 years old preschool children spend most of the day in kindergarten, the comfort of the environment have an important impact on the physical and mental growth of preschool children. However, there are very few research on thermal comfort for preschool children. The preschool children do not have sufficient subjective judgment and independent behaviour. Therefore, the thermal sensation of preschool children about their surrounding thermal environment cannot be expressed subjectively. This paper summarizes the current research on thermal comfort of preschool children and analyses the difference between preschool children and adults. In addition, a questionnaire survey was conducted among 20 preschool children families. The age of preschool children are 3-6 years old. From the questionnaire survey results, the characteristics and health status of 20 preschool children were summarized, as well as the parents how to determine the thermal sensation of their children in daily life etc. It provides necessary condition for the study on the thermal comfort of preschool children to better understand their conditions and find appropriate investigation methods. Meanwhile, it is important to have further investigation of preschool children's thermal comfort model in future.

**Keywords:** Thermal comfort; Thermal sensation; Preschool children; Kindergarten

## 1. Introduction

With the development of living standard of people, at the same time, people pay more attention to the quality of their living condition. People spend 80-90% of their time occupancy in buildings and thus it is essential to evaluate the thermal sensation of occupants in buildings (Rupp, et al., 2015). In 1970, Fanger proposed the thermal comfort equation according to large number of experimental results, known as Predicted Mean Vote (PMV) model and Predicted Percentage of Dissatisfied (PPD) (Fanger, 1970). The previous research indicated that the age differences have effect on the thermal comfort of different groups of people. Furthermore it is important to take account to the other personal physiological factors, for instance, age and body proportion (Sugini, 2016). The particularity of children determines their differences with adults. There are significant differences between children and adults in physiological adaptation, the ability of expression, activity level and clothing style. In addition, the Fanger model is based on experiments with large number of adults. Thus, Fanger model have limit ability to predict the thermal sensation of children.

In recent years, researchers have found that the perception of children of thermal comfort is remarkable different from that of adults (Teli, et al., 2012; Montazami, et al., 2017; Mors, et al., 2011; Corgnati, et al., 2009). Teli et al carried out a study of thermal comfort of primary school children in Naturally Ventilated classrooms in UK. It was found that children have a warmer sensation and prefer lower indoor climate compared with adults. Adaptive comfort temperature for children significant lower than that for adult. Thus, PMV model cannot be used accurately for predicting the thermal comfort of children (Teli, et al., 2012；ISO, 2004； Mors, et al., 2011). Montazami et al suggested that the socio-economic background of children have effect on their perceptions of comfort. In addition, children from particular background might not have ability to take control of managing their own comfort. It is also important to understand the different adaptive factors and the social economic background of children have effect on their approach to achieving thermal comfort (Montazami, et al., 2017).

The above review provides guidance on thermal comfort study for children. Existing studies have used questionnaire surveys and measurements to investigate the thermal comfort for youngster (7-18 years old) in school in recent years. These research in the classroom have found that children prefer lower temperatures than adults. However very few research focus on the thermal comfort of preschool children (3-6 years old) all over the world. The smaller age of children, the greater different of physiology and physiology with adults. The uncomfortable thermal environment can to a great extent lead to the unhealthy development of children (Li, et al., 2015). Thus, the study focus on thermal comfort of preschool children is significant because it can have effect on physical and mental health development of children. Furthermore, it is important to research further the investigation of thermal comfort for preschool children.

## 2. Methodology

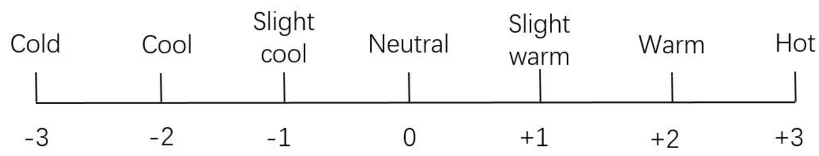
### 2.1. The information of questionnaire investigation

In this study, the questionnaire survey were conducted in 20 families with preschool children. Each family were given an online questionnaire to understand the details situation of their children. Furthermore, the design of questionnaire is based on the perspective of parents in order to investigate how they understand the hot/cold feelings of their children. The questionnaire from 15 of the 20 investigated families were filled out by mothers, in addition, the questionnaire from 5 investigated families were filled out by father. The age of investigated preschool children are from 3~6 years old. The average age of children was approximately 4 years old.

### 2.2. The thermal comfort model of preschool children

The preschool children can be regarded as specific populations and need to consider their requirements for thermal comfort. There are few studies of thermal comfort for preschool children have investigated. In recent years, due to parents' widespread misunderstanding of children's perception of 'cold' or 'hot' and lack of understanding of children common diseases, which causes some serious complications or accidents. For instance, parents put on too much clothing and quilt cover for children, in particular in winter, resulting in local high body temperature of children and lack of oxygen (Zhou, et al.,2013; Health, 2015; Li & Xu, 2007). The clothing of 3-6 year old preschool children are normally determined by their parents according to the own experience and thermal sensation. However, the reliability of this method has not been further verified and investigated. As an example, in China, a substantial proportion of parents are always worried about whether their children will be too cold. So that the parents often put on more clothes than usual for their children, but it may lead to overprotection or even the wrong protection.

Fanger stated that the factors influence the condition of thermal comfort can be divided into two main parts: four environmental factors (air temperature, mean radiant temperature, air velocity and relative humidity) and two personal factors (metabolic rate and clothing insulation) (Fanger, 1970). Fanger's Predicted Mean Vote (PMV) index adopts a seven-level scale:




However, the PMV model was proposed on the large study of experiments of adults. Whether the preschool children can understand the meaning of seven-level scale according to the particularity of limited understanding ability of children. It is worthy to study on thermal comfort model applied to preschool children. The previous studies show that the PMV model and adaptive model have limit ability to reflect actual thermal sensation of children compared with adult in same space (Teli, et al., 2012). Furthermore, PMV model of four environmental parameters can be measured, however the other two personal factors of preschool children are uncertain and different factors from adults. Therefore the metabolic rate and clothing insulation are important factors need to be considered into study of thermal comfort of preschool children.

**Metabolic rate of preschool children**

The physiology of children are different from that of adults, children can be more active and their bodies have a higher surface area to mass ratio. Thus, children have higher heat exchange rate with environment than adults (Parsons, 2001). Parsons indicated different approach to determine the metabolic heat production for children (Mors, et al., 2011). The diversity of activities change level of children in homes and kindergarten is a challenge to environmental design. If the indoor environment is too cold or hot, the preschool children do not have ability to change their thermal sensation through put on/off clothes, open the window etc. The only way is parents and teachers may have to provide adaptive advice and control (Parsons, 2001).

The study were conducted by Havenith indicated that the posture and movement analyses have not been validated in children, so that it is not apply to the assessment of metabolic rate. Based on ISO 8996 show that when adults sitting and doing slight writing, the activity level is 100W/m2. However, the activity value of children at the similar conditions is lower than that of adults. For instance, when children sitting in the class, the range of activity level are from 52~72W/m2. Meanwhile, it was found that there are no relation between metabolic rate and body weight. Therefore, the metabolic rate of adults cannot be directly converted into the metabolic rate of children. However, the sample size of children is too limit to achieve the accurate metobalic rate of children. Thus it is worthy to have further research on it (ISO8996, 2004; Havenith, 2007;Li, et al., 2015).

**Clothing insulation of preschool children**

Clothing provides a thermal resistance between the human body and its environment, the role of clothing is to maintain the body in an acceptable thermal state. Thus clothing insulation value are used in Fanger model. Basic clothing insulation represents the resistance to heat transfer between the skin and the clothing surface. Parsons indicated that it is important to consider the wet clothing because of moisture can transfer heat between the body and the environment. This is particularly important when the skin sweats. Children have higher activities thus the clothing insulation of children are different from adult. It is worthy to find appropriate way to measure the clothing insulation value of children (Parsons, 2001; de Dear, et al., 1997). ASHRAE Standard 55 can get the clothing insulation of whole ensemble or single adults outfit. However, it is not certain whether adult clothing insulation values are appropriate for preschool children. Havenith used regression equation of McCullough et al which is based on clothing insulation of adult, see the equation below (ASHRAE Standard 55, 2013;Havenith, 2007;McCullough & Jones, 1984):

$$I_{cl} = 0.919 + 0.255weight - 0.00874BSA_0 - 0.0051BSAC_1$$

Where,

$I_{cl} = intrinsic\ clothing\ insulation\ (clo)$

$Weight = clothing\ weight(kg)excluding\ shoes$

$BSA_0 = body\ surface\ area\ nude\ (\%)$

$BSAC_1 = body\ surface\ area\ covered\ by\ one\ layer\ of\ clothing\ (\%)$

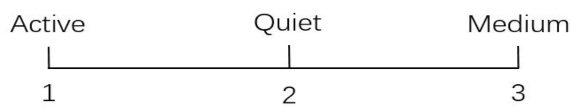
From the study results of Havenith, the difference between clothing insulation of school children and clothing insulation of adults is relatively small. Therefore, in usual, researchers use the clothing insulation value of adults into the study of children. The study of Teli et al found that the age of 7~11 years children, the clothing insulation range are between 0.30~0.49clo during transition seasons. However, it is need to notice that the clothing of preschool children are normally determined by their parents. Thus, the clothing insulation value of preschool children can be calculated by using the single clothing insulation value of ASHRAE Standard 55 (Teli, et al., 2012; ASHRAE Standard 55, 2013).

**2.3. Questionnaire**

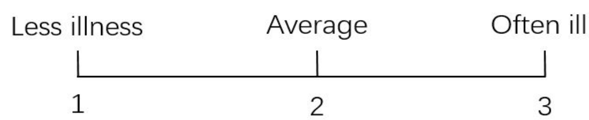
The key point of questionnaire is to investigated the thermal sensation of preschool children and accurately express their feeling. The cognitive ability and psychological difficulties of preschool children is need to be considered and overcome. Thus the form of the questionnaire that is appropriate for adults is not necessarily appropriate for children. In order to ensure the preschool children can have better understanding of questionnaires in further thermal comfort study, and also to know more about the personal information of preschool children, the pre-prepared questionnaire for parents are present. It is provides an important condition for the accuracy of the questionnaire used for thermal sensation investigation of children in future.

The main detail information of questionnaire see below:

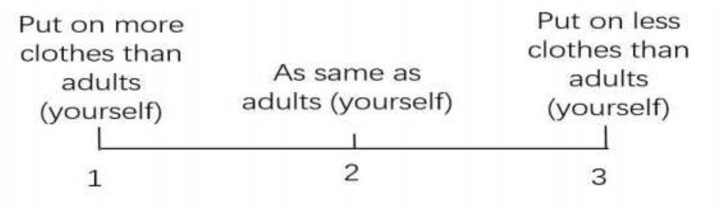
1. The characteristic of your child:



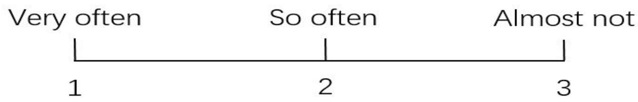

2. General health of your child (compared with other children around):




3. The characteristics of clothes of your child:




4. Does the child will tell you that they are cold/hot?




5. When you put on more clothes to your child, they refused to accept it, you will persist in doing that? (YES / NO)

6. The method of judgement for cold/hot feeling of your child(Table 1):

Table 1. Multiple choice of the method of judgement for thermal feeling of children

| Body parts of child | |
|---|---|
| Hand | To observe whether it too cold or hot |
| Forehead | To observe whether in a fever |
| The back | To observe whether the child sweating |
| Nose and forehead | To observe whether the child sweating |
| Face | To observe the whether the face of child(i.e. redness, panting for breath) |
| Others | N/A |

7. Which do you think the body parts of children are sensitive to temperature (Multiple choice)?

☐Hand

☐Neck

☐Back

☐Forehead

☐Others

### 2.4. Investigation method of thermal comfort for preschool children

As we known, the PMV model is based on four environmental parameters and two personal parameters. However, the equation of PMV cannot be directly used in evaluating the thermal comfort of preschool. Only four environmental parameters can be substituted into the formula of PMV. Furthermore, as above stated that the clothing insulation and metabolic rate of preschool children have particularity in thermal comfort evaluation. The previous studies show that the PMV model and adaptive model have limit ability to reflect actual thermal sensation of children compared with adult in same space. Meanwhile most of previous studies used PMV index and thermal sensation votes (TSV) from children directly to be compared.

Evaluation of thermal comfort normally have two different methods: one is subjective questionnaires that answered by subjects and another is field investigation by objective measurements. The majority of questionnaires research is aiming to investigate the thermal sensation of adults. They can relative easier understand the questionnaires and give the answers. However, it is hard to investigate thermal sensation of preschool children. The understanding of preschool children for questionnaires is different from adult and the determining factor is their cognitive competence. Yun et al conducted the survey of thermal comfort for kindergarten children in Korean, this study was conducted through the questionnaires and measurements of environmental variables. The questionnaires were based on seven-point scales that using in actual thermal sensation investigation. Teachers explained the questionnaires because understanding of children for it is different from adults. They gave the special labels and cartoon emoticon in questions in order to get respond from children. However, there were some children responded unusual answers. It is indicate that the questionnaires pattern for adults maybe not suit for children (Yun, et al., 2014). In the same way, Nam et al used seven-point scale and explained the thermal sensation to preschool teachers, furthermore teachers asked preschool children questions and complete survey forms. It was found that preschool children have worse understanding and cognitive abilities than adults (Nam, et al., 2015). Therefore the questionnaires form for adults maybe not suit for children.

## 3. Discussion of thermal comfort of preschool children

### 3.1. The results of questionnaires

In the investigation survey, there are 20 samples of preschool children aging from 3 to 6 years old can be seen from figure 1.

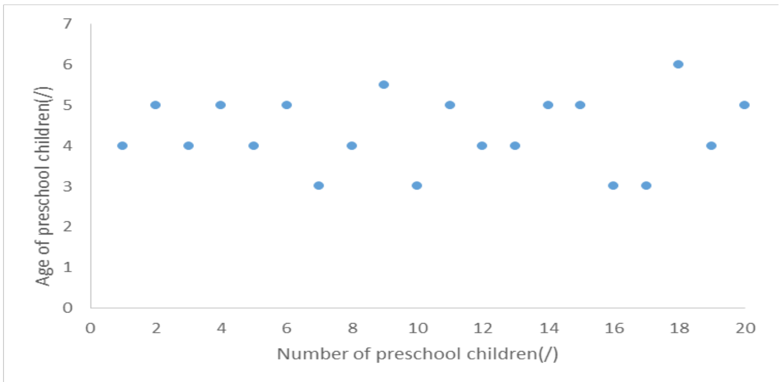



Figure 1. Distribution of age range of investigated children

From questionnaire indicated that there are 65% of the investigated children were characterized by activity and 30% were quiet. The figure 2 reflected that there are 75% of children usually get sick and 25% of children for frequency of illness as same as average level of normal children. Another concern is the characteristic of clothes of investigated children in usual, questionnaire show that 75% of parents normally put on more clothes to children compared with that of adults. Only a few (10%) parents put on their children in the same standards as adults (themselves).

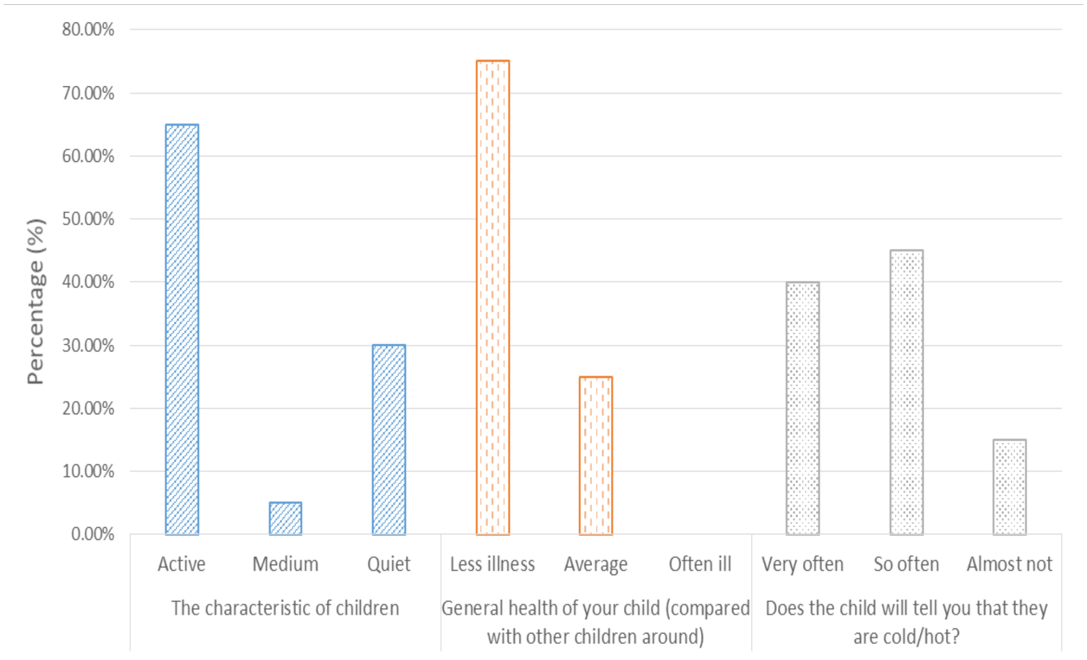



Figure 2. Results of questionnaire survey

From questionnaire investigation of parents, there are 30% of parents persist in putting on the clothes to their children even children refused to accept it. This may reflect that if the indoor climate is too hot, the preschool children do not have ability to change their thermal sensation and get own comfort. The only way is parents have to provide control based on their experience or feeling. It is important to investigate how the parents can judge the cold/hot feeling of their children. It can be seen from the questionnaire results obviously show that the majority of parents estimate the cold/hot feeling of their children by touching the back (see Figure 3). However, the further research needed to determine whether these methods are suitable accurately for preschool children to estimate the cold/hot feeling. Based on the questionnaire survey indicate that the hand, neck and back of the body parts of children regarded as relatively sensitive to temperature by majority of parents(as shown in figure 4).

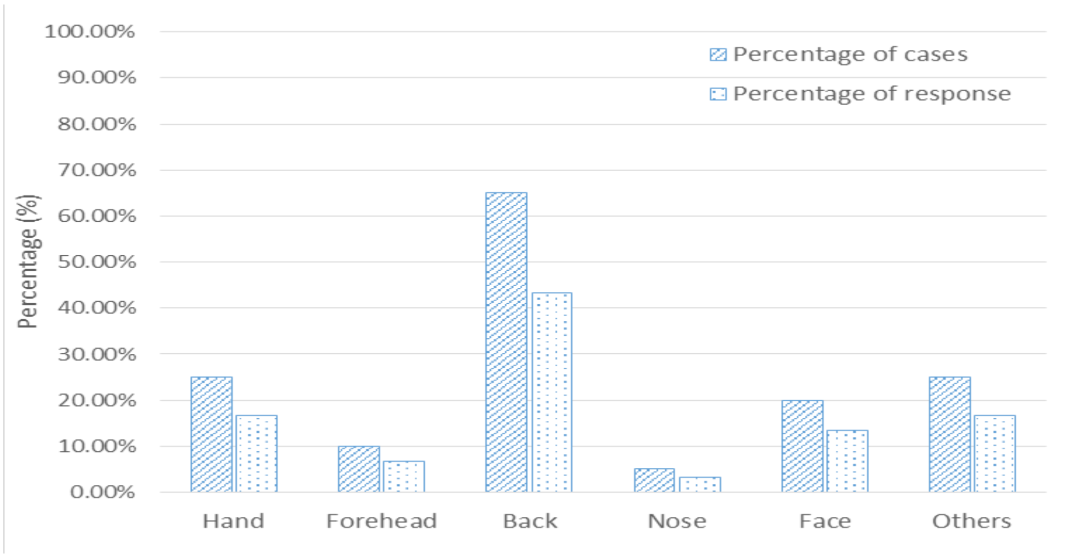



Figure 3 Estimation of method of parents to cold/hot feeling of children

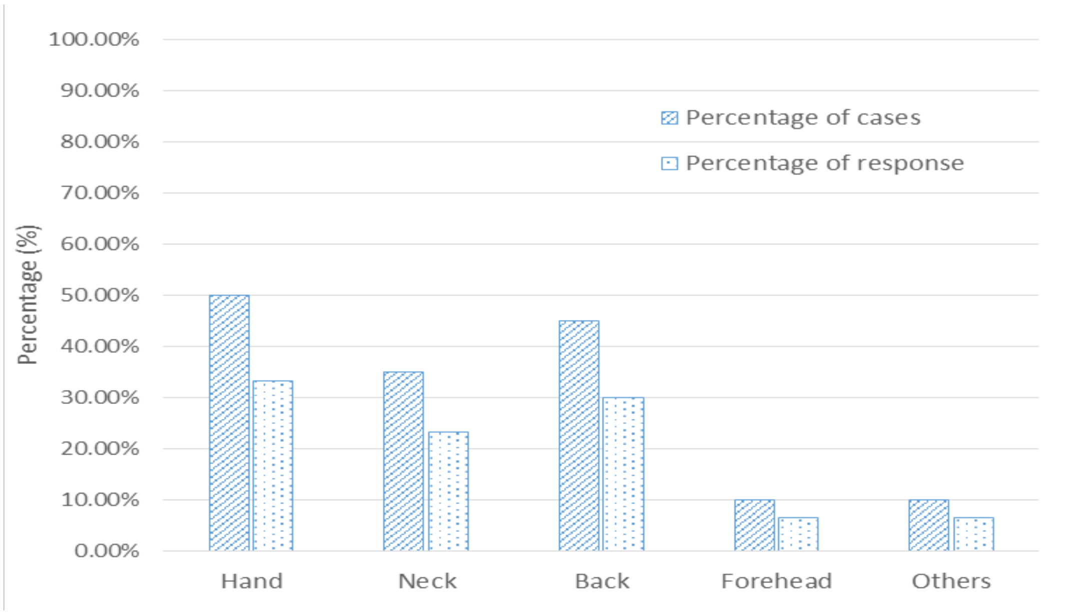


Figure 4. Investigation of which body parts of children are sensitive to temperature

**3.2. The discussion of thermal sensation of preschool children**

From current studies of preschool children, found that there are some deviations between children's thermal sensation and adults, resulting in different thermal comfort conditions and recognition for children. In addition, to understand the actual thermal sensation of preschool children have significant implication on growth, physical and mental health development of preschool children.

**Analysis of the difference of thermal sensation between adults and preschool children**

It is essential to understand the significance of thermal comfort in order to improve children's satisfaction, to control energy consumption and to provide support for setting standards. Due to the different of activity level, metabolic rate and perception of preschool children, result in the difference of thermal sensation between adults and children. According to PMV model, the indoor operative temperature is within 18-23℃, children are more sensitive to thermal sensation than adults. Present studies indicated that the evaluation value of the PMV calculation equation is lower than the actual average thermal sensation vote value of children, aging from 4-6 years old the appropriate Neutral temperature is about 3℃ below that of adults (Nicol, 1993; Sayigh & Marafia , 1998; Omer, 2008; Taleghani, et al., 2013). Therefore, it is hard to use PMV evaluation index to assess the thermal comfort of preschool children.

Furthermore, numerous studies in both thermal environment and thermal responses for preschool children have been investigated. It was found that children have higher heat exchange rate with environment than adults, at same time the physiology of children are different and they have more active. According to actual investigation and research, children are used to passive receiving environment, because they are basically depends on teacher or parents to control it the environmental condition. For instance, for window opening, clothing changed, air conditioning open/close etc (Li, et al., 2015). This is also found in questionnaire survey, there are sectional parents still persist in putting on the clothes to their children even children refused to accept it. Therefore, the above reasons make it difficult for preschool children to change the discomfort sensation caused by the thermal environment through the regulation of their own behaviour.

**Findings from thermal comfort study of preschool children**

Few present field studies have investigated the thermal comfort of preschool children (3-6 years old) and analysed the difference of thermal sensation between preschool children and adults. In addition, majority of research focus on school children age range due to them can understand the question of questionnaires. However, the preschool children are hard to understand the content of subjective questionnaires, and it is very difficult to reflect their thermal sensation through subjective questionnaires. Preschool children have different understanding and perception that significantly related to their inner life. They have limited cognitive capacity and they have to accept passively the discomfort caused by surrounding thermal environment (Fabbri, 2013).

The limitation of understanding and perception of preschool children had been demonstrated by the study of Fabbri. The study was conducted by used PMV model as standard and thermal comfort measurement were carried out. The age range of preschool children are from 4 to 5 years old in kindergarden. In the study, the questionnaire were modified according to a psycho-pedagogical approach, in order to identify how preschool children understand concepts such as temperature or thermal sensation. The results reflected that the predicted mean votes (PMV) of preschool children is slightly higher in respect to adults. Furthermore, the PMV meaningfully lower than actual thermal sensation expressed by preschool children. (Fabbri, 2013).

Yun et al suggested that it is essential to understand the significance of thermal comfort of preschool-aged children due to preschool children are not included in the climate chamber investigation of thermal comfort in Fanger (Yun, et al., 2014; Fanger, 1970). Yun et al conducted survey in 10 Naturally Ventilated kindergartens in Korea, monitoring the environmental parameters and investigating actual thermal sensation of kindergarten children. There are 119 kindergarten children aged 4 to 6 year old were examined. The results show that the comfort temperature for adults is approximately 3℃ higher than that for preschool children (Yun, et al., 2014). It is confirmed that the finding from study conducted by Hwang et al, children prefer lower temperatures than adults (Hwang, et al., 2009).

Conceicao et al developed adaptive model and conducted thermal comfort study in Kindergarten operated with natural ventilation for winter and summer. Numerical models are used in their study, the perception of preschool children were not evaluated with a questionnaire or other tool (Conceicao, et al., 2012; Fabbri, 2013). Fabbri conducted survey in North of Italy, monitoring the environmental parameters with Dataloggers and subjective investigation of children collected through questionnaires based on a psycho-pedagogical approach. They used 'Loris Malaguzzi' pedagogical model to verify how preschool children understand the concepts of temperature or thermal sensation. Results indicated that even though children express their opinion according to specific world models, they are sensible to these well-being issues (Fabbri, 2013). For the appropriate measurement of behavioural for children (i.e. crying or moving), mood changes and distraction can be revealed (Parsons, 2001). Thus, it is essential to find suitable questionnaires form in order to improve the accuracy for investigation of actual thermal sensation of children. According to the current studies of thermal comfort of preschool children, the summaries are present in table 2 see below.

Table 2. Review of field studies on thermal comfort of preschool children

| ***Literature*** | ***Location*** | ***Year*** | ***Subjects*** | ***Methods*** | ***Key findings*** |
|---|---|---|---|---|---|
| (Yun, et al., 2014) | Korean,<br>10 Kindergartens | 2014 | 4-6 years old preschool children | 1.Three month investigation<br>2.Thermal environment measurement and questionnaire of subjective thermal sensation<br>3.The teacher's assistance and explanation of the questionnaires | 1.Preschool children are more sensitive to metabolic changes than adults<br>2.The thermal sensation of preschool children is warmer than that of adults, so they prefer a temperature about 3℃ lower than that of adults<br>3.Girls are more sensitive to higher temperatures |
| (Nam, et al., 2015) | Korean,<br>19 Kindergartens | 2015 | 4-6 years old preschool children | 1.One year of continuous investigation, it divided into four seasons.<br>2.Thermal environment measurement and field investigation in kindergarten classroom.<br>3.Thermal sensation votes (TSV) and metabolism are calculated according to ISO 7730 for the adult ratio and corrected for the metabolic rate of children | 1.Children prefer a lower temperature range than adults due to they have a higher metabolic rate<br>2.Children prefer a lower comfortable temperature than that of adults (0.5℃ in summer, 3.3℃ in winter)<br>3.There is slightly difference in temperature between boys and girls<br>4.The changes of metabolic rate for preschool are greater than that of adults |
| (Conceicao, et al., 2012) | Portugal, Kindergarten | 2012 | 3、4 and<br>5 years old preschool children | 1.The thermal adaptive model was established by combining experimental measurement with subjective questionnaire<br>2.The preschool children were divided into three different groups of trained children<br>3.In the cold and warm thermal conditions of different classrooms, all the subjects gave their subjective thermal sensation | 1.The thermal adaptive model of preschool children was obtained<br>2.Thermal comfort was evaluated according to the Fanger model, and the result was uncomfortable |
| (Fabbri, 2013) | Italy, Kindergarten | 2013 | 4-5 years old preschool children | 1.There are two methods to evaluate the thermal sensation of preschool children: quantitative method and objective method | 1.The PMV of children is slightly higher than that of adults<br>2.The results of study emphasized that the adaptive |

| | | | | | |
|---|---|---|---|---|---|
| | | | | 2.According to the kindergarten teaching method of "Loris Malaguzzi" The questionnaire were modified by educators of school<br>3.This particular approach demonstrate that how preschool children understand the concepts of the temperature or thermal sensation | method must be considered from the perspective of psych-pedagogy. Meanwhile the questionnaire must be refined and revised. In order to ensure the preschool children can better understand concepts of temperature etc. |
| (Yue, et al., 2009) | China,<br>11 Kindergartens | 2009 | Preschool children | 1.Through the survey of the child care staff in the form of questionnaires,<br>2.Using the observational experiment method | 1.The study emphasizes that preschool children lack of the ability and experience to accurately express their subjective feelings. Thus, it is inappropriate to directly use the subjective evaluation test to collect children's subjective feelings in the survey<br>2.The difference in metabolism and activity level is the reason for the difference in thermal sensation between children and adults<br>3.In the unit of children's activity, indoor air humidity between 50% and 60% is conducive to meeting children's thermal comfort requirements |

## 4. Conclusion

The preschool children do not have sufficient subjective judgment and independent behaviour. Thus the thermal sensation of preschool children about their surrounding thermal environment cannot be expressed subjectively. Although there are more and more studies on thermal comfort of children in recent years, they are based on the investigation of school children aged from 7 to 17 years old. However, the preschool age from 3~6 years old have been investigated relatively few. It is hard to achieve the accurate feeling of preschool children by using thermal sensation questionnaire. Thus it is very worthy to find another appropriate method of evaluate the actual thermal sensation of preschool children.

According to the pre-prepared questionnaire survey of information of preschool children, maybe lead to have better understand of preschool children and in future used for thermal sensation investigation of children. In this paper, a questionnaire survey was conducted among 20 preschool children families. The age of preschool children are 3-6 years old. From the questionnaire survey results found that the majority of parents estimate the cold/hot feeling of their children by touching the back. However, the further research needed to determine whether these methods are suitable accurately for preschool children to estimate the cold/hot feeling.

Due to the different of activity level, metabolic rate and perception of preschool children, result in the difference of thermal sensation between adults and children. Furthermore it is difficult for preschool children to change the discomfort sensation caused by the thermal environment through the regulation of their own behaviour. Following the above study performed by conclusion, to understand the actual thermal sensation of preschool children is significant and to solve the problem of thermal comfort for preschool children.

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# TheEnvironmental design criteria for the university buildings in the Northern and Southern regions of the UK

**Mina Jowkar1, Hom Bahadur Rijal2, James Brusey1, Alenka Temeljotov-Salaj3**

[1] Faculty of Engineering, Environment and Computing, Engineering and Computing Building, Coventry University, Priory Street, CV1 5FB, Coventry, United Kingdom
[2] Faculty of Environmental Studies, Department of Restoration Ecology & Built Environment, Tokyo City University, Yokohama Campus, 3-3-1-Ushjkubo-nishi, Tsuzuki-ku, Kanagawa, 224-8551, Yokohama, Japan
[3] Department of Civil and Environmental Engineering, Norwegian University of Science and Technology (NTNU), Building Engineering, 2-233, Gløshaugen, Trondheim, Norway

**Abstract:**
Considering the prevalence of the different climatic conditions in Northern and Midland regions of the UK, this study investigated the occupants' thermal comfort requirements in two university campuses in Scotland and England, UK. The aim of this investigation is to develop a practical, energy-efficient, and thermally comfortable environmental guideline for university classrooms. Indoor environmental measurements were combined with a simultaneous subjective monitoring through a questionnaire survey and observation in two university buildings in Edinburgh (Scotland) and Coventry (England), UK. Field study conducted during academic year of 2017-18 on 3511 university students in the classrooms involved in sedentary activities. Results confirm the influence of students' acclimatization to Scotland and England climates indicating warmer than neutral thermal sensation, cooler thermal preferences, and higher neutral temperatures in England compared to Scotland. In terms of thermal acceptability, an indirect approach (considering the central three thermal sensation votes) is a better predictor of the thermally acceptable zone compared to the direct evaluation approach (analysis of acceptability votes in the questionnaires).
**Keywords:** Thermal comfort, Higher learning environments, Thermal acceptability, Comfort temperature, Thermal satisfaction

## 1. Introduction

European educational buildings are responsible for a considerable part of energy use for heating purposes. In the UK, space heating is reported as the largest and the most expensive source of energy consumer (58% of total energy) in education sector (Carbon Trust, 2010). Higher learning environments in the UK demonstrated a strong commitment to global efforts to combat climate change over the last decade through reducing harmful emissions (Paul and Patton, 2018). Therefore, carbon reduction targets and strategies have been developed for higher learning environments in England (UK Universities, 2013), Scotland, Wales and Northern Ireland (Paul and Patton, 2018), to move towards healthier indoor environments (Clarke et al., 2008). However, given the significant influence of the thermal environment on students' well-being and productivity in educational buildings (Pepler and Warner, 1968; Wyon, Andersen and Lundqvist, 1979; Witterseh, Wyon and Clausen, 2002), occupants' comfort requirements should not be overlooked in such environmental considerations. This suggests a strong understanding of the occupants' thermal requirements to design a practical, thermally comfortable and energy efficient environmental criteria for university buildings.

The subjective nature of thermal comfort perception is well known in the existing literature (de Dear and Brager, 1998; McCartney and Nicol, 2001, 2002; Nicol, Humphreys and Roaf, 2012). Shipworth et al. (Shipworth et al., 2016) and Schweiker et al. (Schweiker et al., 2018) categorized the influencing human characteristics on perception of thermal comfort into the physiological and psychological properties resulting from contribution of the core body heat generation and state of mind, respectively.

Human body can physiologically adapt to a thermal environment as a result of, so called, "thermoregulation" (Humphreys, Nicol and Roaf, 2015), which maintains individual's comfort against thermal environmental fluctuations (Schweiker et al., 2018). As an example, repeated exposure to cold or warmth can decrease or increase core body heat generation, and subsequently make a subject cold or heat adapted, respectively; and change the perception of a thermal environment accordingly (Schweiker et al., 2018). Warmer thermal expectations of the subjects in warmer climate of Malaysia than Japan (Zaki et al., 2017), the relation between the outdoor temperature and neutral temperature in hot climate of Indonesia (Karyono, 2008) and thermal sensitivity of the subjects to cold in hot-humid climate of China (Zhang et al., 2010) confirm the role of climatic adaptation in thermal comfort evaluations. Overall, acclimatization and its impact on thermal perception is already confirmed in university buildings in China (Yao, Liu and Li, 2010; Zhang et al., 2010; Wang et al., 2014), India (Mishra and Ramgopal, 2014a, 2014b), Indonesia (Karyono, 2008), Malaysia (Zaki et al., 2017) and Brazil (C. Cândido et al., 2010; Christhina Cândido et al., 2010), suggesting that the same comfort environmental criteria cannot be applied for different climates (Rupp, Vásquez and Lamberts, 2015).

In the UK, climatic condition differs from region to region. In the Northern areas the weather is cold, damp, windy and rainy for most of the year. Mean daily temperature drops to 4–5°C in winter and goes up to 14–19°C in winter and summer months, respectively. In the Southern parts it is normally temperate, cloudy and sometimes windy in winters. Mean daily temperature is approximately 3–6°C during winter and 19–23°C during summer in the Northern areas (World climate guide, 2019).

Given the human body thermoregulations and physiological thermal adaptation, such climatic differences may lead to diverse thermal perceptions and heating energy demands in different regions of the UK. Thus, this study aims to investigate the thermally comfort and acceptable temperature ranges in university classrooms in the Northern (Scotland) and Southern/Midland (England) regions of the UK.

## 2. Methods

Field experiments took place during the academic year of 2017 – 2018 (i.e. from October 2017 to March 2018) in classrooms in two university campuses in Coventry, England (52.4068° N, 1.5197° W) and Edinburgh, Scotland (55.9533° N, 3.1883° W), United Kingdom (UK). Case study buildings operated on changeover or concurrent mixed modes (Brager, Borgeson and Lee, 2007). Space heating was available through ceiling diffusers or radiators and space cooling was provided through ceiling ducts or floor cooling outlets. Operable windows and fresh air supply ducts were available for ventilation purposes.

Indoor air temperature (Tin), relative humidity (RH), air velocity (Vi) and mean radiant temperature (Tmr) were measured using Multi purposes SWEMA 3000 (Universal instrument, 2019) instrument (working based on ISO 7730) (Table 1). Indoor air temperature and mean radiant temperature probes were positioned at 1.1 m above the floor level, as recommended by EN ISO 7726 (EN ISO 7726, 2001) on a vertical stand. SWEMA kit and one temperature and

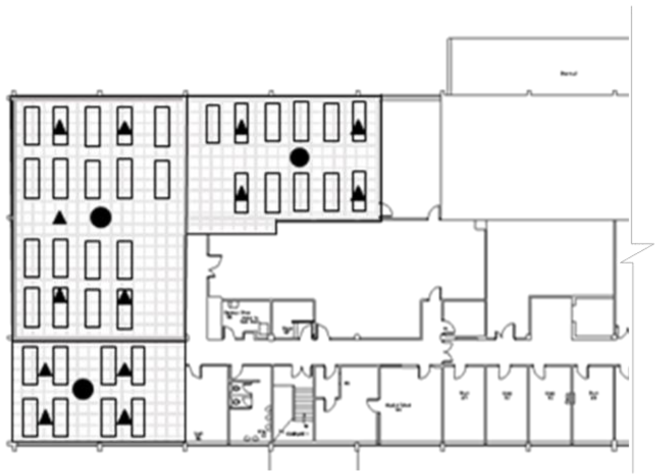
RH logger were placed in the middle of the room, away from the heat/cool sources to register the prevalent ambient environment in the classrooms. Also, six temperature and RH loggers were placed around the room close to the students to register the nearest environmental data to their sensations. Figure 1 indicates the position of the probes and temperature/RH loggers in some type of the classrooms.

Table 1. Description of the instruments

| Measured parameter | Resolution | Range | Accuracy |
|---|---|---|---|
| **Mean radiant temperature (°C)** | **0.1** | **0 - 50** | **±0.1** |
| **Air velocity (m/s)** | **0.03** | **0.05 – 3.00** | **±0.04** |
| **Relative humidity (%)** | **0.8** | **0 - 100** | **±0.8** |
| **Air temperature (°C)** | **0.1** | **−40 - 70** | **±1.0** |

Paper-based questionnaire surveys were conducted on 3511 students (2049 in Coventry and 1458 in Edinburgh) after at least 1-hour of students sitting in the classrooms. All the participants were sitting and listening to the lecturers during the measurements (metabolic rate of 1.1 met (ASHRAE 55, 2017)). They were of both genders with average age of 22 years old in both locations.

Thermal sensation vote (TSV) and thermal preferences (TP) were examined in the questionnaire, based on the ASHRAE 7-point scale (Table 2). Thermal acceptability was also assessed through the direct question of “How do you find the thermal condition of the classroom at this moment?” with the 4-point scale shown in Table 2. Clothing insulation value was evaluated using a checklist covering both underwear and outer garments as per in EN ISO 7730 (EN ISO 7730, 2005). Participants were asked to select the worn clothes at the survey time.



● Black bulb thermometer, RH and air velocity probs

▲ Temperature and RH logger

Figure 1. Position of the instruments in the classrooms of two buildings, as an example

Collected data were statistically analysed to estimate the acceptability, neutrality and preferred temperature in which the majority of students were thermally satisfied. Mean value of the recorded environmental variables in the last 15 minutes of each class (during the period of questionnaire survey) was considered for data analysis. Outdoor air temperature data was obtained from the UK meteorological office (WOW Met-Office, 2019). The weather station was less than 5 km from the study site and thus likely to be representative.

Table 2. Thermal comfort scales in the survey questionnaire

| Scale | −3 | −2 | −1 | 0 | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|
| **Thermal sensation (TSV)** | **Cold** | **Cool** | **Slightly cool** | **Neutral** | **Slightly warm** | **Warm** | **Hot** | |
| **Thermal preference (TP)** | **Much warmer** | **Warmer** | **Slightly warmer** | **No change** | **Slightly cooler** | **Cooler** | **Much cooler** | |
| **Thermal acceptability (TA)** | | | | | **Clearly acceptable** | **Just acceptable** | **Just unacceptable** | **Clearly unacceptable** |

Operative temperature was calculated as the mean of radiant temperature and indoor air temperature for air velocity below 0.2 m/s and through the following formula for the higher air velocity (ASHRAE 55, 2010a). Where $T_{op}$ is operative temperature, A is the constant value introduced as 0.6 (ASHRAE 55, 2010a), $T_{air}$ is indoor air temperature and $T_{mr}$ is the mean radiant temperature.

$$T_{op} = \mathrm{A} \cdot T_{air} + (1 - \mathrm{A})T_{mr} \tag{1}$$

## 3. Results and discussion

The environmental thermal comfort indices during the survey is summarizes in Table 3. Mean outdoor air temperature was higher in Coventry than Edinburgh. However, mean indoor operative temperature, indoor air and mean radiant temperatures are approximately 1°C lower in Coventry than Edinburgh. Indoor air velocity was low and mean indoor RH is almost in a similar range in both locations. Mean thermal sensation votes of $-0.1$ and $0.4$ in Coventry and Edinburgh, respectively shows that occupants in Coventry feel cooler than their counterparts in Edinburgh. This is confirmed by the warmer thermal preferences in Coventry and cooler preferences in Edinburgh (Table 3).

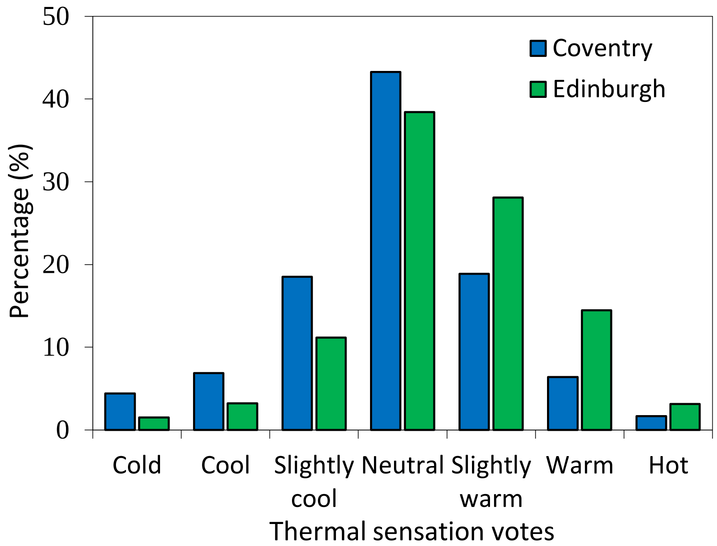
Table 3. thermal comfort indices

| Location | Variables | Number | Mean | S.D. |
|---|---|---|---|---|
| **Coventry** | $T_{out}$ | 2051 | 11.2 | 4.1 |
| | $T_{air}$ | 2051 | 22.9 | 1.6 |
| | $T_{mr}$ | 2051 | 22.6 | 1.6 |
| | $T_{op}$ | 2051 | 22.8 | 1.6 |
| | RH | 2051 | 45 | 12 |
| | $V_i$ | 2051 | 0.07 | 0.03 |
| | Clothing | 1963 | 0.88 | 0.32 |
| | TSV | 2046 | –0.1 | 1.2 |
| | TP | 2041 | −0.04 | 1.1 |
| **Edinburgh** | $T_{out}$ | 1460 | 5.8 | 1.9 |
| | $T_{air}$ | 1460 | 23.9 | 1.6 |
| | $T_{mr}$ | 1460 | 23.5 | 1.1 |
| | $T_{op}$ | 1460 | 23.7 | 1.3 |
| | RH | 1460 | 30 | 6 |
| | $V_i$ | 1460 | 0.04 | 0.04 |
| | Clothing | 1421 | 0.86 | 0.32 |
| | TSV | 1460 | 0.4 | 1.2 |
| | TP | 1459 | 0.30 | 1.1 |

$T_{out}$: Outdoor air temperature (°C), $T_{air}$: Indoor air temperature (°C), $T_{mr}$: Indoor mean radiant temperature (°C), $T_{op}$: Operative temperature (°C), $V_i$: Indoor air velocity (m/s), TSV: thermal sensation vote, TP: thermal preferences, S.D.: Standard deviation

Regarding the distribution of the thermal sensation and thermal preference votes, Figure 2 presents a skewed thermal sensation votes towards colder than neutral side in Coventry and a distinct skewing toward warmer than neutral side in Edinburgh. However, a clear shift toward 'want warmer' and 'want cooler' preference votes can be observed for students in Coventry and Edinburgh, respectively.

(a)




(b)

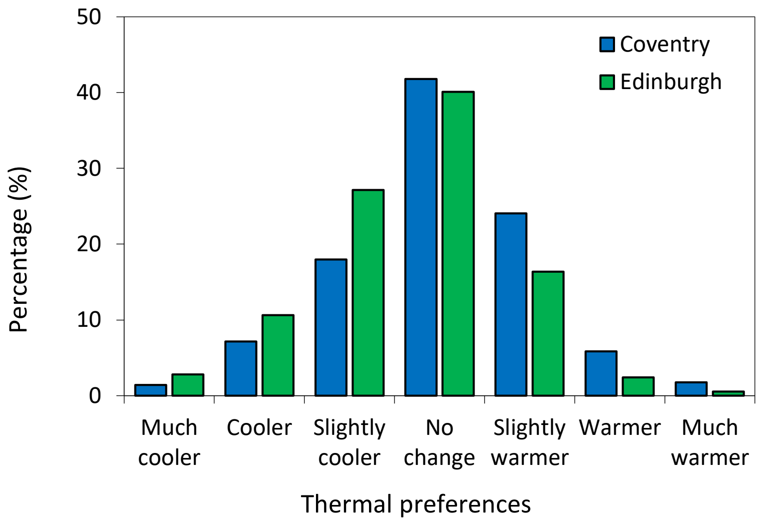



Figure 2. Distribution of thermal sensation (a) and preference(b) votes in Coventry and Edinburgh

### 3.1. Thermal neutrality

Thermal neutrality is determined using a linear regression between the thermal sensation votes (TSVs) and indoor operative temperature, Figure 3. In this work, similar to the previous studies (e.g. Nakano, Tanabe and Kimura, 2002; Wang, 2006), there was a high variety of thermal sensation votes in each indoor air temperature, which is mainly due to the individual differences between the subjects (Shipworth et al., 2016; Schweiker et al., 2018). The raw data caused too low coefficient of determination (R2) between thermal sensation votes and indoor operative temperature, which can be considered acceptable for such type of studies (de Dear and Brager, 1998). Neutral temperature, identified by substitution of 0 for TSV in the equations, is 22.7°C in Coventry and 22.3°C in Edinburgh. Considering regression gradient in the equations, as an index showing how TSVs are dependent on the operative temperature, approximately each 3°C temperature change, leads to variation of one unit thermal sensation vote in a 7-point sensation scale in both Coventry and Edinburgh, which shows similar sensitivity of the occupants to the temperature changes inside the classrooms in both locations.

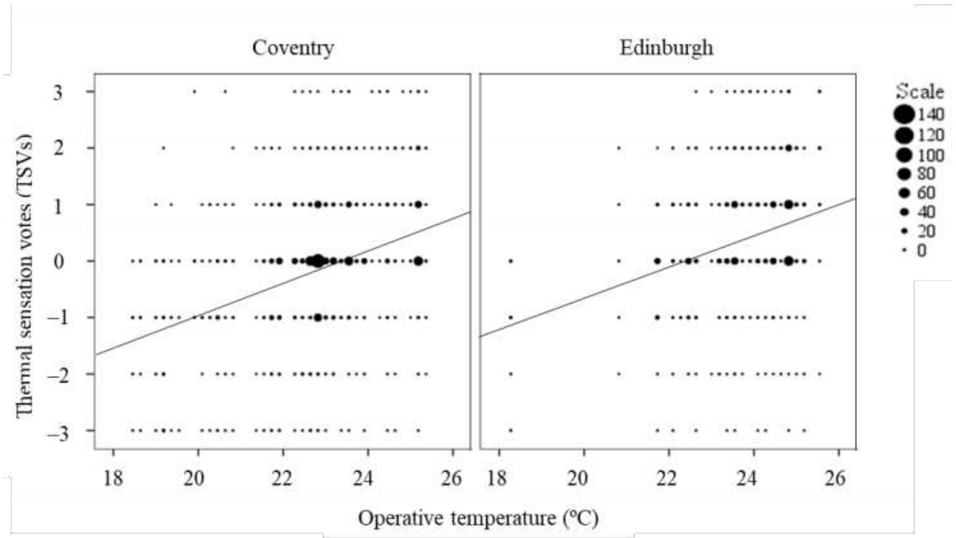



Figure 3. Linea regression of TSV and indoor operative temperature in Coventry (N=2044, $TSV = 0.30\ T_{op} - 6.82$, R2=0.15) and Edinburgh (N=1430, $TSV = 0.29\ T_{op} - 6.47$, R2=0.11)

### 3.2. Preferred temperature

To identify the occupants' preferred temperature, thermal preference votes of 'much warmer', 'warmer', and 'slightly warmer' were classified as 'want warmer' and thermal preference votes of 'much cooler', 'cooler' and 'slightly cooler' were categorized as 'want cooler'. The proportions of warmer and cooler thermal preference votes in relation to the operative temperature was evaluated, as suggested in Jungsoo's and de Dear's studies (de Dear et al., 2015; Jungsoo and de Dear, 2018). In Figure 4, the intersection points between warmer and cooler thermal preference votes is considered as preferred temperature.

The findings in this section is confirmed in some studies showing the influence of acclimatisation on thermal preferences and preferred temperature (Teli, Jentsch and James, 2012; Hwang, 2018; Jungsoo and de Dear, 2018). Results from studies conducted in hot and humid climate of Taiwan (Hwang, 2018), in Australian during summer season (Jungsoo and de Dear, 2018), in the UK during the heating period (Teli, Jentsch and James, 2012) and in Japan, Norway and UK (Shahzad and Rijal, 2019) confirm the gap between the thermal neutrality and preferences.

Table 4 summarizes the equations from probit analysis. Mean temperature is calculated by dividing the constant value by the probit regression coefficient for each equation. Standard deviation is inverse of the regression coefficient. All the equations are statistically significant ($p < 0.001$). Preferred temperature is around 23.5°C in Coventry and 23°C in Edinburgh which is similar in both locations. According to the results from previous sections, preferred temperature is apparently slightly affected by the students' thermal expectation as a result of acclimatisation.

A comparison between the neutral and preferred temperatures shows approximately 1°C higher preferred than neutral temperature in Coventry and less than 1°C higher preferred than neutral temperature in Edinburgh. This suggests that students in both Coventry and Edinburgh may feel comfortable in slightly warmer than neutral thermal sensations. As it is discussed by Shahzad et al. (Shahzad et al., 2018; Shahzad and Rijal, 2019), neutral thermal sensation cannot guarantee thermal comfort of the occupant as the subjects may feel comfortable in thermal sensations rather than neutral. Therefore, thermal preference is shown to be more likely to predict thermal comfort of people in the real world context (Shahzad et al., 2018; Shahzad and Rijal, 2019).

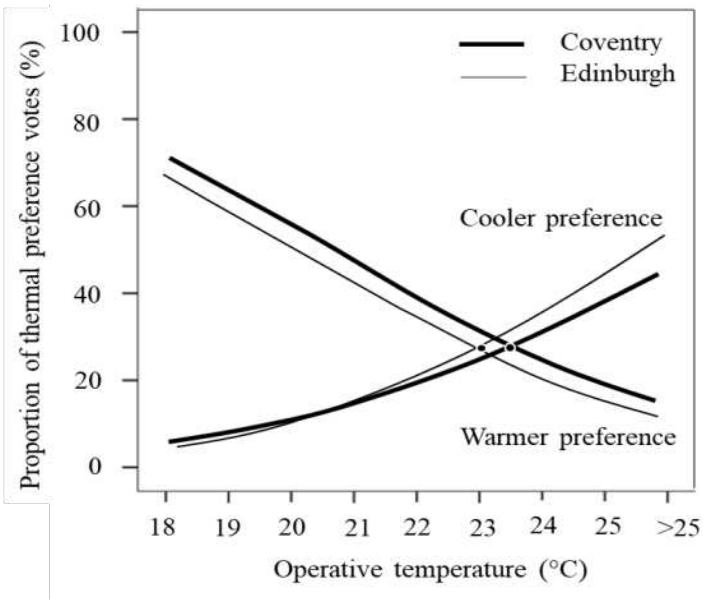



Figure 4. Preferred temperature in Coventry and Edinburgh

The findings in this section is confirmed in some studies showing the influence of acclimatisation on thermal preferences and preferred temperature (Teli, Jentsch and James, 2012; Hwang, 2018; Jungsoo and de Dear, 2018). Results from studies conducted in hot and humid climate of Taiwan (Hwang, 2018), in Australian during summer season (Jungsoo and de Dear, 2018), in the UK during the heating period (Teli, Jentsch and James, 2012) and in Japan, Norway and UK (Shahzad and Rijal, 2019) confirm the gap between the thermal neutrality and preferences.

Table 4. Equations from probit analysis

| Location | Thermal preference votes | Equations | P value | Mean | SD |
|---|---|---|---|---|---|
| **Coventry** | **Warmer preference** | $TP_{warmer} = -0.20\,Top + 0.95$ | < 0.01 | 4.8 | 5.0 |
| | **Cooler preference** | $TP_{cooler} = 0.18\,Top - 1.95$ | < 0.01 | 10.9 | 5.6 |
| **Edinburgh** | **Warmer preference** | $TP_{warmer} = -0.21\,Top + 0.85$ | < 0.01 | 4.1 | 4.8 |
| | **Cooler preference** | $TP_{cooler} = 0.22\,Top - 2.12$ | < 0.01 | 9.6 | 4.6 |

### 3.3. Thermal acceptability

Thermal acceptability level is evaluated with two approaches in this study: 1) an indirect approach: considering the three central thermal sensation votes (TSV= ±1 and 0) on 7-point sensation scale as thermally acceptable range, recommended in (ASHRAE 55, 2010b) and applied in previous studies (Toe and Kubota, 2013; Manu et al., 2016; Zaki et al., 2017); 2) a direct approach: analysing the students' direct responses to the question of "How do you find the thermal condition of the classroom at this moment?" on the 4-point acceptability scale in the questionnaire, Table 2 (Andreasi, Lamberts and Cândido, 2010; Mishra and Ramgopal, 2014b, 2015). In the indirect method, thermal dissatisfaction is considered as thermal sensation votes other than the acceptable zone of –1, 0 and +1 on the 7-point thermal sensation scale (ASHRAE 55, 2017). Therefore, thermal sensation votes of −3 and −2 are recoded as '1, uncomfortably cold' and the other votes recoded as '0, other votes'. The same rule is applied to the warmer than neutral thermal sensation votes where TSVs equal to +2 and +3 are recoded as '1, uncomfortably warm' and the rest are recoded as '0, other votes'. In the direct approach, students vote for "1, clearly acceptable" and "2, just acceptable" are recoded as "1, Acceptable" and the votes for "3, just unacceptable" and "4, clearly unacceptable" are considered as "0, Unacceptable".

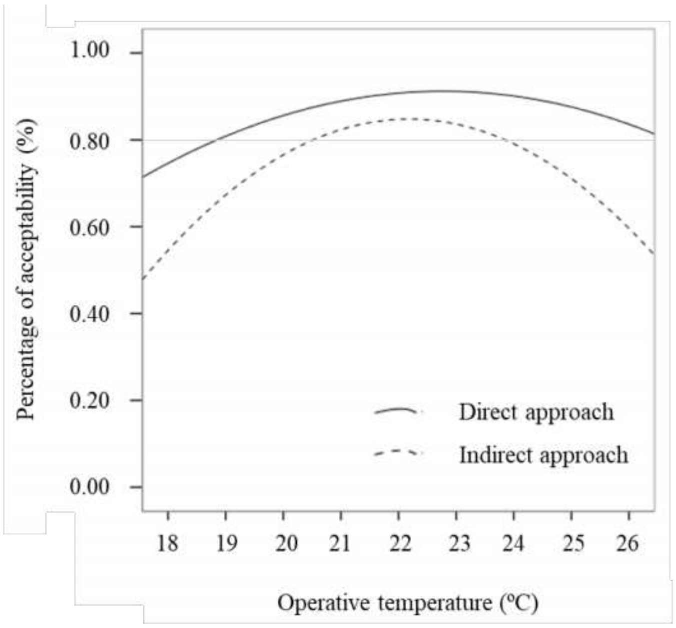



Figure 5. Thermal acceptability in each operative temperature

Thermal acceptability in both methods of evaluation in each 1ºC binned operative temperature is presented in Figure 5. A similar trend can be observed for both approaches with slightly higher acceptability level and a wider range in direct compared to indirect approach. Students in higher learning environments tend to be more forgiving about their thermal environments when consciously evaluating and voting for it, compared to identifying their acceptable zone based on their thermal sensation votes, as recommended in regulatory documents (ASHRAE 55, 2010b). As can be observed, determining the thermal acceptability through indirect approach can already cover the occupants' actual thermal acceptability votes. Therefore, setting the thermal environment based on the indirect method can provide occupants actual satisfaction. However, form an environmental point of view, thermally acceptable temperature range starts from 1.5°C lower indoor air temperature with direct than indirect approach. Thus, setting the classrooms thermal environment based on the results from direct approach may provide a thermally acceptable environment at the same time as saving energy for heating purposes.

Two reasons may contribute to the higher thermal acceptability level in the direct approach; one presumably is due to the students' perception of control on the classroom thermal environment, the impact of which can improve the level of thermal acceptability and lessen their thermal sensitivities in the exposed environment (Nicol et al., 1994; Brager, Paliaga and de Dear, 2004; Rijal et al., 2008; Rijal, Yoshida and Umemiya, 2010). The other reason can be due to the students' diverse physiological and psychological backgrounds resulting in a wide variety of thermal acceptability levels, which could not be predicted through thermal sensation votes in indirect approach.

## 4. Conclusion

This study is part of a comprehensive investigation on thermal performance and the occupants' comfort in the UK higher educational buildings. The potential influencing factors on thermal perception of the occupants in university classrooms are identified and the impact of each is studied. So far, thermal comfort perception of the students in different disciplines in exposure to the various classroom types (Jowkar et al., 2020), thermal comfort of the gender and age groups and the diverse perception of thermal comfort resulted from the students' climatic background, as long-term thermal history, have been investigated by similar authors in the previous works.

Considering the different climatic conditions prevailing in different regions of the UK, this work investigates whether the same thermal environmental criteria can provide comfort in higher learning environments in Southern (Scotland) and Northern regions (England) of the UK. The investigation was conducted in two university campuses in Scotland (Edinburgh) and England (Coventry) in the UK. Simultaneous questionnaire surveys with environmental measurements were conducted in eight mixed-mode university buildings in Edinburgh and Coventry. Overall, 3352 university students were surveyed while being involved in sedentary activities inside the classrooms.

It is concluded in this study that the same environmental criteria for higher learning environments cannot be applicable in Scotland and England. The findings recommend investigating the thermal comfort requirements of the occupants in higher learning environments in different regions of the UK with diverse climatic conditions, which not only provides students comfort and improves their productivity, but also reduces the space energy waste and running cost for heating/cooling purposes.

Furthermore, A comparison between the two methods of thermal acceptability assessments, a direct approach (considering the actual votes of the occupants on thermal acceptability) and an indirect approach (considering the thermal sensation votes between –1 and +1 as acceptable range) shows that in designing the thermal environmental criteria for higher educational buildings, indirect approach is a better predictor of the occupants' thermal acceptability as this method can already cover the students' actual thermal acceptability votes. However, the direct method shows a potential for higher energy saving in university classrooms. Therefore, further investigations on thermal acceptability, occupants' comfort and energy demand is recommended to find the optimum thermal environmental design criteria for the UK university buildings.

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# A multi-domain data collection strategy for capturing relationships between occupant behaviour, comfort, indoor environment, and energy use in offices

**Verena M. Barthelmes[1], Caroline Karmann[2], Dusan Licina[3], Marilyne Andersen[2], and Dolaana Khovalyg[1]**

[1] Thermal Engineering for the Built Environment Lab (TEBEL), École polytechnique fédérale de Lausanne) EPFL, Switzerland
[2] Laboratory of Integrated Performance in Design (LIPID), École polytechnique fédérale de Lausanne) EPFL, Switzerland
[3] Human-Oriented Built Environment Lab (HOBEL), École polytechnique fédérale de Lausanne) EPFL, Switzerland

**Abstract:** A significant corpus of research has shown that occupant behaviour is a key factor of uncertainty when predicting building energy use. Building occupants affect energy use directly and indirectly by regulating their indoor environment according to their comfort criteria and a wide range of contextual, psychological or social factors. Increasing research efforts are being dedicated on developing models able to capture the stochastic nature of the human-building interaction in dynamic simulation programs. However, existing models oftentimes do not include information on multi-domain variables and the global environment. The foundation for the investigation and data-driven modelling of occupant behaviour in the built environment remains measured data, and an effective and extensive data collection remains a key challenge towards gaining a better understanding and modelling of occupant behaviour. This paper provides a structured overview of a monitoring framework for open space offices, eCOMBINE (*"Interaction between **e**nergy use, **COM**fort, **B**ehaviour and the **IN**door **E**nvironment in office buildings")*, aimed at capturing an extensive set of subjective and objective multi-domain variables likely to drive building occupants to perform actions on environmental controls. Towards this end, this paper presents a survey framework and an ad-hoc mobile application developed to capture motivations behind actions in real-time. Finally, we highlight lessons learned and research opportunities one might envision once the collection of such comprehensive datasets will become more mainstream.

**Keywords:** occupant behaviour; open space office; user interface; global environmental comfort; energy use

## 1. Introduction

Improving energy efficiency has become a challenge of primary importance for the building sector, which nowadays accounts for approximately 40% of the global energy demand and generated annual global GHG emissions (European Commission 2010). Increasing effort is put on designing high performing and adaptive buildings that can hit energy performance targets while considering comfort preferences of the occupants. Dynamic Building Performance Simulation (BPS) tools are increasingly used by researchers and practitioners to gain a more precise understanding of the underlying processes of energy flows and to optimize building design and energy use. Despite advances in the field of BPS tools, simulation outcomes are still prone to errors due to a variety of factors such as non-linearity, discreteness, and uncertainty (Hopfe and Hensen 2011). ASHRAE (2007) states that neither the proposed building performance nor the baseline building performance represent actual energy consumption after construction, but that the key items from the listed sources of uncertainty are strictly related to occupancy and building operation. Hence, nowadays, the building energy research community is aware of the pivotal role that occupant behaviour has on impacting both building energy demand and the quality of the indoor environment (Masoso and Grobler 2010; Mahdavi 2011). To reduce current inconsistencies in building energy simulation, several probabilistic and data-driven modelling approaches have been developed, and integrated into advanced simulation programs to account for uncertainties related to human factors when predicting building energy consumption (Hong et al. 2018). These approaches include models for occupancy patterns, occupants' activities, adjustment of thermostat settings, or usage of plug-in appliances, and sometimes also aim to anticipate the operation of windows and lighting controls or the regulation of window blinds/shades as functions of various environmental and contextual drivers (Gaetani et al. 2016).

### 1.1 State-of-the-art

Yan et al. (2015) have attempted to describe the current state and future challenges in occupant behaviour modelling, where they emphasized the many remaining knowledge gaps and the limitations of current methodologies. The same authors also highlighted the importance of moving towards more comprehensive modelling procedures of occupant behaviour, acknowledging that the latter might be influenced by multiple contextual and personal factors. Oftentimes existing models do not yet accurately cover an extensive set of potential drivers and/or do not include qualitative model inputs (e.g. individual characteristics and preferences over the indoor environment). Indeed, individuals tend to perceive the indoor environment in different ways based on multiple factors to which they give a variable importance, to have different motivations and habits, and/or to sometimes be conditioned by certain constraints (e.g. social or technical) when it comes to adjusting their own environment to their liking. While many studies have linked human factor to single comfort-related stimuli, a comprehensive understanding and, therefore, evaluation of environmental comfort, addressing thermal comfort, visual comfort, acoustic comfort and indoor air quality together, seems to be necessary before being able to establish causal relationships with occupant behaviour. The new IEA-EBC Annex 79 "Occupant-Centric Building Design and Operation" (IEA 2019) represents an international effort towards understanding the exposure of the occupant to a multi-dimensional environment and its impact on behaviour and comfort. A key challenge in this endeavour will be to better understand how multiple, interdependent indoor environmental factors may trigger occupant actions.

A number of researchers have put effort on developing more comprehensive IEQ monitoring systems to assess the quality of buildings (Parkinson et al. 2019, Heinzerling et al. 2013, Alavi et al. 2017). However, despite the advancements in our understanding in separate fields of comfort (visual, thermal, indoor air quality (IAQ), acoustics), the question of how the combined effect of IEQ factors affects the ultimate users' perception and behaviour in real buildings has not yet been answered (Schweiker 2017). For example, while a large number of studies addresses the relationship between behaviour and thermal, IAQ, and visual aspects, the acoustic dimension has been mostly overlooked. This gap might also be due to the fact that researchers focus on their own area of expertise and priority is not given to analyse the global environment as such, neither in direct relation to human-building interactions. Multidimensional comfort studies would ideally require a collaboration between experts in different areas to achieve high quality results. Furthermore, multi-dimensional monitoring campaigns can turn out to be costly, leading to restrictions in the feasibility of this type of studies (Parkinson et al. 2019). The high cost of such complex monitoring campaigns can also limit the type and the number of buildings or space typologies (small private vs. open space offices) that can realistically be selected as case studies, the number of observed occupants, and/or the duration of the study, which in turn will limit the generalisation potential of the gathered datasets. To develop more reliable models, we need comprehensive datasets, that capture key variables both related to the environment and to the occupants (Wagner et al. 2017). And to be able to rely on different datasets – each one having its own limitations – to build a more comprehensive understanding, they must be comparable and thus be collected with a consistent data collection strategy (Yan and Hong, 2018), so that they can be replicable.

### 1.2 Towards a multi-dimensional approach

The newly-developed eCOMBINE framework (*"Interaction between **e**nergy use, **COM**fort, **B**ehaviour and the **IN**door **E**nvironment in office buildings"*) aims at contributing to new knowledge on the human-building interactions in office environments, with a dedicated focus on open plan offices, by developing an integrated approach to study the cause-effect relationships between occupant behaviour and combined indoor environmental factors (thermal, visual, air quality and noise). The data collection involves environmental variables, including the 4 IEQ categories (thermal, IAQ, visual, and acoustics), occupant's input (personal characteristics, comfort perception and actions) through point-in-time and long-term surveys. Surveys indeed remain important to understand the experience and motivation of users, while physical measurements of the occupants' environment provide an objective characterization of the indoor and outdoor conditions that they are exposed to.

The objective of this paper is to provide insights on the multi-dimensional eCOMBINE data collection framework. This framework includes a monitoring of the four key dimensions of the indoor environment (thermal, IAQ, visual, acoustic) performed simultaneously with a survey of the occupants' preferences and action triggers. To conduct the latter, an ad-hoc mobile application named OBdrive was developed, that captures the perceived motivations behind interactions with building controls.

## 2. The eCOMBINE monitoring framework

The eCOMBINE data collection framework aims to capture relevant variables to describe the relationship between the indoor and outdoor environment, global environmental comfort, occupant behaviour and energy use, as illustrated in Figure 1. With the term "global environmental comfort" the authors refer to an overall comfort estimation based on occupant's subjective votes from four IEQ categories, namely: thermal, visual, olfactory, and acoustical comfort. The data in this research project consists of newly collected and falls into four key categories: (i) environmental factors, (ii) occupant behaviour indicators, (iii) energy consumption, and (iv) answers to a survey. The objective is to highlight key influencing factors and the most relevant motivations behind the interaction occupants have with controls, in relation to their perception of comfort and physical measurements of the environment. To be able to reveal potential seasonal effects, the study was carried out in different seasons for a minimum of two weeks in selected open space office buildings with a minimum of 40 participants in total for each monitoring campaign.

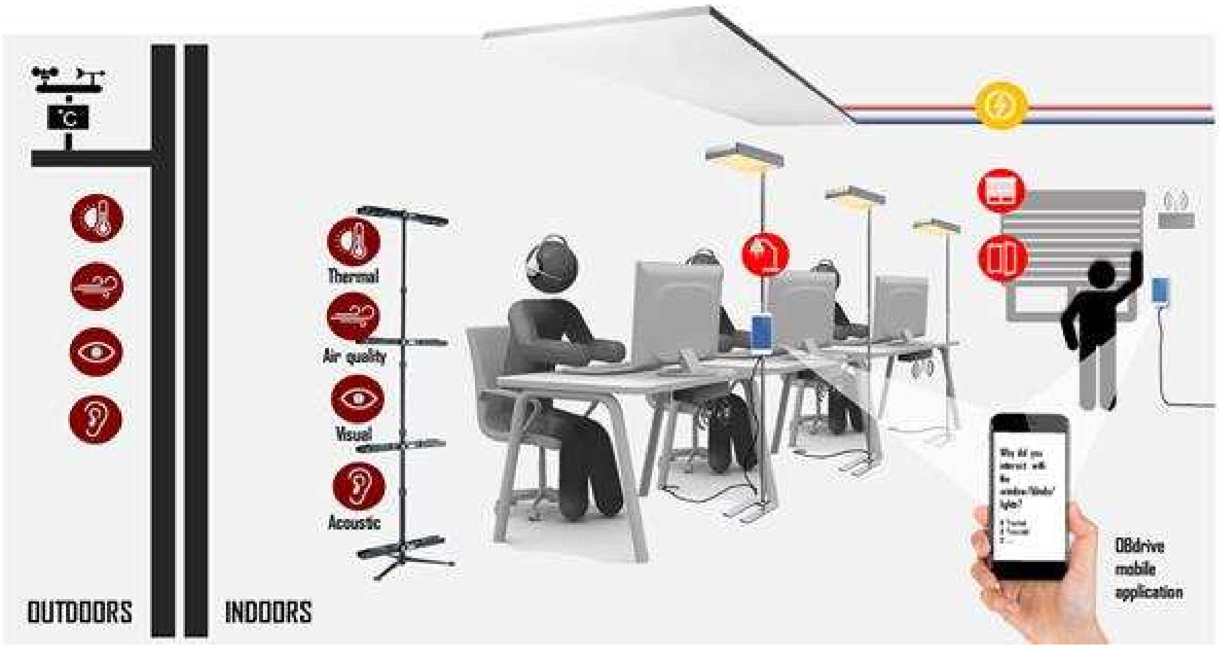


Figure 1. Simplified rendering of the eCOMBINE campaign used to inform occupants on the environmental, behavioural and energy monitoring (burgundy, red and yellow logos). Occupants are triggered to report comfort and motivation via desktop and app surveys.

## 2.1. Environmental data

The detailed list of measured physical variables (and their associated sensors) can be found in Table 1. The variables are classified by IEQ categories: thermal comfort, indoor air quality, lighting and acoustics.

### 2.1.1. Thermal environment

Data on a wide range of thermal variables were collected in order to capture global microclimate and local discomfort parameters. Air and globe temperature, relative humidity, and air speed were measured at the desk level of occupants (between 0.7 and 1.2 m height). Draft rate, vertical air temperature difference between the ankle and head level, and radiant temperature asymmetry (in vertical and horizontal plane) were measured to evaluate local thermal discomfort. In addition, outdoor environmental measurements were taken with a dedicated weather station installed on-site, that monitored outdoor air temperature, relative humidity, precipitation, wind speed, wind direction, and solar radiation.

### 2.1.2. Indoor Air Quality

In order to better understand whether and to what extent office workers were exposed to various airborne pollutants, the eCOMBINE project monitored the temporal and spatial variation of gaseous and particulate air pollutants at multiple locations in the office environment. Specifically, five types of sensors were used for monitoring seven major air pollutants indoors and outdoors, including carbon dioxide ($CO_2$), total volatile organic compounds (TVOC), formaldehyde, ozone ($O_3$), carbon monoxide (CO), nitrogen dioxide ($NO_2$), sulphur dioxide ($SO_2$), and particulate matter smaller than 2.5 microns ($PM_{2.5}$).

### 2.1.3. Visual environment

Visual comfort, views and lighting conditions play a fundamental role in ensuring a satisfying and healthy occupant experience in buildings. Discomfort glare is known to be one of the major sources of complaints in offices and was thus part of the key factors to monitor. On the other hand, we have in the last 20 years become increasingly aware of the critical role played by light in synchronizing our internal clock. The so-called non-image forming effects of light, mediated by the intrinsically photosensitive Retinal Ganglion Cells (ipRGCs), have a demonstrated impact on human health and well-being, and must thus be carefully taken into account when discussing the environmental quality of the workplace (Amundadottir et al. 2017). Of particular importance to those effects are the intensity, spectrum and timing of the light exposure, as it may trigger both phase-shifting (circadian, e.g. impacting sleep quality) and acute effects (e.g. impacting alertness). This project offered the first opportunity to continuously measure both light spectrum and intensity in a Post-Occupancy Evaluation (POE).

#### 2.1.4. Acoustic environment

Workspace noise can cause stress or fatigue and be distracting, resulting in a decrease of productivity. Despite its importance in the perceived quality of a workspace, acoustic quality remains a difficult parameter to assess in the context of post-occupancy evaluations, mostly because of the evaluation method. As measurements typically require some form of recording, they are often perceived as intrusive. In this project, it became a priority to address privacy concerns through a careful selection of the measurement device: the chosen approach was to record sound pressure level integrated over time as well as at the different octave bands without recording people's conversations while they work.

Table 1. Summary table of the physical measurements for the four IEQ categories.

| | I/O(1) | Parameter(2) (unit) | Accuracy | Sensor | Frequency/Location |
|---|---|---|---|---|---|
| **Thermal environment** | I | $T_a$ (°C) | ±0.15°C | Digital thermometer | every 5'/every 2-3 workstation |
| | | $T_{globe}$ (°C) | ±0.15°C | Digital thermometer | |
| | | RH(%) | ± 2.5% | RH sensor embedded in the datalogger | |
| | | Radiant temperature asymmetry | ±0.20°C | Thermocouples (T-type) | |
| | | Air velocity (m/s) | ±0.02 m/s ± 1.5% of reading | Omnidirectional anemometers | every 0.2'/every 2-3 workstation |
| | O | Ta (°C) | ±0.60°C | Digital weather station | every 5'/roof |
| | | RH (%) | ±3% | | |
| | | Solar radiation (W/m$^2$) | ±5% of measurement | | |
| | | Wind speed (m/s) | ±0.3 m/s | | |
| | | Wind direction (°) | ±5° | | |
| | | Precipitation (mm/h) | ±5% of measurement | | |
| **Air quality** | I | $CO_2$ (ppm) | ±50 ppm ±5% of reading | Nondispersive infrared (NDIR) CO2 logger | every 5'/every 2-3 workstation |
| | | CO (ppm) | ±2 ppm | Multigas sensor | every 5'/every 2-3 workstation |

| | | | | | |
|---|---|---|---|---|---|
| | | $SO_2$ (ppm) | ±2 ppm | | |
| | | $O_3$ (ppm) | ±2 ppm | | |
| | | $CO_2$ (ppm) | ±3% of reading (ppm) | | |
| | | Formaldehyde (ppb) | LOD[(3)] < 5 ppb | | |
| | | TVOC (ppb) | LOD[(3)] < 5 ppb | | |
| | | $CO_2$ (ppm) | ±7% of reading (ppm) | Air quality sensing module | every 15'/every 2-3 workstation |
| | | TVOC (ppb) | ±14% of reading (ppb) | | |
| | | $NO_2$ (ppb) | ±30 ppb | | |
| | | $PM_{2.5}$ mass (μg/m3) | ±10 μg/m$^3$ ($PM_{2.5}$) | | |
| | O | $CO_2$ (ppm) | ±7% of reading (ppm) | Air quality sensing module | every 15'/roof |
| | | $NO_2$ (ppb) | ±30 ppb | | |
| | | TVOC (ppb) | ±14% of reading (ppb) | | |
| | | $PM_{2.5}$ mass (μg/m3) | ±10 μg/m$^3$ ($PM_{2.5}$) | | |
| **Visual environment** | I | Illuminance meter (lux) | ±10% of reading (lux) | Photodiode sensor connected to a data logger | every 5'/every 2-3 workstation (horizontally-mounted) |
| | | Spectral intensity (W/m$^2$/nm) | ±25nm resolution | Optical spectrometer sensor with embedded data logger | every 5'/near each façade and near the core (vertically- / horizontally-mounted) |
| | | High Dynamic Range (HDR) image | - | Digital single-lens reflex camera | 1x per season (spot measure)/every 2-3 workstation |
| | | Luminance meter (handheld) (cd/m$^2$) | ±2% ±1 digit of reading (cd/m$^2$) | Luminance Meter | 1x per season (spot measure)/every 2-3 workstation |
| | | Illuminance meter (handheld) (lux) | 7% of reading (lux) | Photodiode sensor (hand held device) | 1x per season (spot measure)/every 2-3 workstation |
| | O | Global (Total) and Diffuse irradiance (W/m$^2$) | 5% ±10 W/m$^2$ | Pyranometer | every 5'/roof |
| **Acoustical environment** | I | SPL across the octaves (dB) | | Integrating averaging sound level meter | every 1'/every 2-3 workstation |

(1) I/O = indoor/outdoor

(2) Acronyms used for the parameters: Ta = indoor air temperature, Tglobe = globe temperature, RH = relative humidity, CO = Carbon monoxide, $CO_2$ = Carbon dioxide, TVOCs = Total Volatile Organic Compounds, $NO_2$ = Nitrogen dioxide, $SO_2$ = Sulfur dioxide, $O_3$= Ozone, PM=Particulate matter, SPL = Sound pressure level

(3) LOD = limit of detection

## 2.2. Occupant Behaviour

In the eCOMBINE pilot study, four different types of occupant behaviours were tracked: window control, window blinds control, light switching and occupancy (Table 2). Thermostat and mechanical ventilation controls were neglected since occupants in the planned pilot case studies did not have direct control over the space heating and cooling system. If in future case study buildings such kinds of controls were to be available, these types of human-building interactions should also be tracked through the building management system or a dedicated sensor network. If employees have no control over space heating, cooling, and mechanical ventilation systems, operating windows and blinds remain the only possible (human-building) actions that allow for improving thermal comfort. The impact on energy use of these not automatically controlled interactions needs to be carefully evaluated and is a main point of investigation of the eCOMBINE project.

Table 2. Summary table of measurements for occupant behaviour tracking.

| Behaviour | Parameter | Sensor | Frequency/Location |
|---|---|---|---|
| Window control behaviour | Window state position | Bluetooth enabled low energy contact sensors | Event-based/on window frame |
| Window blinds control behaviour | Window blinds position | Wireless window blinds | Event-based/on slats |
| Light switch behaviour | Instant power | Wireless smart plug load meter | 1'/on desk light plugs |
| Occupancy | Presence at desk | Wireless occupancy sensor | 5'/under each desk |

## 2.3. Energy metering

The monitoring of energy use by HVAC systems, one of the main energy users in office buildings, is essential for bridging the gap between the real performance with predicted values from building energy simulation outcomes. Monitoring approach and instruments to measure energy use should be selected based on the specifics of the BMS system and HVAC system installed in the case study building. If energy metering is pre-installed in the case study building, it is possible to get direct measurements. However, in some cases, no direct metering of the energy usage by the HVAC system is possible either because of no energy metering pre-installed or no possibility to retrieve energy use for conditioning and ventilation of a particular zone. It was the case in the COMBINE pilot study, where studied office areas were in large office buildings. The energy use by the HVAC system was indirectly measured by recording thermal energy removed or supplied to space by the thermal conditioning system and required pre-conditioning of fresh air for adequate ventilation. Heating and cooling in one case study office were provided by radiant ceiling panels, while only radiators for heating were used in the second case study office. Heat supplied/removed from the space was measured using heat flux sensors placed directly on each heating/cooling surfaces. Supplied fresh air for ventilation was pre-conditioned in one of the case study spaces, and thermal energy provided for pre-conditioning was estimated by knowing the volumetric air flow rate and the temperature difference between the outdoor air and air supplied into office space. The volumetric air flow rate was measured at the air supply diffusers by means of a ventilation hood and dedicated read-out device, while hourly air temperature difference was taken from the BMS system.

### 2.4. Survey framework

The eCOMBINE project relies on a mixed experimental approach that combines environmental measurements with subjective responses of the occupants. The study involves two types of long-term (LT) questionnaires and three types of point-in-time (PIT) questionnaires, as detailed in Table 3 and 4, respectively.

The LT surveys were designed to gather occupant's background information and general comfort perception. They fall into two categories:

- **LT-A** captures employees' general personal data and information not sensitive to seasonal variations (e.g., personal characteristics, work routines, global personal preferences). It occurs only one time over the entire study.
- **LT-B** captures the occupant's general comfort preferences, perception, satisfaction, knowledge of control, and usual group dynamics in the office. As these responses might change with seasons, this survey was conducted at the end of each seasonal monitoring campaign.

Table 3: Detail of the eCOMBINE long-term surveys.

| **Survey type / name** | **Contents** | **Timing (duration)** | **Tool** |
|---|---|---|---|
| LT-A: Background information of the participants | ● Background (gender, age, height, weight, eye colour, use of glasses or lenses, origin, time spent in the country/at this office space)<br>● Workstation & working routines (position, location on floor plan, working days / week, type of office work)<br>● Personal comfort perception: sensitivity (5-pt scale) and preferences (5-pt scale) to temperature, air freshness and air movement, light, noise.<br>● Perception and satisfaction (7-pt scale) of control (perceived control related to the thermostat, windows, window blinds, desk lights, ceiling lights, and mechanical ventilation; level of difficulty to interact with controls; satisfaction (7-pt scale) with controls, preferences in terms of manual or automatic controls)<br>● Control and group dynamics (environmental control decision-makers, most important reasons when taking an action, (dis)agreement with energy- and action-related statements) | once (at the start of the study)<br>(10') | PC (triggered by e-mail) |
| LT-B: Seasonal perception of global (dis)comfort | ● Workstation & working routines (position, location on floor plan, working days / week, type of office work)<br>● Satisfaction with the indoor environment over the past two weeks (satisfaction with the thermal, IAQ, visual, acoustic environment; investigation of causes for dissatisfaction and discomfort)<br>● Control and interaction (frequency of reporting the action on the app, frequency of discussions/negotiation with co-workers, causes for not interacting with controls)<br>● Adaptive opportunities (selection and ranking of actions taken when feeling too hot/cold) | 1x /season<br>(5-10') | PC (triggered by e-mail) |

PIT surveys were designed to gather direct feedback on comfort perception and on motivations behind occupants' interactions with controls over the two weeks of monitoring that were run during each season. They fall into 3 categories:

- **PIT-A** captures occupants' general perception of experience comfort 'right-now'. It touches all 4 IEQ categories. It occurs twice a day, at specific times of the day. Occupants are invited via an email to complete the survey on their desktop.
- **PIT-B and PIT-C** capture the occupants' actions, motivation behind these actions and group dynamics (social interactions). PIT-B covers window and window blinds control (opening/closing), and PIT-C desk lights controls (switch on/off, dim up/down). These surveys occur when specific actions are completed. They are administrated via mobile phones installed right next to controls (windows and light switch). The *OBdrive* app was developed for the purpose of the eCOMBINE project (see Figure 2).
- **PIT-D** captures occupants' glare perception. It occurs towards the end of each seasonal monitoring campaign, when direct sun enters the workspace. It is supplemented by High Dynamic Range (HDR) photographs and spot luminance measurements (taken at the workstations) to inform on the luminance distribution in the field of view.

These subjective responses of the occupants were matched with the environmental measurements of the indoor environment to allow for a comparison. Conducting qualitative and quantitative analyses in parallel enabled to offer a better understanding of cause-effect relationships between drivers and actions.

A general prerequisite for the design of all point-in-time surveys was the minimization of number of questions and input needed in order to allow for a simple and fast compilation of the questionnaires. Therefore, the drop of response rates due to survey fatigue is to be reduced as much as possible, while still gathering all information necessary to answer the selected research questions. As an example, daily surveys (PIT-A, B, C) were designed to take under 1 minute to be completed.

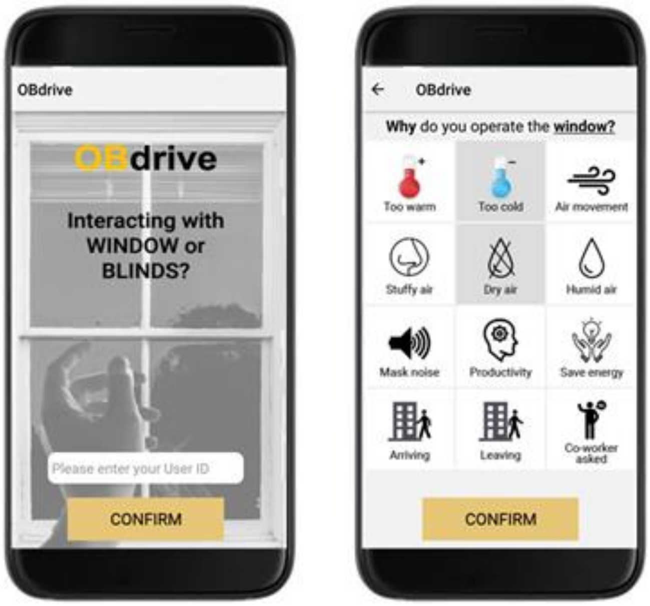


Figure 2: Selected screenshots from the *OBdrive* application: PIT-B on window control motivations.

Table 4: Detail of the eCOMBINE point-in-time surveys.

| **Survey type / name** | **Contents** | **Timing (duration)** | **Tool** |
|---|---|---|---|
| PIT-A: Perception of global (dis)comfort in the workspace | ● Metabolic rate, clothing insulation,<br>● Perception of the global environment (thermal, IAQ, visual, acoustic) on a 5-pt scale (extremely uncomfortable to comfortable)<br>● Preferred or desired changes of:<br>○ temperature (colder/no change/warmer)<br>○ air movement (less/no change/more)<br>○ air (no change/fresher air)<br>○ humidity (less /no change/more)<br>○ light (less /no change/more)<br>○ contrasts (less/no change/more)<br>○ noise (less/no change/more)<br>● Branching question on the sources of discomfort related to the thermal environment (e.g. hot/cold surfaces, hot/cold body parts, drafts), the indoor air quality (e.g. strong odours), the visual environment (e.g. glare, reflection on screen), and the acoustic environment (e.g. outdoor noise, indoor noise) | 2x /day<br>(1’) | PC (triggered by e-mail) |
| PIT-B: Motivations behind window/window blinds control behaviour | Indication of the action, motivation and interactions:<br>● Type of action:<br>○ opening/closing windows<br>○ opening/closing window blinds<br>● Motivation behind:<br>○ *window operation*: too warm, too cold, air movement, stuffy air, dry air, humid air, mask noise, productivity, save energy, arriving, leaving, co-worker asked<br>○ *window blinds operation*: too warm, too cold, prevent overheating, too bright, too dim, glare, reflection, view outside, save energy, arriving, leaving, co-worker asked<br>● Report on consultation with co-worker(s) before interacting with controls (gain understanding on the social norms and dynamics in the work environment) | Every time an action is performed<br>(1’) | OBdrive app |
| PIT-C: Motivations behind light switching behaviour | ● Type of action: turn on/off light, dim up/down light<br>● Motivation behind:<br>○ *lighting operation*: too bright, too dim, glare, reflection on screen, reflection on desk, save energy, arriving, leaving, co-worker asked<br>● Report on consultation with co-worker(s) before interacting with controls (gain understanding on the social norms and dynamics in the work environment) | Every time an action is performed<br>(1’) | OBdrive app |
| PIT-D: glare perception | ● Overall comfort on a 5-pt scale (extremely uncomfortable to comfortable)<br>● Glare perception (4-pt scale from imperceptible to intolerable) and reflexions on screen (yes/no)<br>● Satisfaction with view out (7-pt scale) and obstruction rating of the shading device (4-pt scale) | 1x /season, (right before glare measures)<br>(5') | PC or paper form |

## 3. Lessons learned: challenges and opportunities of the chosen approach

This section is aimed at providing first insights into the challenges and opportunities of the developed framework and the in situ monitoring study.

### *Finding case-study buildings*

The preparatory planning phase involved the selection of suitable case study buildings that meet the requirements of an open space office and in which employees have the possibility to interact with controls (windows, blinds, lights). However, the increasing number of automatization processes of environmental control through BMS (e.g. not openable windows and automatic lighting or window blinds controls) made many office spaces unsuitable. Communication protocols with existing building systems shall be accurately verified to ease the retrieving of valuable data (e.g., energy use). Further, our protocol requires the consent of both the building manager and the occupants to a dense monitoring strategy. Employers might be concerned by the involvement of their employees in the study (e.g. time needed to fill the surveys). Finally, privacy issues (e.g. concerns of having microphones and phones in the space) needs to be clarified carefully. It is hence of primary importance to clearly outline expectations and implications of the study from the start in order to avoid that case-study buildings renounce to participate during the course of the project.

### *Occupant's involvement*

The active involvement of occupants is a key to a successful implementation of the proposed eCOMBINE framework. Gathering direct feedback from the occupants allows to gain insights on the motivations behind their actions. However, it is not realistic that all employees agree to participate in the study. It is hence possible that participating and non-participating employees sit side-by-side and that the latter feel disturbed by the neighbours' sensors. We also experienced that the tolerance of participating employees varied significantly. Some occupants were concerned about having sensors near them (e.g. fear that sensors may emit a signal that has negative impact on their health) or had privacy issues related to reporting personal or monitored data to their employers. A comprehensive information session at the start of the project is therefore essential to detail the functionalities (and safety) of the sensors and the precautions taken for data protection. Further, to maximize the participation rate, occupants were motivated to participate in the study with the provision of a gift at the end of each monitoring campaign. Additional incentives and motivation strategies (e.g. peer comparison, social or monetary rewards) should be investigated, but might conflict with privacy concerns or the willingness to share personal attitudes and data with co-workers.

During the monitoring phase, ideally, the employees should pursue their normal habits and everyday activities in their usual work environment. However, a comprehensive monitoring campaign (like eCOMBINE) has the down-side to increase the *Hawthorne effect*, which means that occupant's knowledge of being studied might affect their natural behaviour (Adair 2000). It is therefore preferable that researchers avoid invading the studied spaces (Wagner et al. 2017) and we planned our site visits and installation of the sensors during non-working hours. When this was not possible, we made sure to assemble multiple sensors on stands beforehand to ensure a quick set-up and minimize the disturbance of employees. Since the campaign stretches over four seasons, it is expected that occupants eventually notice the presence of the sensors less and less and this type of study therefore presents an interesting opportunity to evaluate the Hawthorne effect analytically.

Finally, we noticed that occupants who were particularly dissatisfied with their work environment provided extensive feedback (comparable to a “complain log”) with the hope that somebody intervenes to improve their situation. It is therefore essential to clarify the researcher’s role in order to manage expectations.

***Sensors deployment***

The monitoring framework foresees the installation of a wide range of sensors (multiple dimensions with high spatial resolution), and is more cost-intensive than more classical one-dimensional campaigns. Since measurements are taken at different resolutions (workstation vs. office level), the study provides the opportunity to identify the minimum set/kit of sensors that would be needed to usefully describe occupant behaviour, so as to move towards cost-effective solutions with maximum information.

In order to measure many parameters at one location, different sensors had to be assembled on stands. Setting up a neat and non-invasive sensor environment is not a trivial task and needs to be planned carefully so that sensors do not interfere with each other. Occupants shall be made aware of the functionality of the sensors in order to not alter it (e.g. by covering them). Further, data acquisition from many different sensors implies possible redundancy and time-stamp misalignments. These issues should be tackled in advance to save storage space and ease the post-processing of the data. The development and deployment of integrated Internet-of-Things solutions might be useful to further optimize the data acquisition. On the other hand, we noticed that having a large number of wireless sensors in the open space could lead to connectivity issues with important data loss. It should finally be noted that the installation and maintenance of sensors, as well as the analysis of gathered data considering the their data and diversity, requires research manpower and knowledge from sometimes very different fields, best handled through interdisciplinary collaborations.

***Replicability of the approach***

Each case study building represents its own challenges due to different limitations related to the building envelope and system characteristics, space layout, and available controls. The eCOMBINE framework provided an opportunity to move closer to a unified multi-dimensional approach for investigating the cause-effect relationships between the indoor environment, energy use and occupant behaviour.

## 4. Conclusions and research opportunities

This paper introduced the eCOMBINE monitoring framework that aims to collect and synthesize an extensive dataset that will permit a deeper understanding on the cause-effect relationships between human-building interactions, global environmental comfort, the indoor environment, and energy use. Detailed monitoring strategies for the collection of objective (indoor and outdoor environment, occupant behaviour and energy metering) and subjective data (survey framework) were described, including the challenges and lessons learned. Such data is the starting point for a wide range of research opportunities towards a more comprehensive analysis of the human factor in the built environment, especially in terms of how the latter may influence both energy use and the indoor environment.

The large number of data collected together with their variety allowed us to engage in a multitude of prospective research paths, such as:

- Studying the combined effect of IEQ (multi-dimensional) and determining interactions between IEQ parameters on human perception of comfort and on behavioural actions. This would also include (non exclusively): (1) determining the importance of the different dimensions studied; (2) investigating what are the key drivers within one dimension; (3) investigating of the trade-off between sources of discomfort and interactions (e.g., occupants accept discomfort glare to enjoy the view outside (forgiveness factor)).
- Studying the impact of occupant's personal characteristics and preferences on adaptive actions.
- Studying the impact of behavioural actions on indoor conditions and on energy use.
- Analysing human-human interaction in terms of impact of group dynamics and social norms on occupant behaviour in open-space offices, especially as they pertain to agreement/disagreement on comfort and on control of the environment
- Developing a model of occupant behaviour (OB) able to capture and predict human-building interactions in open-space offices. This model would have the potential to further bridge the gap between measured and predicted energy use.
- Comparing subjective responses (in particular motivations for action captured via *OBdrive*) with existing comfort and behavioural models.
- Investigating impact on human health: the multi-dimensional sensing strategy would allow us to determine long-term exposure to air pollutants, noise and daylight for each occupant.
- Developing a fully-calibrated simulation model. Such a model can then be used to analyse indoor scenarios (e.g., desk-positioning) and improve indoor building design in regard to IEQ and energy.

The aim is to extend this study to other office buildings, ideally in different geographical locations, and make the datasets openly accessible. It is hoped that fully anonymized open access datasets will be made available by other groups so they can be shared amongst researchers to further advance our understanding of the complex inter-relationships between comfort, energy and behavioural aspects.

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# Investigating dependencies between indoor environmental parameters: thermal, air quality and acoustic perception

**Stephanie Gauthier[1] and Leonidas Bourikas[2]**

[1] Sustainable Energy Research Group, Faculty of Engineering and the Environment, University of Southampton, SO16 7QF, United Kingdom, s.gauthier@soton.ac.uk;
[2] Lancaster Institute for the Contemporary Arts, Lancaster University, LA1 4YW, United Kingdom, l.bourikas@lancaster.ac.uk

**Abstract:** In buildings, occupants' interactions with systems and their behaviour is often influenced by environmental discomfort; thermal, visual, acoustic or air quality. Many studies have investigated the relationships between occupant behaviour and one of these discomforts, but very few studies have addressed multi-stressor effects. This paper reviews the results of a field study in two office buildings (N=1,420). Questions were applied to estimate the state of seven environmental controls and three environmental parameters; thermal perception, air quality and background noise level. As the data is ordinal, linear-by-linear association tests followed by Goodman Kruskal Gamma tests were undertaken to ascertain the significance and the strength of relationships between the three environmental parameters. Most results showed no relationship between the parameters; only a modest association between air quality and background noise level. Further analysis explored the relationships between the three parameters when environmental controls were at play, e.g. state of window opening or air-conditioning. In such cases, moderate to strong relationships were uncovered, notably between thermal perception and air quality. These new insights may inform the basis for drawing causal relationships between occupant behaviour and environmental parameters in a view to re-thinking and managing behaviours in affordable comfort for all.

**Keywords:** thermal comfort, air quality, acoustics, mixed-mode, office buildings

## 1. Introduction

In buildings, occupants often have to balance between environmental comforts. For example, switching on ventilation systems or opening a window to control air temperature may alleviate thermal discomfort, but at the same time this behaviour may increase the noise level, causing acoustic discomfort (Pellerin & Candas, 2003). Building standards and guidance typically consider each environmental parameter in silo (BS EN 16798), but in practice the occupants respond to many environmental parameters simultaneously, including thermal, acoustics and air quality. Few studies have explored this multi-parameter dependencies (Andargie & Azar, 2019; Fanger et al., 1977; Freihoefer et al., 2015; Geng et al., 2017; Pellerin & Candas, 2004; Ricciardi & Buratti, 2018; Yang & Moon, 2019). These studies have used measured and/or model variables as indicators of perception and assess those in controlled environments. Thermal perception relates to perceived warmth or coolness; measured variables include operative temperature ($t_o$) ($^oC$), activity levels (M) (met) and clothing ($I_{cl}$) (clo) levels (CIBSE, 2015, Table 1.5.). Acoustic perception relates to sounds or vibrations, preventing speech or music intelligibility and privacy. Measured variables used are sound frequency (Hz) and sound pressure level ($N/m^2$) or sound level (dB) (CIBSE, 2006). Perceived air quality relates to smell, sensitivity to irritants (pollen, smoke, other pollutants) and "fresh" air. There are no accepted measured variables for air quality, only a requirement to achieve a “healthy” air quality that is stipulated as a minimum level of air change rate is required for a given activity; e.g. 10 l/s/person in offices (CIBSE, 2015, Table 1.5.). The few studies, that have explored the multi-parameter aspect of perception, have focused on the relationships between measured variables and reported levels of perception or comforts.

On the relationship between thermal and acoustic perception, Yang & Moon (2019) have exposed participants (N=60) in a controlled environment to thirteen environmental settings; including combinations of five sound types, five sound levels and three temperature levels. For combinations of these environmental settings, surveys were undertaken to capture participants’ thermal perception and noise perception. Then, relationships were drawn between physical environmental factors (i.e. sound type, sound level, temperature) and reported comfort (i.e. thermal perception and noise perception). Results showed that acoustic comfort increases at thermoneutrality and thermal comfort increases with a decrease in sound levels. Furthermore, in relation to indoor comfort the effect of acoustic factors was the greatest, followed by air temperature. Associations have been drawn between physical environmental parameters and the reported comfort levels, but not between the reported comfort levels themselves.

On the relationship between thermal and air quality perception, Zhang et al. (2011) have reviewed field studies’ surveys from the ASHRAE database and undertook two controlled environment studies (N=36). Results showed that perceived air quality is associated with thermal comfort rather than temperature. Similar results were found in the study by Humphreys et al. (2002) reviewing field studies’ surveys from the SCAT database. Besides, it was reported that when respondents were thermally uncomfortable then they rated air-quality more severely.

On the relationship between acoustic and air quality perception, Lee and Aletta (2019) found a significant and strong association between acoustic performance and olfactory comfort. It is suggested that olfactory comfort measure may be an indirect method for increasing acoustic performance in workspace.

Most studies have used measured variables to report on building indoor environmental quality (Jain, 2019); only very few studies have explored the relationships between perceived indoor environmental parameters. Geng et al. (2017) have exposed participants (N=21) in a controlled environment to seven thermal conditions (air temperature varying from 16°C to 28°C) and studied their perceived thermal comfort and satisfaction with indoor air quality, lighting, acoustic and the overall environment. Their analysis introduced the notion of “comparative” impact caused by occupants’ different comfort expectations. As the environment was perceived as too cold or too hot, thermal dissatisfaction was high, which lowered expectations on other environmental factors and therefore showed an increased satisfaction with air quality, lighting and acoustics. Besides, when thermal satisfaction was high, the expectations on other environmental factors increased, which resulted in a decrease in air quality, lighting and acoustic satisfaction.

To address the research gaps highlighted above, this paper reviews field studies’ surveys of reported perceived indoor environmental parameters. The paper first explores relationships between thermal, air quality and acoustic perceptions. The prior hypothesis that interactions amongst these three parameters might be weak, as all are directly related to ventilation, heating and cooling strategies; e.g. opening a window will affect thermal, acoustic and air quality perception. The second part of the analysis explores relationships between thermal, air quality and acoustic perceptions while different indoor environmental controls were at play.

## 2. Study design

The study was undertaken in two office buildings (B1 and B2) in Southampton, UK, over a period of twelve months (from July 2017 to June 2018). 15% of the survey responses were completed during summer, 27% in autumn, 23% in winter and 34% in spring. According to Köppen-Geiger classification, the climate in Southampton is defined as oceanic, marine west coast (Cfb). Daily mean external temperatures in the Test Reference Year (TRY) weather file span across the range of -1.4°C to 22°C, with a mean of 10.5°C and standard deviation of 5.1°C (CIBSE, 2016). Both buildings are mixed-mode, providing heating in winter and peak cooling only when required in summer. Building B1 has an East/West orientation. Its East facade is runs along a service road; the road traffic noise levels, $L_{Aeq,16h}$ [1], is estimated below 55 dB at receptor's height of 4m above ground (Extrium, 2017). Building B2 has a North/South orientation. Its South facade is aligned with an A road; the road traffic noise levels, $L_{Aeq,16h}$ [1], is estimated between 60 and 65 dB at receptor height of 4m above ground (Extrium, 2017). Neither of the two buildings are in a Local Air Quality Management (LAQ) area. The study participants' characteristics are summarised in Table 1.

Table 1. Characteristics of the participants and individual control opportunities

| Bdg. | No. of particip ants | No. of participants with perceived individual control | | | | | | No. of participants per office type | | | Age (no.) | | | Sex (no.) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Door | Wind ow | Blind | Heati ng | Cool ing | Fan* | Single office | Small shared office ** | Large shared office | <30 | 30 to 39 | >39 | F | M |
| B1 | 41 | 5 | 13 | 13 | - | - | - | 3 | 5 | 30 | 14 | 6 | 17 | 29 | 8 |
| B2 | 28 | 10 | 16 | 16 | 6 | 8 | - | 16 | 10 | 2 | 12 | 7 | 6 | 11 | 14 |
| ALL | 69 | 15 | 29 | 29 | 6 | 8 | - | 19 | 15 | 32 | 26 | 13 | 23 | 40 | 24 |

* Ceiling, pedestal and/or desk fan ** Small shared office; i.e. 2 to 4-person office

The study applied a mixed method approach. Concurrently to environmental monitoring, three questionnaires were completed; an initial background survey, a weekly survey and a feedback survey. The weekly survey included three perceptual scales; thermal perception (ASHRAE 7-point scale), noise perception (7-point scale) and air quality perception (7-point scale) (see Table 2). These three scales originate from the SCAT survey (McCartney & Nicol, 2002). The number of completed weekly surveys was N=1,420; which is an average of 20 weekly surveys per participants (N=69). The weekly survey also recorded which environmental settings were used while completing the survey. The seven environmental settings are as follows: internal office door open, window open, blinds/curtains shut down, lights on, space air conditioning (AC) on, local heater on, local fan on.

[1] $L_{Aeq,16h}$ is defined as the annual average noise level (in dB) for the 16-hour period between 07:00-23:00.

Table 2. Questions from the weekly questionnaires

| | | | | | | |
|---|---|---|---|---|---|---|
| **Thermal perception *'How do you feel right now?' (TSV)*** | | | | | | |
| Cold *[coded: -3]* | Cool | Slightly cool | Neutral | Slightly warm | Warm | Hot *[coded: +3]* |
| **Noise perception *'How do you find the background noise level?'(NSV)*** | | | | | | |
| Very noisy *[coded: -3]* | Noisy | Slightly noisy | Neither noisy nor quiet | Slightly quiet | Quiet | Very quiet *[coded: +3]* |
| **Air quality perception *'How do you find the air quality?'(ASV)*** | | | | | | |
| Very bad *[coded: -3]* | Bad | Slightly bad | Neither bad nor good | Slightly good | Good | Excellent *[coded: +3]* |

This study reviews the relationship between these three perceptual scales and associated three variables; thermal perception (TSV), acoustic perception (NSV) and air quality perception (ASV). As these three variables are ordinal, linear-by-linear association tests followed by Goodman Kruskal Gamma tests were undertaken to ascertain the significance and the strength of relationships between the three variables.

## 3. Results

### 3.1 Descriptive analysis

As shown in Figure 1, most surveys reported neutrality; TSV was reported 'neutral' in 39% of all surveys, NSV 'Neither noisy nor quiet' in 34% of all surveys, and ASV 'Neither bad nor good' in 48% of all surveys. For TSV, cold perception accounted for 28% of all surveys, while warm perception accounted for 32% of all surveys. The odds of a participant feeling warm were 1.16 times higher than a participant feeling cold; although only 15% of the surveys were completed in summer. For NSV, noisy perception accounted for 46% of all surveys, while quiet perception accounted for 23% of all surveys. The odds of a participant perceiving the environment being noisy were 2 times higher than perceiving the environment being quiet. For ASV, bad air quality perception accounted for 36% of all surveys, while good air quality perception accounted for 16% of all surveys. The odds of a participant perceiving the air quality being bag were 2.2 times higher than perceiving the air quality being good.

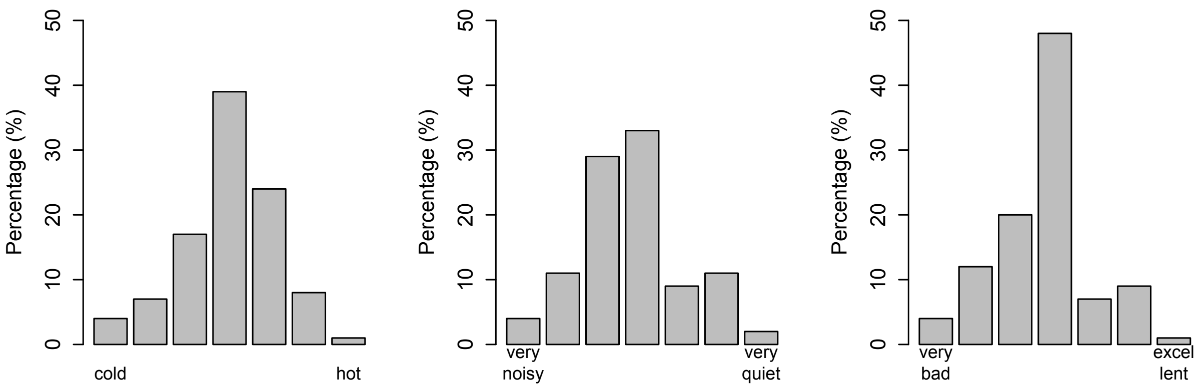


Figure 1. Distributions of thermal perception (TSV, left), acoustic perception (NSV, middle) and air quality perception (ASV, right) survey results.

### 3.2 Inferential analysis dataset level

The first part of the inferential analysis reviews the relationships of amongst the three variables (TSV, NSV and ASV) for the entire dataset (see Figure 2).

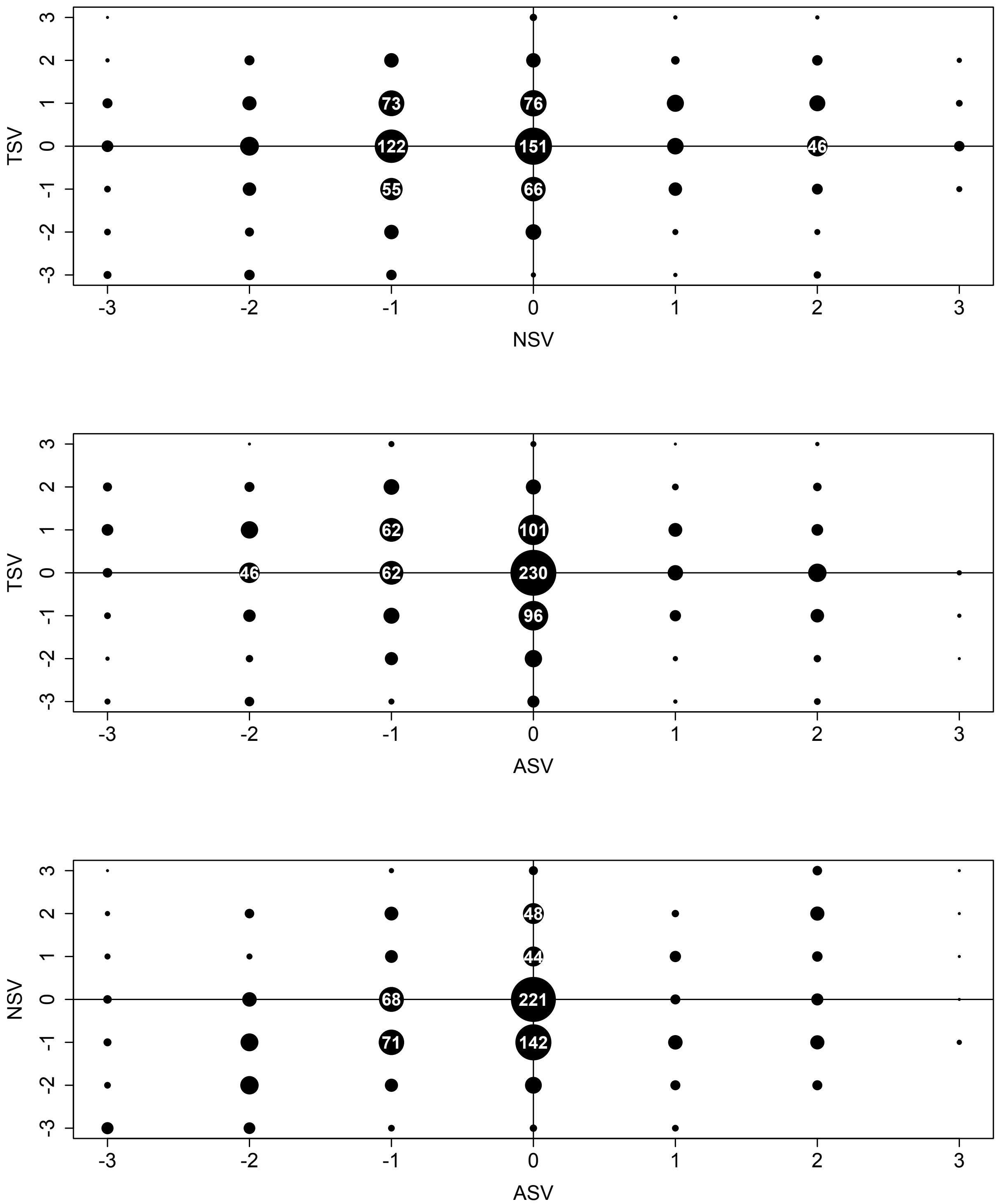


Figure 2. Comparison of agreement between the three variables from the individual surveys (number of responses shown within circles and proportional to the area of circles).

There was a significant but negligible positive correlation between TSV and NSV (G=0.11, p<0.05). There was a significant but negligible negative correlation between TSV and ASV (G=-0.11, p<0.05). There was a significant, moderate and positive correlation between NSV and ASV (G=-0.25, p<0.05). The findings indicate that a noisy environment is associated with poor air quality, while a quiet environment is associated with good air quality; e.i. occupants in noisy environments are likely to perceive bad air quality.

### 3.3 Inferential analysis subset level

The second part of the inferential analysis reviews the relationships of between the three variables (TSV, NSV and ASV) while the different environmental controls were at play. The results shown in Table 3 indicate moderate to very strong relationships. There were significant, moderate and positive correlations between TSV and NSV, when windows were open ($G=0.22$, $p<0.05$), when blinds/curtains were down ($G=0.23$, $p<0.05$), or when space air conditioning (AC) was on ($G=0.31$, $p<0.05$). Noisy environment was associated with cold thermal perception, while a quiet environment was associated with warm thermal perception. As participants felt warm and there is little external noise, they may have opened windows. There was a significant, negative and very strong correlation between TSV and ASV, when local fans were on ($G=0.76$, $p<0.05$). A warm environment was associated with poor air quality, while a cool environment was associated with good air quality. Participants may have switched on local fans to increase cooling sensation; this would have consequently increased convection and might explain the "good" perceived air quality. There were significant, positive and moderate to strong correlations between NSV and ASV, when blinds/curtains were shut down ($G=0.2$, $p<0.05$), space air conditioning (AC) was on ($G=0.19$, $p<0.05$), or local heaters were on ($G=0.25$, $p<0.05$). Quiet environments were associated with good air quality, while noisy environments were associated with poor air quality. Participants may have switched on the AC to improve the perception of fresh air; this action will have increased the internal noise level.

Table 3. Value of Gamma

| | Door | Window | Blinds/curtains | Light | AC | Heater | Fan |
|---|---|---|---|---|---|---|---|
| **Sample Size** | **272** | **86** | **154** | **774** | **259** | **16** | **41** |
| **TSV vs. NSV** | - | 0.22 * | 0.23 * | - | 0.31 * | 0.41 | - |
| **TSV vs. ASV** | - | -0.22 | - | - | - | - | -0.76 * |
| **NSV vs. ASV** | - | - | 0.2 * | - | 0.19 * | 0.62 * | - |

* p<0.05

## 4. Discussion and conclusions

The results of the dataset analysis showed no relationship between variables; only a modest positive association between air quality and background noise level. Further analysis explored the relationships between the three different perceptions when environmental controls were at play. In such cases, moderate to very strong relationships were uncovered; these are summarised as follows:

- Noisy environments were associated with cold thermal perception, while quiet environments were associated with warm thermal perception.
- Warm environments were associated with poor air quality, while cool environments were associated with good air quality.
- Quiet environments were associated with poor air quality, while noisy environments were associated with good air quality.

These results show that in general there was no association between the studied environmental factors, i.e. thermal, acoustic and air quality perceptions. Correlations were evident only when heating, cooling and/or ventilation systems (HVAC) were in use. For example, when a window is open, the occupants will have to balance among their different environmental preferences of thermal, acoustic and air quality. This may often be challenging to achieve. In the case of window opening or local fan being used, these comfort adaptation driven behaviours will have to balance between indoor and outdoor heat, pollutants and noises, as summarised in Table 4.

Table 4. Non-exhaustive list of heat, pollutants, noises in buildings

| | **Thermal** | **Air-Quality** | **Acoustic** |
|---|---|---|---|
| **Indoor** | Internal heat gains<br>Temperature gradients<br>Air flows | Odours<br>Carbon dioxide ($CO_2$)<br>Particulates (PM)<br>Volatile organic compounds (VOC)<br>Sulfur dioxide ($SO_2$)<br>Nitrogen oxide ($NO_x$) | Airborne sounds (speech, equipment, building mechanical systems)<br>Structure-borne sounds (foot fall, equipment) |
| **Outdoor** | External heat sources (equipment, etc.)<br>Solar gains (direct / indirect)<br>External weather conditions | Odours<br>Nitrogen oxide ($NO_x$)<br>Particulates (PM)<br>Volatile organic compounds (VOC) | Airborne sounds (speech, road, rail, aviation, etc.)<br>Structure-borne sounds (road work, etc.) |

Occupants perceive their environment and may act upon discomfort through behavioural adaption by changing the HVAC system settings. In this study, discomfort may be thermal, acoustic and/or related to air quality. As described by CIBSE (2006), discomfort occurs when (1) environmental "changes are too fast for adaptation to take place", (2) environmental changes "are outside individual control", or/and (3) perception is beyond personal comfort boundaries. To address the second point, perceived occupant control over the environment is key to achieve higher tolerance of less than ideal conditions, which will certainly occur while balancing between different environmental preferences. Therefore, it is recommended that HVAC control strategies are at the core of building design and management. To address the third point, thermal or acoustic perceptions vary widely from person to person (Gauthier et al., 2020; CIBSE - Section 1.10.1, 2015). Moreover, environmental perceptions will depend on the situation and activity undertaken in the space (e.g. lone working, meeting, video call, etc.) Therefore, it is recommended that a wide range of different environmental conditions are design within office buildings. A popular design may follow the concept of 'hot-desking'. A desk may not be allocated to a specific person, but to a group of individuals with similar environmental preferences and activities. However, other spaces may require to be designed with flexibility and may adopt personal environmental control systems.

In this paper, a multi-domain approach was applied to study the interactions amongst three environmental perceptions (thermal, acoustic, air quality) based on questionnaire surveys in two office buildings; no measured variables were reviewed. This addresses a gap in research, as very few studies have reviewed reported perception and have been undertaken in 'free-living' environments. Indeed, most studies have used measured or modelled variables as substitutes for perception. However, human perception does not depend entirely on physiological and physical mechanisms, but also depends on thermal experiences, expectations, social norms, efficacy of control, etc. (Brager & de Dear, 1998). As online survey tools have developed in recent years, making data collection more affordable, future research should and can now gather reported environmental perceptions. Furthermore, research should adopt a holistic approach as associations amongst indoor environmental parameters may be have an important role in behavioural adaptation.

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# Experienced temperature: Characterizing a person's immediate thermal environment through a body-worn sensor

**Harry Kennard[1], Gesche Huebner[1], Tadj Oreszczyn[1], and David Shipworth[1]**

[1] University College London, Energy Institute, 14 Upper Woburn Place London WC1H 0NN, UK

**Abstract:** Temperatures in dwellings are usually measured with stationary sensors at fixed locations, often following specific standards such as BS EN ISO 7726. Whilst such standardized temperatures are crucial for a range of applications, they are not very informative of the thermal environment an individual experiences. Creating a more dynamic way of measuring temperatures allows better understanding of the temperatures people experience and indirectly indicate thermal comfort preferences across locations and situations. More importantly, it is well established that cold exposure can have significant health implications. The primary epidemiological evidence for this is the seasonal variation in mortality, i.e. excess winter deaths. However, there is hardly any directly measured data for personal cold temperature exposure. In this paper, we discuss the concept of experienced temperature, i.e. a temperature measure that characterizes the immediate thermal environment of an individual through a body-worn sensor. In the UK Biobank study, more than 100,000 participants wore an activity monitor on the wrist for a week that for internal calibration purposes also measured temperatures. We discuss the accuracy of this measure which is influenced both by wrist temperature and the thermal environment, and limitations to the interpretation of the data. Analysis showed a significant difference in experienced temperature of about 1.8°C between the periods of coldest and hottest external temperature and certain variations across demographic groups. However, we did not find an association between experienced temperatures and ill health.

In summary, we suggest that experienced temperature is a useful alternative – or addition – to temperatures measured with stationary sensors but that more research is needed to validate this measure, in particular in disentangling the components of skin versus ambient temperature.

**Keywords:** Experienced temperature, body-worn sensor, health, UK Biobank

## 1. Introduction

Exposure to cold is known to have severe health impacts. From an epidemiological perspective, the primary evidence comes from seasonal variations in mortality and hospital visits (Hajat, 2017). Laboratory studies have shown cold exposure increases blood pressure, and therefore exacerbates cardiovascular (Liu et al., 2015) and respiratory conditions (D’Amato et al., 2018). However, there is a paucity of directly measured data for personal cold temperature exposure. Most studies looking at the effect of cold on health measure temperature in a building using stationary sensors (e.g. Huebner et al., 2018). However, such measures are unable to determine the temperatures an occupant is exposed to, either in the internal or the external environment.

This paper is important in the context of recent evidence that mild cold exposure has the potential to offer moderate improvements to patients suffering from diabetes (Hanssen et al., 2015) and metabolic health more generally (van Lichtenbelt et al, 2017). The adaptive potential of humans to cold environments may also guard against cardiovascular disease (Kralova Lesna et al., 2015).

This paper uses the experienced temperature, which aims to capture an individual's exposure to cold (Kennard et al. 2018). This technique takes the experienced temperature to be a measure of the immediate thermal envelope of an individual. It is measured using a wrist worn sensor, which was given to 103,707 participants as part of the UK Biobank longitudinal health study. While the sensor was initially designed to measure activity levels using the on-board accelerometer, a thermistor was included in the device with a view to calibrating the accelerometer, positioned at its outer surface but embedded within the device. It was shown that this thermistor picks up both heat from the wrist as well as the ambient environment of the wearer (Kennard et al. 2018). This Windsor 2020 paper describes the concept and development of experienced temperature, and then tests if the experienced temperature is related to people's likelihood of having particular conditions associated with winter mortality and cold exposure. Each year, in the UK and in other temperate countries, more people die in winter than in summer (ONS, 2019). The statistic of 'excess winter deaths' (EWDs) characterises the number of people who die in the winter months over and above the average for other times of the year. The principle cause of death in these instances is either respiratory conditions (48.2% of EWDs in 2018/19) and cardiovascular conditions (39.6% of EWDs in 2018/19). The EWD measure itself suffers from methodological shortcomings, such as the observation that not all cold related deaths occur in winter, and that not all winter deaths are cold related (Hajat & Kovats, 2014). Despite this, deaths which are primarily caused by cardiovascular and respiratory conditions are strongly seasonal, and peak at the coldest time of the year (Hajat, 2017). This paper therefore uses the conditions associated with excess winter deaths ($C_{EWD}$) as the basis of the analysis to understand how their prevalence relates to experienced temperature.

## 2. Methods

A pre-analysis plan was developed and submitted to the EGAP repository (Kennard et al., 2018) prior to the analysis of the data. This not only allows research questions and hypotheses to be recorded but also guards against the possibility of data mining or significance hacking (Huebner et al, 2017). Any deviations from the pre-analysis plan are detailed subsequently.

### 2.1. Data source

All variables except average external temperature (see below) are drawn from the UK Biobank dataset. The UK Biobank is an on-going cross-sectional health study of UK adults. The variables used in this study were selected from the wide range of potential variables to provide a detailed but not over-fitted model.

The study recruited over 500,000 people from the UK population. A random selection of participants who had provided valid email addresses (236,519 participants) were invited to wear an Axivity AX3 wristband sensor for the duration of one week to gather data on physical activity. Participants from the North West were excluded following concern that they had already been used in study trials and might be overburdened (Doherty et al., 2017). The Axivity device collects accelerometer, temperature and lux data into a single CWA file. 103,707 CWA files were available for analysis in this study. The median age of the participants when wearing the wristband was 64 years (range 43 – 79). In general, the whole Biobank sample suffers from the 'healthy volunteer bias" (Fry et al. 2017), i.e. participants smoke, drank alcohol and were obese at lower rates than the general population, and the same is likely true for the subset wearing the Activity device, and the age distribution differs from the general population.

## 2.2. Variables

### 2.2.1. Experienced temperature

Baseline demographic data collection was completed in 2010. The AX3 data were collected between June 2013 to December 2015. Processing the UK Biobank was done as follows. For each participant, the device needed to have been worn for at least 90% of the time. 80,050 participants remained after applying this criterion. 78,578 remained after excluding participants with conditions associated with abnormally cold hands (Raynaud's disease, anaemia and carpal tunnel syndrome) or disrupted circadian rhythms (dementia and Alzheimer's disease) (Harfmann, Schroder & England, 2017). Shift workers were also excluded (Jang et al. 2017, Ferreira et al. 2013, Bracci et al. 2016), as were participants with missing data or those who opted to withdraw. The final sample consisted of 77,762 participants. The total number of participants in each season across the 2.5 years of data collection were winter: 16,108, spring: 21,317, summer 17,682 and autumn 22,655. There were no wear-periods which began in the first week of the year. The data was first processed to a 5-second interval (in line with the study by Doherty et al. using the same device) and then subsequently downsampled to a 1-minute time period. This duration was chosen as a trade-off between data manageability and providing as much temporal data as possible.

To calculate the experienced temperature variable from the temperature time series we proceeded in the following way. The first and last day's data were deleted to guard against the impacts of transient behaviour, associated with the device recording temperature but not yet being worn. For each participant, all data points with an activity reading greater than the participant's median value were excluded to remove times at which someone was particularly active / exercising. Whilst there were a number of different ways to summarize the resultant time series, we decided to focus on value of the first decile to represent 'cold exposure'. We use the expression $t^m_{10}$ to characterize this summary measure; *10* indicating that the measure separates the lowest 10% of measurements from the rest, and *m* indicating that only temperature data recorded when the participant was below the median activity level were included. The minimum was not used as it could likely be an outlier, corresponding to sticking your hand in the freezer for a moment, i.e. it is susceptible to being biased by single brief cold temperature readings. The mean is dominated by the warm microclimate of the bed at night time and so is not a good measure of cold exposure.

It needs to be emphasized that the experienced temperature is a mixture of ambient and wrist temperature. Hence, it should not be interpreted as an actual value of the temperatures someone experienced, or as an indicator of the thermal comfort temperature. Rather, its value tracks the thermophysical response of the wearer: lower values of $t^m_{10}$ likely indicate that a participant was in a cold environment, since wrist temperature is also lower in such environments. For details on this please see the PhD thesis by Kennard (2019).

### 2.2.2. Covariates

According to the pre-analysis plan, the following participant demographic and housing variables were used: age, sex, accommodation type, tenure type, household income and size, employment status, whether the participant's home has gas or solid fuel cooking or heating apparatus, and the participant's ethnicity. Following the submission of the PAP, two further variables were deemed essential: body mass index, as a general, if complex, indicator of health (Corbin & Timpson, 2016), and activity level as recorded by the wrist band as a proxy for exercise levels.

The external temperature for the week during which the Axivity AX3 wristband was worn was given by gridded NASA MEERA-2 dataset (GMAO, 2015). Each participant's approximate home location was matched to the corresponding grid square and the 5-day average of the 2-m air temperature calculated. The grid resolution in the NASA MEERA-2 dataset is 0.625°×0.5° which corresponds to ~70 × 35 km—around 200 grid squares cover the UK (GMAO, 2016)

### 2.2.3. Conditions associated with excess winter deaths

A binary variable for those who had a condition associated with excess winter deaths ($C_{EWD}$) was constructed from the UK Biobank dataset – a value of 1 was given to participants who either had a respiratory disease (defined as ICD-10 codes J00 to J99) or a circulatory disease (ICD-10 codes I00 to I99). While dementia and Alzheimer's disease are also related to excess winter deaths, they were excluded as they are also associated with circadian disruption, which may impact wrist temperature readings (Hatfield et al. 2004). $C_{EWD}$ was constructed from the database of diagnosed conditions, which form part of the UK Biobank dataset. The extent to which a given participant was suffering from acute symptoms of the condition at the time at which the AX3 was worn was not available.

## 3. Analysis

For experienced temperature per se, we show descriptive statistics and a link to external temperature. For analysis of a link between experienced temperature and a condition associated with excess winter deaths, we used regression analysis. The regression model was a generalised linear model using a binomial outcome variable ($C_{EWD}$) with predictor variable experienced temperature ($t^m_{10}$) and the above demographic factors. For binomial regression, it is typically the odds ratio that is calculated. However, since odds ratios only approximate risk ratios when the outcome is rare (Cummings, 2009), and $C_{EWD}$ has a value of 1 for 13.5% of participants, the risk ratio was calculated for this study.

## 4. Results

### 4.1. Descriptive statistics of experienced temperature

Figure 1 shows the probability density function of experienced temperature for the sample as a whole. Data are normally distributed with a substantial spread. The mean value of $t^m_{10}$ is 28.6°C, and the standard deviation 1.9°C. It should be emphasised that the values of $t^m_{10}$ are a mixture of both ambient temperature and heat from the wrist.

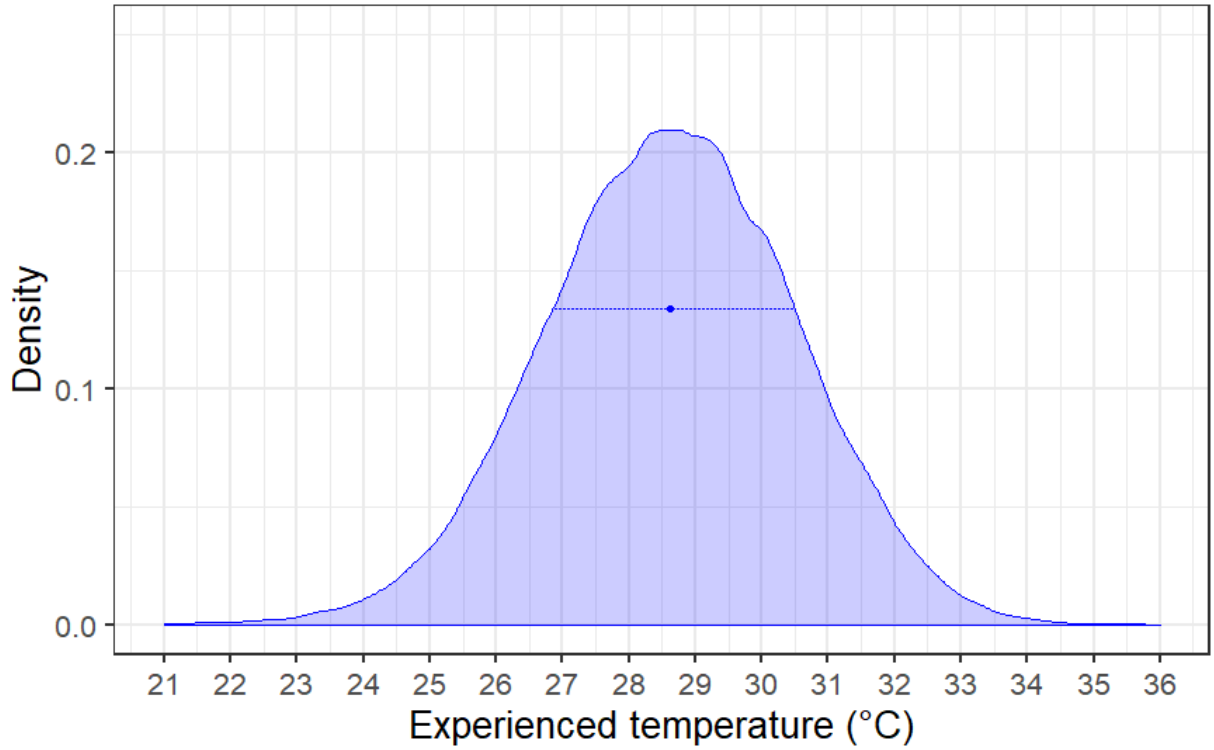


Figure 1 The probability density of $t^m_{10}$. The mean value of 28.6°C is shown as the central point, with a value of one standard (1.9°C) either side as the dotted line.

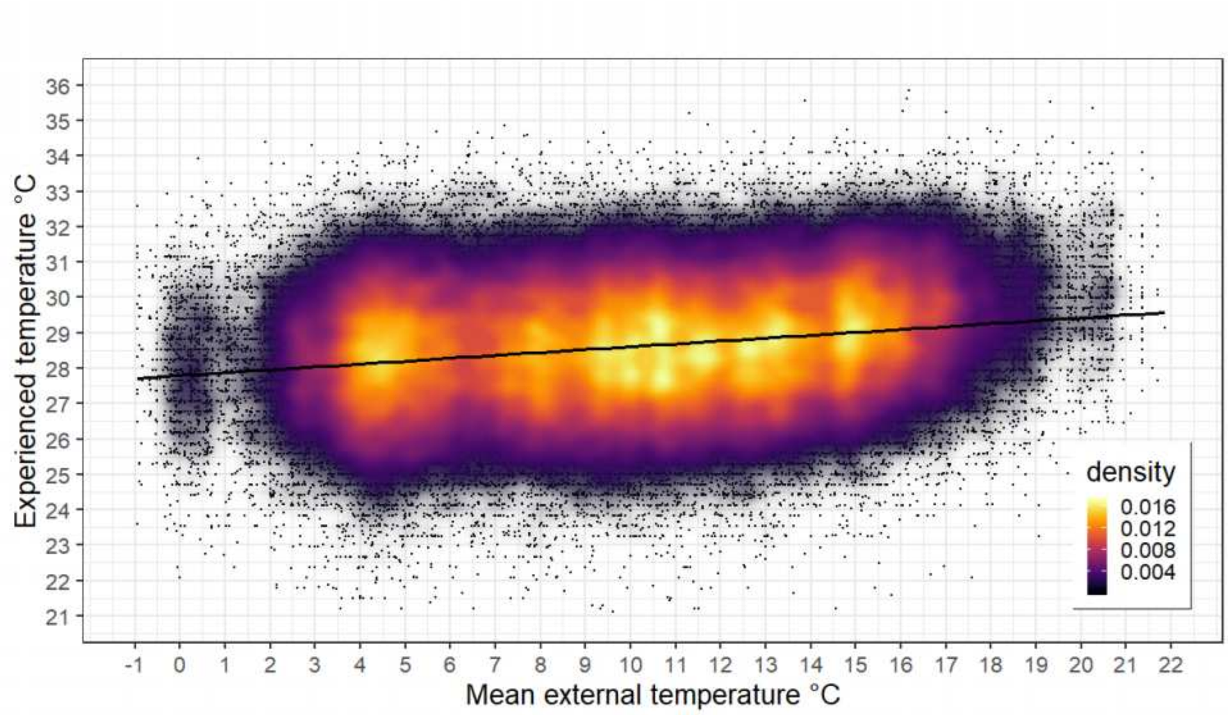


Figure 2 The relationship between the mean external temperature and the experienced temperature $t^m_{10}$. Since a high number of points are shown, they are represented as a density cloud. The black line shows the least squares fit, the equation $t^m_{10} = 0.08\ t_{external} + 27.8$, $R^2$=0.04

An earlier aspect of the present study sought to understand the variation of $t^m_{10}$ with the sociodemographic factors described above. The substantive statistically significant results of a multiple linear of these factors are now given for completeness. As figure 2 shows, for each degree increase in average external temperature, $t^m_{10}$ was found to increase by 0.08°C. Those aged 70-79 years were found to have $t^m_{10}$ of 0.28°C warmer than those aged 40-49. Those living in flats were found to have $t^m_{10}$ of 0.13°C warmer than those living in a house or bungalow. $t^m_{10}$ was found to be colder in homes with an open solid fuel fire (by between 0.08°C and 0.39°C depending exactly on heating configuration) compared to homes without. As activity levels of the participant increase, $t^m_{10}$ was found to decrease – the highest quintile of activity level showed values 0.45°C lower than the lowest quintile. It is important to emphasise that it is not possible to determine the direction of causality with these findings. For example, it is plausible that a lower $t^m_{10}$ is measured for more active participants because either most activity occurs in cooler environments, or the effect of a cool environment encourages greater activity by the participate (Gauthier, 2016) or a combination of both effects. The following section reports the main research results regarding the prevalence of conditions associated with excess winter mortality as a function of both experienced temperature and the other covariates described above. No significant relationship between household income and experienced temperature was observed.

### 4.2. The link between experienced temperature and symptoms associated with excess winter deaths

Full results are given in table 1. All risk ratios of having a condition associated with excess winter deaths ($C_{EWD}$) are reported with their respective 95% confidence interval (CI). Since the number of participants in the dataset is very large (n=77,762), a more stringent condition for significance was imposed – the table highlights p<0.01, p<0.001 and p<0.0001 levels. The column '$C_{EWD}$=1 measured' and '$C_{EWD}$=1 predicted' give the percentages of those who have a condition associated with excess winter deaths. It is worth emphasizing that these are raw values of the prevalence in the sample, not taking account any intercorrelations of variables. The risk ratio results from the regression, and hence reports effects when controlling for other factors.

Following the pre-specification outlined in the PAP, using $t^m_{10}$ alone the following relationship with $C_{EWD}$ was found: RR = 1.02 (1.01 to 1.04, p<0.001) for each °C increase $t^m_{10}$. However, following the addition of covariates, given below, this relationship became non-significant, RR = 1.00 (0.99 to 1.02, p=0.4).

Older participants were found to have a higher relative risk of $C_{EWD}$, those aged between 70-79 have a RR = 2.72 (2.42 to 3.05) over those aged 40-50. Male participants had an RR of 1.53 (1.47 to 1.58) of having a condition associated with excess winter deaths compared to female participants.

Body mass index was found to be a significant predictor of $C_{EWD}$. Obese participants had RR = 1.52 (1.35 to 1.72) above participants of normal weight. Those participants who were unable to work due to sickness or disability had RR = 1.83 (1.67 to 2.00), relative to those in paid or self-employment. Higher activity levels were associated with a reduced risk of $C_{EWD}$. Relative to owning a home outright, participants with a mortgage had increased risk of $C_{EWD}$ RR=1.08 (1.03 to 1.13), as did those who rent from the local authority RR = 1.23 (1.11 to 1.36). RR of $C_{EWD}$ also increased as a function of number of inhabitants in the home. Relative to the lowest income bracket (<£18,000/year) increasing income had a monotonic decreasing impact on $C_{EWD}$ risk, with those earning over £100,000 having the lowest risk ratio relative to the <£18,000/year of 0.64 (0.58 to 0.71).

Other variables yielded no significant relationships. Two additional variables, financial situation satisfaction and household heating type were only available for a subsample of the dataset, due to the UK Biobank data collection process. The addition of these variables yielded no significant impact on $C_{EWD}$. Finally, interaction effects between the variables were considered and tested, but none produced significant results.

**Table 1 Significant results of the regression model. * p<0.01, ** p<0.001, *** p<0.0001. N=77,762**

| **Categorical variables** | **Subcategory** (first entry is reference category) | **Coefficient** | **Risk ratio** |
|---|---|---|---|
| Age | 40-49 | | |
| | 50-59 | 0.391 | 1.48 [1.33 – 1.65] *** |
| | 60-69 | 0.745 | 2.11 [1.89 – 2.35] *** |
| | 70+ | 0.999 | 2.72 [2.42 – 3.05] *** |
| Sex | Female | | |
| | Male | 0.423 | 1.53 [1.47 – 1.58] *** |
| Household income | Less than 18,000 | | |
| | 18,000 to 30,999 | -0.091 | 0.91 [0.87 – 0.96] ** |
| | 31,000 to 51,999 | -0.224 | 0.80 [0.75 – 0.85] *** |
| | 52,000 to 100,000 | -0.330 | 0.72 [0.67 – 0.77] *** |
| | Greater than 100,000 | -0.447 | 0.64 [0.58 – 0.71] *** |
| | Prefer not to say | -0.176 | 0.84 [0.77 – 0.91] ** |
| Tenure type | Own outright | | |
| | Mortgage | 0.075 | 1.08 [1.03 – 1.13] * |
| | Rent Local Authority | 0.205 | 1.23 [1.11 – 1.36] ** |
| Body mass index | normal | | |
| | overweight | 0.153 | 1.16 [1.12 – 1.21] *** |
| | obese | 0.420 | 1.52 [1.35 – 1.72] *** |
| Activity level during study week, by quintile, lowest to highest activity | 1st quintile | | |
| | 2nd quintile | -0.178 | 0.84 [0.80 – 0.88] *** |
| | 3rd quintile | -0.215 | 0.81 [0.77 – 0.85] *** |
| | 4th quintile | -0.270 | 0.76 [0.72 – 0.81] *** |
| | 5th quintile | -0.344 | 0.71 [0.67 – 0.75] *** |
| Household size | Single occupant | | |
| | Two | 0.125 | 1.13 [1.07 – 1.20] ** |
| | Three | 0.185 | 1.20 [1.13 – 1.29] ** |
| | Four or more | 0.165 | 1.18 [1.10 – 1.27] ** |
| Employment status | In paid/self-employment | | |
| | Unable to work due to sickness or disability | 0.604 | 1.83 [1.67 – 2.00] *** |

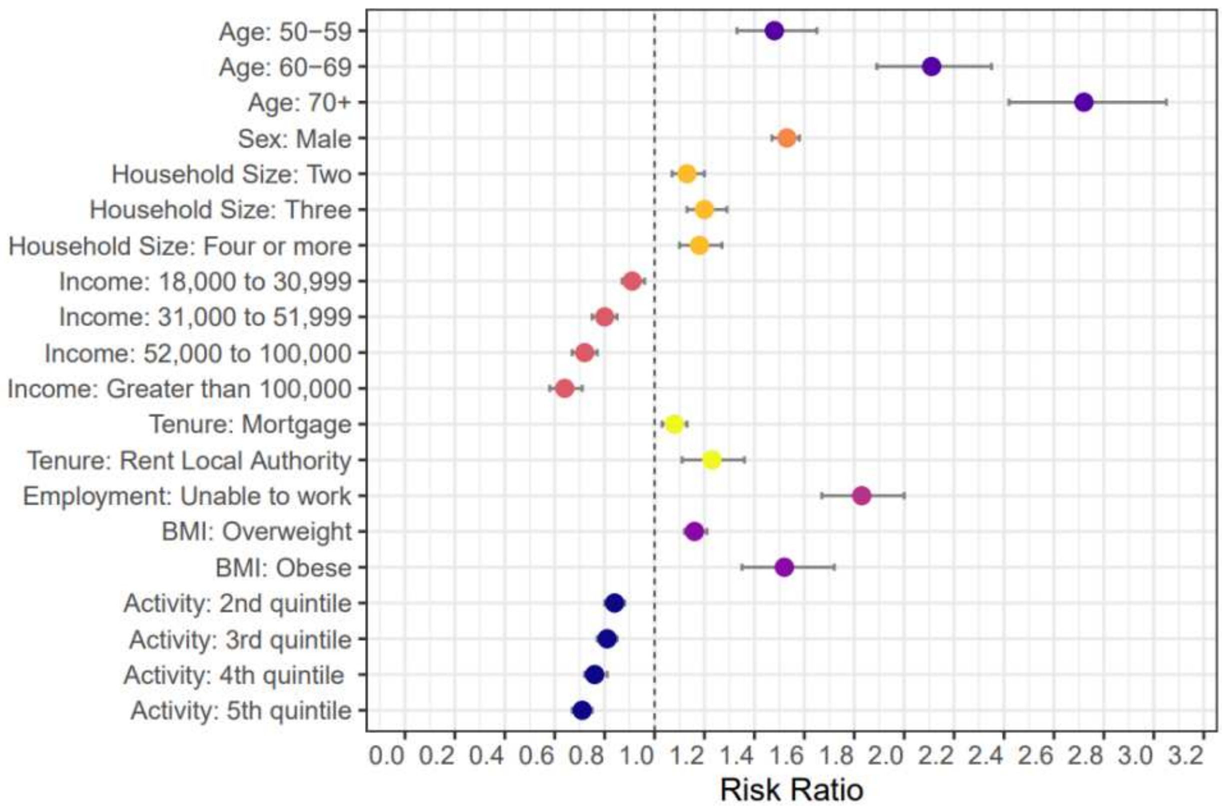


Figure 3 The significant risk ratio estimates represented in graphical form, with the error bars corresponding to 95% confidence intervals. The corresponding values for all variables are given in Table 1.

### 4.3. Experienced temperature as an alternative metric

This paper discussed a novel method to describe a wearer's immediate thermal environment. The experienced temperature cannot be used to describe the actual ambient temperature that was experienced given that it is a mixture of ambient and wrist temperature. Yet, when comparing participants of similar activity level, it does track whether a person is exposed to comparatively warmer or colder temperatures over the entire course of a day at any location, making it much more informative than e.g. stationary measured temperatures.

### 4.4. Principle findings

A binomial regression model of whether a participant had conditions associated with excess winter deaths ($C_{EWD}$) yielded no significant relationship with the first decile ($t^m_{10}$) of experienced temperature. Of the notable covariates, income yielded highly significant results: the relative risk of having a condition associated with EWDs dropping steadily as income increased. Participants living in local authority housing had an increased risk of $C_{EWD}$ compared to those who own their home outright.

### 4.5. Study Strengths

The finding that, without covariates included, the $t^m_{10}$ experienced temperature increases with increased likelihood of having a condition associated with excess winter deaths accords with current understanding. Huebner et al 2017, for example, found that households with occupants who had a long-term disability were warmer than households without. Behavioural explanations are plausible for this finding; people who are aware that they have

respiratory conditions, for example, may seek out warmer environments to ease symptoms. It is also possible that warmer experienced temperatures point to a narrowing of the range of thermal environments that people with adverse health conditions experience. The absence of a statistically significant result for the relationship between experienced temperature and $C_{EWD}$ when covariates are included is compatible with the finding by Kennard et al. (2019), which found that the experienced temperature varies with demographic and housing factors, and may indicate that variables such as income and BMI are more important than a one-week post-diagnosis experienced temperature measurement in relation to $C_{EWD}$.
The finding that higher household income is associated with lower risk of participants have conditions associated with excess winter deaths is notable and begs the question why such unambiguous relationships are not observed in cold related mortality data (Hajat, 2017). One possible explanation is that despite the strong relative effect between income brackets, the risks are small compared to other factors which ultimately contribute to death.

**4.6. Limitations of study and further research**

In the ideal case, alongside experienced temperature, participant location would be recorded whether the participants were located inside their home, other buildings, or outside. Whilst some guesses could be made with the current data based on time of day, temperature, occupation information, etc. any estimate would likely contain many errors. Ideally, a study such as this would include health outcome data both before and after the sampling of experienced temperature. It also does not incorporate mortality data, therefore cannot assess excess winter deaths themselves, only the prevalence of conditions related to them.
The measurement of experienced temperature was limited to a single week for each participant – this limitation will be addressed in a forthcoming study for which participants wore the sensor at four different times throughout the year. As discussed by Kennard et al. (2019), the experienced temperature is not readily comparable with other more traditional static temperature measures. The temperature readings and specific values of $t^{m}_{10}$ should be interpreted as a relative measure. Furthermore, the method described here cannot estimate the risk of breathing cold air while wearing warm clothing, which is currently not well examined in the literature.
The lack of evidence as to the relative impact on health of short-term more intense cold exposure versus long-term mild cold means that the method producing an effective summary of the time-series temperature data is challenging. Other summaries of the temperature data should be explored, such as focusing on minimum temperatures or variability in temperatures.

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# How can the Thermal Sensation be Objectively Determined in Order to Analyse Different Vehicle Air Conditioning Concepts?

**Andreas Rolle[1], Bastian Schmandt[2], Cyril Guinet[2] and Klaus Bengler[1]**

[1] Technical University of Munich, GER, Department of Mechanical Engineering, Chair of Ergonomics, a.rolle@tum.de

[2] Audi AG, GER, Bastian.Schmandt@audi.de, Cyril.Guinet@audi.de

**Abstract:** As electro mobility and autonomous driving is advancing continuously, climate concepts are developed to meet the demands of energy efficiency and thermal comfort. The current problem concerning the travelling range of electric vehicles requests that available energy is used more efficiently. Air conditioning is the second highest consumption factor and thus has a large influence on the overall range. New climate concepts have to satisfy various requirements. The clients' expectation concerning the thermal wellbeing in a vehicle indicates the significance of thermal comfort as an interpretation factor. In several investigations presented in this paper various climate concepts were analysed and evaluated. The equivalent temperature according to ISO 14505-2 was used as the basis for the evaluation. The influence of surface heating systems as well as overhead ventilation systems were investigated in a vehicle mock-up in a climate chamber at different temperatures. Furthermore, the behaviour of an extended ventilation field on thermal comfort of a SUV was investigated. The investigations clearly showed that the equivalent temperature is a suitable evaluation factor since it reduces multiple environmental conditions to a single parameter.

**Keywords:** Thermal comfort, equivalent temperature, objective analysation.

## 1. Introduction

Electric vehicles (EVs) and hybrid electric vehicles (HEVs) have received increased attention over the last years due to a growing environmental awareness. The world-wide amount of EVs has increased more than tenfold since 2013. Globally a total of 5.6 million vehicles were brought into market (ZSW, 2019). In the case of battery electric vehicles the transition from lead-acid to Lithium-ion (Li-on) batteries increased the user's acceptance as the driving range could be increased. Compared to lead-acid batteries, Li-ion batteries have an improved cell chemistry which offer higher specific energy and power density. The EVs are now able to travel longer distances and the used energy can be recharged by speedy charging techniques within shorter and shorter times. However, battery lifetime remains a key issue as the battery is the most expensive component of an EV. The cost are about 135€ per kilowatt hour so that the efficient usage of energy is of decisive significance (Horváth & Partners, 2018). The powertrain as well as the air conditioning in an EV are the highest consumers of energy. Unlike vehicles with combustion engines, there is no waste heat available so that the energy, necessary for air conditioning, must be obtained from the battery. During the winter months it is possible that the driving range of EVs can be halved in extreme cases (Bader, 2014). The development of newer energy saving air conditioning concepts can thus lead to a significant increase of the driving range. Not only an efficient air conditioning system is of great importance, but also the thermal comfort should be considered. Travel comfort is one of the most important, independent variables influencing the customer's satisfaction in the mobile society of today (Marggraf-Micheel & Jäger, 2007). The thermal comfort of the occupants in the car significantly contributes to the over-all feeling of comfort (Stuke & Bengler, 2014).

During the development of modern automobiles the air conditioning system, as part of the vehicle interior, has a high priority.

As clients demand a high standard of well-being while travelling, comfort becomes an essential technical objective. New air conditioning concepts though, will only gain the client's acceptance if they reconcile unchanging comfort while reducing the energy consumption. Technically the energy consumption can be rapidly ascertained by measurements or simulation. It is though more difficult to find a comparable criterion for measuring comfort. The evaluation of comfort in the vehicle industry developed over the past years and is mainly based on the subjective evaluation of research engineers.

In this study a new measuring method is introduced to evaluate air conditioning concepts objectively by using the directed equivalent temperature according to DIN EN ISO 14505-2:2007-04. A new generation of climate measurement systems forms the foundation of this investigation.

## 2. Methods

Numerous evaluation methods, which are more or less suited to be used in vehicles, can be found in the literature. After a comprehensive analysis of the requirements in the automotive section as well as an extensive comparison of established measuring methods Schwab and Grün (2013) came to the conclusion that the equivalent temperature is a suitable evaluation criterion. A general definition for the equivalent temperature is: 'The temperature of an imaginary enclosure with the mean radiant temperature equal to air temperature and still air in which a person has the same heat exchange by convection and radiation as in the actual condition' (Håkan Nilsson, 2004, p. 37). Thus, the equivalent temperature can be used to measure the effects of non-evaporative heat loss from the whole human body (Dufton, 1936; Madsen et al., 1984; H. Nilsson et al., 1999). The above definition can be extended to include the measurements of sensors on specific body parts. In the case of directed equivalent temperature non-evaporative heat loss is not measured from the whole human body but from specific small flat, heated surfaces on the body. This is necessary to objectively evaluate differences of the thermal perception of each body part depending on the air conditioning concepts used.

### 2.1. Climate Measuring System

The climate measuring system 'Comfortis Measurement System' from the company Comlogo GmbH. consists of 16 heated sensors and an evaluation unit which is connected to a measuring computer via WLAN or CAN-Bus. In a pre-test the 16 sensors were stuck onto a foam dummy with wire frame inside. The sensor consists of a heated surface with constant heat flow. The handling of this dummy was unsuitable as it was difficult to position the dummy into the vehicle and the sensors slightly slipped out of their positions. Based on the insights received by the pre-test, another dummy was designed to fasten the sensors. Figure 1 shows the construction of the climate dummy as well as it features. For a good handling, all cables as well as the evaluation unit can be placed inside the dummy. The dummy constitutionally corresponds the 50. percentile man.

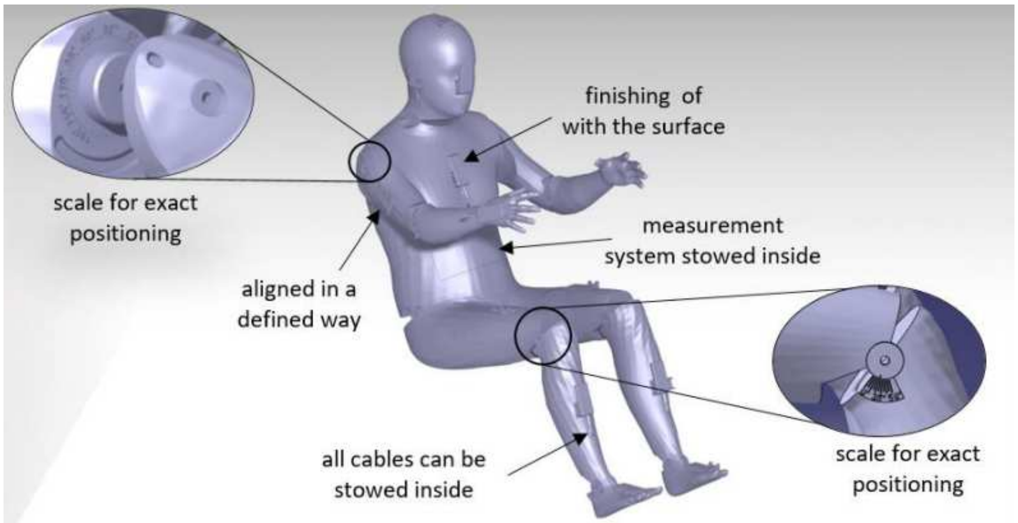



Figure 1. Features of the climate dummy

This climate dummy allows a standardized positioning in the vehicle as all joints can be adjusted according to a reproducible scale. Every sensor is embedded on the surface of the dummy to ensure a natural air flow behaviour (see figure 2). In the case of a normally attached sensor the resistance of the air flow is increased. The sensors are located to the scalp, face, left and right temple, neck, thorax, left and right upper arm, hand, thigh, shin and on both feet. Body regions, such as the head and neck, have more thermos-receptors and are thus very sensitive (Schmidt et al., 2011). These regions have a high number of sensors to get a better resolution for the evaluation of thermal perception. It is thus important to measure the equivalent temperature of every body part as different climate concepts have varying effects on the overall thermal wellbeing.

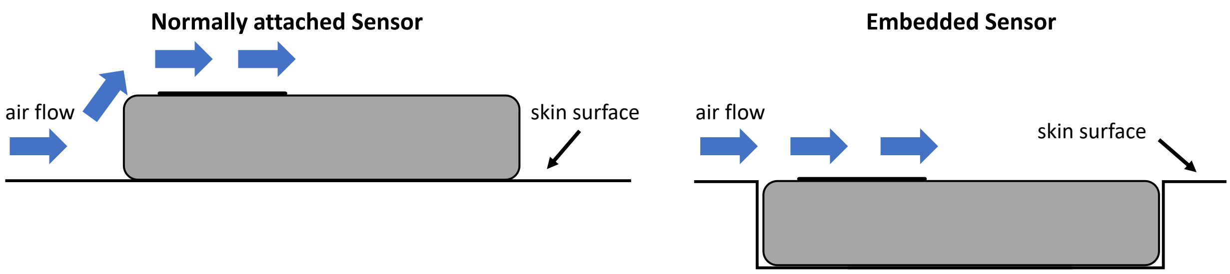



Figure 2: Comparison between a normally attached sensor and the optimized embedded sensor

## 2.2. Pre-tests

Modern vehicle seats can be adjusted in a variety of ways. It is known that the sitting position has a direct influence on the measuring results of the equivalent temperature. Therefore, the influence of the lengthwise adjustments of the seat on the directed equivalent temperature are investigated in a pre-test.

For this purpose, a vehicle is conditioned at -10°C in a climate chamber. In a vehicle with an automatic climate system, adjusted at AUTO 22, conditions reached in the car cabin stays steady after about an hour. At the beginning of the test the passenger seat with the dummy is in the lowest position and as far back as possible. Every 20 minutes the seat is moved 6 cm to the front and the equivalent temperature is measured. Five positions can be measured until the seat reaches its maximum adjustment track of 24 cm. Figure 3 shows the equivalent temperature reaction to the described sitting positions.

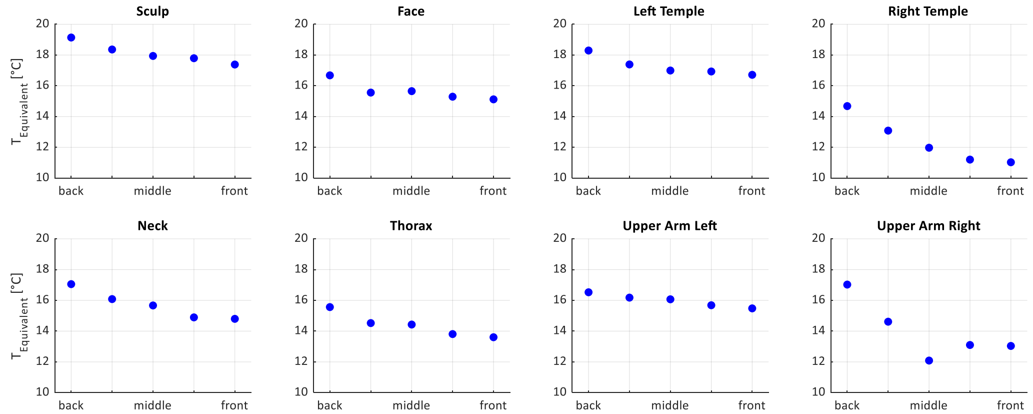



Figure 3. The equivalent temperature in relation to the sitting position; seat maximum at the back = 'back' (0 cm); seat in the middle position = 'middle' (16 cm); seat maximum to the front = 'front' (24 cm)

The equivalent temperature shows slight deviations when the passenger seat is adjusted to the middle position. The deviation is greatest between the furthest back and most front sitting position. The influence of the cold side-window can be clearly noticed, by a low equivalent temperature. Thus, the measured values of the right temple and right upper arm were colder in the middle, up to the more front adjustment range. If the seat is further back the sighting factors concerning the side-window are reduced and the equivalent temperature increases. In general values of a maximum of 19°C are reached during the test as the vehicle was idling and consequently not enough heating power was produced.

The pre-test has shown that the measured values only varies slightly when the seat is in a position close to the middle. This means that small inaccuracies during the adjustment of the seat should not have a significant influence on the measuring values. Furthermore, the Comfortis Measurement System in the vehicle showed an asymmetric but satisfactory temperature distribution. The equivalent temperature is measured with an accuracy of 5%. The resolution is high enough to reflect the inhomogeneities in the vehicle.

### 2.3. Experimental Design

As mentioned before the evaluation of new climate concepts are often done subjectively which can lead to many individual fluctuations. It is also difficult to compare single physical parameters as the effect of different climate factors can mutually compensate each other. Three climate concepts which are evaluated on the bases of the equivalent temperature will be discussed in the following. The climate concepts discussed are surface heating, overhead and seat ventilation, as well as the extended ventilation field which are schematically illustrated in figure 4.

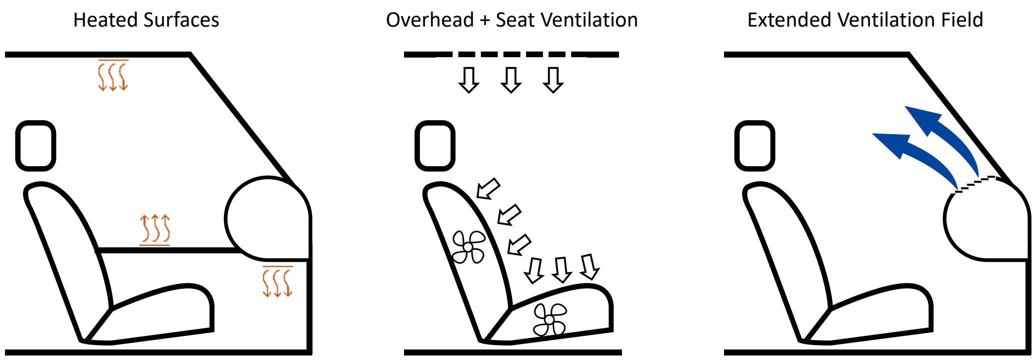



Figure 4: Schematic illustration of the three climate concepts

### 2.3.1 Experiment 1: Surface Heating

Surface heating has a local effect on the thermal comfort and therefore has the potential to increase comfort while energy consumption is reduced at the same time. The additional heat input via surface heating maintains thermal comfort while the temperature of the car interior can be reduced to save energy. The effect of the surface heating is investigated more accurately by the construction of a test station to quantify well-being. The test station consists of a supply platform and a simplified car cabin. The dimensions of the internal space in the cabin is similar to the space at the front end of a B-class vehicle. The supply platform consists of an air conditioning unit with a heating- and cooling circuit. The circuits supply the air conditioning unit with the necessary power for air conditioning. The air conditioning unit can be adjusted freely and supplies the car cabin with climatized air. This air conditioning system coincides with a classical air conditioning system (2 air vents in the footwell, 4 air vents in the dashboard, 4 air vents for defrosting) in a vehicle. The experimental set-up enables us to compare new climate concepts with standard air conditioning. Figure 5 shows the set-up of the simplified car cabin with the supply platform in the climate chamber.


Figure 5. Simplified car cabin with supply platform (Wöhr, 2018, p. 36)

Besides standard air conditioning, the internal space can also be climatized by integrated heating panels during cold environmental conditions (T < 15°C). The surface temperatures of the dashboard, upper- / and lower side, central console and headliner can be adjusted separately from each other. Additionally, every window pane can be heated to simulate solar radiation, which would only be done during the summer mode. The main objective of this experiment is to test the influence of different heating panels on the thermal comfort of the occupant.

The experiments were done with an ambient temperature of 5°C in the climate chamber. The supply air temperature is changed in 10°C steps from 20°C to 60°C and the surface temperatures are also changed in 10°C steps from 30°C to 70°C according to the scheme in figure 6. The supply air temperatures are similar to normal temperatures for climatization in vehicles and the surface temperatures are selected according to DIN EN ISO 13732-1. For the sake of convenience, the supply air temperature is kept constant for a measurement series and the surface temperature is increased stepwise. After each temperature change the thermodynamic condition of the car cabin is in a non-steady state. Steady conditions are only reached after 20 minutes before the equivalent temperatures can be measured.

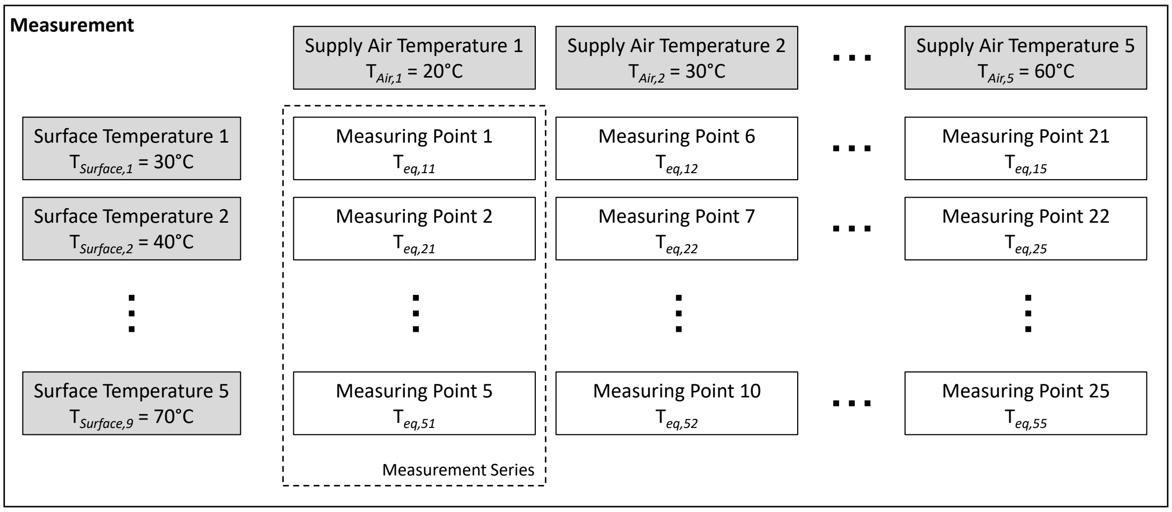



Figure 6. Measuring scheme heated panels. Measured at a temperature of 5°C in the climate chamber.

### 2.3.2 Experiment 2: Overhead Ventilation

Similar to the concept of surface heating overhead ventilation is also used for close-to-body climatization. In this experiment the overhead ventilation is combined with a climatized seat. The seat sucks off the cooled air coming from the overhead ventilation. Energy is saved because only the immediate surrounding of the occupant needs to be cooled to enhance thermal comfort. This climate concept is also suited to be used for air conditioning during autonomous driving as climatization of the surrounding air is independent of the alignment of the car seats. A simplified car cabin in a climate chamber was also used for this experiment. The construction of this test station was simpler than in experiment 1. The temperature in the climate chamber was adjusted to the same value as the temperature of the car cabin.

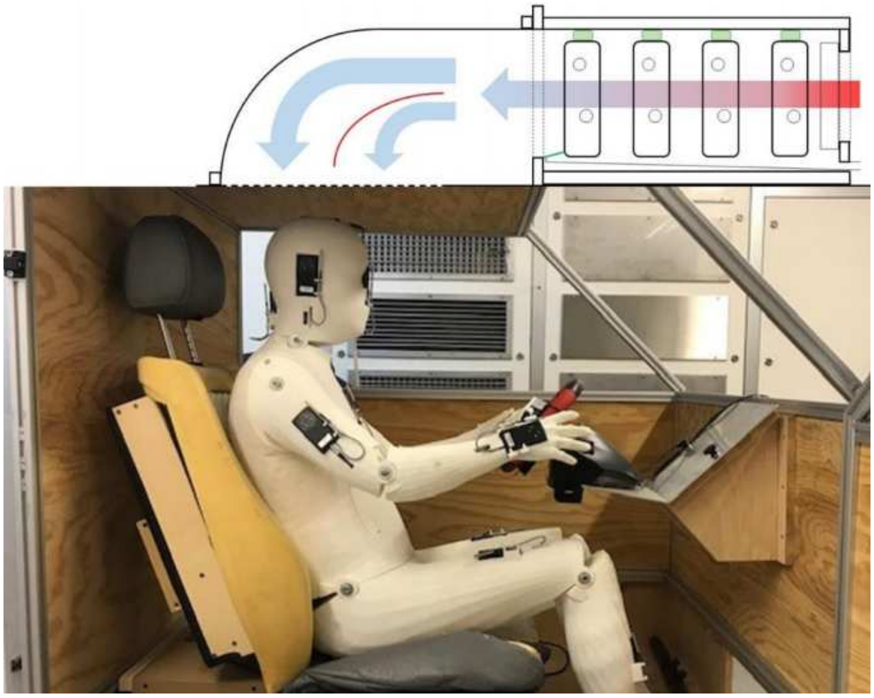


Figure 7. Simplified car cabin with overhead ventilation system

Overhead ventilation was the only method of climatization. The air of the climate chamber is specifically climatized by three series-connected heat exchangers. The climatized air leaves the headliner via air outlets and cools the occupants on the conditioned seat (see figure 7). The heat exchangers are supplied with air via the cooling circuit of the climate chamber.

The main factors having an influence on air conditioning are changed in a similar way as in experiment 1. The interior temperature is changed in 5°C steps from 20°C to 55°C and the overhead outlet temperatures are changed in 4°C steps from 8°C to 22°C according to the scheme in figure 8. For the sake of convenience, the interior temperature is kept constant for a measurement series and the overhead outlet temperature is increased stepwise. To every paring of the interior- and overhead outlet temperatures the air mass flow rate is additionally changed in three steps ($\dot{m}_1$ = 1.48 kg/min, $\dot{m}_2$ = 1.87 kg/min, $\dot{m}_3$ = 2.4 kg/min). Measurements of the equivalent temperature are taken once stationary conditions are reached.

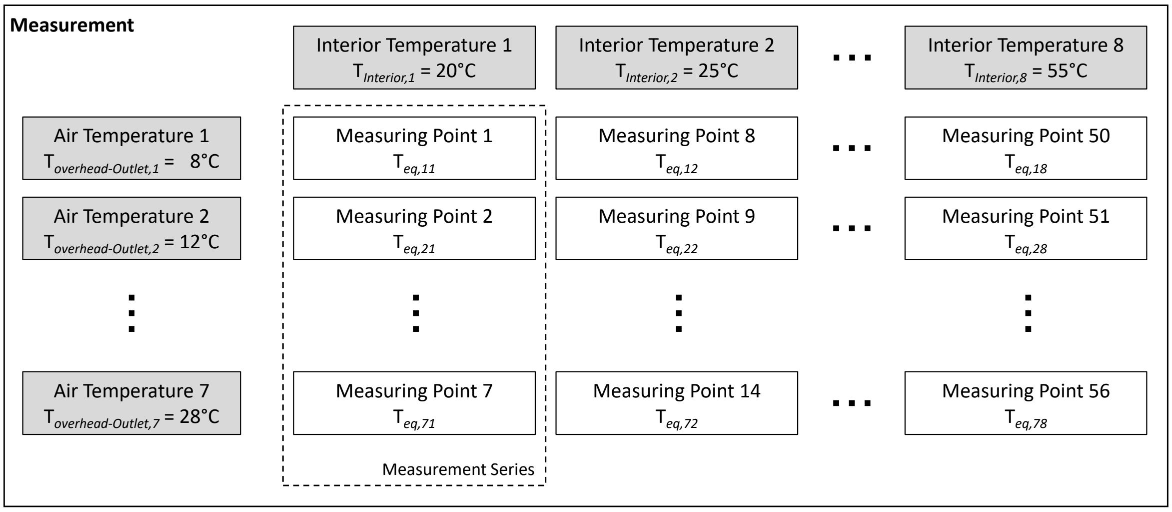


Figure 8. Measuring scheme for the overhead ventilation concept

### 2.3.3 Experiment 3: Extended Ventilation Field

During the first two experiments new climate concepts are investigated. In this last experiment a standard concept is analysed. In the case of an SUV an extended ventilation field (EVF) is used (see figure 9).

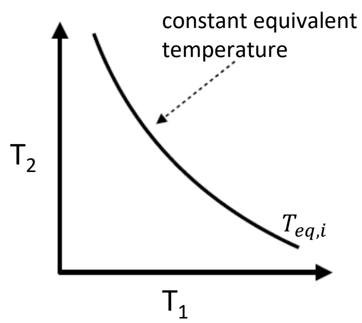
Figure 9. Standard air conditioning with EVF

Contrary to the classical vents, the EVF cannot be adjusted. It can only be activated or deactivated by the infotainment display. To assess the climatization with and without the EVF, two experiments are conducted in a climate wind tunnel. The vehicle is positioned onto a dynamometer to simulate an actual driving environment. A climate dummy is sitting on the passenger seat during the duration of the experiment.

Before starting the experiment, the vehicle is conditioned at a temperature of 40°C and a solar intensity of 1000 W/m$^2$ for 1 hour. Afterwards a cool-down experiment is started, lasting for 1h25min leading to steady conditions. Next the solar simulation is deactivated, and the ambient temperature of the climate wind tunnel is reduced in 2°C steps until a temperature of 34°C is attained. At this stage the climate control is adjusted from MAX A/C, climatization style 'intense' to AUTO 22, climatization style 'medium'. After each reduction 20 minutes are needed before conditions are stable again. This is done to investigate whether a lower ambient temperature still has any influence on the EVF. At the last ambient temperature of 34°C the climatization style is changed to 'gentle' to investigate whether climate styles have any influence on the equivalent temperature. The mentioned climate styles differ in terms of supply air temperature, air flow velocity and air distribution. In the case of 'intense' the temperature is the coolest and the air flow velocity the highest. All these different adjustments are done to find out how the EVF influences the interior climate. It is also investigated whether the EVF is an effective climate concept having a positive influence on the thermal wellbeing.

### 2.4. Iso-Comfort Diagram

New climate concepts can only be evaluated under consistent comfort conditions. For this purpose, a new evaluation method, using iso-comfort diagrams is introduced. As can be seen in figure 6 and 8 two main factors ($T_1$ and $T_2$), influencing the climate concept, are varied and the resulting equivalent temperatures are measured. In this way a constant equivalent temperature, subject to its influencing factors, can be depicted (see figure 10). The effect of different climate variables at a constant equivalent temperature results in the same heat loss. This assures that only the conditions which result in consistent thermal comfort are being considered. Lines with a constant equivalent temperature are described as iso-comfort lines. The gradient provides information on the effect of $T_2$ on $T_1$ (see figure 10). The gradient on its own is inadequate for a detailed evaluation. The numerical values of the attained equivalent temperatures are also important. Suggestions according to DIN EN ISO 14505-2:2007-04 give an indication what the thermal perception is like subject to the equivalent temperature.




$$\text{Effect} \sim \frac{1}{\text{Gradient}}$$

$$\text{Gradient} = \eta = \left|\frac{\Delta T_2}{\Delta T_1}\right|_{T_{eq,i}=const.}$$

Figure 10. Iso-comfort diagram

Iso-comfort diagrams are used to analyse the climate concepts of the surface heating and overhead ventilation for a huge variety of different climate conditions. In this way the thermal perception for each climate concept can be objectively evaluated.

## 3. Results

The results of the objective comparisons will be given in the following section. In experiment 1 the equivalent temperature is presented as a function of the surface temperature and of the supply air temperature. In the case of experiment 2 the equivalent temperature is a function of the outlet temperature of the overhead ventilation and temperature of the cabin interior. The average of the measured values for head, torso and leg regions of the climate dummy are used to allow a large number of variables to be presented.

### 3.1. Experiment 1: Surface Heating

Figure 11 shows the iso-comfort diagrams for the head, torso and legs during heating via the headliner (a), central console (b) and lower section of the dashboard (c). On the x-axis of the diagram the outlet temperature is shown and on the y-axis the respective surface temperatures are shown. Additionally, the average gradient ($\overline{\eta}$) for the iso-comfort-lines are given for each diagram. The values of the gradient indicate how much the surface temperature has to be increased when the temperature of the in-blowing air is decreased by 1°C. This means that with an average gradient of 2 for the headliner the surface temperature must be increased by 2°C (see figure 11a). In this case the thermal comfort of the head region

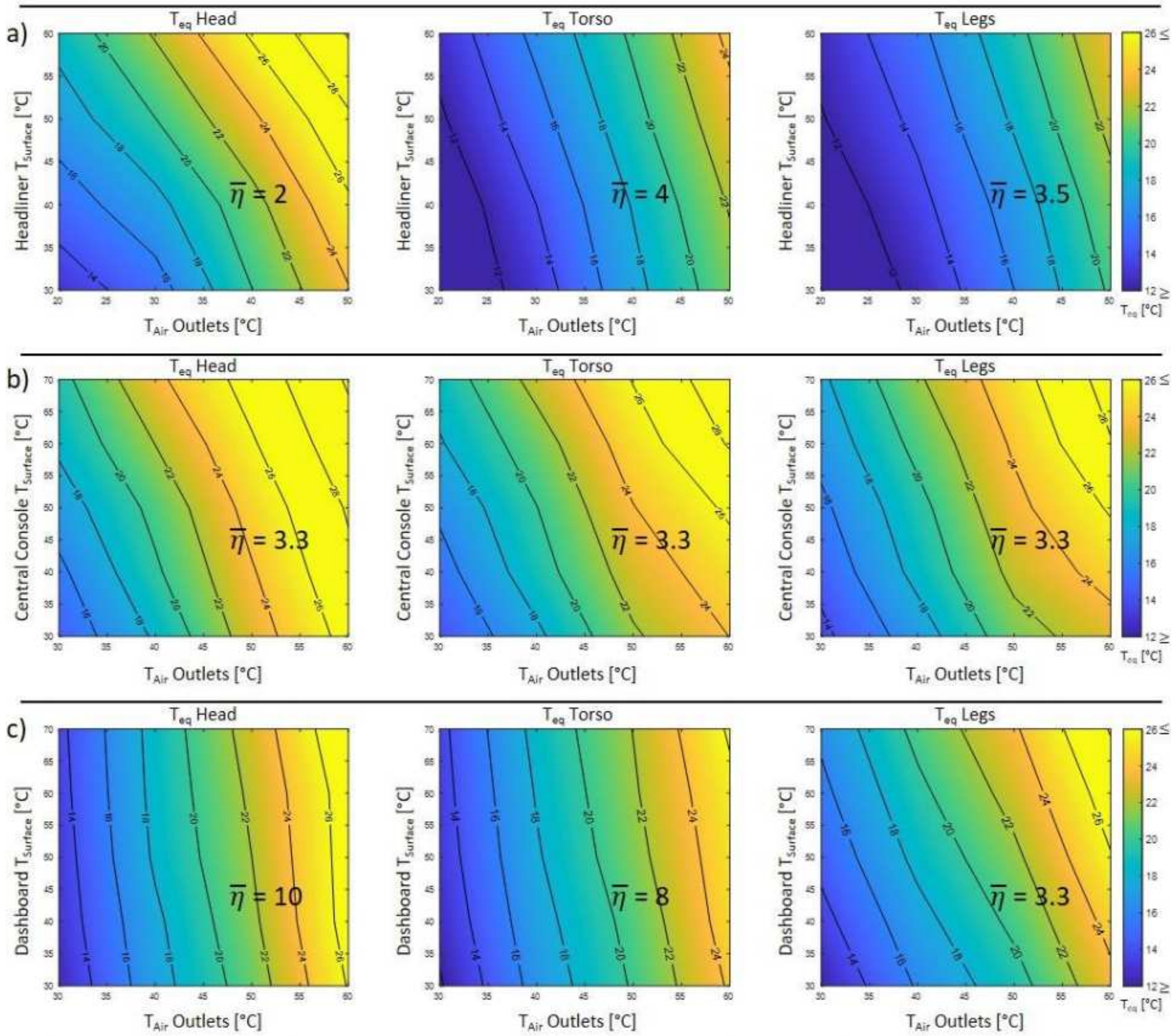



Figure 11. The gradients of the iso-comfort lines for head, torso and legs during heating via the headliner (a), central console (b) and lower section of the dashboard (c) (Based on Wöhr, 2018)

remains constant. When the values of the gradient are higher the course of the equivalent temperatures is steeper. The values of the equivalent temperature of various combinations of the surface temperature and the in-blowing air temperature are also crucial. An equivalent temperature of the head region of 22°C is attained at a surface temperature of 60°C and an outlet air temperature of about 39°C. With the same parameters the equivalent temperature for the torso is reduced to about 16.5°C and for the legs to about 15.8°C. This proves that the headliner is suited to locally heat the head region but from a global perspective the torso and leg regions are too cold.

The situation is different in the case of heating via the central console (see figure 11b). A gradient of 3.3 for the head-, torso- and leg regions has a positive heating effect on the global thermal comfort of the body. At a surface temperature of 50°C and an outlet air temperature of about 45°C the resulting equivalent temperature is 22.5°C for the head-, 22.0°C for the torso- and 21.5°C for the leg region. These results proof that similar equivalent temperatures are attained for the same combinations of surface temperatures and outlet temperatures. The similar values can be explained by the high view factors between the central console and the three body regions.

There are major differences when heating via the lower section of the dashboard (see figure 11c). The gradient of the head and torso regions are respectively 10 and 8 which means that these regions are heated insufficiently. This can be explained by the fact that the view factors between the lower section of the dashboard and head and torso regions are very low. The heating effect is therefore limited to the leg region.

In summary it can be said that by a combination of heating via headliner, central console and the lower section of the dashboard global thermal comfort can be achieved by reducing the in-blowing air temperature. Local asymmetries can also be minimized by a combination of these surface heating systems.

### 3.2. Experiment 2: Overhead Ventilation

Contrary to the surface heating system, overhead ventilation is investigated for warm summer temperatures. Figure 12 shows the iso-comfort diagrams for the head, torso and legs at an air mass flow rate of 1.48 kg/min (a), 1.87 kg/min (b) and 2.4 kg/min (c). The interior temperatures are reflected on the x-axis of the diagram and the overhead outlet temperatures on the y-axis. Identical to figure 11, the average gradient ($\bar{\eta}$) for the iso-comfort-lines are given for each diagram. In this case the value of the gradient indicates to which amount the overhead outlet temperature has to be decreased when the temperature of the interior is increased by 1°C. In figure 12a an average gradient of 0.5 means, that the comfort remains constant if the overhead outlet temperature is decreased by 0.5°C. For the head region an outlet temperature of 21°C and an interior temperature of 30°C lead to an equivalent temperature of 18°C. Under the same conditions the equivalent temperatures for the torso and leg regions are respectively 23°C and 25°C. Considering the range of equivalent temperatures the maximum values for the torso and leg regions rise to 38°C and 44°C. With a value of 28°C the equivalent temperature for the head is comparatively low. The cooling effect of the overhead ventilation for the head region is intensive, whereas the torso and legs are not cooled sufficiently.

When the air mass flow is increased to 1.87 kg/min the gradient of the iso-comfort lines decreases for all body regions. Identical to the prior, high equivalent temperatures are reached in the regions of the torso and legs as can be seen in figure 12b. An equivalent temperature of the head region of 17°C is attained at an overhead outlet temperature of 21°C and an interior temperature of 30°C. With the same parameters the equivalent temperature for the torso rises to 22.2°C and for the legs to about 24.3°C. A higher air mass flow leads to more cooling power and thus to lower equivalent temperatures. This means that distribution of the cooling power is still concentrated on the head region, whereas the torso and legs remain too warm.

At a maximum air mass flow rate of 2.4 kg/min the changes are similar to those in figure 12c. All the gradients increase more, and the equivalent temperature reaches its lowest values for head, torso and legs. With the same combination of 21°C overhead outlet and 30°C interior temperature the equivalent temperature of the head region decreases to 15°C. In this case the equivalent temperatures for torso and leg regions are respectively 20°C and 23°C. Especially for higher interior temperatures the cooling power is inadequate for these body regions.

All together the overhead ventilation is not able to provide global thermal comfort. Locally the head region can be climatized very sufficiently, even at high interior temperatures. A positive cooling effect for the torso and leg regions can only be achieved if the interior temperature is not higher than 30°C.

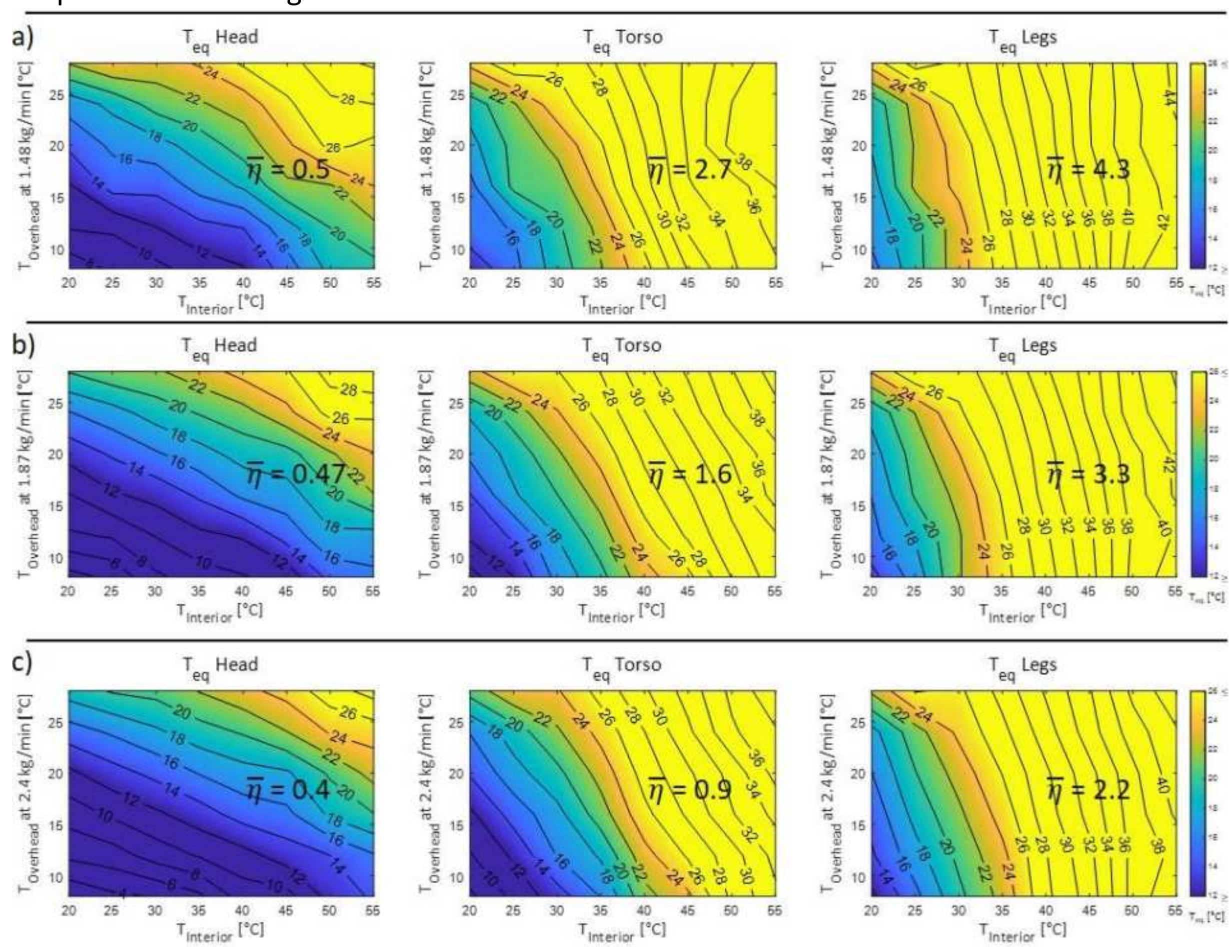



Figure 12. The gradients of the iso-comfort lines for head, torso and legs at an air flow mass rate of 1.48 kg/min (a), 1.87 kg/min (b) and 2.4 kg/min (c) (Based on Zierer, 2019)

### 3.3. Experiment 3: Extended Ventilation Field

The authors focus on the most effective results attained by the following two tests. The cool-down test is done in the climatization style 'intense' at an ambient temperature of 40°C and solar intensity of 1000 W/m². The climate control is adjusted to MAX A/C. The comfort zone diagram in figure 13 (right) shows the equivalent temperature measured by the 16 different sensors on the surface of the climate dummy. The x-axis of the diagram reflects the measured values of the equivalent temperature and the y-axis shows the different body segments. These measurements are done with and without the EVF. They can be explained in more detail by the corresponded colour visualisation in figure 13 left.

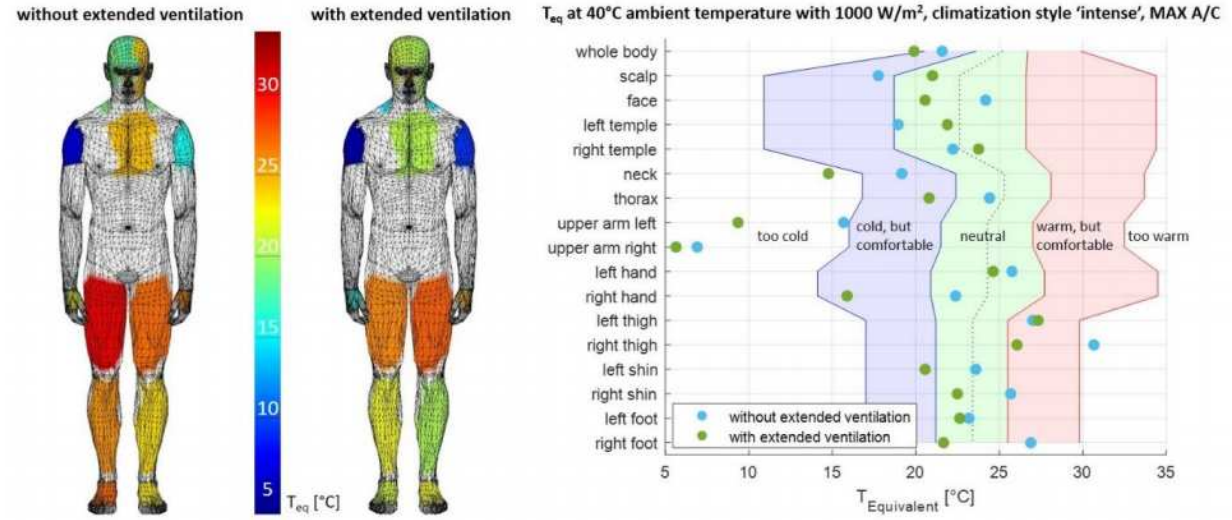



Figure 13. Colour visualisation of the measured equivalent temperatures (left) and comfort zone diagram (according to Håkan Nilsson, 2004) of the results from the first test at 40°C

Looking at the comfort zone diagram it can be seen that the equivalent temperature for the whole body is 1.7°C lower when the EVF is activated. Of the 16 body segments 12 regions were cooled more intensively when the EVF is activated. When the EVF is deactivated three segments are warm, but comfortable and only one segment on the right thigh is too warm. The equivalent temperatures of the head region vary considerably without EVF. The coldest body region with and without the EVF is the upper arm with values of respectively 5.6°C and 6.9°C. In this case the sensor is influenced by the cold air stream coming from the right outlet in the dashboard.

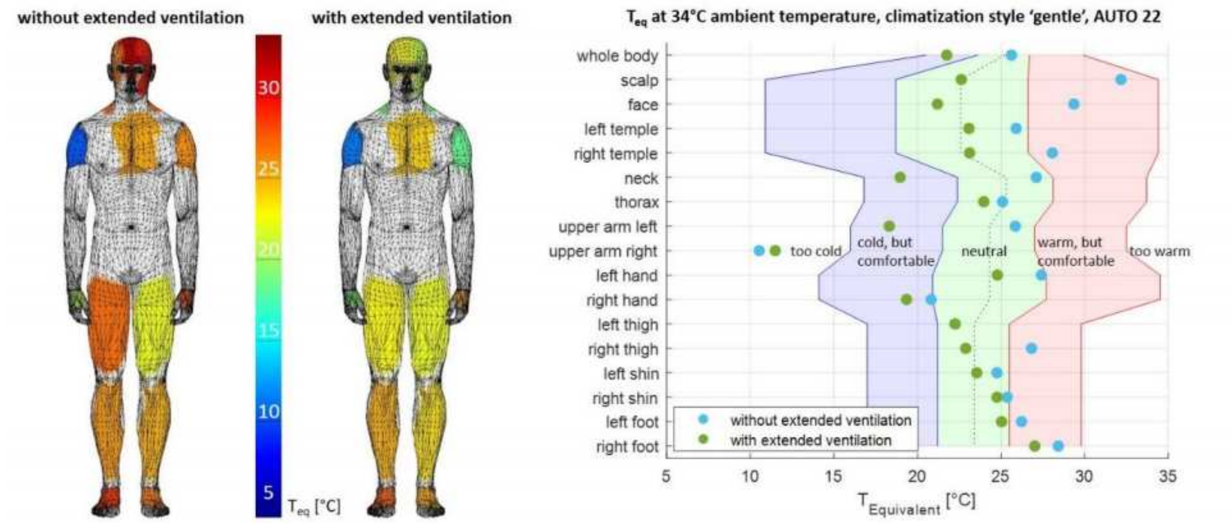



Figure 14. Colour visualisation of the measured equivalent temperatures (left) and comfort zone diagram (according to Håkan Nilsson, 2004) of the results from the last test at 34°C

The last test was done with the climatization style ‘gentle’ at an ambient temperature of 34°C without sun radiation (see figure 14). Without the EVF the temperature of the scalp increases with nearly 10°C and is significantly warmer compared to the situation when the EVF is activated. Looking at the comfort zone diagram it is noticeable that all the measured values without the EVF are considerably higher and fluctuate more. The only exception is the right upper arm. The EVF provides enough cooled air to realize ‘gentle’ climate conditions which largely lead to a neutral thermal sensation.

**4. Discussion**

The focus of this study is the objective evaluation of the thermal comfort in order to analyse three different vehicle climate concepts. The newly introduced iso-comfort diagram allows a detailed analysis of the described close-to-body climate concepts. In the case of the experiment with the heating panels, local heat supply can compensate a reduced interior temperature. Heating via the central console has a positive effect on the thermal comfort of the head, torso and leg regions. The headliner and the lower section of the dashboard mostly has a local influence on respectively the head and leg regions which causes an inacceptable radiant asymmetry. The energy consumption, used for air conditioning, can be reduced during the winter months by a combination of the mentioned heating panels. Simultaneously the thermal comfort can be improved. Future investigation will focus on the energy saving potential combined with the increase of thermal comfort at the same time.

In the second experiment overhead ventilation is investigated at summer temperatures. Here the aim is to cool down the occupants’ close-to their bodies without cooling down the total air volume of the car interior. Amongst other temperatures an interior temperature of up to 55°C is used to investigate the efficiency during cool-down. Such boundary conditions are regularly attained when the vehicle is parked in the direct sun. High equivalent temperature values for the torso and leg regions show that only the head region can be effectively cooled under these extreme conditions. In general, it can be shown that overhead ventilation can cool down the head region effectively and potentially has sufficient cooling power for the torso region. Constructive adaptions of the overhead ventilation could improve the air distribution. In general, overhead ventilation is not able to provide adequate cooling power for the leg region. Therefore, additional climate measures are necessary to provide thermal comfort for the whole body and to ensure that the car interior does not get too warm.

In the case of experiment 3 a standard concept is investigated more elaborately. Here various operation points with and without EVF are compared with each other. In the first test a cool-down is conducted to reduce the interior temperature of vehicle cabin as fast as possible. The equivalent temperature is reduced faster with the EVF as more cold air is blown into the vehicle cabin. Considering the temperature distribution, it is also noticeable that the EVF reduces asymmetries. In the last test the climate style ‘gentle’ is investigated. Here the outlet velocities are reduced so that climatization in the vehicle cabin is draft-free. Without EVF the cooling power is insufficient, and the temperatures increase significantly while the thermal comfort is maintained.

**5. Conclusion**

The evaluations of the different climate concepts are done on the basis of the equivalent temperature as this is an objective climate index to assess thermal comfort. By using the introduced climate dummy, valid and reliable measurements are attained. Furthermore, the newly developed iso-comfort diagram allows the presentation of the equivalent temperature in correlation with two influencing parameters.

This investigation leads to the following core statements. In the case of surface heating individual body parts (head and leg regions) are sufficiently heated. A combination of headliner, central console and the lower section of the dashboard is necessary to ensure thermal wellbeing for the whole body. The overhead ventilation only climatizes the head region sufficiently, torso and leg regions though are inadequately cooled down. This climate concept on its own does not provide thermal wellbeing of the whole body in summer. The extended ventilation field ensures an evenly distributed and draft-free air conditioning in the vehicle cabin and is therefore a rational supplement to the classical air climatization system.

This study further shows that thermal comfort can be determined objectively by measuring the equivalent temperature and thus can be used to analyse different vehicle air conditioning concepts.

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# Consideration of seasonal history in transition season: the case of occupant behaviours and thermal comfort in Japanese dwellings

**Hikaru Imagawa[1] and Hom Bahadur Rijal[2]**

[1] Graduate School of Environmental & Information Studies, Tokyo City University, Japan, /JSPS Research Fellow DC2

[2] Department of Restoration Ecology & Built Environment, Tokyo City University, Japan

**Abstract:** Japan has both “hot and humid summer” and “cold and dry winter”. It means that Japan also has transition season as spring and autumn. In transition seasons, there are similar outdoor temperature range. However, the outdoor temperature is increased in spring and decreased in autumn. This difference may influence to our thermal history. Some previous studies analysed the short period thermal history, and the historical effect was 15 minute, 1 week and 8 days. Our previous studies also showed that there may be seasonal history in spring and autumn for thermal comfort and occupants’ behaviours such as air conditioning (AC) cooling and heating use, window open and clothing adjustment. In next step, it is important to analyse the overall trend of long period thermal history as seasonal changes. In order to consider the residents’ thermal comfort as seasonal changes, we analysed the dataset which was obtained from the field surveys of Japanese dwellings in Kanto area. The occupant behaviours are different in spring and autumn, especially the AC cooling use is significantly different. The historical difference may be useful to make the resilient comfort during transition season as complex periods.

**Keywords:** Seasonal History, Transition Season, Occupant Behaviour, Thermal Comfort, Japanese Dwellings

## 1. Introduction

### 1.1. Over view of study

Thermal adjustment is one of the most important behaviour for health and comfort. Japan has both “hot and humid summer” and “cold and dry winter”. It means that Japan also has transition season as spring and autumn. In transition seasons, there are similar outdoor temperature range. However, the outdoor temperature is increased in spring and decreased in autumn. This difference may influence to our thermal history.

Some previous studies analysed the short period thermal history. For example, Shukuya et al. (2018) conducted the experiments considering 15 minute and 1 week thermal history. Liu et al. (2018) conducted the field survey and found that the clothing adjustment was affected cumulatively by past outdoor temperature of the preceding 8 days. Li et al. (2015) also conducted the field survey in transition season and calculated the relationship between the probability of window opening and outdoor temperature. Chen et al. (2018) show the relationship between thermal sensation vote and physiological equivalent temperature (PET) as physiological parameter for four seasons. However, the occupant behaviours related to long period as seasonal thermal history were not analysed much in previous studies. So, it is important to analyse them as seasonal changes. Wu et al. (2019) conducted the field survey in university dormitory in China, for example, the clothing insulation is different between the presence of AC unit in buildings. Jowkar et al. (2020) verified the relationship between thermal comfort and students' climatic background as their thermal history in UK university.

In Japan, the residents use various thermal adjustments. The clothing adjustment, the AC use and standing fan use are commonly available in Japanese dwellings.

**1.2. Our previous studies**

In our previous studies (Imagawa & Rijal 2018), we try to find the difference of transition seasons. At first, in order to know the difference of transition season as the AC cooling or heating use and window open/closed, we calculated these behaviours by stochastic models for Japanese four seasons. Comparing the same outdoor air temperature range between spring and autumn, the proportion of cooling behaviour including the AC cooling use and window open in autumn is higher than spring, and proportion of AC heating use in spring is higher than autumn. From these findings, we concluded that the residents often use the AC cooling in autumn, and AC heating in spring despite the similar outdoor air temperature. When we presented this study, we have noticed that we may need to analyse by monthly data.

Thus, we have analysed the monthly mean values (Imagawa et al. 2019) by establishing the conceptual models considering the transitional season as shown in the Figure 1. We have considered the thermal sensation vote, clothing insulation and comfort temperature in FR mode (the AC is not used during the voting), and showed the relationship between clothing insulation or thermal sensation and air temperature in XY axis which is similar to the "climograph". In this previous study, we wanted to know the necessities of the difference of transition seasons for adaptive model in FR mode. When the FR mode is operated in dwellings, the clothing adjustment is important for thermal comfort. Thus, we showed not only adaptive model and thermal comfort but also clothing insulation. We found that the monthly mean thermal sensation vote for increased indoor air temperature is higher than that of the decreased temperature. And, the monthly mean clothing insulation for decreased daily running mean outdoor air temperature is higher than that of the increased temperature except December. These mean that the residents felt the different thermal sensation in transition seasons when temperature is increased or decreased. In spring, the residents felt a bit hotter than the autumn, and thus their clothing insulation is also a bit thinner than autumn, and vice versa.

It is interesting that the comfort temperature and daily running mean outdoor air temperature are very similar in spring and autumn. Even though we found the transition seasonal difference in the thermal sensation, we do not need to consider this difference in the adaptive model due to the clothing adjustments.

Our previous studies showed that the thermal adjustments might be key issue for the transition seasonal difference. However, we did not analyse about the transition seasonal difference of AC use and window open in each month.

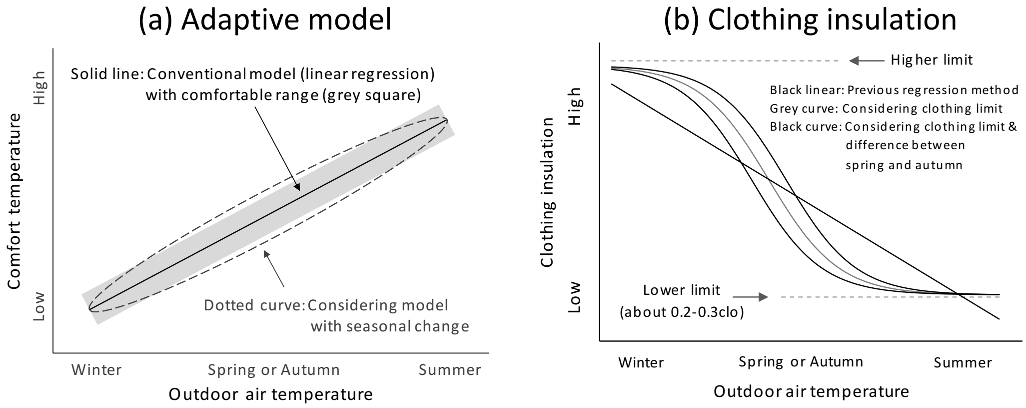


Figure 1 Concept of adaptive model and clothing adjustment model (Imagawa et al. 2019)

### 1.3. Objectives

In this study, we calculated the proportion of AC/fan use, window open and thermal comfort in each month. And, in order to know the transition seasonal difference of occupant behaviours, we compared the each behaviour, and analysed the relationship between each behaviour. From these analysis, we tried to find the hint of resilient comfort during transition season in Japanese dwellings.

## 2. Study methods

### 2.1. Field study

We have conducted a series of field survey in 120 Japanese dwellings in Kanto region of Japan (Rijal et al. 2018, 2019). The data were collected in living room and bedroom. The survey times were from morning to nighttime in living room, and before or after sleep in bedroom. The number of subject was 120 residents. The period was from 6$^{th}$ July 2010 to 9$^{th}$ August 2014. In this survey, we conducted the thermal environment measurement and the thermal comfort survey simultaneously. We measured the indoor air temperature and relative humidity in 10 minute intervals. Thermal sensation vote was collected using the seven point scales (Rijal et al. 2018, 2019). When the residents voted their thermal comfort, they also recorded the states of the window opening/closed, cooling or heating by air conditioner and fan use on binary data (opening or use: 1, closed or no use: 0). We have collected altogether 36154 responses. The outdoor air temperature was obtained from the Japan meteorological station.

### 2.2. Statistical analysis

We used the SPSS version 21 for the statistical analysis. In this study, the “proportion” is calculated using binary data of each occupant behaviour. The “proportion” means the “amount of the occupant behaviour opportunity”. The error bar shows the 95% confident interval: mean±2S.E. (standard error).

The residents may conduct the various occupant behaviours regardless the variation of indoor and outdoor thermal environment during the sleeping. In order to analyse the self-motivating occupant behaviours explained by air temperature, we analysed only the data of the living room.

## 3. Results and discussion

### 3.1. Monthly proportion of fan, AC use and window open

In order to know the yearly variation of occupant behaviours, we calculated the proportion of fan, AC cooling or heating use and window open for each month. Figure 2 shows the proportion of each behaviour in each month. The proportion of window open, fan and AC cooling use were higher in hot season. Especially, the proportion of window open was high from May to October, which is longer period than fan or AC cooling use. The proportion of fan or AC cooling use were reached maximum value in August. On the other hand, the proportion of window open was reached maximum value in June. The reasons might be that the residents wanted to use to the natural ventilation in transition season and mechanical cooling in hot summer season. The proportion of AC heating use was reached maximum value in January.

Due to the variation of these proportions, the residents conducted various behaviours by seasonal changes.

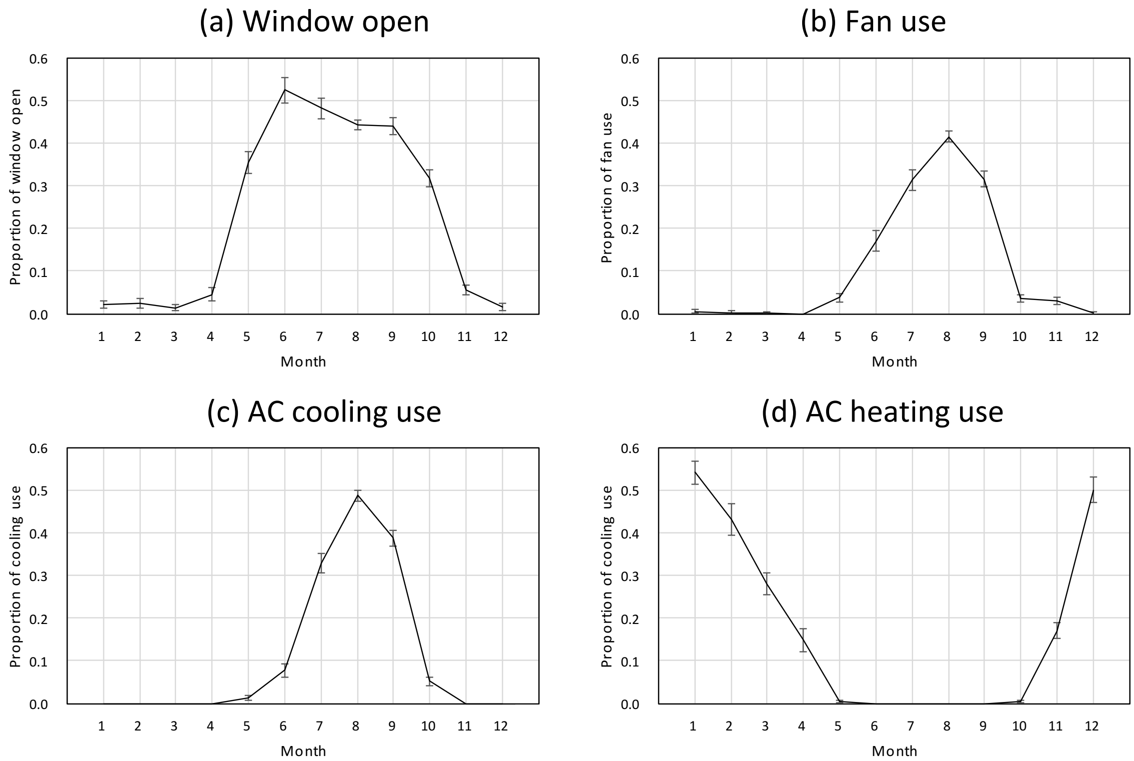


Figure 2 Proportion of occupant behaviours in each month

### 3.2. Yearly variations of outdoor and indoor air temperature

In order to relate the environmental parameter to the occupant behaviours, we analysed the monthly mean outdoor or indoor air temperature (Figure 3).

In August, the maximum mean outdoor air temperature was 28.3°C, and maximum mean indoor air temperature was 28.5°C. On the other hand, the minimum mean outdoor and indoor air temperature were in January and February. The yearly variations of monthly mean air temperature were 23.1°C for outdoors and 10.8°C for indoors.

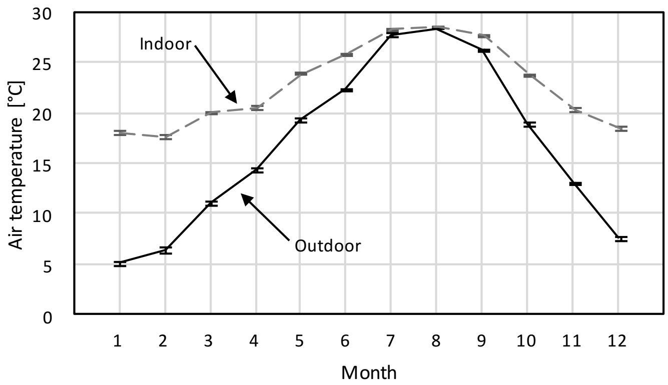

Figure 3 Monthly mean outdoor and indoor air temperatures

**3.3. Relationship between proportion of occupant behaviours and air temperature**

In order to relate the environmental parameter and occupant behaviours, Figure 4 shows the relationship between the proportion of occupant behaviour and monthly mean outdoor air temperature. Each month is shown on the figure. The result shows that the proportion of each occupant behaviour varied during the year, and thus the residents selected and conducted each behaviour for a given outdoor air temperature. However, the trend of each behaviour is different. At first, we confirm each occupant behaviour.

The proportion of window open was increased from May and reached to maximum in June. Despite the increasing the outdoor air temperature until August, the proportion of window open was about 0.45 in August. And, when the outdoor air temperature was significantly decreased in October, and the proportion of window open is also decreased, and this proportion is similar to May for similar outdoor air temperature. Generally, the window is closed when air conditioning is used in Japanese dwellings to increase the efficiency of AC unit running. The results showed that there are rivalry relationship between window open and AC unit use. So, we have to confirm the relationship between window open and AC cooling use.

The proportion of fan use is also increased when the outdoor air temperature is increased. The mean outdoor air temperature in July and September are statistically different. In May and October, the proportion of fan use is also similar for similar mean outdoor air temperature, and thus there are no transition seasonal difference in both months.

The proportion of AC cooling use has clear transition seasonal difference. The proportion was reached maximum in August when outdoor air temperature is also reached maximum. And, the proportion of the period (August to October) when outdoor air temperature is decreased was higher than that of the period (May to August) when outdoor air temperature was increased. Especially, the proportion is different in May and October despite the similar outdoor air temperature.

The proportion of AC heating use is similar in February and December for different outdoor air temperature range. In addition, there is no difference in March to December.

In the next step, we would like to analyse overall trend. The proportion of AC heating use was reached maximum when the mean outdoor air temperature was minimum in January, and the proportion of AC cooling use and fan use also reached maximum when the mean outdoor air temperature was maximum in August. On the other hand, the proportion of window open was reached maximum in June when mean outdoor air temperature is not reached maximum, and thus this trend is different than the other behaviours. And, the proportion of AC cooling use from July to September was higher than in June. Due to the low proportion of both window open and AC cooling use from October to May, the residents were not conducted the both behaviours. From these results, despite the similar outdoor air temperature range, the residents often conducted the behaviour which is related to natural ventilation when the outdoor air temperature is increased, and the mechanical cooling behaviour in the period when the outdoor air temperature is decreased.

We thought that these results are related to thermal history of occupants' behaviours. In the period when the outdoor air temperature is increased, the residents often conducted the natural ventilation by window open as a cooling behaviour. When the outdoor air temperature is increased further, the residents used the AC cooling with window closed. However, when the outdoor air temperature is decreased from September, some residents still use AC cooling because they may not notice that the outdoor air temperature was reached similar to June. And, the residents also may not notice that the window open behaviour can be used as a choice of cooling behaviour because they often used the AC cooling as a cooling behaviour.

From these results, it can be said that the residents conducted the different behaviours when outdoor air temperature is increased or decreased. Especially, the relationship between window open and AC cooling is depend on the seasonal difference.

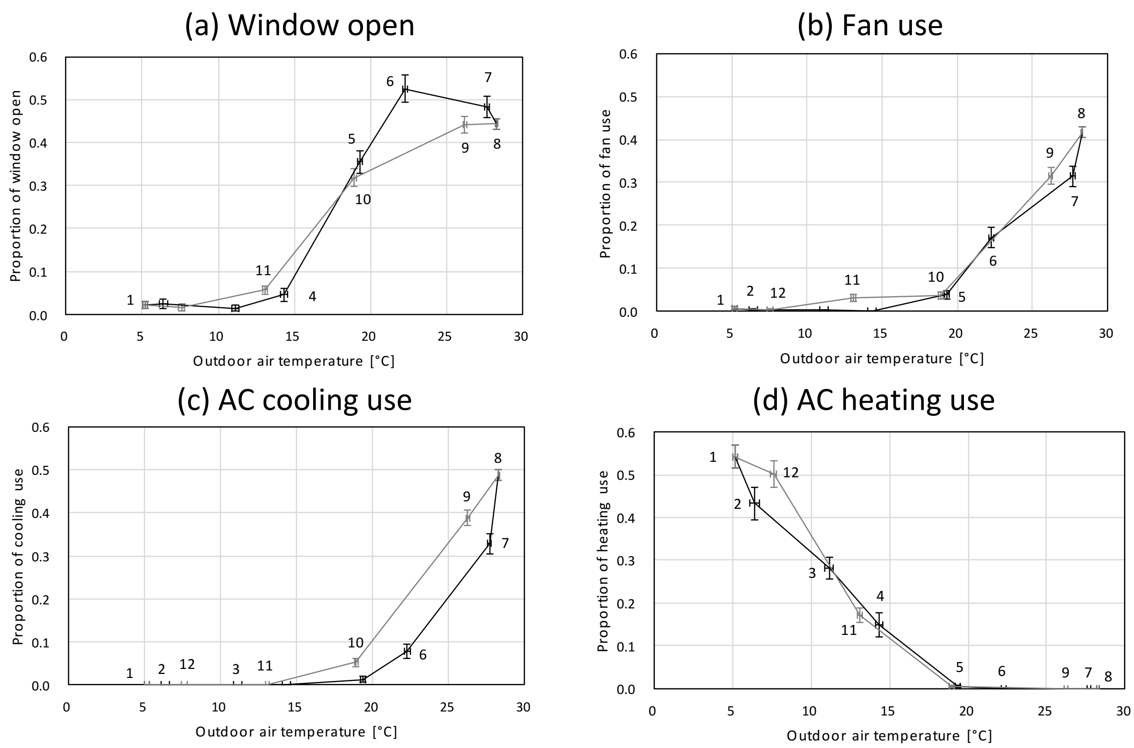


Figure 4 Relationship between proportion of occupant behaviours and outdoor air temperature

### 3.4. Development of the stochastic models for increasing and decreasing outdoor air temperature

As we explained in the previous section, the proportion of AC cooling use is different in "May to July" and "September to October. In order to compare these difference, we developed the stochastic model for increasing and decreasing outdoor air temperature. As shown in Figure 3, the monthly mean outdoor air temperature is increased from January to August, and decreased from August to January. We separated them in two groups "January to August" and "August to January" (Figure 5(a)). We conducted the logistic regression analysis for the AC cooling use for each group. Figure 5 (b) shows regression line with monthly mean values. The proportion of AC cooling use for decreasing temperature (group of Aug. to Jan.) is higher than that of the increasing temperature (Jan. to Aug.). For example, when the outdoor air temperature is 27.1°C, the proportion of AC cooling use is 0.398 for decreasing temperature group which is 0.05 higher than that of increasing temperature group. These differences showed that the residents often conducted AC cooling use in the periods of decreasing the monthly outdoor air temperature than the period of increasing one. Thus, it is important to develop the AC cooling behaviour model considering thermal history of the outdoor air temperature.

(a) Definition of group and legend (b) AC cooling use model

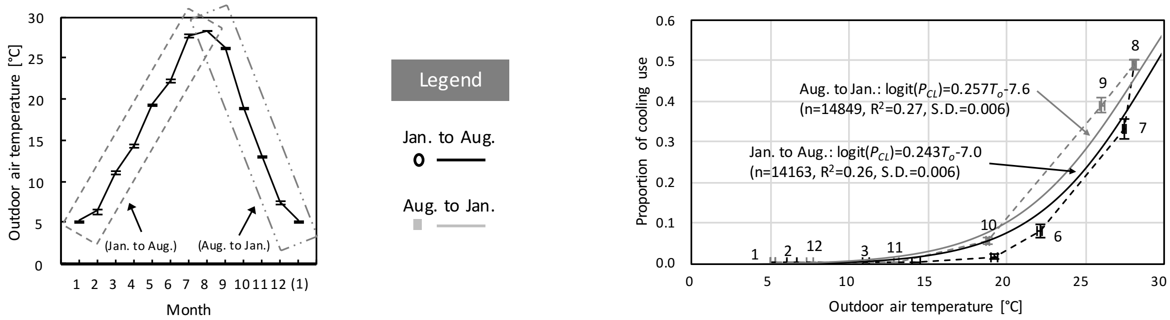


Figure 5 (a) Definition of two groups for increasing and decreasing outdoor air temperature, and (b) AC cooling use stochastic models for increasing and decreasing outdoor air temperature.

### 3.5. Relationship between thermal sensation and air temperature in each month

In order to know the yearly variation of residents' thermal comfort, Figure 6 shows the relationship between the mean thermal sensation vote and outdoor or indoor air temperature in each month. The range of monthly mean thermal sensation is about 1.0 which is smaller than the original vote range. However, they are different by month when outdoor air temperature is increased or decreased. For example, the mean thermal sensation in May and October are significantly different despite the similar indoor air temperature. This trend was seen in March, April and November. And, the mean thermal sensation in June and September were similar despite the significant different in indoor air temperature. These trends also are seen in the outdoor air temperature. The results showed that the residents felt different thermal sensation, i.e. when air temperature was increased they felt hotter than in the period when air temperature was decreased.

(a) Indoor air temperature (b) Outdoor air temperature

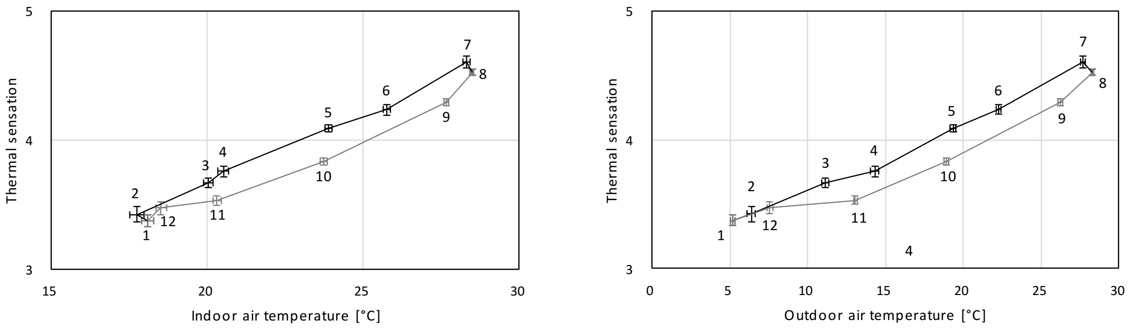


Figure 6 Relationship between monthly mean thermal sensation vote and air temperature

### 3.6. Relationship between comfort temperature and outdoor air temperature

Adaptive model is the relationship between comfort temperature and outdoor air temperature. In order to investigate the effect of transition season, Figure 7 shows the relationship between comfort temperature and outdoor air temperature. The comfort temperature was calculated by Griffiths' method (Rijal et al. 2019). Figure 7(a) shows that there are small difference of comfort temperature between the periods when outdoor air temperature is increased or decreased. On the other hand, as shown in Figure 7(b), the band of comfort temperature is about 5 °C for any given outdoor air temperature range. Thus, the band of comfort temperature of the raw data is larger than that of the monthly mean variation. The results indicated that we do not need to consider transition seasonal effect in the adaptive model. It may be related that the residents may select some occupant behaviours for each season despite the different thermal comfort in transition season.

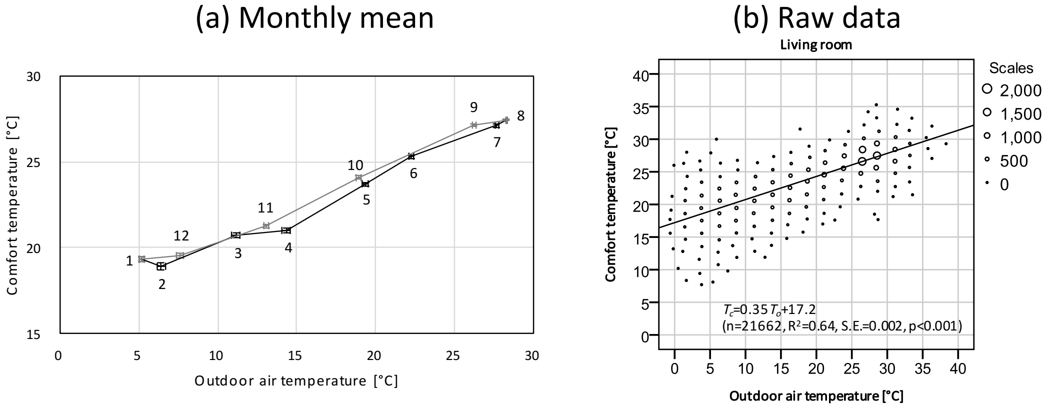


Figure 7 Relationship between comfort temperature and outdoor air temperature

## 4. Conclusions

In this study, we analysed the yearly variation of occupant behaviour and thermal comfort using the field survey of Japanese dwellings. We have found the following results.

1) The residents in Japanese dwellings conducted various occupant behaviours by seasonal changes.
2) The residents conducted the different behaviours when the outdoor air temperature is increased or decreased. Especially, the relationship between window open and AC cooling is depend on the seasonal changes. We also developed the AC cooling behaviour stochastic model based on increasing or decreasing monthly mean outdoor air temperature.
3) On the other hand, the difference between the comfort temperature for increased or decreased outdoor air temperature is smaller than that of the occupant behaviours. The reason might be related that the residents may select some behaviours for each season despite the different thermal comfort in transition season. The results showed that we do not need to consider the transition seasonal effect in the adaptive model.

The results in this study showed the importance of seasonal difference in the occupant behaviours in transitional season based on monthly mean comparison. The difference in thermal history may be useful to make the resilient comfort during transition season as complex periods. In future, we will validate these findings by some statistical tests.

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# On the linguistic challenges of cross-national research in thermal comfort: The effects of language choices in Greek and Swedish thermal perception questionnaires used in two large-scale surveys conducted two decades apart

**Eleni Ampatzi[1], Despoina Teli[2] and Marcel Schweiker[3]**

[1] Welsh School of Architecture, Cardiff University, Cardiff, UK, ampatzie@cf.ac.uk.
[2] Division of Building Services Engineering, Department of Architecture and Civil Engineering, Chalmers University of Technology, Gothenburg, Sweden, teli@chalmers.se
[3] Building Science Group, Karlsruhe Institute of Technology, Karlsruhe, Germany, marcel.schweiker@kit.edu.

**Abstract:** Recent analyses on translations of the widely used ASHRAE scale have highlighted differences between the interpretation of thermal perception scales attributed to contextual factors. This study examines the influence of language choices for thermal perception scale anchors used in questionnaire studies. It focuses on the translations of the subjective scales for thermal perception in the Swedish and Greek languages, which differed between the two surveys. The first set of translations and datasets belongs to the Smart Controls And Thermal Comfort project whilst the second set belongs to the surveys conducted within the framework of the International Energy Agency - Energy in Buildings and Communities Program Annex 69 “Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings”. This paper presents the findings of a comparative analysis between the two datasets in relation to the wording of the scales and the resulting category widths. The method of successive categories is used to estimate the psychological widths of the scale categories in order to examine the scales’ behaviour. The paper discusses linguistic and climatic factors that may influence the way the translations are perceived and used.

**Keywords:** thermal sensation, scales translation, psychological continuum, successive categories

## 1. Introduction

The widely used thermal perception (sensation, comfort, preference, acceptance) scales have been developed in English and are included in international standards on the indoor environment, i.e. ASHRAE standard 55 (ASHRAE, 2017) and ISO 17772 (CEN, 2017). International standard ISO 10551 (CEN, 2019) provides guidance for the construction of appropriate subjective scales for the evaluation of the physical environment, based on the English version. The use of translated versions of such subjective scales, in surveys with native speakers, is meant to limit the risk of linguistic misunderstandings and improve the outcomes’ reliability and relevance. It has however become evident that the translated versions of a scale do not always maintain the meaning and assumptions of the original (Rijal, 2012; Pitts, 2020; Schweiker *et al.*, 2020). For example, recent analyses on translations of the widely used ASHRAE scale have highlighted differences between the interpretation of thermal perception scales (Humphreys et al, 2016; Khatun et al., 2017; Schweiker et al., 2020), some of which are attributed to contextual factors. This creates problems in cross-national research that aims to unearth factors, other than language, that may influence subjective perceptions and votes.

Therefore, this paper discusses linguistic and climatic influences on the way the translations are perceived and used.

### 1.1. Aim

The aim of this work is to examine the behaviour of two sets of such scales developed and tested in two separate research projects. Out of the range of languages involved in both projects, this work focuses on the Swedish and Greek versions to examine in particular a) within each set whether the assumed equivalence of neutrality and preference for 'no change' is indeed present, and what this may indicate, and b) how the scales' category widths and their distribution differ. The parallel analyses of two different language sets provides the opportunity to make preliminary observations of -other than linguistic- factors that may have further influenced the scales' behaviour in the course of the last two decades.

## 2. Methods

### 2.1. The method of successive categories

In line with previous studies (Humphreys et al, 2016; Williamson et al, 2018; Al-Khatri et al, 2019), for each language version the method of successive categories is used to establish the psychological widths of the scale categories. The method of successive categories was originally developed by Louis Thurstone and Rensis Likert for the analysis of psychophysics (Guilford, 1954). It was introduced to thermal comfort research by Humphreys et al (2016) and has since been used for examining the changing thermal comfort expectations with time (Williamson et al, 2018) and the behaviours of translated thermal perception scales in Arabic (Al-Khatri et al, 2019). The application of the method in this area of research relies on the assumption that the responses on warmth and coolness in thermal sensation scales and the equivalent responses in thermal preference, acceptance and comfort scales exist on a 'psychological continuum', i.e. the series of responses form a straight line, "signifying changes in a single direction" (Guilford, 1954). The psychological continuum is assumed to represent the response to a physical (stimulus) continuum that describes the change of physical properties that cause that response. Despite the fact that the 'psychological' data is ordinal, there is the notion that it can approximate a continuous distribution which– when the data is of sufficient size- is expected to tend to the Normal form, in line with the Central Limit Theorem (Humphreys et al, 2016).

The method starts with the calculation of cumulative proportions for each scale category, followed by their transformation into Probits, which when plotted represent the upper category boundaries. The scale can then be renumbered by estimating each (apart from the end extremes) category's middle point, as the mean of its upper and lower margins. This process allows i) juxtaposing and examining the relations between different scales used within the same survey and ii) transforming such ordinal scales to interval scales for further statistical analyses. In this paper we apply the method to four datasets, and primarily examine [as per (i) above] the relationships between thermal sensation and preference scales in each case, aiming to establish the usefulness of the existent scales' translations in providing researchers with a true account of a population's thermal experience.

### 2.2. The surveys and scales' translations

This study uses two large-scale cross-national questionnaire studies conducted two decades apart. It specifically focuses on the translations of the subjective scales for thermal sensation and preference from English to Swedish and Greek, as these translations differed between the two surveys (see also Table 1).

The first set of translations and datasets belongs to the *Smart Controls And Thermal Comfort* (hereafter referred to as SCATs) project that ran in the period 1996 to 1998 and formed the basis of the adaptive comfort model in the European standard EN 15251. The SCATs project has provided the research community with a large dataset of multi-variate comfort information collected from native speakers in the UK, Sweden, Greece, France and Portugal (McCartney and Nicol, 2002; Ličina et al., 2018). The transverse questionnaire used (administered monthly) included thermal sensation (TS) and thermal preference (TP) scales for the evaluation of the parameter 'temperature'. The questionnaires were first produced in English and then translated into the four additional languages. To minimise the chance of inappropriate wording choices in the translations, a standard procedure was followed, with a subject-expert translating each scale into their native language and a non-expert, who was a native speaker of the particular language and fluent in English, independently retranslating them back to English (Humphreys et al, 2016). The translations were then further improved if discrepancies between the retranslation and the original English version were observed (Nicol at al, 2000). The project recruited in total around 850 participants.

The second set of translations and datasets belongs to the surveys conducted in 2017/18 within the framework of the International Energy Agency - Energy in Buildings and Communities Program (IEA-EBC) Annex 69 "Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings" (hereafter referred to as Annex 69) with the aim of assessing the perception of thermal comfort scales. This dataset and its analyses have recently been published (Schweiker *et al.*, 2019)(Schweiker *et al.*, 2020). For this study, 20 additional language versions of the 'same' questionnaire, originally conceived in English and using verbal anchors[1] from ISO 10551, were prepared and used. The questionnaire was translated in the other languages by participating subject-experts. Pilot tests were performed with at least seven individuals (laypersons and experts) to ensure that questions were perceived as intended and revisions were made following these tests if needed.

Table 1: Translations of verbal anchors for thermal sensation scale in SCAT and Annex 69.
** denotes language type, as defined in* (Schweiker *et al.*, 2020) *and reproduced here in Table 2.*

| **English ASHRAE SCAT & Annex 69** | **Greek (SCAT)** | **Greek (Annex 69)** | **Swedish (SCAT)** | **Swedish (Annex 69)** |
|---|---|---|---|---|
| Cold (-3) | Ελαφρύ κρύο | Κρύο | Kall | Mycket kall |
| Cool (-2) | Πολύ δροσερά | Δροσερά | Sval | Kall |
| Slightly cool (-1) | Αναπαυτικά λίγο δροσερά | Λίγο δροσερά | Något sval | Något kall |
| Neutral (0) | Άνετα ιδανικά | Ουδέτερα | Neutral | Varken varm eller kall |
| Slightly warm (1) | Αναπαυτικά λίγο ζεστά | Λίγο ζεστά | Något varm | Något varm |
| Warm (2) | Πολύ ζεστά | Ζεστά | Varm | Varm |
| Hot (3) | Πάρα πολυ ζεστά | Πολύ ζεστά | Het | Mycket varm |
| 2* | 3c* | 3c* | 2* | 1* |

[1] The scale divisions represent category centres in this case.

Table 1 and Table 3 show the translations of the verbal anchors used for the TS and TP scales in both SCATs and Annex 69, for the Swedish and Greek language versions.

Table 2: Language type characterisation used in Annex 69, reproduced here from (Schweiker *et al.*, 2020)

| | | |
|---|---|---|
| Language type | group of language with respect to the number of adjectives used for the sensation scale | 1: one adjective for cool and warm side each (e.g. slightly warm, warm, and very warm)<br>2: two adjectives for cool and warm side each (e.g. slightly warm, warm, and hot)<br>3c: two adjectives on the cold side and one adjective on warm side of sensation scale<br>3h: two adjectives on the warm side and one adjective on the cold side of sensation scale |

The translations in Greek and Swedish produced in Annex 69 addressed limitations identified in (Humphreys et al, 2016) for the TS scale[2]. The application of the Greek survey in SCATs had resulted in:

a. No votes for 'hot' (+3) whilst the 'slightly warm' (+2) region was comparatively wide. One explanation for this- other than the influence of the ambient conditions- is that the scaling of the word 'ζεστά' (meaning warm or hot, depending on context) achieved using adverbs corresponding to 'slightly/very/very much' created a meaning for the equivalent of 'hot' that is not commonly experienced in the built environment.
b. Very few votes for 'cool' (-2) and of a similar number to the 'cold' votes. One possible explanation for this is that the equivalent of 'cool' (-2) used in the Greek version in SCATs would translate into 'very cool', having little difference in meaning to the phrase used for the 'cold' category (-3) that translates to 'slightly cold'.

A further observation on the Greek translation of the sensation scale in SCATs is that it has confounding affective qualities, whereas nowadays a distinction between objective and evaluative ratings is recommended (CEN, 2019):

c. The equivalent of 'neutral' translates in English as 'comfortable ideal' and has a similar leading meaning in Greek too.
d. Equally the 'slightly warm' (+1) or 'slightly cool' (-1) equivalents contain the word 'αναπαυτικά' that in English would translate as 'comfortably'. In fact the verbal anchors of these two categories are nearly equivalent to the 'comfortably warm' and 'comfortably cool' categories of the Bedford scale, which was devised for coding interview results concerning thermal (dis)comfort.

In addressing (c) and (d), the Greek version of the thermal sensation scale used in Annex 69 was designed to be free of evaluative or preferential clues. It uses the direct translation of the word neutral for (0). In addressing (b) it uses a different adjective to denote 'cold' (κρύο) from 'cool' (δροσερά) but differently to SCATs. The word-to-word translation in English is:

in SCATs: *slightly cold (-3) very cool (-2) comfortably slightly cool (-1)*
in Annex 69: *cold (-3), cool (-2), slightly cool (-1).*

In addressing (a) it uses a variation of the word 'warm' (ζεστά) to describe the three positive points of the scale. The latter is similar to the SCATs version, but with a different use of adverbs. The word-to-word translation in English is:

in SCATs: *comfortably slightly warm (+1) very warm (+2) very much warm (+3)*
in Annex 69: *slightly warm (+1), warm (+2), very warm (+3).*

[2] No publication is known to the authors discussing the other scales' translation used in SCATs.

In Annex 69 the number of adjectives used by each language version (i.e. the 'language type' in Table 1 and Table 2) was monitored so its influence on the scales' behaviour could be examined. The language type applicable to the Greek version was shared only with one other language version (Farsi) amongst the total 21 included in that survey (more in discussion). An alternative translation of 'hot' (for +3) in Greek would be '*καυτά'*. However, during the preparation of the Annex 69 translation the use of the term was reviewed in relation to point (a) but rejected, as it was felt that in the description of the indoor environment the term would only suit very hot surfaces that are hazardous to the touch, e.g. a radiator. No other suitable term was identified to use as equivalent of warm or hot other than 'ζεστά' in this context.

It is worth noting here that in Annex 69 all translations had to follow a uniform approach to questioning and presentation of the scales. An alternative translation in Greek could have employed a verb that encompasses the meaning of "feeling warm" ('ζεσταίνομαι) and another for "feeling cold" ('κρυώνω'), and create scalable meanings using adverbs. This version would correspond better to everyday language used to express thermal sensation in Greek. It would however result to a communication of thermal sensation that would deviate from the other language versions, with potentially negative implications for data analysis.

The Swedish version in the SCATs survey had fewer limitations compared to the Greek version, but some issues were identified:

a. The word 'sval' used in (-2), despite it being a word-to-word translation of 'cool', has a generally positive meaning ('fresh'). Its use in the scale may result to evaluative ratings. This is interesting as it shows that even if a translation is the closest possible to the base language (in this case English), it may not provide a suitably equivalent meaning.
b. 'Het', although the direct translation of 'hot', is not typically used in this context in everyday life. Similar to the Greek word 'καυτά', the word 'het' would be used to describe, for example, a hot object.

In Annex 69 it was decided to replace the leading phrasing for 'cool' and the unusual wording for 'hot' to address these issues. The word used for 'warm' (varm) was combined with an adverb equivalent to 'very' (mycket) to represent 'hot'. The scale produced uses one adjective for the cool and warm side each (language type 1 in Table 2) and an adverb meaning 'slightly' (något) in points -1 and +1. In the SCATs version, the direct translation of 'neutral' was used for 0. In Annex 69 'neutral' is replaced by 'neither warm nor cold', as proposed by ISO10551 for language type 1.

Table 3: Translations of verbal anchors for thermal preference scale in SCAT and Annex 69.

| **English (SCAT) 5pt** | **English (Annex 69) 7pt** | **Greek (SCAT) 5pt** | **Greek (Annex 69) 7pt** | **Swedish (SCAT) 5pt** | **Swedish (Annex 69) 7pt** |
|---|---|---|---|---|---|
| - | much cooler | - | Πολύ πιο δροσερά | - | Mycket kallare |
| much cooler | cooler | * | Πιο δροσερά | Mycket varmare | Kallare |
| a bit cooler | slightly cooler | * | Λίγο πιο δροσερά | Lite varmare | Något kallare |
| without change | without | * | Καμιά αλλαγή | Ingen | Varken kallare |

| | | | | | |
|---|---|---|---|---|---|
| | change | | | förändring | eller varmare |
| a bit warmer | slightly warmer | * | Λίγο πιο ζεστά | Lite svalare | Något varmare |
| much warmer | warmer | * | Πιο ζεστά | Mycket svalare | Varmare |
| - | much warmer | - | Πολύ πιο ζεστά | - | Mycket varmare |

**The Greek SCAT translation of the TP scale was not traced.*

**2.3. SCATs survey context**

The SCATs sample population were office workers recruited on a voluntary basis, as the project required their involvement in a yearlong study with monthly interruptions (Stoops, 2001).

The SCATs transverse, monthly surveys in Greece took place in the period September 1998 to September 1999 but no data was obtained between November 1998 and January 1999 and August 1999. Data was collected from 5 different office buildings in Athens, with two being naturally ventilated (heating in winter), one being mixed mode (heating in winter, cooling when needed in summer) and two centrally air-conditioned (heating and cooling). In total 325 subjective votes for TS and TP (each) were collected. The measured indoor air temperature during data collection ranged between 19.1°C to 30.5°C.

The SCATs transverse, monthly surveys in Sweden took place in the period August 1998 to September 1999 but no data was obtained for January and July 1999. The data was collected from 5 different office buildings located in Malmo, Gothenburg and Halmstad, with four being centrally air conditioned (heating and cooling) and one using air-conditioning for heating and partial cooling. In total 970 subjective votes for TS and TP (each) were collected. The measured indoor air temperature during data collection ranged between 18.8°C to 26°C.

**2.4. Annex 69 survey context**

All surveys conducted within Annex 69 involved University students who had no prior specialist knowledge in thermal comfort. Each student participated only once.

The surveys conducted in Athens took place at the National Technical University of Athens, in October 2018 (autumn) and December 2018 (winter). Participants were undergraduate students. All students were native Greek speakers (including Greek Cypriots). The questionnaires were distributed in the form of hard copies in naturally ventilated, free-running lecture theatres in both seasons. The measurement of internal air temperature at the time of the survey was 24°C in autumn and 19°C in winter. The distribution of TS responses varied between seasons but the conditions experienced were considered by the majority as comfortable or slightly comfortable and clearly or just acceptable.

The surveys in Gothenburg were conducted at Chalmers University of Technology in May 2017 and January/February 2018. All participants were undergraduate students. Four surveys were conducted, two in each season, and all took place in mechanically ventilated, lecture halls. The measurement of internal air temperatures at the time of the survey was 22.5°C and 21.8°C in spring and 20.4°C and 21.9°C in winter. Most of the respondents felt either neutral or slightly warm, which was considered by the majority comfortable and acceptable.

## 3. Results and discussion

### 3.1. Stability of subjective scale behaviour in Annex 69 and SCATs

To check the stability of the scale versions analysed here, a comparison of the psychological category widths of the same scale used in different occasions within each project is performed, as in (Humphreys et al, 2016). For Annex 69 the distinction is made between the seasons studied. For SCATs the distinction is made between the first and the second half of the year-round survey.

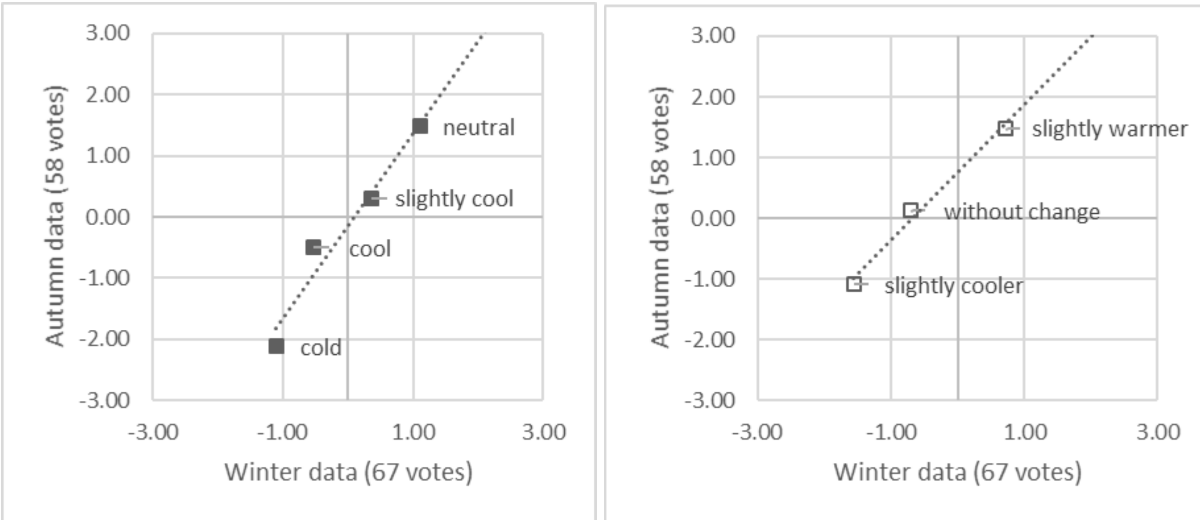


Figure 1: TS (left) and TP (right) scales' stability in Annex 69 for Athens autumn and winter surveys. The graphs show comparisons of category upper boundaries between the two seasons (correlation is high in both cases with r=0.977 for TS and r= 0.993 for TP).

A stability check for the TS and TP scales in Greek used in Annex 69 is done by applying the method of successive categories to the data from each season (winter and autumn) separately. The comparison depicted in Figure 1 (TS at the left hand side, TP at the right hand side of the figure) shows that there is a high correlation between the two sets of category boundaries for both scales (r=0.977 for TS and r=0.993 for TP). This indicates that the TS and TP scale categories had the same meaning in both seasons and therefore the scale had a stable behaviour[3] across different thermal conditions. A similar test is done for the SCATs data and the results in Figure 2 show consistency in the way the scales were interpreted by the survey participants in the two batches of data.

[3] It is observed that the gradient is not unity, as noted also in Humphreys et al (2016) and attributed to the different environmental conditions present.

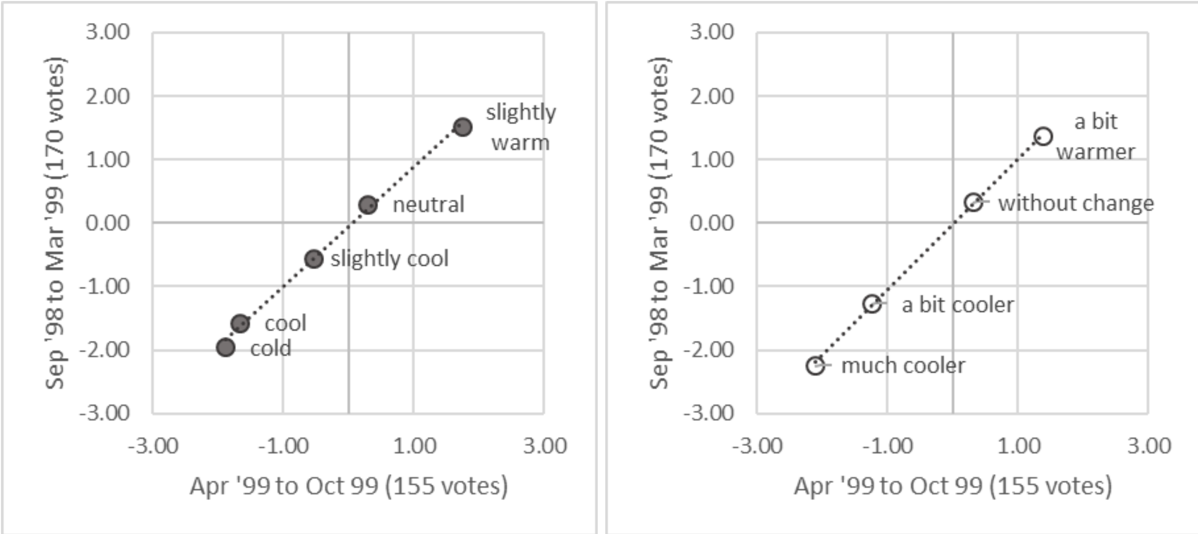


Figure 2: TS (left) and TP (right) scales stability in SCATs, first and second half of year-round survey done in Greece (Athens). The graphs show comparisons of upper category boundaries between the two batches of data (correlation is high in both cases with r=0.998 and r=0.999 respectively).

The results for the Swedish data show similar consistency in the relative category widths as seen in Figure 3 and Figure 4. Following these checks the combined data from each survey (data from both seasons in Annex 69 and year-round data for SCATs) is used in the analyses below, even though the thermal environments represented in the combined data are not always similar. This is in line with how the method was previously applied (Humphreys et al, 2016). It is observed that some category upper boundaries are missing in Figures 1-4. This is due to lack of data for that category in either or both seasons (no Probit value).

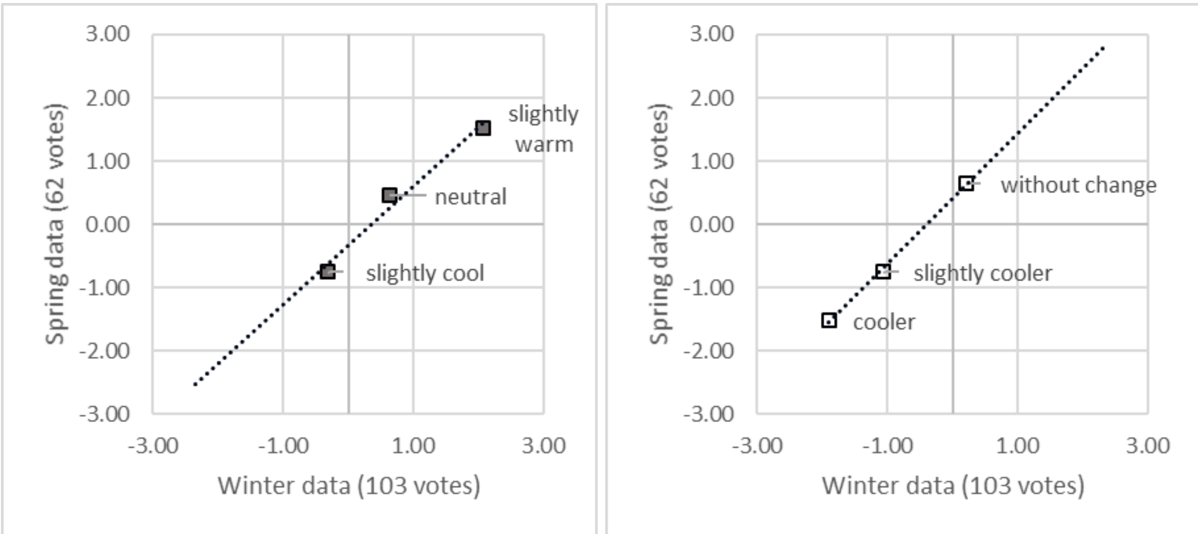


Figure 3: TS (left) and TP (right) scales stability in Annex 69, Gothenburg spring and winter surveys. The graphs show comparisons of upper category boundaries between the two surveys done in spring and winter (correlation is high in both cases with r=0.988 for TS and r= 0.999 for TP).

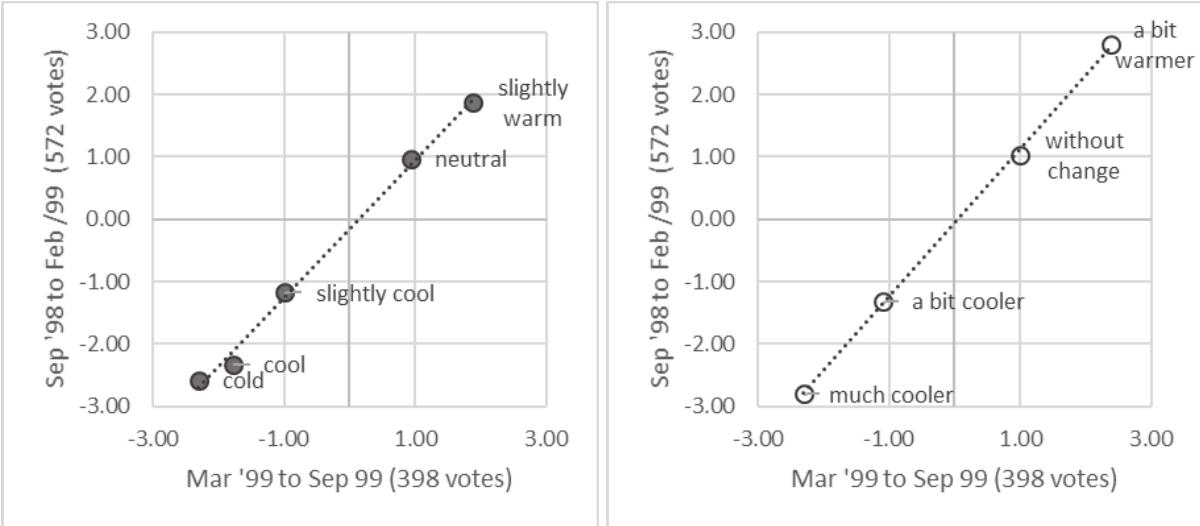


Figure 4: TS (left) and TP (right) scales stability in SCATs, first and second half of year-round survey done in Sweden (Malmo, Goteborg and Halmstad). The graphs show comparisons of upper category boundaries between the two batches of data (correlation is high in both cases with r=0.997 for TS and r= 0.999 for TP).

### 3.2. Category widths and scales' characteristics

A comparison between the category widths resulting from the Greek questionnaires used in SCATs and Annex 69 is shown in Figure 5, along with calculated Standard Error (SE) in probit units[4].The method used does not allow for direct comparisons between different versions of scales, but a visual comparison is useful as it shows the behaviour of each version and the accuracy of the category widths presented.

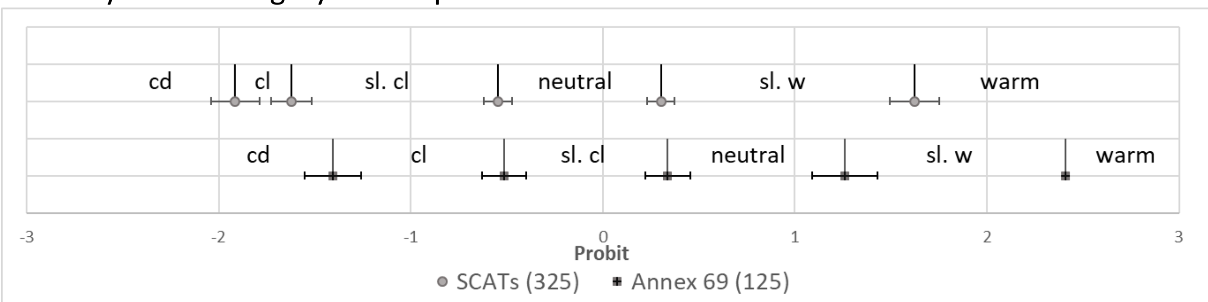


Figure 5: TS category widths for the two scales used in the questionnaires in Greek in SCATs and Annex 69 and standard error in probit units (not shown for upper boundary of slightly warm in Annex 69).
*Wording used is from the equivalent English translation given in Table 1.*
*Legend: cd: cold, cl: cool, sl. cl.: slightly cool, sl. w: slightly warm*

The SE is higher in Annex 69 due to the smaller sample (125 votes) in comparison to SCATs (325 votes). The SE is also higher at the margins of the scale, due to small differences in proportions resulting to large differences in Probit units. The SE of the upper boundary of the slightly warm category in the Annex 69 scale in Greek (SE=1.604) is not depicted as it is so large that it would conceal the category boundaries of the slighty warm and neutral categories. The accuracy levels presented in this figure indicate that for both sets of surveys we may draw reliable conclusions for the centre of the data, but any observations made for the margins need to be interpreted with caution.

The properties of the two scales appear dissimilar, with the scale used in Annex 69 producing a better distribution of category widths on the continuum. It appears that the

[4] As in (Humphreys et al., 2016), with SE of a binomial proportion being $\sqrt{(\frac{p(1-p)}{n})}$, where $p$ is the cumulative proportion and $n$ is the total number of responses in that dataset.

rewording of the categories, using the rationale discussed previously, has addressed the issues encountered in SCATs with the category widths of the cool side of the scale. However, similarly with the SCATs survey, none of the respondents in the Greek surveys of Annex 69 felt ‘hot’, hence this category is not depicted in Figure 5. In both Annex 69 and SCATs the ‘slightly warm’ category is larger than any other, however the boundaries are subject to a large SE and therefore of questionable accuracy. It is likely that as the data from Annex 69 is not numerous and the surveys took place in autumn and winter, the lack of responses for ‘hot’ in this dataset is due to the thermal conditions experienced (24°C in autumn and 19°C in winter). Indeed the median respondent in this case (the zero point on the Probit scale) is found in the slightly cool category. In the SCATs data the middle of the neutral category falls near the zero point of the psychological continuum, reflecting on the sensation of the median participant in the office buildings surveyed. As the SCATs data for Greece is more substantial in size than in Annex 69 and it includes subjective responses from an annual survey that was more detailed in summer than in winter, the absence of ‘hot’ votes stands out and may indeed be due to the wording choices made. However this observation needs to be further examined in future studies using sufficiently large samples for analysis together with a larger variation of prevailing thermal indoor conditions. Another possible reason for the behaviour of the warm side of the scale can be deduced from the outcomes presented in (Schweiker et al., 2020). The Annex 69 study included a set of free-positioning tasks for establishing the perceived widths of categories in each scale and the relationships between scales. The existence of participants’ subgroups sharing common perceptions with regards to the scales was examined. It was found that there was a significant difference due to language type in the distribution of subgroups for the free-positioning task for TS anchors on the thermal comfort scale, with the language type 3c (applying to the Greek translation) having the highest impact amongst all language types on the respondents’ interpretation of the scales. This seems to indicate that the use of two adjectives on the cold side and one adjective on warm side of sensation scale results to an interpretation of the scale that is distinct to other language types and needs to be revisited.

A comparison between the category widths resulting from the Swedish questionnaires used in SCATs and Annex 69 is shown in Figure 6, along with calculated Standard Error (SE) in probit units. As with the Greek data, a visual comparison is made to examine the behaviour of each version and the accuracy of the category widths. The boundaries between the three middle categories are more precisely defined in comparison to the same boundaries resulting from the Greek data. This is due to the larger samples available from the Swedish surveys. As with the Greek data, the reliability of any conclusions drawn for the margins of the data is low.

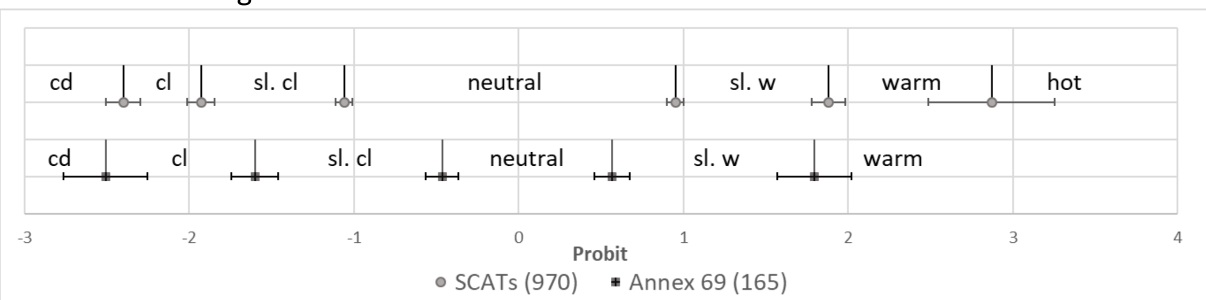


Figure 6: TS category widths for the two scales used in the questionnaires in Swedish in SCATs and Annex 69 and standard error in probit units.
*Wording used is from the equivalent English translation given in Table 1.*
*Legend: cd: cold, cl: cool, sl. cl.: slightly cool, sl. w: slightly warm*

The properties of the two scales appear dissimilar, with the scale used in Annex 69 producing a better distribution of category widths on the psychological continuum. The rewording of the neutral category appears to have significantly contributed to this improvement, indicating that in some languages the recommendation made by the relevant standard is useful or that in general, the usage of “neither cold nor warm” should be preferred compared to “neutral”. It also appears that the rewording of the categories, using the rationale discussed previously, has addressed the issues encountered in SCATs with the category widths of the cool side of the scale. However, none of the respondents in the Swedish surveys of Annex 69 felt ‘hot’ (‘mycket varm’) due to the moderate thermal conditions experienced during the surveys (22.5°C and 21.8°C in spring and 20.4°C and 21.9°C in winter), hence this category is not depicted in Figure 6.

The middle of the neutral category in both Swedish scales falls near the zero point of the psychological continuum, reflecting on the sensation of the median participant in the buildings surveyed. In SCATs this position is slighlty offset to the cool side, whilst in Annex 69 is offest to the warm side. These differences are however comparable to the SE shown, and are potentially insignificant to any conclusions drawn.

**3.3. Comparing the behaviour of TSV and TPV scales**

Humphreys et al (2016) presented a comparison between TS and TP scales within the same body of survey data, using an example that applied the method of successive categories on data collected using the ASHRAE (sensation) and the Nicol preference scales. The same process is applied here to examine the relationship between the TS and TP scales used in SCATs, separately for the Greek and the Swedish surveys. This is a straightforward comparison in the SCATs questionnaire, given that the order of categories in the two scales are in agreement:

*TS: How do you feel at this time:*
*Cold/ Cool/ Slightly cool/ Neutral/ Slightly warm/ Warm /Hot*

*TP: I would prefer to be:*
*Much warmer/A bit warmer/No change/A bit cooler/Much cooler*

However performing the same for the TS and TP scales in Annex 69 requires some data adjustment because the TP scale was presented to participants in the reverse order to the Nicol preference scale:

*TS: How do you feel right now:*
*Cold/ Cool/ Slightly cool/ Neutral/ Slightly warm/ Warm /Hot*

*TP: At this moment, would you prefer to be:*
*Much Cooler/Cooler/ Slightly cooler/ Without change / Slightly warmer/Warmer/ Much warmer*

The rearrangement of the data involves recoding the scale so that category 1 (-2) is Much warmer and category 5 (+2) is Much cooler. The cumulative proportions and Probits for TP are then calculated for this new order. This manipulation assumes that the presentation of the scale in the reverse order has no effect on the scale behaviour and on the notion of the psychological continuum.

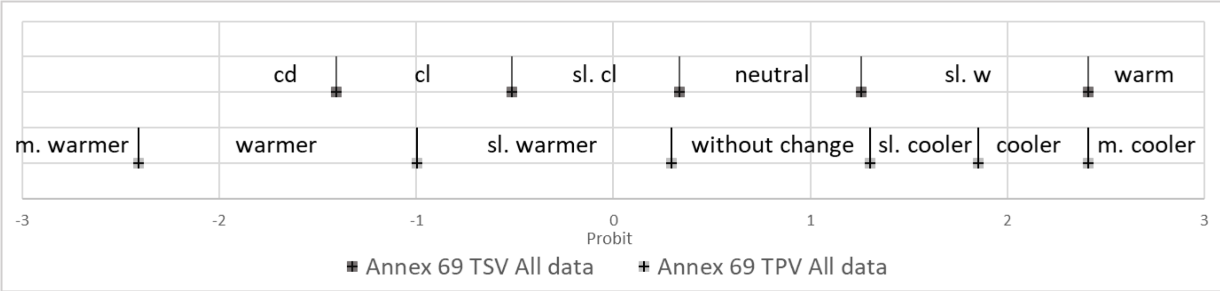


Figure 7: Relationship between TSV and TPV categories for Greek survey data, Annex 69.
*Wording used is from the equivalent English translations given in Tables 1 and 3.*
*Legend: cd: cold, cl: cool, sl. cl.: slightly cool, sl. w: slightly warm, m.: much, sl.:slightly (warmer/cooler)*

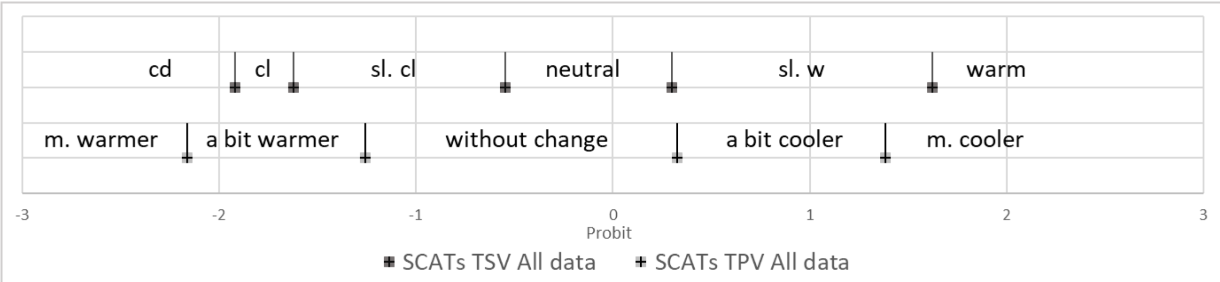


Figure 8: Relationship between TSV and TPV categories for Greek survey data, SCATs.
*Wording used is from the equivalent English translations given in Tables 1 and 3.*
*Legend: cd: cold, cl: cool, sl. cl.: slightly cool, sl. w: slightly warm, m.: much (warmer/cooler)*

The ‘neutral’ and ‘without change’ categories of the Greek translations produced in Annex 69 are more aligned, in comparison to the same categories in SCATs. In SCATs the “without change” category is quite wide, corresponding to a wider part of the psychological continuum. This may be due to the leading meaning given in the -1 and +1 categories in SCATs for this language version, as previously discussed. More specifically, the data analysis shown in Figure 8 may indicate that in this context most of the respondents who felt ‘comfortably cool’ (in those conditions), may in fact thought that this was the ideal environment and preferred no change. The fact that the upper boundaries of the two categories appears to be in agreement may indicate that the sensation of ‘comfortably warm’ is less equivalent of the ideal in comparison to the ‘comfortably cool’, corresponding to a preference for ‘a bit cooler’. No further conclusions are drawn from this comparison for the margins of the data, as the expected accuracy (as previously discussed) is low.

A similar set of analyses is performed for the Swedish versions of the TS and TP scales. Figure 9 shows that there is a strong agreement between the TS and TP scales in Annex 69 for this language version and in particular for the cool side of the scales. There is less agreement in the warmer side of the scales, starting with the upper boundary of the ‘without change’ category falling within the region of the ‘slightly warm’ sensation. This may indicate that in a cold context like this, some of the respondents who feel ‘slightly warm’ may find this environment ideal and prefer no change. The existence of votes for a ‘much cooler’ preference may be seen as evidence that the wording chosen for the +3 category of TS was unsuccessful or that a ‘warm’ sensation is experienced more intensely in a cold context. Figure 10 shows the relationship between the TS and TP scales in Swedish used in SCATs. In this case, there is relatively good agreement between the ‘neutral’ and ‘without change’ categories, which could be due to the use of the word “neutral” in this version. People’s interpretation of the word “neutral” in relation to thermal sensation and its equivalence to “neither cool nor warm” is a matter for further investigation as presented by

Schakib-Ekbatan et al. (2018) for the German context. No other patterns are observed with regards to the boundaries of the other categories in Figure 10.

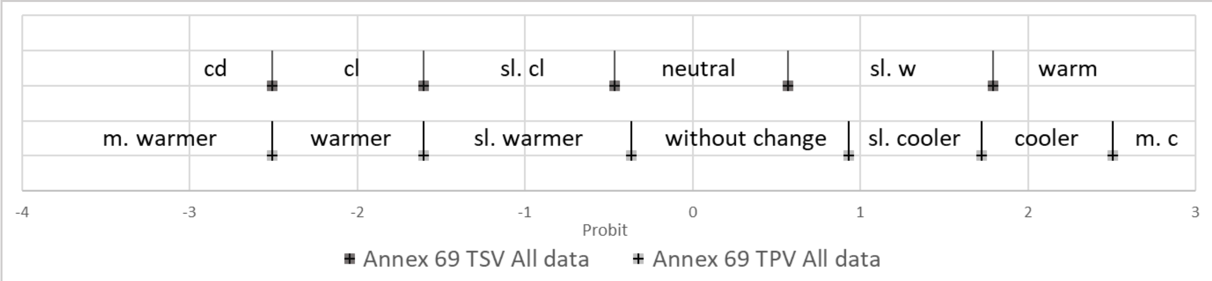


Figure 9: Relationship between TSV and TPV categories for Swedish survey data, Annex 69.

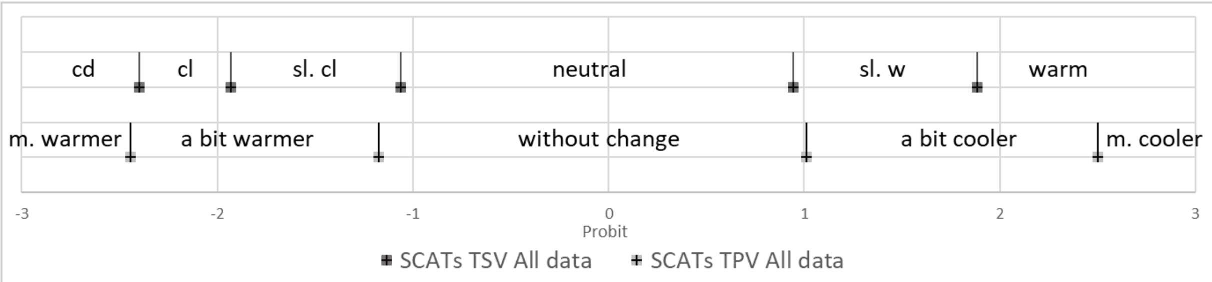


Figure 10: Relationship between TSV and TPV categories for Swedish survey data, SCATs

## 4. Conclusions

The TS scales produced in Annex 69 for the Greek and Swedish questionnaires addressed limitations previously observed with the equivalent scales used in SCATs. These revised scale translations were found to produce a better distribution of category widths on the psychological continuum, in particular with regards to irregularities previously noted with the cool side of thermal sensation in both language versions. As the marginal category boundaries are subject to a large SE (as resulting from the use of small survey samples), it is impossible to deduce whether the lack of any votes for 'hot' in both language versions in Annex 69 is due to inappropriate wording choices or due to the prevailing cool survey conditions. However some suggestions for further improving these translations were presented in the discussion above.

Juxtposing the category widths of the TS and TP scales reveals that the assumed equivalence between neutrality and preference for no change may not exist, especially when the TS and TP scales are designed with the intention to separate objective and affective ratings within a survey; in the cold Swedish climate, respondents may rate the environment as warm but ideal, whilst in the warm, fuel-poor Greek context a "comfortably cool" sensation incorporates a preferential clue for 'no change'. The findings presented here indicate that if conclusions are to be drawn for a particular environment from the subjective votes collected using more than one scale, the vertical association of terms (between the related categories across these scales) needs to be carefully considered as much as the horizontal (between categories within the same scale). Equally important is the correct alignment (of ranking order) of the various scales considered, as any rearrangements made retrospectively may introduce error to the analyses. In fact future work needs to revisit the assumption made here, that the reversing of the TP Annex 69 data has no impact on the resulting scale properties, as recent observations on the distinct behaviour of right-to-left languages may suggest that this is not always true (Schweiker et al., 2020).

## 5. Acknowledgements

The authors would like to thank Michael Humphreys for the advice offered in relation to the method of successive categories and the reordering of the thermal preference scale. They are also grateful to Aris Tsagrasoulis, Fergus Nicol and John Stoops for sharing information and data from the SCATs project.

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# Thermal Comfort and Gender: A Practical Study in the Eastern Province of Saudi Arabia

**Abdulrahman M. Alshaikh* and Mohammed A M Alhefnawi**
Department of Architecture, College of Architecture and Planning, Imam Abdulrahman Bin Faisal University, P.O.Box 2397 Dammam 31451, Saudi Arabia.
*Corresponding author: aalshaikh@iau.edu.sa

## ABSTRACT

Although there are many studies on thermal comfort and gender, the outcomes indicate clear differences regarding how both genders feel in the same thermal conditions. Many studies found no obvious differences in this regard at neutral temperatures. Others have found significant differences and have shown that females are more likely to express heat discomfort than men, especially in low temperatures and cold climates. While a few studies have shown that males are more likely to feel uncomfortable than females.

This paper examines the effect of gender on the feeling of thermal comfort in the indoor environment. The study is based on thermal comfort analysis of a sample of 29 men and women distributed in 18 housing units in the same geographical area in Dammam. The responses of the sample group are presented as of ASHREA Feeling Scale, which is associated with indoor temperature and humidity. The paper examines the possible relationships between the levels of ASHREA Thermal Sensation, and four variables: gender, age, body mass index (BMI), and clothes index (clo) separately as independent variables, taking into account the daily lifestyle of the sample that may affect the feeling of comfort or discomfort. The study was carried out during the months of July and August 2018, in the normal lifestyle of the sample regarding turning the AC on or off as needed.

**Keywords**: *Age group;; Gender; Saudi Arabia; thermal comfort; ASHRAE; thermal sensation; hot humid climate; air-conditioned homes; Body Mass Index BMI; Clothing Index clo*

## INTRODUCTION

Human individual differences should be wisely considered, when designing and operating the built environment, as they broadly affect the sensation of thermal comfort of the occupants. This issue has been noticed and undergone different studies since the 1970s, when Fanger started to investigate the influence of individual differences such as age, gender, adaptation and other factors on thermal comfort. Many of research papers have been published on this topic since then, and recently more personalized thermal comfort systems and devices emerged on the market. Some of them are local heating/cooling and wearable devices, that provide thermal comfort conditioning on personal level rather than working zone or building levels (Wang et al, 2018). On the other side, the buildings sector, as a leading energy consumer, steadily needs to lead in energy conservation. There is an increasing consent that variable indoor conditions can be tolerable to inhabitants, (Mishra et al, 2016). So, it is useful to refocus on the concept of individual difference and variable acceptable indoor conditions related to gender in the built environment to improve comfort sensation and reduce energy consumption.

**Gender Difference and Thermal Comfort**

In Brazil, Maykot and others investigated the comfort temperature for men and women in two different environments, one naturally ventilated and/or air-conditioned and one fully air-conditioned. Overall results showed that the comfort temperature was higher for females than for males. In the mixed-mode building, comfort temperatures recorded 23.7 °C and 23.0 °C, for females and males respectively. Whereas, they recorded 24.2 °C and 23.4 °C, respectively in the fully air-conditioned building (Maykot et al, 2018a). In addition, a similar study, carried out in southern Brazil, assessed the effects of gender on thermal comfort in three office buildings in fully air-conditioned and mixed operation mode strategies of air-conditioning to natural ventilation. Results showed significant differences between males and females regarding thermal sensation and thermal preference in both modes of operations (Maykot et al, 2018b).

In India, a study investigated occupant behavioral adaptation to different thermal conditions in air-conditioned and naturally ventilated building in Chennai and Hyderabad. Occupants adaptively used air-conditioners and or fans during the temperature excursions. Females and low body mass index occupants had higher comfort temperatures than males and obese occupants with a difference of 0.3–1.0K. In naturally ventilated environments females were comfortable at 28.5 ℃ and males at 27.8 ℃. (Indraganti et al, 2015). A similar field study on naturally ventilated dwelling unit was done in the summer and wet season of 2008 in Hyderabad in composite climate. The results were analyzed under gender, age and income groups. Thermal acceptance of women was higher than of men. In addition, economic levels showed significant effect on the thermal sensation and acceptance. The comfort band for lowest economic group was found to be higher above the standard between 27.3 and 33.1 ℃ with the neutral temperature at 30.2 ℃ (Indraganti and Rao, 2010). This is an indication that limited income people usually try to thermally adapt themselves in far extended thermal limits which might be above or under the standard limits.

In western Australia, a field study investigated the effects of individual and environmental factors on thermal sensations in the hot-arid climate. Females wore around 0.1 *clo.* less than males, with a mean clothing insulation of 0.66 *clo.* in winter and 0.43 in summer. Females were further tending to feel warm and thermally dissatisfied in winter than males.

Comparisons with a study in a hot-humid location in Australia, indicated that the respondents in hot- humid locations were more adapted to the climatic conditions than in hot-arid locations. It was argued that the limited home air-conditioning in hot-humid areas enabled the respondents to adapt more than in hot-dry conditions (Erlandson et al, 2005).

In Finland, a study examined gender differences in thermal comfort and use of thermostats. The results showed that males are more satisfied with room temperatures than females. They prefer lower room temperatures than females who feel both uncomfortably cold and uncomfortably hot more often than males. On the other hand, and despite that females are more critical of their environments, males use thermostats to adjust the thermal conditions more often than females (Karjalainen, 2007).

In Turkey, a study investigated thermal perception differences between males and females for different airflow, temperature, and metabolic rate conditions. Results showed that females steadily felt warmer, less tolerance towards the warm conditions and more uncomfortable than males under the same conditions. The neutral temperatures were 26.4°C for males and 23.9°C for females when people felt neither cool nor warm (Urgusal and Culp, 2013). Deng and others tested thermal sensation in a cool environment with personalized heating. The effect of personalized heating on improving thermal sensation was consistent in different age and gender. Adults and the females were more sensitive and felt cooler and less comfort than children, elderly and the males respectively (Deng et al, 2017).

In China, gender difference in thermal comfort was investigated. Results proved that males are less sensitive to temperature and more sensitive to humidity than females who preferred neutral or slightly warmer conditions. Male comfortable operative temperature (25.3℃) is lower than female's (26.3℃), although both males and females have almost the same neutral temperature. It was also noticed that there is no gender difference in thermal sensation close to neutral conditions (Lan et al, 2008).

In USA, a study investigated the effects of occupant gender on thermal satisfaction in office environments. The results revealed that females are more dissatisfied with their thermal environments than males especially in the summer season with high significance (Choi et al, 2010).

In general, we can conclude that there is a gender difference in the sensation of thermal comfort between males and females. The variations in the values of thermal comfort thresholds vary between cold areas such as Turkey and Finland, hot regions such as India and Brazil, and wetlands and drylands as in Australia and China.

This paper investigates the effect of gender difference on the sensation of thermal comfort in Saudi Arabia, where the climate varies in humidity and temperature during the year. Scarcity of similar studies in Saudi Arabia's climate region encouraged the authors to search in this area.

## METHODOLOGY

This research was undertaken in Dmmam using a standard longitudinal thermal sampling method (Nicol et al., 2012) in eighteen mixed-mood homes. The survey involved dwellings that occupied by middle-class families with an average of more than 6 people in each home, distributed within a radius of 7 miles within the city. The field measurements and survey were carried out between the 24th of July to the 12 of August 2018 during an extremely hot season.

This paper used air temperature as its principal physical variable. Air temperatures and relative humidity were obtained using standing station data loggers that collected and stored results automatically in an optional strain choice. The data loggers were fitted in two different places in each dwelling, in the living rooms and the main bedrooms. The positions of the data loggers were located to minimize heat from direct radiation, either from solar radiation, mechanical or human sources with a proper distance from the subject normal physical place. Measurements of the environmental data were taken every five minutes.

Using the “ComfApp” that developed by (Alshaikh & Roaf, 2016) which works in all smartphones, making it much easier and accessible for subjects thermal sensation votes. As the environmental variables were being recorded concurrently, each subject was asked to vote at least twice a day and all of the subjects used the smart phone platform to record their votes. The subjective data were collected over an average of two weeks for each household at regular intervals of around ten hours between each vote over the day.

The comfApp provided five hundred and eighty-six votes from a total number of twenty-nine subjects with a gender split of 16 males and 13 females. The ages of the subjects ranged from 22 to 58 years, with a mean age of 37 years old. All subjects were in good health during the time of the questionnaires, and when calculating the body mass index, 46% and 14% of the subjects were overweight and obese respectively. On average, occupants stay inside their homes around twelve hours per day, with women spending on average three hours more than men.

## RESULTS AND DISCUSSION

As indicated previously, the paper examines the possible relationships between the levels of ASHREA thermal sensation, which is a dependent variable on one side, and between four variables: gender, age, body mass index (BMI), and clothing index (*clo.*) separately as independent variables in the kingdom of Saudi Arabia. Moreover, data logger readings were grouped in terms of the ASHREA seven points thermal sensation scale.

**Insight of the Experienced Temperatures and the Reported Thermal Neutrality**

An illustration of a scatter plot, in figure 1, of the whole set of the indoor and outdoor temperature recorded during the study period in these dwellings in contrast with Alshaikh & Roaf (2016) dataset.

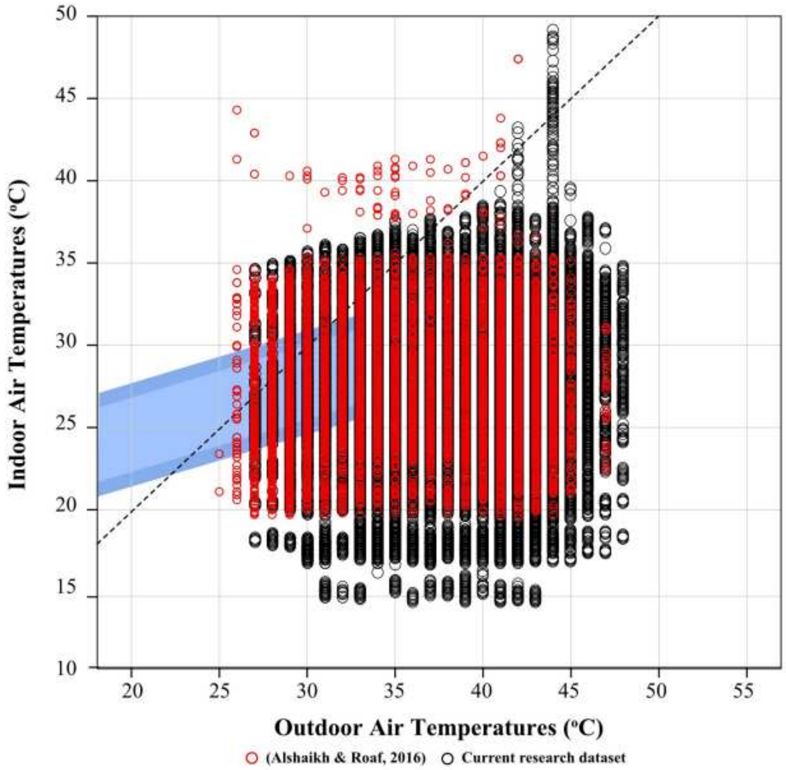


**Figure 1: A comparison scatter diagram of 2013 Alshaikh & Roaf (2016) dataset and the current 2018 dataset, showing the ASHRAE adaptive standard acceptability limits during both hot seasons.**

From table 1, the indoor temperature variation recorded, ranging between 14.1°C to a 49.2°C, whereas the outdoor temperature has reached 48°C. Perfect temperature control could not be expected especially when all of the dwellings had operated different HVAC systems with different temperature set points. The scatter comparison of both datasets showed in figure 1, alongside with the ASHRAE adaptive standard of 80% and 90% acceptability limits, ratify that people in Dammam clearly inhabit in what occupants of western's societies would categorise as insufferable and extreme hot condition. Moreover, it is evident that the widely varying range of indoor temperatures accommodated by people affected by the ordinary course of their routine in their homes.

Table 1: The maximum, minimum, mean and standard deviation of all measured indoor and outdoor air temperatures (Ta °C), Relative humidity (RH%) in all examined Dammam's homes.

| Date | Indoor Temperature | Indoor Humidity | Outdoor Temperatures | Outdoor Humidity |
|---|---|---|---|---|
| ***Maximum*** | 49.20 | 81.00 | 48.00 | 70.00 |
| ***Minimum*** | 14.10 | 11.00 | 26.00 | 4.00 |
| ***mean*** | 27.23 | 34.71 | 37.48 | 23.07 |
| ***S.D.*** | 4.95 | 10.66 | 4.65 | 13.00 |

The mean indoor and outdoor air temperature was in Alshaikh and Roaf (ibid) 27.4°C and 35.4°C respectively, where the outdoor air temperature in this study showed an increment of around 2K. However, the mean indoor air temperature of 27.2°C exactly matching with the current study, and also above the standard guidelines of maintaining indoor operative temperatures between 22°C and 24°C.

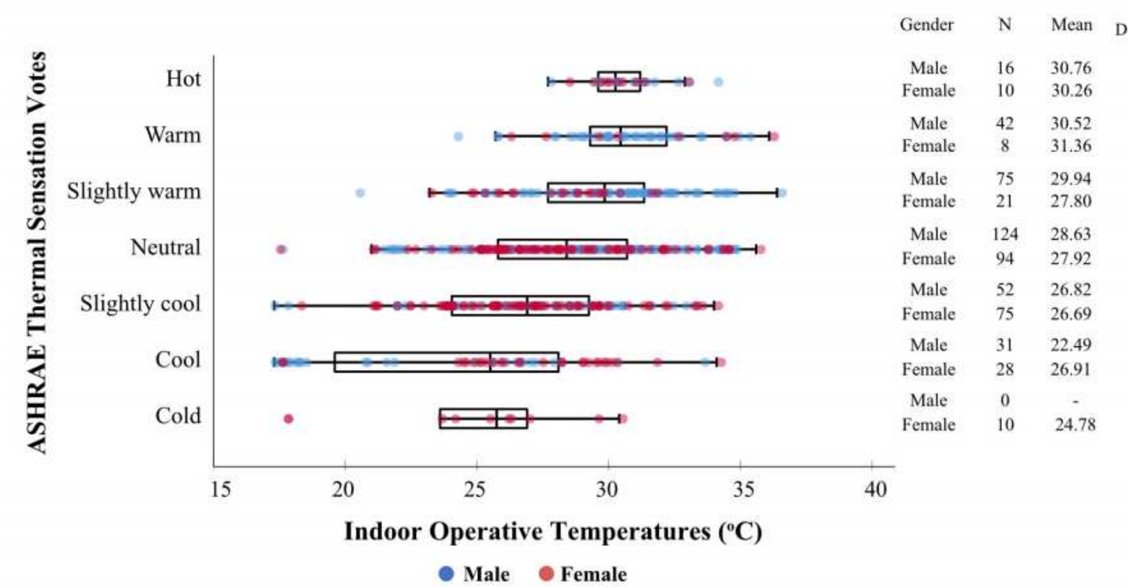


**Figure 2: Boxplots and dot plots of ASHRAE seven-point thermal sensation scale, and in the right a statistics summary of the indoor air temperatures (°C) associated with ASHRAE votes and filtered by gender.**

Turning to the point of occupant's thermal sensation, it shows in figure 2 the variation of all measured thermal sensations of the occupants, we can see that of the total 586 valid responses, 37% of the whole sample described themselves as being thermally neutral. 96 respondents were slightly warm and 127 were slightly cool. 145 of the responses, or 25% of the dataset, reported being warm or hot, or cool or cold, (responses of 2, 3, or -2, -3) at the time they recorded their comfort vote. Seventy-six of the respondents were feeling warm or hot and three-quarter of these votes were experiencing a temperature equal or above 30°C. 25% of the last responses were female which provide additional insight into how the gender perceptions of conditions is different.

## Statistical Correlation Analysis

The SPSS software was used to perform the statistical analysis. The analysis measures the strength of association between two variables and the direction of the relationship. A value of ±1 shows a perfect degree of association between the two variables. As the correlation coefficient value goes towards the zero, the relationship will be weaker. Cohen's standard is used to assess the correlation coefficient to define the strength of the relationship. Coefficients between 0.10 and 0.29 indicate a small association, coefficients between 0.30 and 0.49 indicate a medium association, and coefficients of 0.50 and above indicate a large association (Cohen et al, 2013).

In this paper Pearson correlation coefficient is used to examine; a statistical relationship signification between gender, as classified into males and females, with ASHREA thermal sensation scale, a statistical relationship signification between age groups with ASHREA thermal sensation scale, a statistical relationship signification between (BMI), and ASHREA thermal sensation scale, a statistical relationship signification between (clo.), and ASHREA thermal sensation scale.

The Null hypothesis assumes that there is no relationship between the ASHRAE thermal sensation scale, as a dependent variable, with gender, age, BMI, or clothing index, separately as independent variables. Table 3 shows the Pearson correlation coefficients, as well as the significance p value for the variables under examination.

Table 2 Tabulation of Pearson correlation coefficients and its significance of the ASHREA sensation scale, Gender, Age, body mass index, and clothing index.

| ***N=568*** | | **ASHREA** | **Gender** | **Age** | **BMI** | **Clo.** |
|---|---|---|---|---|---|---|
| ***Pearson Correlation*** | *ASHREA* | 1.000 | -0.250 | -0.214 | -0.093 | 0.011 |
| | *Gender* | -0.250 | 1.000 | -0.121 | -0.290 | -0.388 |
| | *Age* | -0.214 | -0.121 | 1.000 | 0.370 | 0.088 |
| | *BMI* | -0.093 | -0.290 | 0.370 | 1.000 | 0.164 |
| | *Clo.* | 0.011 | -0.388 | 0.088 | 0.164 | 1.000 |
| ***Sig. (1-tailed)*** | *ASHREA* | . | 0.000 | 0.000 | 0.012 | 0.394 |
| | *Gender* | 0.000 | . | 0.002 | 0.000 | 0.000 |
| | *Age* | 0.000 | 0.002 | . | 0.000 | 0.017 |
| | *BMI* | 0.012 | 0.000 | 0.000 | . | 0.000 |
| | *Clo.* | 0.394 | 0.000 | 0.017 | 0.000 | . |

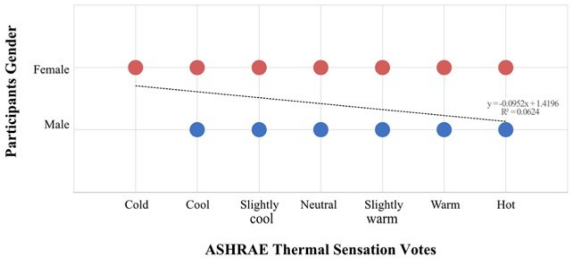


Figure 3: A scatterplot of the occupant's gender with the ASHRAE seven-point thermal sensation scale.

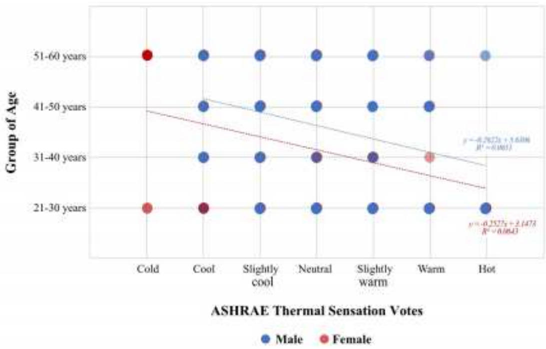


Figure 4: A scatterplot of the occupant's group of age with ASHRAE seven-point thermal sensation scale and filtered by gender.

It is obvious from Figures 3 and 4, there is a descending or negative relationship between ASHREA scale and gender, and between ASHREA scale and age as well. The values of Pearson Coefficients, Table 2, are -0.250 and -0.0214 respectively. Applying the Cohen standard to determine the strength of the association between the variables, the relationship between ASHRAE scale and gender represents a small association, and so is the case between ASHRAE scale and the occupant's group of age. The degree of association in the latter variable is even less than in the former one. The significance *p* values for the previous two variables are also recorded less than 0.001, as shows in Table 2. The results reflect the significance to reject the null hypothesis that there is no relationship between those variables.

However, Figure 4 shows that the trend lines of both gender categories are almost parallel, which means that both genders have an almost equal value of the Pearson correlation coefficient. Hence, gender type has no significant impact on the relationship between the average age of the overall investigated samples.

The values of Pearson correlation coefficients for the relationship between the thermal sensation with occupant's body mass index, and the thermal sensation with clothing index, as shown in Table 2, are -0.9 and -0.01, respectively. Applying the Cohen standard, the relationship between the thermal sensation and BMI represents a very small association and is almost null in the case between the thermal sensation and clothing index. A very weak association is also confirmed by the small values of significance *p* value for both variables that equal to 0.12 and 0.39, respectively, as both values are greater than the significance of 0.05.

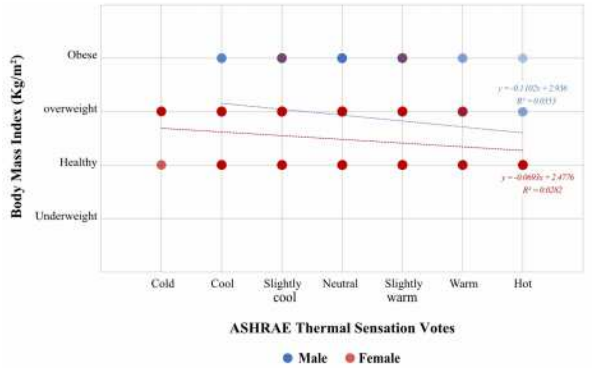


Figure 5: A scatterplot of the Body Mass Index (Kg/m2) plotted with ASHRAE seven-point thermal sensation scale and filtered by gender.

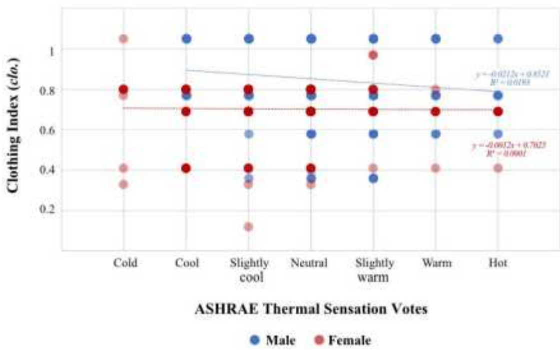


Figure 6: A scatterplot of the occupants clothing index (clo.) with ASHRAE seven-point thermal sensation scale and filtered by gender.

Figures 5 and 6 confirm the very weak relationship between the variables as the trend lines in the scatterplots appear semi-horizontally, which indicates the failure to reject the null hypothesis in both cases. Consequently, for the examined dataset, there is no confirmation of the relationship between the thermal sensation and body mass index, or between the thermal sensation and clothing index. Although it can be argued that the previous result is not consistent with the results of others studies recorded in other regions, it might be due to the lack of BMI variations between the tested sample, the lack of a wide variety of clothes among the sample, as well as the occupants' perception of outdoor conditions, which led to the experiment's failure to confirm the impacts of those two factors on ASHRAE thermal sensation

the samples of the study have a great diversity in BMI that reached high degrees of obesity, as well as diversity in clothes to a large extent, including woolen and multilayers clothes.

Moreover, figures 5 and 6 show that gender type has a slight impact on the relationship between ASHREA Thermal Sensation and both BMI and clo. As the male's trend lines are more inclined than the female's ones.

**ASHRAE Thermal Sensation vs Gender**

Figure 7 illustrates the descriptive analysis and relationship distribution between ASHREA thermal sensation levels, indoor air temperature and gender. Moreover, it is obvious that females are more sensitive to the cold temperature than males where having more females votes than males 10 and 0 respectively. Although males are more sensitive to hot temperature than females, which is noticed in the hot categories where having more males than females 16 and 10 respectively. This result could be explained by the fact that male occupants spending more time outside the home and been exposed to the outdoor conditions. Moreover, the previous result complies with the outcomes of both studies by Deng et al (2017), and Choi et al (2010).

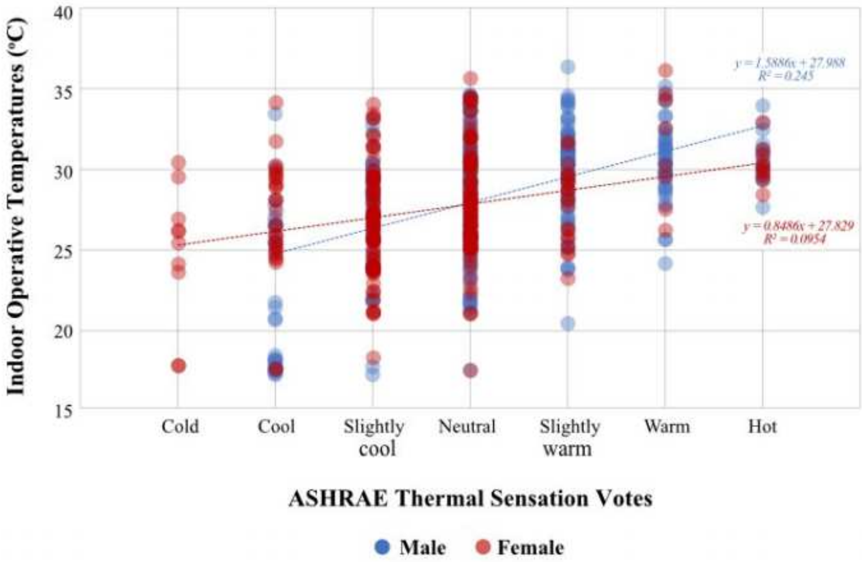
Indoor Operative Temperatures (°C)
40
35
30
25
20
15
y = 1.5886x + 27.988
R² = 0.245
y = 0.8486x + 27.829
R² = 0.0954
Cold
Cool
Slightly cool
Neutral
Slightly warm
Warm
Hot
ASHRAE Thermal Sensation Votes
Male
Female

Figure 7: A scatter plot of the indoor operative temperature (°C) with ASHRAE seven points thermal sensation scale and filtered by gender.

In addition, figure 2 also showed that there is a slightly over 2k different between the mean neutral temperature in both males and females, which records 29.94°C and 27.80°C respectively. This variation was recorded in other studies such as Lan et al (2008), Urgusal & Culp (2013), Indraganti et al (2015), and Maykot et al (2018). Having the mean neutral temperature greater for males than females is concluded only in the study of Urgusal and Culp (2013) as they are recorded 26.4° and 23.9° respectively. On the other hands, the other three studies conclude higher mean neutral temperature for females than males.

**CONCLUSION**

The purpose of this study is to examine the possible relationships between the ASHREA thermal sensation, which is a dependent variable, and four other variables: gender, age, body mass index (BMI), and clothes index (*clo*.) as separate independent variables in occupants of Dammam homes in Saudi Arabia. The results reveal that there is a descending small association and relationship between ASHREA thermal sensation and gender as well as a relationship between ASHREA thermal sensation and age. Moreover, ASHREA thermal sensation and BMI represents a very small association. The association is almost null in the case between ASHREA thermal sensation and clothing index. Lastly, the results showed that females are more sensitive to the cold temperature than males, although males are more sensitive to hot temperature than females.

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# Living in Extremes: Thermal physiology of Nomadic Pastoralists

**Wouter van Marken Lichtenbelt[1], Adam Sellers, Dolaana Khovalyg[2]**

[1] Department of Nutrition and Movement Sciences, NUTRIM, Maastricht University, Maastricht, The Netherlands, e-mail: markenlichtenbelt@maastrichtuniversity.nl

[2] Thermal Engineering for the Built Environment Lab (TEBEL), École Polytechnique Fédérale de Lausanne (EPFL), Switzerland, e-mail: dolaana.khovalyg@epfl.ch

## Abstract

A study on the temperature adaptations of the Tuvan nomadic pastoralists living in yurts has been carried out in January 2020. These nomads are unique to study since they live in a region with extreme temperature variation between summer and winter, and in the wintertime, they are exposed to daily (indoor, outdoor) variation of temperatures up to 50°C! This multi-disciplinary study encompasses physiological, health, and sociological aspects in combination with the physics of the built environment.

Here we report preliminary results of the temperature conditions and physiological measurements (body temperatures and physical activity) of one pastoralist living in a yurt. The main question is to what temperatures are pastoralists exposed in wintertime and to what extent does that affect their body temperatures. The yurt conditions, indoor climate and climate are described in a separate paper (1).

The results show frequent exposure to extreme temperatures, ranging from -15 to +38 °C. Skin temperature variations, however, are mild and correspond to skin temperatures experienced in indoor climate conditions in temperature climate regions.

## Introduction

Due to the application of the conventional standards and the resulting small variation of the indoor climate, the human thermoregulatory system is less and less challenged to maintain a constant body core temperature. This affects our metabolism and makes occupants vulnerable to temperature variations. More frequent exposure to heat and cold can affect positively our metabolic health and may create more resilience to these deviant temperature conditions (2, 3). Some more naturally living peoples, such as nomadic pastoralists in Siberia and Mongolia, are still exposed to temperature variation. Adaptations of nomads to extreme environments can be a source of inspiration for how we should design healthy, sustainable buildings.

Both comparative studies between populations as well as seasonal effects clearly show that people are able to metabolically adapt to these more extreme thermal conditions (4). It is well known that exposure to regular cold conditions increases our basal metabolic rate in winter compared to summer (5). However, there are only a few elaborate studies on thermophysiological adaptations to extreme climatological conditions. Classical studies encompass the studies on the Australian Aborigines by Scholander *et al.* (6), and by

Andersen in nomadic Lapps (7). The Siberian Yakuts, that are regularly exposed to extremely cold outdoor temperatures, have been studied with respect to their energy metabolism (5). These studies revealed seasonal changes in resting metabolic rate (5), and the potential effect on blood pressure (8). These studies, however, did not include actual measurements on living conditions, body temperatures and related parameters. We take the next step by applying a multidisciplinary approach to simultaneously study housing conditions, physiological and psychological adaptations to extreme thermal conditions of people frequently exposed to extreme conditions.

In January 2020, we studied nomadic pastoralists in Tuva, the region in the south of Siberia in Russia, who are living in traditional conditions in yurts (Figure 1) and exposed to temperature extremes.

Nomadic pastoralism is a form of pastoralism when livestock are herded in order to find fresh pastures on which to graze. In Tuva, a region in the south of Siberia, the herded livestock include cattle, sheep, goats, and horses in most of the region. Most nomads nowadays show two times a year seasonal migration: in spring they move to the lowland planes with the richest pastures in summer time, and in autumn a transition to mountainous regions takes place, where winter temperatures are relatively high compared to the planes and the grasses are easier accessible by the grazers. The main housing consists of yurts (Figure 1). The temperature variation, both seasonal and daily, to which the people are exposed is extremely large, making these hardly documented communities very interesting to study from an ecological perspective, but also in view of the recent climate changes and for comparison with the westernized comfortable indoor environments.

This multi-disciplinary study encompasses physiological, health, and sociological aspects in combination with the physics of the built environment.

*Figure 1. Yurt in the winter.*

Here we report preliminary results of the temperature conditions and physiological measurements (body temperatures and physical activity) of one pastoralist living in a yurt. The main question is to what temperatures are pastoralists exposed in wintertime and to what extent does that affect their body temperatures. The yurt conditions, indoor climate and climate are described in a separate paper (1).

## Methods

The physiological measurements encompassed body composition (anthropometry and isotope dilution), energy expenditure (doubly labeled water technique), resting metabolic rate and cold induced thermogenesis (indirect calorimetry), standardized metabolic and local cold exposure responses, physical activity (actigraphy), cardiovascular health, and body temperatures (core and skin temperatures). All these measurements were carried out in 12 subjects. Here we restrict ourselves to body composition, body temperature and physical activity of one male pastoralist.

Body weight, length and body fat were determined using anthropometry. Body fat was calculated by the Skinfold thickness on four sites using the equation of Durnin and Womersly (9). Skin body temperatures were measured at five-minute intervals by means of dataloggers (iButton, DS1923, Maxim) (10). They were placed at the chest, shoulder, thigh and shin, following the procedure of (11) (Figure 2). To measure the actual thermal environment experienced by the subject, two buttons were placed on the outer clothing, one on the vest the other on the outer jacket.

Actigraph GTX3 accelerometers (Actigraph, Pensacola, FL, USA) were used to determine physical activity. The tri-axial accelerometer measures 4.6 cm × 3.3 cm × 1.5 cm and weighs 19 g and is a validated tool that has shown to be reliable for the assessment of PA (12) (Figure 2).

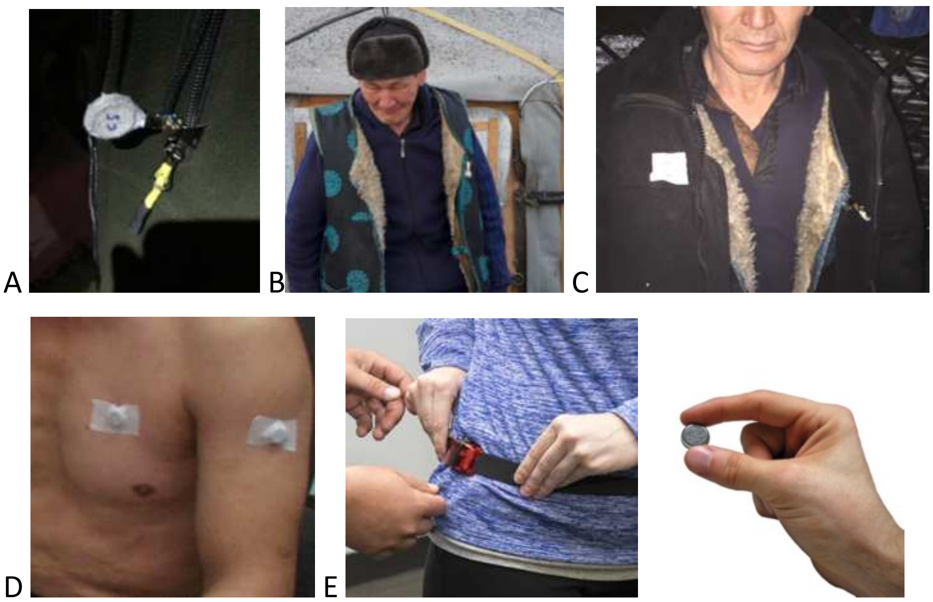


*Figure 2. Temperature data logger (iButton) on a clip (A). iButton on a vest (B) and on vest and jacket (C). Two iButtons on the skin. Actigraph placed on the hip (D).*

## Results and discussion

The owner of the yurt was a man of 47 years old. He weighed 62.7 kg and had a hight of 176 cm (BMI is 20.2 kg/m2). Body fat percentage was 14.1%.

He primarily lives in the yurt, while friends and relatives visit him regularly. Together with a neighbor he takes care of the livestock. He wears several layers of clothing: three layers of trousers (1 lightweight and 2 thick), three layers of sweaters, a T-shirt, three pairs of socks and winter boots. When he goes outdoors, he in addition wears a lamb skin-pelt vest with or without a winter jacket (see results below) and a winter hat as shown in Figure 2(B). His typical clothing ensemble when he is indoors has the total clothing insulation value of approximately 2 clo.

The following results are presented of three contiguous days in January 2020 of the occupant of the yurt. The temperatures were obtained by indoor air quality and weather instruments (see (1)). The outdoor temperature ranges from -32 to -15 °C. Indoor temperatures, depending on the location in the yurt, vary from -10 to +38 °C (Figure 3).

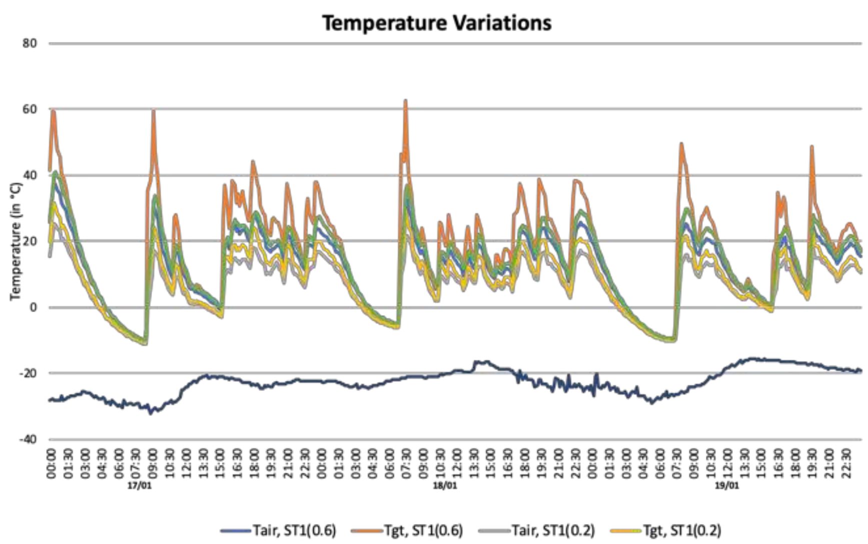


*Figure 3. Temperatures inside of the yurt and outdoor temperature during a 72 h measurement period. Temperature inside the yurt: Air temperature (Tair at 0.6 m and 0.2 m); globe temperature (Tgt at 0.6 m and 0.2 m). Dark blue line is outdoor temperature.*

The temperatures that the occupant of the yurt experienced close to his body were obtained by the temperature sensors on the outside of two jackets which were worn daily. The outer jacket sensor shows that the lowest temperature was -25 °C and the highest +34 °C (figure 4). The range of the inner jacket was -27 to 32 °C. The outer jacket was not always worn as can be seen for instance on the morning of 17 Jan and part of the afternoon of 18 and 19 January. In those cases, the temperature of the inner jacket reaches the lowest value while the temperature of the outer jacket stays in the positive range indicating that it was indoors.

The extremes are slightly less than the indoor and outdoor temperatures measured by the environmental instruments. Nevertheless, the temperature of the inner jacket varied substantially and indicates that the occupant regularly went in and out of the yurt. He was frequently exposed to extremes and the dynamic temperature range reached 50 °C.

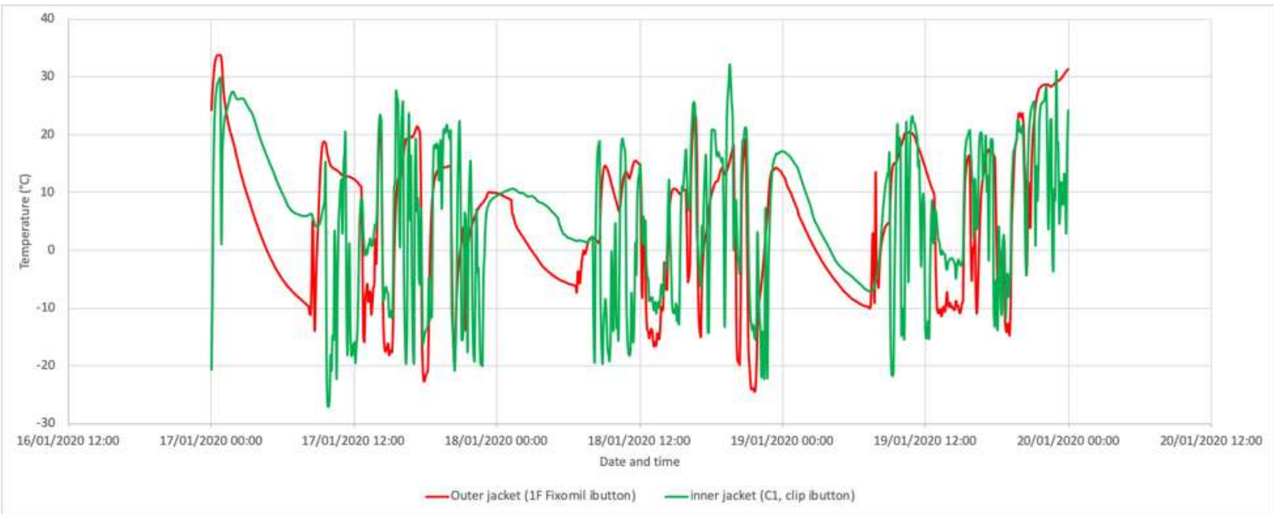


*Figure 4. Temperatures of the outer layer of the clothing during a 72 h measurement period.*

Next, we wanted to see to what extent the large temperature range that the occupants are exposed to affects their skin temperature. It is interesting to note that the skin temperatures had a much more blunted response compared to the environmental conditions as measured by the jacket temperatures. Chest and shoulder temperatures range from 31-38 °C (figure 5). Lowest temperatures were recorded for the thigh, just after waking up (minimum 23 °C). Even those temperatures are relatively high. Most likely exposed parts of the body (in practice this is only the face) must have been cooler. Those temperatures are not recorded, because metal iButtons may cause local cold injury such as blisters.

It is also noteworthy to mention that during the night, when temperatures in the yurt decrease significantly, there is only a slight decrease of distal (shin and fhigh) temperatures and even an increase of the chest body temperature. In general, the range of skin temperatures is similar to those reported in thermoneutral conditions with clothing under laboratory conditions (13, 14).

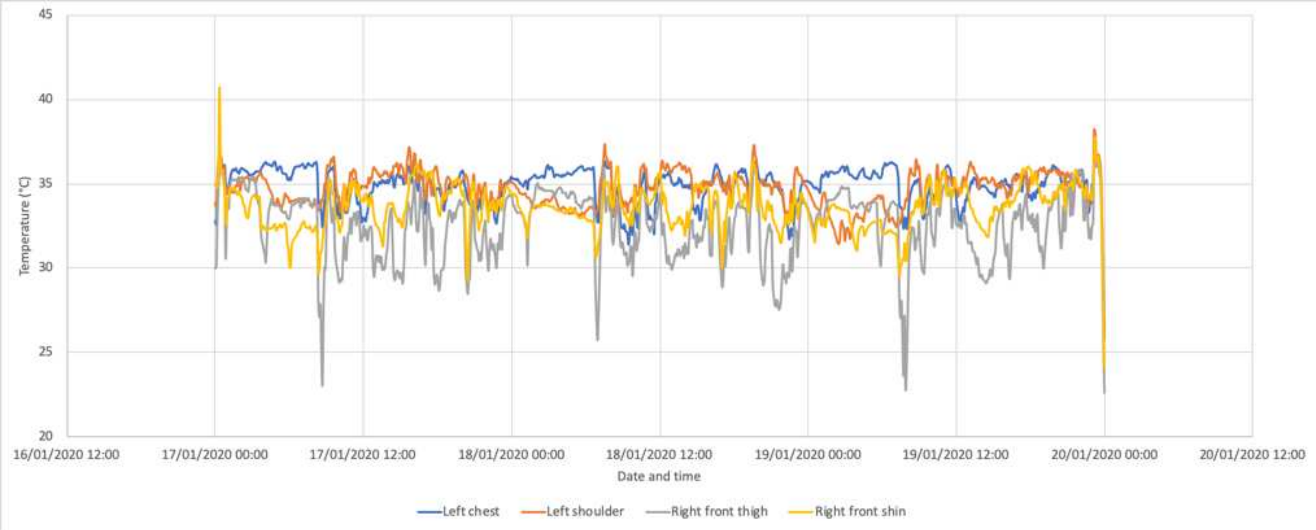


*Figure 5. Skin temperatures of the chest, shoulder, thigh and shin during a 72 h measurement period.*

Physical activity shows a distinct day/night rhythm (figure 6). Highest activity was noted during midday. Both the physical activity data combined with the temperature data indicate that this subject went in and out of the yurt frequently and probably did not go out herding his sheep, which lasts multiple hours, in those days. It is likely that he stayed close to the yurt.

There is a significant negative relationship between the temperature of the thigh and physical activity (Figure 7). This may be caused by the slightly higher temperatures of the skin during the night (having a low physical activity). However, even when night time activity and temperatures were excluded, leaving only daytime data, the relation remains significant. This may be caused by higher activities while being outside and exposed to the cold.

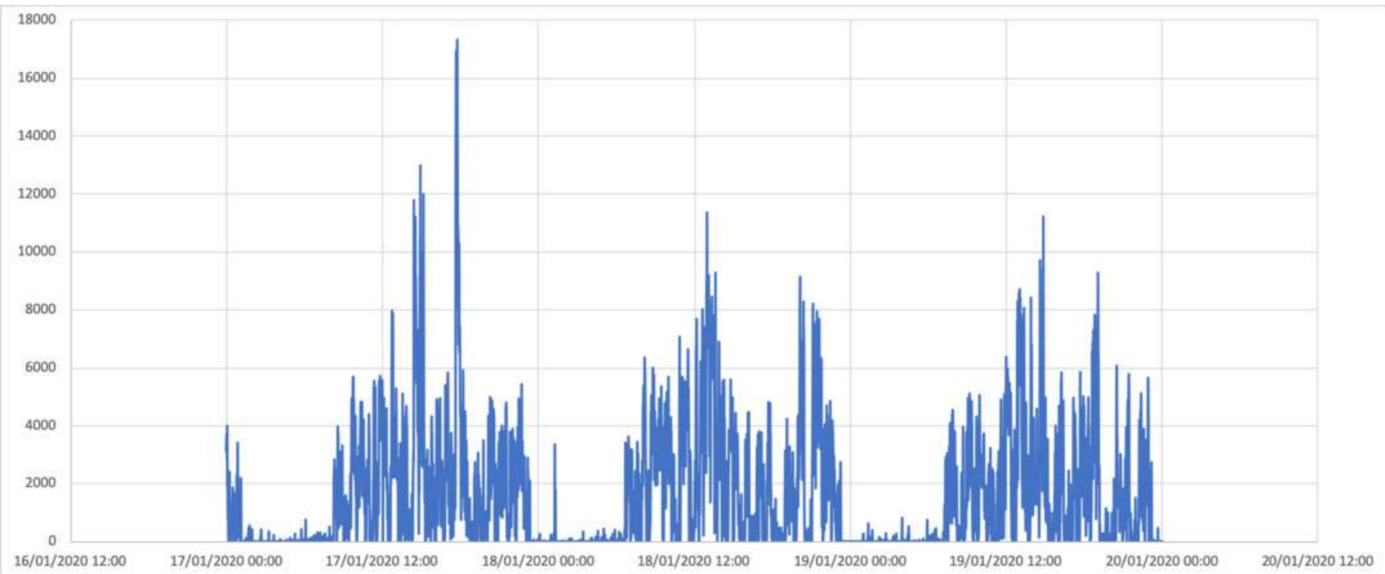


*Figure 6. Activity recordings over time. Activity in arbitrary units.*

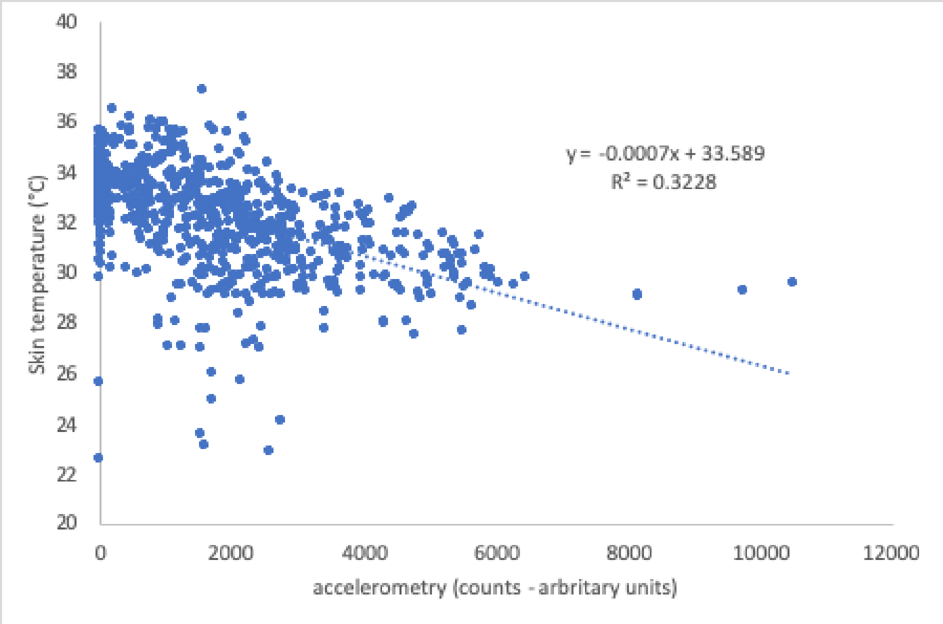


*Figure 7. correlation between thigh temperature and activity.*

## Conclusion

Temperature data and activity during three days of a specific pastoralist were presented. These data show frequent exposure to extreme temperatures, ranging from -15 to +38 °C. Skin temperature variations, however, are mild and correspond to skin temperatures experienced in indoor climate conditions in temperature climate regions. Whether is is caused by an increased metabolism in the cold is subject to more in depth analyses of our measurements.

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# Effect of metabolic rates on walkability in outdoor environments: A case study

**Vivek Anand[1] Devi.S[1] Rajasekar.E[1]**

[1] Indian Institute of Technology, Roorkee, Uttarakhand 247667, India

**Abstract**: The case study deals with outdoor thermal comfort assessment focusing on metabolic rates of pedestrians and its impact on walkability. The objectives of the paper are to (a) evaluate the impact of metabolic rates on outdoor thermal comfort of pedestrians, (b) establish the impact of thermal comfort on walkability. The paper is based on experimental field measurements of thermal comfort and subjective surveys with pedestrians in a multi-modal hub in Delhi, India which represents a humid subtropical climate. Resting metabolic rate test and cardiorespiratory fitness test is performed on subjects followed by measurement of oxygen consumption and heart rate for a designated set of pedestrian routes. Metabolic rates are estimated as per ISO: 8996-2004. A total of 18 subjects volunteered for the experiments. The subjects wore the portable metabolic analyser and registered sequential thermal responses at designated locations as well as time intervals during the survey. The paper presents the distribution of metabolic rates through the walking sequence and highlights the variation between standard metabolic rates in published literature. The change in comfort response with respect to various walking sequences and speeds are discussed. The paper summarizes the allowable walking distances for a given threshold of thermal comfort.

**Keywords:** Walkability, Metabolic rate, Indirect calorimetry, Outdoor environments

## 1. Introduction

Walking is an economical means of transport to work (Redfern, 2008). As the population is increasing, traffic is rising; hence the preference of commute has shifted to walking (Koska, Rudolph, & Umwelt, 2016). Cutting carbon footprint in the changing environment is also taken care is also taken care by promoting walking habits. In megacities of India like New Delhi, where the population is 30 million approx., at least 3 lakh people travel to their workplace on foot (Census 2011, India). Walkability index score for Delhi is 0.87 (clean air initiative, 2011). The extent to which the urban atmosphere is pedestrian-friendly has become a crucial area of research in the recent past. Improving walkability in the neighbourhood is vital in making society more sustainable (Bekiaris, Tsami, & Panou, 2017; Rafiemanzelat, Emadi, & Kamali, 2017; Serna, Gerrikagoitia, Bernabé, & Ruiz, 2017).

Human thermal comfort varies with different primitive factors (Jamei, Rajagopalan, Seyedmahmoudian, & Jamei, 2016; Rupp, Vásquez, & Lamberts, 2015). Apart from meteorological factors, there are various physiological factors which impact the outdoor thermal comfort of a pedestrian. Outdoor thermal comfort indices like MENEX (Monteiro & Alucci, 2006) Index of Thermal Stress (ITS) (L. Chen & Ng, 2012; Epstein & Moran, 2006; KURAZUMI et al., 2012), Physiologically Equivalent Temperature (PET) (Höppe, 1999; Matzarakis & Amelung, 2008; Matzarakis, Mayer, & Iziomon, 1999), Modified Physiologically Equivalent Temperature (mPET) (Y.-C. Chen & Matzarakis, 2014), OUT-SET are commonly used for assessment of thermal comfort. In these thermal comfort indices, metabolic rate is one of the key factors. Metabolic rate measures the energetic cost of muscular load and gives a numerical index of activity (ISO, 2004). For different activity levels, human metabolism shows different patterns (Speakman & Mitchell, 2011). It depends on different physiological measurements like heart rate, oxygen consumption (VO2), respiratory quotient and carbon dioxide consumption (VCO2) (Ciesielska, Mokwinski, & Orlowska-Majdak, 2009; Frankenfield, Ashcraft, Wood, & Chinchilli, 2016; Neary, McKenzie, & Bhambhani, 2005; Oldenburg, McCormack, Morse, & Jones, 1979) . The ISO 8996: 2004 defines different methods of calculating metabolic rate of humans for different activities.

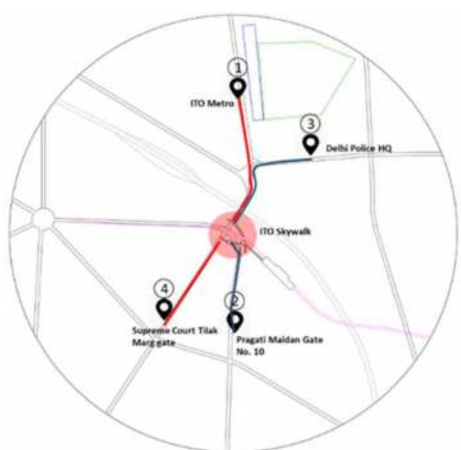
This case study assesses the thermal comfort and metabolic rates of the pedestrians at the ITO skywalk, New Delhi. The entire study pertains to the Indian scenario of walkability (clean air initiative, 2011). The importance of increasing the ease and ability to walk in public interconnected spaces has become vital. This study focuses on the (i) Evaluation of the impact of metabolic rates on outdoor thermal comfort of pedestrians and (ii) Establishing the impact of thermal comfort on walkability.

## 2. Methods & Materials

The walkability of pedestrians was studied at one of the busiest ITO crossing junction in New Delhi- India, where 30,000 pedestrians cross different lanes around ITO crossing. This place connects six major locations of the city with around 25 major office complexes, two Delhi Metro stations, seven major arterial roads and the Tilak Bridge Railway Station complies with being one of the busiest stretches in the city. The study is limited to the humid subtropical (Beck et al., 2018) climate zone and urban locality since the selected site is at New Delhi, India. This study is done on human subjects aged between 21-30 years. To understand the effect of metabolic rate on walkability, the ITO skywalk which is 400m long and 5m wide with the length of the loop and ramp being 130m with width 3m is taken. This paper focuses on evaluating walkability using variables like metabolic rate, distance, economic status, office time, daily routine and history of the pedestrian. The pedestrian's walkability is studied through field studies. In multiple environmental circumstances, the level of oxygen during inhalation is tracked using indirect calorimetry and the walkability check is performed, as the neighbourhood walkability can influence physical activity. Field validation is performed using real-time survey subjective answers in locations such as the intersection where pedestrians walk around.

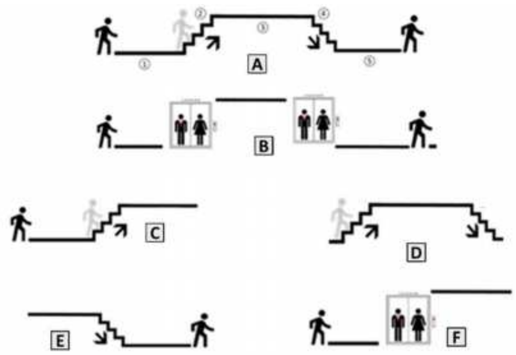
### 2.1. Walk Scenario identification

A reconnaissance survey is performed at the ITO skywalk, New Delhi, to identify the major walk scenarios. The main points of origin and destination are identified near the site and related possible routes are determined. The three most preferred routes are selected for the study based on pedestrian choice and density, as shown in figure 1.




| Route no | Origin | Destination | Origin to skywalk distance (m) | Skywalk length (m) | Skywalk to destination distance (m) | Total walking distance (m) |
|---|---|---|---|---|---|---|
| 1 | ITO metro | Supreme court- tilak marg gate | 470 | 450 | 530 | 1450 |
| 2 | Delhi police head quarters | Pragati maidan gate no. 10 | 510 | 450 | 480 | 1440 |
| 3 | Delhi Police head quarters | Supreme court – Tilak Marg gate | 510 | 350 | 530 | 1390 |

Figure 1. ITO Skywalk, New Delhi map showing major pedestrian routes.




| Scenario | Stage 1 | Stage 2 | Stage 3 | Stage 4 | Stage 5 |
|---|---|---|---|---|---|
| **Scenario A** | 500 m walk | Step up | 500 m walk | Step down | 500 m walk |
| **Scenario B** | 500 m walk | Elevator up | 500 m walk | Elevator down | 500 m walk |
| **Scenario C** | 1000 m walk | Step up | 500 m walk | --------------- | ---------------- |
| **Scenario D** | Step up | 500 m walk | Step down | --------------- | ---------------- |
| **Scenario E** | 500 m walk | Step down | 500 m walk | --------------- | ---------------- |
| **Scenario F** | 500 m walk | Elevator up | 500 m walk | -------------- | ---------------- |

Figure 2. Different walking scenarios considered

The first route starts from ITO metro to Supreme court –Tilak Marg containing three legs of 500m each. The second route starts from Delhi police headquarters to Pragati Maidan (gate number 10). It also has three legs of 500 m each. The third route starts from the Delhi Police Headquarters, IP estate to the Supreme Court entrance, going through ITO skywalk in between. It has three legs of 500 m each. Based on selected three routes, six different walk scenarios are possible. Out of these six scenarios, Scenario A and B has three alternate stages of 500 m walking with steps and elevators for transition from one stage to the another. Indirect calorimetry method as per ISO: 8996 – 2004 has been used to calculate the metabolic rate of the subjects during different activities. In this method, metabolic rate is calculated using oxygen consumption (VO2) and Energetic Equivalent which is a constant. For the study, eighteen healthy middle-aged subjects are selected comprising nine males and nine female subjects. The measurement accuracy of the device is mentioned in Table 1.

Table 1. Metabolic analyser measuring accuracy

| SENSORS | TYPE | RANGE | ACCURACY | RESOLUTION |
|---|---|---|---|---|
| Oxygen | Galvanic fuel cell | 0-25% | 1 m Bar O2 | 0.006% Vol O2 |
| Flowmeter RMR 18mm | NA | 0-50 L/min | <2% | <10 ml |
| Flowmeter VO2 max 28mm | NA | 5-300 L/min | <2% | 24 ml |
| Barometric pressure | piezo-resistive | 300-800 mmHg | ±1 mmHg | NA |

Figure 3. Field measurements using Metabolic Analyser

To measure the oxygen consumption and heart rate of the subjects during the walk trip, cardio-respiratory fitness test is done using indirect calorimetric method performed using a portable metabolic analyser. The distance traversed during the trip is measured using a hand-held measuring wheel. The test is performed as per the experimental protocol as shown in figure 2. The total number of stairs in each case is sixty-eight with riser of 150 mm each.

## 3. Results and Discussion

### 3.1. Observed heart rate and oxygen consumption

Figure 4. shows the data recorded by the metabolic analyser during the cardiorespiratory fitness test. Oxygen Consumption and heart rate measurement is plotted against time for the activity throughout. The spikes in both the measurement is clearly observed during the step-up process. The bold black line denoted by 'AT' represents the anaerobic threshold of the subject. It is observed that the heart rate reaches its maximum when subjects climb the stairs. The heart rate range for females is slightly higher than those of males.

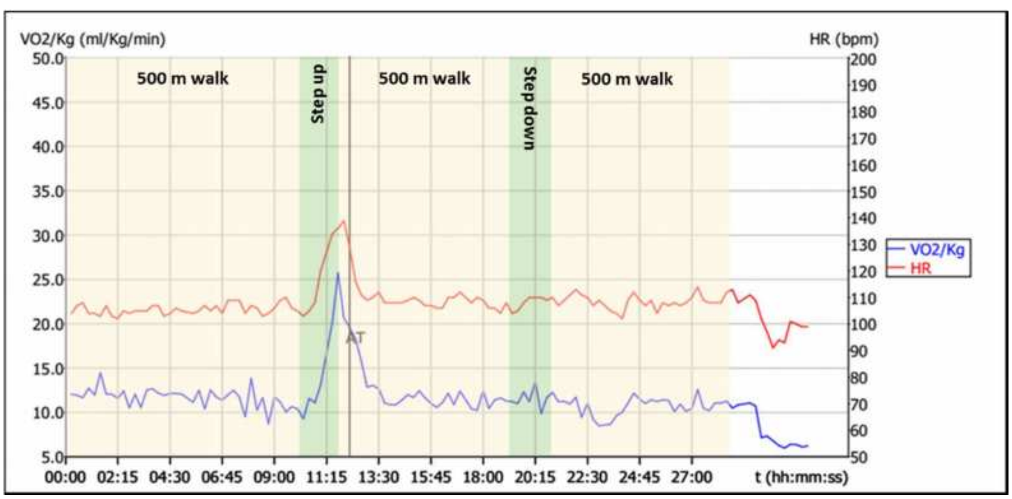



Figure 4. Variation of heart rate (HR) and Oxygen consumption (VO2) during the cardio-respiratory fitness test of a sample subject.

### 3.2. Average time taken in different activities

Figure 5. shows that the average time taken for each 500 m lap decreases with time for both the genders. The average speed observed for each lap is 3.5 Km/h, 3.8 Km/h and 4.0 Km/h for male and 3.7 Km/h, 3.9 Km/h and 4.2 Km/h for female. It suggests that people tend to walk

fast in the latter part of their trip. It is also observed that female walk slightly faster than males on average. For step up and step down activity, the average time taken is less than or equal to 1 minute to climb 68 steps, each having riser of 150 mm.

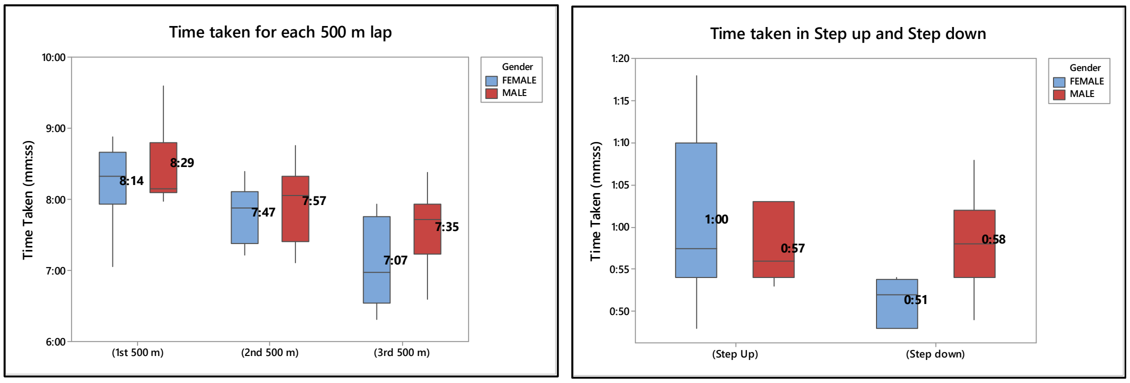



Figure 5. Impact of time difference on time taken by the subjects during each activity

Figure 6 and Figure 7. Presents the range of heart rate and variation of mean heart rate of male and female for different activities. The step-up activity is showing the highest mean heart rate of 128 beats/minute for males and 140 beats/minute for females. For 500 m walk activity, the first 500 m lap shows the lowest mean heart rate for both the genders. For second and third 500 m lap, it is 126 beats/minute and 125 beats/minute for male subjects and 113 beats/minute and 111 beats/minute for female subjects.

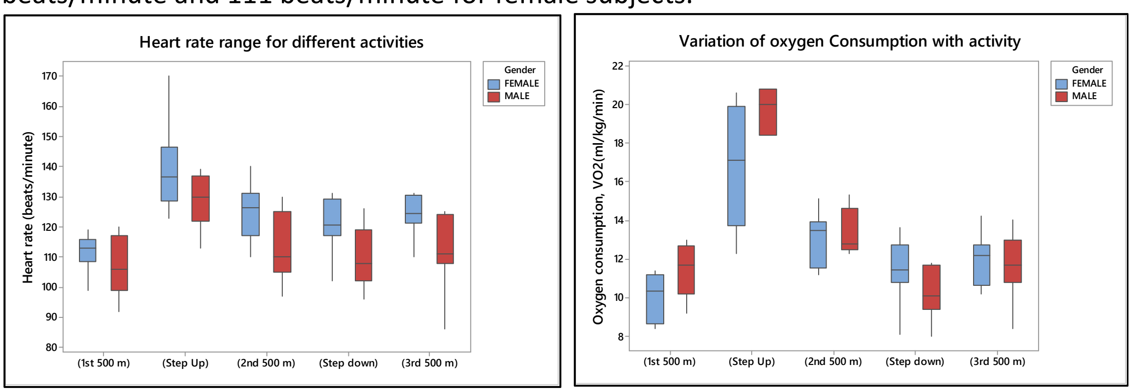



Figure 6. Heart rate variation with activity; Variation of Oxygen Consumption with activity

Figure 7. Also shows a similar trend for oxygen consumption (VO2) with the step-up activity having the highest mean value of 19.4 ml/kg/min for males and 16.2 ml/kg/min for females. For step down activity, it is 10.3 ml/kg/min and 11.5 ml/kg/min for males and females, respectively. In case of 500 m walk, the lowest value is observed for the first 500 m lap for both the genders, registering a mean oxygen consumption value of 11.4 ml/kg/min and 10.0 ml/kg/min for male and female subjects respectively. For second and third lap, it is 13.4 ml/kg/min and 12.0 ml/kg/min for male subjects and 12.0 ml/kg/min and 11.7 ml/kg/min for female subjects.

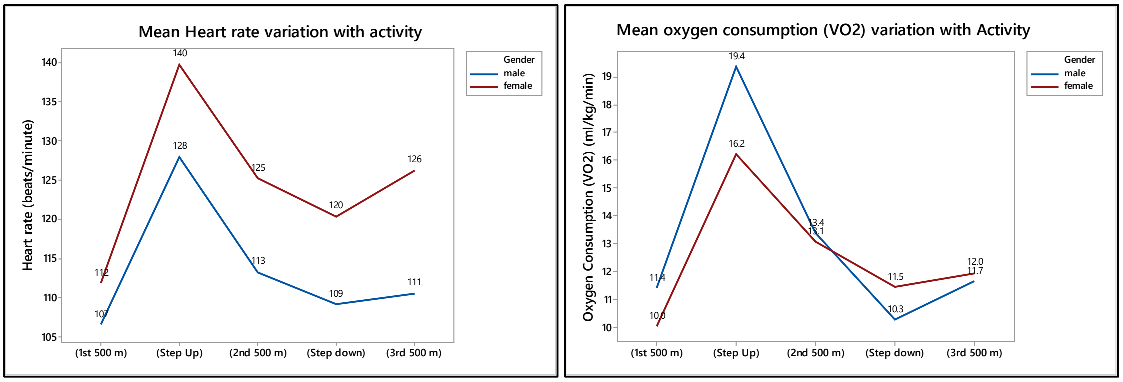



Figure 7. Mean heart rate variation with activity; Variation of Oxygen Consumption with activity

### 3.3. Variation of metabolic rates and energy expenditure with activity.

The metabolic rate is calculated from the oxygen consumption data from the test using equation (1) obtained from ISO: 4996 – 2004.

$$\boldsymbol{M = EE * VO_2 * \frac{1}{A_{D_u}}} \quad \textbf{(1)}$$

Here, energetic equivalent (EE) is taken as 5.68 from the equation (EE = (0.23 RQ + 0.77)5.88), with respiratory quotient of 0.8. $\boldsymbol{A_{D_u}}$ is the Du-bois area obtained using equation (2)

$$\boldsymbol{A_{D_u} = 0.202 * W_b^{0.425} * H_b^{0.725}} \quad \textbf{(2)}$$

The calculated metabolic rate is also showing a similar trend as VO2. The step-up activity is responsible for the highest mean metabolic rate (250.1 W/m$^2$ for male subjects and 204.3 W/m$^2$ for female subjects) during the activity for both the genders, as observed in Figure 7. For the first 500 m walk, the metabolic rate is least for both males and females (150.1 W/m$^2$ and 126.0 W/m$^2$ respectively). For second and third 500 m lap, there is very little difference in the metabolic rate which is 175.8 W/m$^2$ and 160.2 W/m$^2$ for male and 163.9 W/m$^2$ and 151.5 W/m$^2$ for female. For step down activity, the metabolic rate is less as compared to walking activity, which is evident from the figures.

Table 2. Metabolic rate and speed for walking activity

| **Activity** | **Speed** | | **Metabolic rate (W/m$^2$)** | | |
|---|---|---|---|---|---|
| | *Male* | *Female* | *As per Experiment* | | *As per Standard* |
| | | | Male | Female | |
| 1$^{st}$ 500 m walk | 3.5 | 3.7 | 150.1 | 126 | |
| 2$^{nd}$ 500 m walk | 3.8 | 3.9 | 175.8 | 163.9 | 165 (for 4 Km/h) |
| 3$^{rd}$ 500 m walk | 4.0 | 4.2 | 163.9 | 151.5 | |

The metabolic rates obtained are compared with the standard metabolic rate as per the ISO 8996:2004(E) and are tabulated in table 2. This comparison shows that the difference between the experimental and standard metabolic rate is very less for the speed close to 4Km/h.

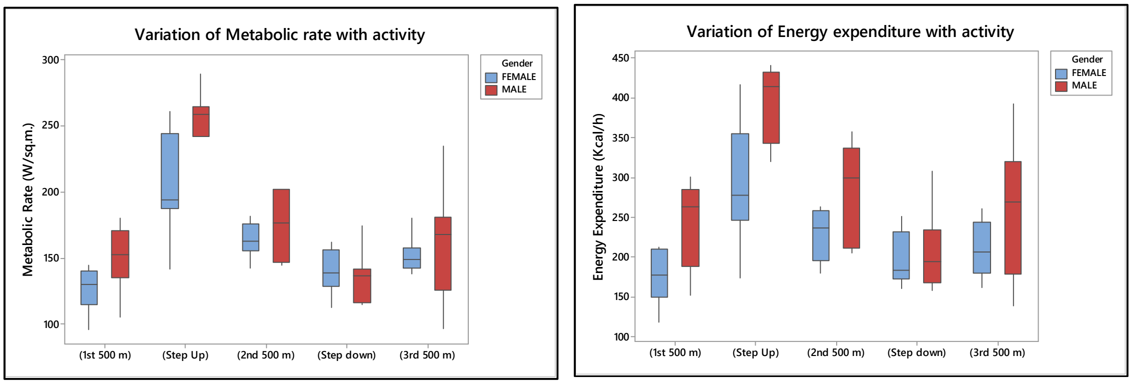



Figure 8. Variation of metabolic rate and energy expenditure with various activity

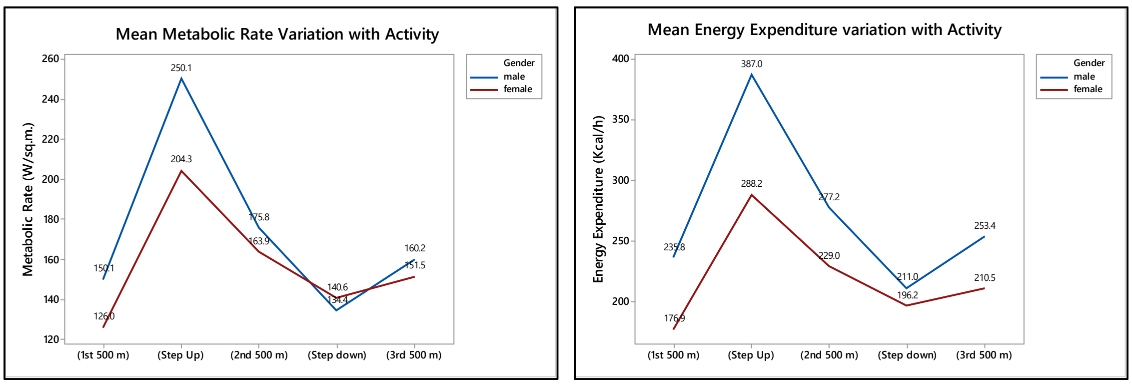



Figure 9. Mean metabolic rate variation with activity; Variation of Mean Oxygen Consumption with activity

The energy expenditure also shows the peak increase in the case of step-up activity with an average of 387.0 Kcal/h for males and 288.2 Kcal/h for females.

### 3.4. Comparison of various walk scenarios experienced in ITO skywalk

Table 3 compares different physiological variables for all the six scenarios. The time averaged value for both male and female subjects are taken. It is evident from the table that metabolic rate is high in case of scenario A and B. For scenario F, metabolic rate is lowest. It shows that when the walk scenario includes climbing stairs (Step up), the overall metabolic rate becomes more. Comparatively, when there is no step up activity and only elevators are used to access the skywalk, metabolic rate is less.

Table 3. Comparison of the variables during the walking scenarios

| Scenario | Metabolic rate($W/m^2$) | | Heart rate (beats/minute) | | Oxygen consumption (ml/kg/min) | | Energy expenditure (kcal/hr) | |
|---|---|---|---|---|---|---|---|---|
| | Male | Female | Male | Female | Male | Female | Male | Female |
| A | 163.9 | 148.7 | 111 | 122 | 12.3 | 11.8 | 258.1 | 207.8 |
| B | 152.4 | 136.1 | 108 | 103 | 11.5 | 11.1 | 236.7 | 198.8 |
| C | 168.5 | 157.2 | 115 | 110 | 12.6 | 12.2 | 248.3 | 203.5 |
| D | 148.3 | 142.7 | 98 | 102 | 10.6 | 10.1 | 215.3 | 188.4 |
| E | 143.2 | 138.1 | 101 | 103 | 11.2 | 10.8 | 223.4 | 191.3 |
| F | 138.6 | 132.9 | 98 | 93 | 10.1 | 9.6 | 204.2 | 184.5 |

### 3.5. Impact of metabolic rate on outdoor thermal comfort of pedestrians

The impact of metabolic rate on outdoor thermal comfort is assessed using PET (Physiologically Equivalent Temperature) and mPET (Modified Physiologically Equivalent Temperature). For this assessment, most of the factors associated with PET and mPET are kept constant except the Activity factor based on metabolic rate. Table 3. Shows the value of PET and mPET for different activity based on the metabolic rate. RayMan Pro 2017 is used to calculate the values of these indices.

Table 3. Calculation of PET and mPET values for different activities.

| ACTIVITY | MALE | | | | FEMALE | | | |
|---|---|---|---|---|---|---|---|---|
| | W | Clo | PET (°C) | mPET (°C) | W | Clo | PET (°C) | mPET (°C) |
| **$T_{air}$ = 25** °C | | | | | | | | |
| **1st 500 m walk** | 150.1 | 0.7 | 15.1 | 22.1 | 126.0 | 0.7 | 16.3 | 21.2 |
| **Step up** | 250.1 | 0.7 | 13.9 | 26.2 | 204.3 | 0.7 | 14.0 | 24.6 |
| **2nd 500 m walk** | 175.8 | 0.7 | 14.3 | 23.2 | 163.9 | 0.7 | 14.7 | 22.9 |
| **Step down** | 134.4 | 0.7 | 15.7 | 21.5 | 140.6 | 0.7 | 15.7 | 21.9 |
| **3rd 500 m walk** | 160.2 | 0.7 | 14.6 | 22.5 | 151.5 | 0.7 | 15.3 | 22.3 |
| **$T_{air}$ = 28** °C | | | | | | | | |
| **1st 500 m walk** | 150.1 | 0.9 | 21.0 | 26.5 | 126.0 | 0.9 | 21.3 | 26.0 |
| **Step up** | 250.1 | 0.9 | 20.5 | 30.6 | 204.3 | 0.9 | 20.9 | 29.2 |
| **2nd 500 m walk** | 175.8 | 0.9 | 21.1 | 28.0 | 163.9 | 0.9 | 21.1 | 27.5 |
| **Step down** | 134.4 | 0.9 | 21.3 | 26.3 | 140.6 | 0.9 | 21.3 | 26.6 |
| **3rd 500 m walk** | 160.2 | 0.9 | 21.2 | 27.4 | 151.5 | 0.9 | 21.2 | 27.0 |

It can be observed from the table that PET is decreasing with an increase in the activity intensity. For clo value 0.7, all the activities result in the PET value range of 13 ºC – 18 ºC which signify ''slight cold stress'' as per the PET index. For step-up activity, mPET value is 26.2 (for male subjects) which is more than the provided Air Temperature ($T_{air}$) of 25 ºC. For females also, the corresponding mPET value is 24.6, which is very near to the Tair of 25 ºC. When clo value is taken as 1.3, the PET value varies insignificantly for different activities, which shows that PET is variable only for clo values less than 1. Whereas, the mPET displays a good correlation with metabolic rate, showing an increasing trend with an increase in activity intensity for both the genders.

### 3.6. Impact of thermal comfort on walkability

From the above results, it is observed that the mean heart rate increased rapidly for the step up activity for both the genders (From 112 beats per minute – 140 beats per minute for females and 107 beats per minute – 128 beats per minute for males). The recommended heart rate for moderate-intensity activities varies from 100 – 170 beats per minute for a 20 years old to 95 – 162 beats per minute for a 30 years old, as per Centre for Disease Control, USA. It shows that the subjects are uncomfortable during the course of the step-up activity.

Table 4. Possible walking distances without physical stress based on mPET in each route in ITO skywalk

| Scenario | Total distance (m) | mPET at the point of exertion | Distance travelled without physical stress (m) |
|---|---|---|---|
| A | 1500 | 24.6 | 500 |
| B | 1500 | 22.3 | 900 |
| C | 1500 | 21.6 | 900 |

| | | | |
|---|---|---|---|
| **D** | 500 | 25.2 | 500 |
| **E** | 1000 | 22 | 850 |
| **F** | 1000 | 21.3 | 850 |

From Table 4. It can be inferred that Walking after the mentioned distances can be uncomfortable to the pedestrians if the temperature is further increased from 25 $^{o}$C. The first 500 m walk doesn't impact much to the metabolism as evident from figure 8 and figure 9, but after the step up activity, the second and third 500 m walk shows an increase in metabolism as well as the corresponding mPET value as observed in the table 3. The obtained mPET value comes in the range of 18 - 23 $^{o}$C.

## 4. Conclusion

This study dealt with thermal comfort and walkability of the pedestrians at the interconnected junction in urban locality. The effect of the metabolic rate during different activity sequences are hence assessed through physiological field measurements. The impact of the metabolic rate on walkability is reported. The mean metabolic rates varied from 150 W/m$^2$ to 176 W/m$^2$ for males and 126 W/m$^2$ to 164 W/m$^2$ for females during walking activity. For step-up and step-down activity, the mean metabolic rate is observed to be in the higher and lower end. It is 250 W/m$^2$ and 204 W/m$^2$ for male and female respectively during step-up. During step-down, the mean metabolic rate is 134 W/m$^2$ for male and 141 W/ m$^2$ for females. Comparison of different walk scenarios demonstrated that scenario with step up activity and same walking distance leads to higher metabolic rate as compared to other scenarios.

Also, the findings of the field study showed that the heart rate (HR) and oxygen consumption (VO2) increased steeply when the activity changed from walking for 500 meters to climbing up the stairs. Steep increase in metabolic rate is observed due to increased rate of oxygen consumption during the same part of the protocol. Maximum discomfort is felt during the transition from the stage 1 and 2. The range of comfortable walking distance is observed from 500 m to 900 m in which the scenario having step-up activity showed early physical exertion. Further studies are required in different seasonal conditions and with subjects of different age groups. Incorporating ethnicity and health history can add a new dimension to this study.

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# Experimental evaluation of the effect of body mass on thermal comfort perception

**Aleksandra Lipczynska[1,2], Asit Mishra[2] and Stefano Schiavon[3]**

[1] Department of Heating, Ventilation and Dust Removal Technology, Faculty of Energy and Environmental Engineering, Silesian University of Technology, Gliwice, Poland, aleksandra.lipczynska@polsl.pl;
[2] Berkeley Education Alliance for Research in Singapore, Singapore, asit.mishra@bears-berkeley.sg;
[3] Center for the Built Environment, University of California Berkeley, United States, schiavon@berkeley.edu

**Abstract:** Globally 39% of adults are overweight, 13% are obese, and 9% are underweight. Current thermal comfort standards, catering to the normal-weight occupant, may hence be ignoring nearly 60% of the population. This could have significant comfort, productivity and energy implications. We performed a climate chamber study of the thermal response of 76 subjects in all the body mass index (BMI) categories, from 17 and 37 kg/m$^2$. Every participant underwent the same four sessions at average operative temperatures of 19.9, 22.4, 25.3, and 28.2 °C. We obtained subjective feedback from participants on their thermal sensation and preference, humidity sensation and preference, thermal comfort rating, and air quality perception. We also measured skin temperature, blood pressure, pulse rate, blood glucose level, weight, height, waist and hip circumferences and body composition. Overall, we did not find a significant impact of BMI on the thermal sensation. However, the overweight and obese participants preferred lower temperatures compared to normal-weight and underweight participants which may indicate a practical implication for control strategies.

**Keywords:** thermal comfort; thermal preference; body type differences; BMI; obesity

## 1. Introduction

Standards for the built environment (ANSI/ASHRAE 55, 2017; EN 16798-1, 2019) are based on two conventional approaches for thermal comfort models: the Predicted Mean Vote (PMV) model (Fanger, 1970) and adaptive models (de Dear and Brager, 1998; Nicol and Humphreys, 2002). Both approaches have limitations and have poor accuracy in the estimation of individual comfort parameters because they are aggregate models designed for the average population (Cheung et al., 2019; de Dear et al., 2013; Humphreys and Nicol, 2002; van Hoof, 2008). Several factors such as weight, height, basal metabolic rate, and sex were studied to check their effects on body temperature distribution, thermal sensation and individual preferences (Beshir and Ramsey, 1981; Dougherty et al., 2009; Fanger, 1970; Grivel and Candas, 1991; Lan et al., 2008). Personal factors are not given due consideration in the conventional approaches (Zhang et al., 2001).

So far, there is limited knowledge about the impact of body mass index (BMI), which takes into account weight and height, on thermal comfort. Some laboratory studies have been done with a small sample size, without firm conclusions or they had different research focus (Blaza and Garrow, 1983). Research shows that the skin temperature decreases with increase of body fat percentage (BF) (Chudecka et al., 2014; Salamunes et al., 2017). Thermal sensation is closely related to skin temperature (Benzinger, 1969; Yao et al., 2007), and as skin temperature correlates with BF, it is likely that thermal sensation, in turn, may be related to BMI. Obese people are under higher heat strain than lean people, and are under increased risk of heat-related disorders (e.g., heatstroke, heat cramps, and heat exhaustion) (Bar-Or et al., 1969; Buskirk E. R. et al., 2006; Chung and Pin, 1996). Some surveys have suggested that people with higher BMI tend to prefer lower temperatures (Daly, 2014; Rupp et al., 2018). In the tropics, this would imply higher cooling energy needs for people with higher BMI, we may speculate that this may also affect the issue of building overcooling.

World Health Organization qualifies obesity as a global epidemic (WHO, 2018): 39% of adults were overweight in 2016, and 13% were obese. The percentage is higher in the high-income countries, where overweight and obese people account for over 60% of the population. In Singapore, the percentage of overweight and obese people is 33%, and this fraction has an increasing trend (Epidemiology and Disease Control Division, 2011). Additionally, the percentage of underweight people in Singapore (9%) is nearly triple that of other developed countries. So, traditional thermal comfort requirements do not consider ~43% of Singaporeans. We aim to explore if and how body mass index is related to thermal comfort, sensation, and preference, and physiological parameters for typical thermal conditions found indoors.

## 2. Methods

### 2.1. Facilities and measuring equipment

The experiments were conducted in two identical physical chambers (5.6×4.3×2.6 m) located at SinBerBEST in the CREATE Tower, Singapore. Simultaneously, conditions were kept the same in both rooms. The first chamber was arranged with 6 computer workstations for participants, while the other was used for experimenters' workstation, measurements of body composition and changing rooms (Figure 1).

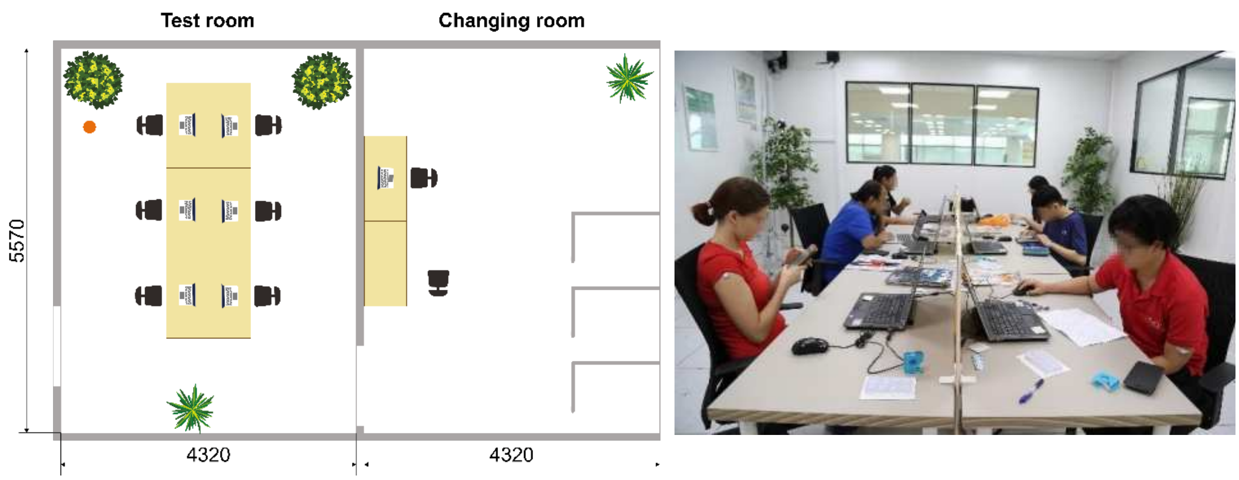


Figure 1. (Left) Plan view of the climatic chambers (orange dot – placement of ThermCondSys). (Right) Photo of the test room during the experiments.

All measurement instruments fulfilled requirements for accuracy according to EN ISO 7726 (2001). Prior to the investigation, all sensors were calibrated. We used ThermCondSys 5500 measuring system (Sensor Electronics, Poland) to monitor the room conditions at the reference point during experimental sessions. The system is equipped with omnidirectional thermal anemometers (accuracy of ±0.02 m/s ±1% of readings), air temperature and black globe temperature sensors (accuracy of ±0.1 °C), and relative humidity probe (accuracy of ±2% in range 10-90% *RH*). The skin temperature was measured with iButtons (DS1922L, Maxim Int., UK; accuracy of ±0.5 °C). Body composition was estimated based on hand-to-foot measurements with an 8-electrode, dual-frequency, bioelectrical impedance analysis (BIA) scanner (Tanita RD-545, Japan).

### 2.2. Study conditions

The study included an examination of four conditions with the design temperature set-points of 20 °C, 23 °C, 26 °C and 29 °C. Humidity levels were maintained at 55±5% for all sessions and mean radiant temperature was kept within 0.5 °C of the air temperature. All other indoor environmental parameters were kept unchanged across the sessions. Selected conditions were roughly corresponding to predicted thermal sensation "cool", "slightly cool", "neutral" and "slightly warm" (Hoyt et al., 2019) assuming clothing insulation of 0.57 clo and metabolic activity of 1.0 met (more details in the next paragraph). Table 1 summarizes the studied conditions.

Table 1. Experimental conditions (mean ± standard deviation)

| Condition: | 20 °C | 23 °C | 26 °C | 29 °C |
|---|---|---|---|---|
| **Predicted thermal sensation based on PMV** | cool | slightly cool | neutral | slightly warm |
| **Air temperature (°C)** | 19.9 ± 0.2 | 22.5 ± 0.3 | 25.5 ± 0.3 | 28.5 ± 0.2 |
| **Operative temperature (°C)** | 19.9 ± 0.2 | 22.4 ± 0.4 | 25.3 ± 0.3 | 28.2 ± 0.2 |
| **Relative humidity (%)** | 53.5 ± 1.0 | 54.3 ± 1.9 | 51.3 ± 1.4 | 51.3 ± 3.0 |

### 2.3. Procedure and questionnaires

Participants were asked to arrive 15 min before the start of the experimental session. During this preparation time, they put on 8 iButtons, with medical grade tape, for the skin temperature measurements (forehead, right scapula, left upper chest, right arm in upper location, left arm in lower location, left hand, right anterior thigh, left calf) (ISO 9886, 2004). Afterward, they filled the first questionnaire to record their response at the beginning of acclimatization. During the remaining part of the acclimatization phase, the body composition analyses were performed. Participants filled the remaining two questionnaires at the $35^{th}$ and $55^{th}$ minute of the experiment, between which the blood pressure and glucose level were measured. Participants were seated for the most time of the experiment and could use their phone or bring in their books, magazines, paperwork, etc. However, they needed to answer the questionnaires when prompted and to cooperate with the performance of measurements when asked. During experiments, participants wore their own clothes that they chose based on some guidelines from us (no tie, short sleeve shirt or T-shirt, long trousers, full shoes—estimated clothing insulation of 0.57 clo). The chairs they sat on had estimated insulation of 0.1 clo. We asked them to keep the same set of clothes for all four sessions.

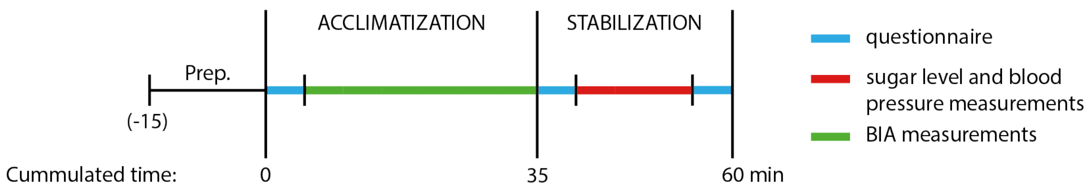


Figure 2. Experimental procedure.

We used a continuous scale with 7-points (the ASHRAE scale: −3 – cold; 0 – neutral; +3 – hot) to examine current thermal sensation (ANSI/ASHRAE 55, 2017). Similarly, 7-point continuous scales were used for air movement sensation (−3 – much too breezy; 0 – neutral; +3 – much too still) and humidity sensation (−3 – very humid; 0 – neutral; +3 – very dry). The acceptability of thermal sensation, air movement, humidity and air quality were examined with a 5-point discrete scale to achieve fine gradation in respondents' perception (Revilla et al., 2014). Likewise, a 5-point Likert scale was used for assessment of thermal comfort, air freshness and self-reported wellbeing. The intensity of odor and mucous irritation (nose, throat, eyes) were evaluated with a 6-point scale (0 – no, 6 – overwhelming). The first questionnaire, answered by participants immediately after the session started, included questions about participants' transportation, last meal and drinks, sleep quality in the previous night, and menstrual cycle phase (for female participants). The questions are shown in Appendix A.

Table 2. Descriptive characteristics of participants (mean ± standard deviation for normally distributed; median (1st quartile, 3rd quartile) for non-normally distributed)

| | **All (N = 76)** | **Males (N = 29)** | **Females (N = 47)** |
|---|---|---|---|
| **Age (yrs.)** | 29.0 (24.0, 36.0) | 28.0 (23.0, 32.0) | 29.0 (24.0, 38.0) |
| **Height (cm)** | 165.7 ± 8.8 | 172.8 ± 7.6 | 161.3 ± 6.2 |
| **Weight (kg)** | 69.4 ± 15.4 | 73.6 ± 16.7 | 66.7 ± 14.1 |
| **BMI (kg/m$^2$)** | 25.1 ± 5.2 | 24.4 ± 5.1 | 25.6 ± 5.3 |
| ≤ 18.4 | 13 (17%) | 5 (17%) | 8 (17%) |
| 18.5–24.9 | 25 (33%) | 12 (41%) | 13 (28%) |
| 25.0–29.9 | 23 (30%) | 7 (24%) | 16 (34%) |
| ≥ 30.0 | 15 (20%) | 5 (17%) | 10 (21%) |
| **Waist circumference (cm)** | 86.0 (73.5, 93.5) | 86.6 ± 12.7 | 83.5 (72.0, 93.0) |
| **Hip circumference (cm)** | 101.3 ± 9.8 | 99.5 ± 9.5 | 102.4 ± 10.0 |
| **Waist-to-hip ratio** | 0.83 ± 0.09 | 0.87 ± 0.07 | 0.81 ± 0.09 |
| **Total body fat (%)** | 31.0 ± 10.1 | 22.5 ± 7.0 | 36.3 ± 7.8 |
| **Muscle mass (kg)** | 42.6 (37.6, 49.5) | 53.3 ± 9.1 | 39.1 ± 4.7 |
| **Visceral fat (level)** | 7.6 (4.0, 11.4) | 8.9 ± 5.4 | 7.3 (4.1, 10.3) |
| **Metabolic age (yrs.)** | 34.0 (26.0, 45.0) | 29.0 (23.0, 37.0) | 39.1 ± 12.8 |
| **In tropics (yrs.)** | 23.0 (4.0, 30.0) | 21.0 (4.0, 28.0) | 24.0 (4.5, 35.2) |

### 2.4. Participants

We recruited the study population from adult volunteers who responded to local announcements at the campus of the National University of Singapore and advertisements published on social media platforms. The inclusion criteria included the BMI as the objective of the study was to recruit 25 subjects within each BMI range: below 18.5 kg/m$^2$ (underweight), from 18.5 to 25 kg/m$^2$ (normal-weight), 25 to 30 kg/m$^2$ (overweight) and above 30 kg/m$^2$ (obesity) (WHO, 2018). The major problem encountered was recruiting underweight and obese participants. Overall, we included 76 participants in the study (29 men and 47 women). For all participants, we measured height, weight, and waist and hip circumferences. Body composition parameters were measured four times and averaged.

Baseline characteristics of studied participants are shown in Table 2. All participants were living in Singapore and were acclimatized to the tropical climate in which the study took place (*Mdn* = 24.0 yrs. in tropics, IQR [4.5, 35.2]). One of the recruitment criteria was a conservative 6 months of constant stay in a tropical climate as De Freitas and Grigorieva (2014) showed 3 months are sufficient for short-term acclimatization. The University of California Berkeley Ethics Committee approved the study protocol (Protocol # 2018-06-11181), and all recruited participants gave their written consent.

### 2.5. Statistical analyses

Analyses were carried out using R version 3.6.2 software (R Core Team, 2016). The normal distribution of data and residual was tested with Shapiro-Wilk's W test. Brown–Forsythe test was used to analyze the equality of group variances. As analyses showed non-normal distribution for survey data, Spearman's rank coefficient was used to measure the degree of similarity between variables, and to assess the significance of the relationship between them. Wilcoxon rank-sum test was used to compare results between participant groups. Bonferroni correction was used for multiple comparisons with non-parametric tests to avoid (adjusted critical level of significance $p$ = .05/4 = .0125). Graphs were prepared using "GGplot2" (Wickham, 2009). The data distributions are shown with box-and-whisker plots (horizontal line – median, rhombus – mean, and circles – outliers).

## 3. Results and Discussion

In this paper, we present preliminary results focusing on the thermal comfort perception. To study the impact of body mass index, we plotted the trend of changes in thermal sensation with the increase of BMI (Figure 3). Overall, we did not find any practical effect of BMI on thermal sensation both for the entire dataset (TS~BMI+TO, BMI linear model coefficients $b$ = -0.01 (*SE* .01), $t$ = -1.14, $p$ = .26) and when separated for the four temperature conditions (TS~BMI+TO, BMI linear model coefficients at 19.9 °C: $b$ = 0.02 (*SE* .02), $t$ = 1.16, $p$ = .25; 22.4 °C: $b$ = -0.01 (*SE* .02), $t$ = -.67, $p$ = .50.; 25.3 °C: $b$ = -0.04 (*SE* .02), $t$ = -2.48, $p$ = .016; 28.2 °C: $b$ = -0.01 (*SE* .02), $t$ = -.42, $p$ = .68). The Spearman's rank correlation did not indicate the significance of those changes ($p$ = .65 and $r_s$ = -.06 at 19.9 °C; $p$ = .56 and $r_s$ = -.08 at 22.4 °C; $p$ = .32 and $r_s$ = -.13 at 25.4 °C; $p$ = .21 and $r_s$ = -.17 at 28.2 °C). Analogous trends, not reported here, were obtained for the thermal sensation in the relation to the total body fat percentage. No significant differences ($p$ < .0125) in thermal acceptability between BMI categories were noticed.

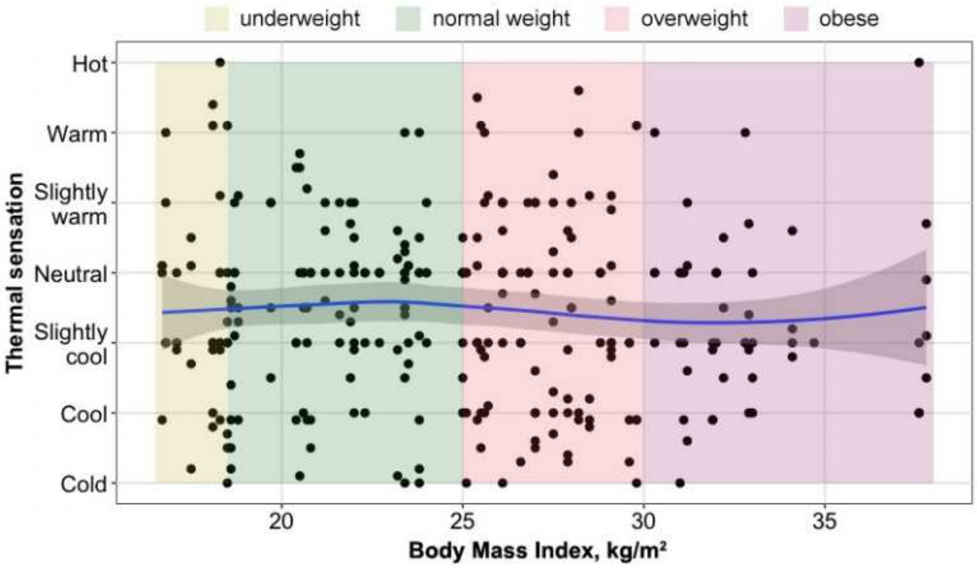


Figure 3. Thermal sensation in the function of the body mass index (BMI) – LOESS regression with 95% confidence intervals.

Error: Reference source not foundParticipants' thermal preference responses are shown in Figure 4. Thermal preference is arguably more important than thermal sensation because it is a direct indication of what people would like to have. Results indicate that overweight and obese participants preferred cooler environments. At the temperature set-point of 19.9 °C, obese participants in 50% of responses indicated a desire for "no change". Conversely, the underweight and normal-weight participants substantially preferred warmer conditions (85% and 77% respectively). The temperature set-point of 22.4 °C was the most preferable for overweight (59%) and obese (84%) responses declared "no change". The favorable condition for underweight and normal-weight participants was the temperature set-point of 25.3 °C (77% and 50% of responses for "no change" respectively).

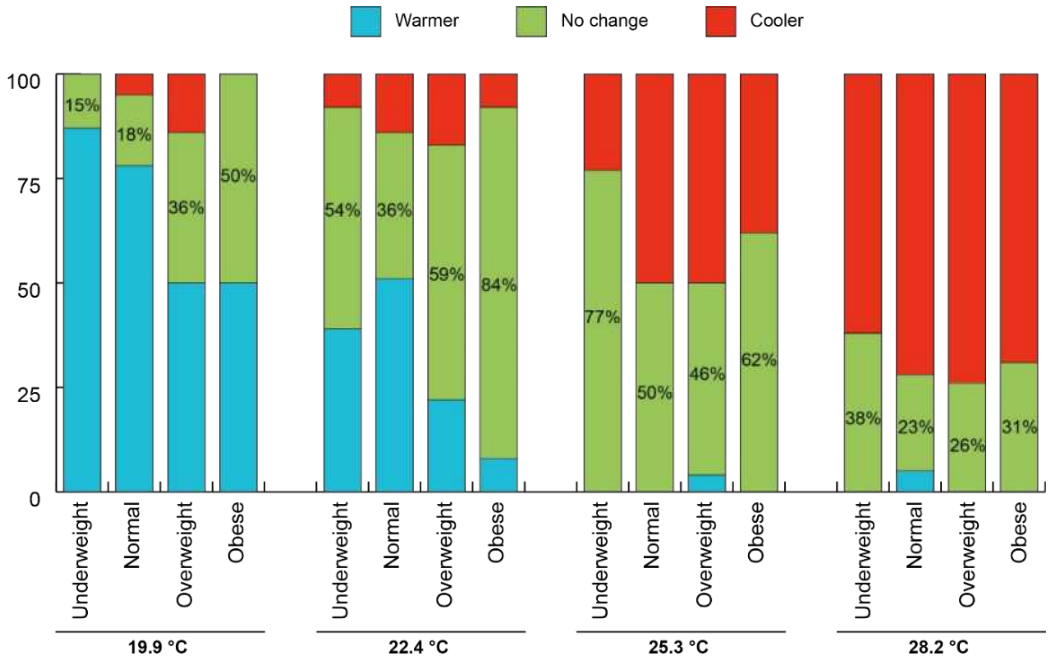


Figure 4. Thermal sensation preferences depending on the BMI category at each experimental condition.

To further study how BMI affected thermal preference over the range of investigated conditions, we used the quadratic discriminant analysis (QDA) algorithm to create a classification model for thermal preference, using BMI and operative temperature as inputs. The model is shown in Figure 5, the actual data is also shown. The predicted thermal preference areas from the application of QDA show that for temperatures under 23 °C, participants with higher BMI (> 26 kg/m$^2$) have a clear likelihood of desiring no change of their thermal environments. The distinction on the lower BMI side is less prominent, but the prediction is that for BMI under 20 kg/m$^2$, a participant is likely to be okay with temperatures of 26-27 °C. Counterintuitively though, the model suggests that people with high BMI (> 34 kg/m$^2$) may accept temperatures warmer than the limits expressed for people with BMI between 20 and 34 kg/m$^2$ – though not more than people with BMI under 20 kg/m$^2$.  This could be due to the small number of participants at such high BMI values, who might have had specific personal preferences.

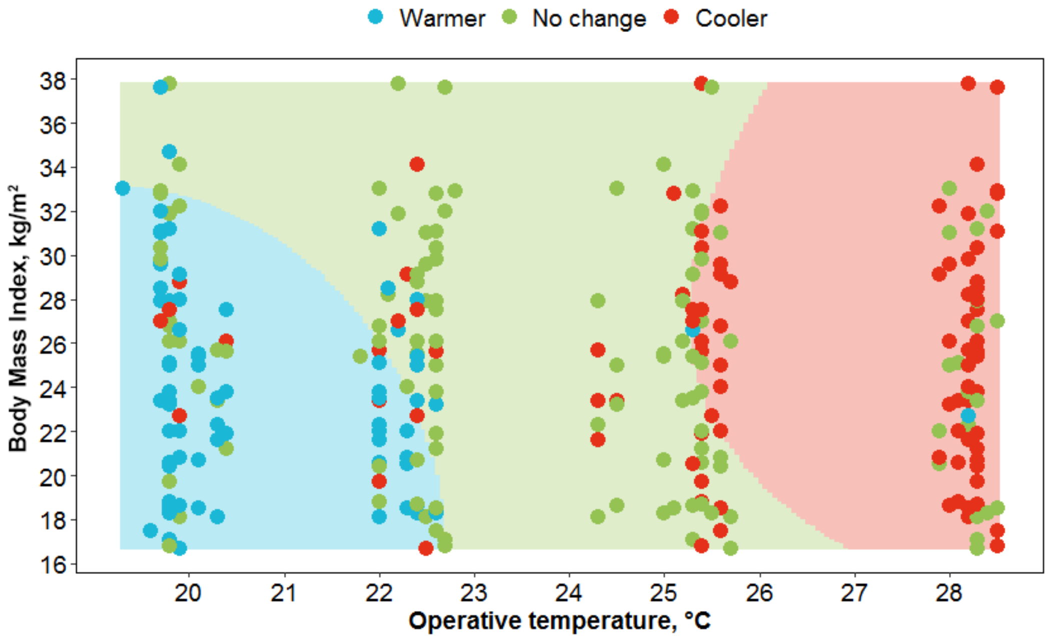


Figure 5. Thermal preference classification (QDA) with body mass index (BMI) and operative temperature as inputs, along with actual participant votes (circles in foreground).

After adjusting the criteria for significance level due to multiplicity, no statistically significant differences were observed in thermal sensation due to the BMI. However, assuming neutral thermal sensation as preferred temperature could be misleading. Results of our study, in laboratory conditions, confirmed conclusions of field surveys that occupants with higher BMI values tend to prefer lower temperature set-points (Daly, 2014; Rupp et al., 2018). Taking into account the increasing prevalence of overweight and obesity in the population, it could limit energy-saving strategies for tropical climates (Duarte et al., 2017; Lipczynska et al., 2018), while in temperate and cold climates support energy-efficient controls.

The limitation of the study was that the obese and underweight participation groups were underrepresented compared to others. Nonetheless, conducted study has the biggest sampling size compared to previous works on similar topics.

## 4. Conclusions

Data analysis revealed preferences of people with higher BMI for lower temperatures of around 22 °C. For people with BMI indicating normal weight, the preferred temperature lays between 22.5 and 27 °C. Conversely, underweight participants substantially preferred warmer conditions of around 25 °C.

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# Appendix A

**Enter your ID** ____________________

**Rate your current thermal sensation**

| cold | cool | slightly cool | neutral | slightly warm | warm | hot |
|---|---|---|---|---|---|---|
| -3 | -2 | -1 | 0 | +1 | +2 | +3 |

**Rate your current sensation of air movement**

| much too breezy | too breezy | slightly breezy | neutral | slightly still | too still | much too still |
|---|---|---|---|---|---|---|
| -3 | -2 | -1 | 0 | +1 | +2 | +3 |

**Rate your current sensation of air humidity**

| very humid | humid | slightly humid | neutral | slightly dry | dry | very dry |
|---|---|---|---|---|---|---|
| -3 | -2 | -1 | 0 | +1 | +2 | +3 |

**At the moment, how acceptable for you is ...?**

| | Very unacceptable | Somewhat unacceptable | Neither acceptable nor unacceptable | Somewhat acceptable | Very acceptable |
|---|---|---|---|---|---|
| **thermal sensation**: | ○ | ○ | ○ | ○ | ○ |
| **air movement**: | ○ | ○ | ○ | ○ | ○ |
| **air humidity**: | ○ | ○ | ○ | ○ | ○ |
| **air quality**: | ○ | ○ | ○ | ○ | ○ |

**Right now, are you thermally...?**

| | | | | | | |
|---|---|---|---|---|---|---|
| uncomfortable | ○ | ○ | ○ | ○ | ○ | comfortable |

**Would you prefer to feel...?**

| | | | |
|---|---|---|---|
| **thermal sensation**: | ○ Cooler | ○ No change | ○ Warmer |
| **air movement**: | ○ Less air movement | ○ No change | ○ More air movement |
| **air humidity**: | ○ Less humid | ○ No change | ○ More humid |

**The air is...**

| | | | | | | |
|---|---|---|---|---|---|---|
| stuffy | ○ | ○ | ○ | ○ | ○ | fresh |

**Right now, do you feel...?**

| | No | Light | Moderate | Strong | Very Strong | Overwhelming |
|---|---|---|---|---|---|---|
| Odor | ○ | ○ | ○ | ○ | ○ | ○ |

**Right now, do you have...?**

| | No | Light | Moderate | Strong | Very Strong | Overwhelming |
|---|---|---|---|---|---|---|
| **Eyes** irritation | ○ | ○ | ○ | ○ | ○ | ○ |
| **Nose** irritation | ○ | ○ | ○ | ○ | ○ | ○ |
| **Throat** irritation | ○ | ○ | ○ | ○ | ○ | ○ |

**Right now, how do you feel?**

| | | | | | | |
|---|---|---|---|---|---|---|
| I am **sleepy** | ○ | ○ | ○ | ○ | ○ | I am **alert** |
| It is **difficult** for me to concentrate | ○ | ○ | ○ | ○ | ○ | It is **easy** for me to concentrate |
| I do **not** feel **productive** | ○ | ○ | ○ | ○ | ○ | I feel **very productive** |

---

(Following questions were included only in the first questionnaire during acclimatization)

**How did you arrive here?**

○ By car

○ By bus

○ Other. Please specify: ______________________________

○ On foot

○ By bike

**For how long and how well did you sleep tonight?**

I went to bed by: ___________________________________________________
I woke up at: ___________________________________________________
My sleep was disrupted: (No/Yes, please specify how:)
___________________________________________________

**Overall, how would you rate your sleep quality last night?**

- ○ Very good
- ○ Fairly good
- ○ Fairly bad
- ○ Very bad

**What did you eat for your last meal and when?**

I ate my last meal at: ___________________________________________________
I ate: ___________________________________________________

**How many liquids have you drunk so far today?**

I drank last time at: ___________________________________________________
I have drunk so far (ml): ___________________________________________________

**Have you taken any medication today? If yes, please specify what and when.**

- ○ Yes. Please specify: ___________________________________________________
- ○ No

**Currently, what is your menstrual cycle phase?**

- ○ Not applies (men)
- ○ Menstruation. Typically: Days 1-5. Day 1 is the first day of bleeding.
- ○ Follicular. Typically: Days 1-13
- ○ Ovulation. Typically: Day 14
- ○ Luteal. Typically: Days 15-28

# On the prediction of dynamic thermal comfort under uniform environments

**Marika Vellei[1] and Jérôme Le Dréau[1]**

[1] LaSIE (UMR CNRS 7356) - La Rochelle University, La Rochelle, France
corresponding author: marika.vellei@univ-lr.fr

**Abstract:** To help researchers to evaluate uniform but not stationary (thus transient) thermal conditions, we describe, show the performances and provide a new simple tool, which can be used to predict the whole-body dynamic thermal sensation and thermal comfort. The tool comprises a thermo-physiological model able to predict the body core and mean skin temperatures under uniform and transient environmental conditions and a dynamic thermal perception model, which uses the simulated temperatures to predict thermal sensation and thermal comfort. The selected thermo-physiological model is an updated version of the classical Gagge's two-node model. For predicting the thermal sensation vote, we use an updated version of Fiala's Dynamic Thermal Sensation (DTS) model. Finally, for modelling the last step of thermal perception, i.e. thermal comfort, we derive a new dynamic version of the well-known Fanger's Predicted Percentage of Dissatisfied (PPD) index. We show that our novel models have better performances than the original ones. Furthermore, their simplicity and low computational cost are important advantages over more complex and computationally expensive multi-segment and multi-node thermo-physiological models.

**Keywords:** dynamic thermal comfort, Gagge's two-node model, Fiala's Dynamic Thermal Sensation model, Fanger's PPD model

## 1. Introduction

The physical interaction between an occupant and a dynamic indoor environment can be modelled by mathematical models of human thermoregulation, which predict detailed body core and skin temperatures [1]. The predicted temperatures can then be used as inputs for thermal perception models, which are developed from regression analysis of experimental thermal sensation and/or thermal comfort votes and simulated or monitored physiological parameters [2].

Even though several multi-segment and multi-node thermo-physiological models have been developed in recent years (e.g. Tanabe [3], Fiala [4,5], the Berkeley Comfort Model [6] and ThermoSEM [7]), yet they have not been largely applied for the prediction of thermal sensation and thermal comfort in the built environment. These models simulate body core and skin temperatures for different regions of the human body under asymmetric environmental conditions. Their complexity (and the computational burden associated with their implementation) is of little utility in most building energy simulations, which only provide average environmental conditions for the simulated thermal zones. Moreover, the high level of insulation of new buildings leads to little asymmetry and rather homogenous temperature distributions.

In practice, building modellers continue to stick to the traditional Fanger's PMV/PPD model, even for the evaluation of dynamic conditions characterized by rapid changes in either environmental or personal variables [8–15]. However, Fanger's model is derived from a steady-state heat balance equation and steady-state laboratory experiments [16] and is, therefore, only suited to predict thermal comfort under steady-state or slowly changing indoor conditions (temperature gradients less than 2 °C/h) [2]. Furthermore, the model is not able to predict thermal comfort under dynamic levels of activity.

To help researchers to break away from the bad habit of using the PMV/PPD model when evaluating uniform but not stationary (thus transient) conditions, we describe, test and provide a new simple tool for the prediction of the whole-body dynamic thermal sensation and thermal comfort. The novel tool comprises two main elements:

- a thermo-physiological model able to simulate the body core and mean skin temperatures under uniform conditions,
- a dynamic thermal perception model which uses the simulated body core and mean skin temperatures to predict both thermal sensation and thermal comfort.

The selected thermo-physiological model is an updated version of the classical Gagge's two-node model, also known as Pierce's two-node model [17]. For predicting the dynamic thermal sensation, we opt for an updated version of Fiala's Dynamic Thermal Sensation (DTS) model [18]. Finally, for predicting the dynamic thermal comfort we derive a new model, which is able to calculate the Dynamic Percentage of Dissatisfied (DPD) from the dynamic thermal sensation, thus mimicking the structure of the classical Fanger's PPD index. The original Gagge's and Fiala's models are reviewed in Section 2.1, 2.2 and 2.3. The derivation of the updated Gagge's two-node model is illustrated in Section 4.1. The development of the two parts, i.e. thermal sensation and thermal comfort, of the novel dynamic thermal perception model is illustrated in Section 4.2 and 4.3, respectively.

## 2. Literature

### 2.1. Gagge's two-node model

In Gagge's two-node model, the human body (i.e. the passive/controlled system of human thermoregulation) is simulated as two concentric thermal compartments: a core cylinder (simulating muscle, subcutaneous tissue and bone) surrounded by a thin skin outer layer. The model simulates the heat transfers between the two compartments and between the outer layer and the environment and the temperature within each compartment is assumed to be uniform. The active/controlling system (which simulates the regulatory responses of shivering, vasoconstriction, vasodilatation and sweating) is based on a simple linear, temperature-based control theory of human thermoregulation.

The model was originally developed in 1971 [17,19] and has undergone many iterations and refinements, so that several versions are now available. The version of the model that was used in this work is mainly based on the BASIC and C++ code provided by Fountain and Huizenga [20–22] and has been re-coded in Python and validated against simulated data provided by Haslam [23], which uses a similar version of the model.

Several researchers have tested the performances of Gagge's model against experimental data [21,23,24] and have shown that:

- the model's predictions are very accurate in neutral conditions, reasonable for warm and hot conditions and less accurate in the colder environments (for air temperatures less than 5°C),
- the model is not able to accurately predict conditions of moderate to high exercise intensity (approximately 3.5 met to 8 met), especially during complex fluctuations, characterized by short work and rest cycles.

For additional information on the performances of the model the reader is referred to the works of Haslam [23], Doherty & Arens [21] and Smith [24]. In this paper, a small validation of the model is carried out in Section 5.1.

## 2.2. Fiala's DTS model

The literature offers three main models for predicting the thermal sensation in steady-state and transient conditions from physiological states (inputs parameters are shown in parenthesis):

- Fiala model ($\Delta T_{core}$, $\Delta T_{sk,mean}$, $\frac{\partial T_{sk,mean}}{\partial t}$) [18],
- Zhang model ($\Delta T_{sk,mean}$, $\Delta T_{sk,local}$, $\frac{\partial T_{sk,local}}{\partial t}$) [25–27],
- Takada model ($\Delta T_{sk,mean}$, $\frac{\partial T_{sk,mean}}{\partial t}$) [28].

where $\Delta T_{core}$, $\Delta T_{sk,mean}$, $\Delta T_{sk,local}$ are the differences between the body core, mean skin and local skin temperatures in the actual conditions and their values for thermo-neutral conditions (neutral points); $\frac{\partial T_{sk,mean}}{\partial t}$ and $\frac{\partial T_{sk,local}}{\partial t}$ are the rates of change (first derivatives with respect to time) of the mean and local skin temperatures, respectively. Between the three models we opted for Fiala's DTS model, which has been shown to perform better than the other two for both steady-state and transient exposures [2] and which does not require local skin temperatures as inputs.

Fiala's DTS model was developed from regression analysis of selected experiments including 220 exposures to air temperatures ranging between 13°C and 48°C and activity levels between 1 met and 10 met [18]. The model is able to predict the whole-body thermal sensation on the seven-point ASHRAE scale and is composed of three main parts:

- a first part, as a function of $\Delta T_{sk,mean}$, to model the response of sedentary subjects under steady-state environmental conditions,
- a second part, as a function of $\Delta T_{core}$ weighted by $\Delta T_{sk,mean}$, accounting for effects associated with exercise and warm body core temperatures,
- a third part, as a function of both positive and negative $\frac{\partial T_{sk,mean}}{\partial t}$, dealing with the dynamic components of thermal sensation observed in transient thermal conditions.

Fiala refers to the first and second parts as *the static comfort model*, while the third part represents *the dynamic component* of the human thermal sensation. The complete model has the following form:

$$\boldsymbol{DTS = 3 \cdot tanh\left[a \cdot \Delta T_{sk,mean} + g + \left(0.114 \cdot \frac{\partial T_{sk,mean}}{\partial t}^{(-)} + 0.137 \cdot e^{-0.681t} \cdot \frac{\partial T_{sk,mean}}{\partial t}^{(+)}_{max}\right) \cdot \frac{1}{(1+g)}\right]} \quad 1$$

where $a$ is 0.301°C$^{-1}$ and 1.078°C$^{-1}$ for $\Delta T_{sk,mean} < 0$ and $\Delta T_{sk,mean} > 0$, respectively. $\boldsymbol{\frac{\partial T_{sk,mean}}{\partial t}^{(-)}}$ is equal to 0 for $\frac{\partial T_{sk,mean}}{\partial t} > 0$ and $g$ is calculated from:

$$\boldsymbol{g = 7.94 \cdot e^{\left(\frac{-0.902}{\Delta T_{core}+0.4}+\frac{7.612}{\Delta T_{sk,mean}-4}\right)}} \quad 2$$

where $g = 0$ for $\Delta T_{core} \leq -0.4\ K$ or $\Delta T_{sk,mean} \geq 4\ K$. Thus, the effect of $g$ on thermal sensation vanishes for either cold core temperatures or too warm skin temperatures.

The term $0.114 \cdot \boldsymbol{\frac{\partial T_{sk,mean}}{\partial t}^{(-)}}$ of the dynamic component accounts for overshoots (i.e. abrupt decreases) of thermal sensation caused by transient cooling of the skin. The term $0.137 \cdot \boldsymbol{e^{-0.681t} \cdot \frac{\partial T_{sk,mean}}{\partial t}^{(+)}_{max}}$ represents the time-weighted maximum positive rate of change of the skin temperature and accounts for abrupt increases of thermal sensation caused by transient warming of the skin. This dynamic term is based on Fiala's assumption that, during skin warming, the thermal sensation is governed by the most intense rate of change of skin temperature, weighted by a function of the time elapsed since its occurrence. Cooling and warming overshoot responses appear under both cold and warm skin conditions and have been first observed by Gagge during temperature step-change variations [29]. During exercising conditions, the thermal sensation is less sensitive to transient changes in skin temperatures, therefore the dynamic component is weighted by $\frac{1}{(1+g)}$, where g is the term responsible for changes in thermal sensation due to exercise.

**2.3. Fiala's active system model**

Fiala's empirical control equations for sweating, shivering, and cutaneous vasomotion (i.e. constriction and dilatation) are derived from statistical analysis of 27 different experiments covering a range of air temperatures between 5°C and 50°C, and exercise intensities between 0.8 met and 10 met [4]. In Fiala's empirical control model, for conditions of internal hot stress, the sweating and vasodilatation responses are described using the warm temperature error signal from the body core $\Delta T_{core}^{(+)}$. While, for conditions characterized by not significant changes in the body core temperature, sweating and vasodilatation are governed by the warm skin temperature error signal $\Delta T_{sk,mean}^{(+)}$. The cold skin temperature error signal $\Delta T_{sk,mean}^{(-)}$ is the governing variable for the responses against cold, i.e. vasoconstriction and shivering. The effect of the cold body core temperature error signal $\Delta T_{core}^{(-)}$ on vasoconstriction is negligible, while it is more substantial for shivering. It is important to highlight that cold skin temperature error signals $\Delta T_{sk,mean}^{(-)}$ have an inhibiting effect on sweating and warm body core temperature error signals $\Delta T_{core}^{(+)}$ have an inhibitory effect on shivering. Furthermore, sweating and shivering can be respectively inhibited and stimulated by negative rates of change of the mean skin temperature $\frac{\partial T_{sk,mean}}{\partial t}^{(-)}$. When sweating is elicited due to $\Delta T_{core}^{(+)}$ (e.g. when working in a cold environment) shivering is set to zero.

Fiala's control equation for the cutaneous vasodilatation in W/°C is given by:

$$\begin{aligned} \boldsymbol{Dl} = \mathbf{16} \cdot \left[\boldsymbol{tanh}\left(\mathbf{1.92} \cdot \boldsymbol{\Delta T_{sk,mean}^{(+)}} - \mathbf{2.53}\right) + \mathbf{1}\right] \cdot \boldsymbol{\Delta T_{sk,mean}^{(+)}} \\ + \mathbf{30} \cdot \left[\boldsymbol{tanh}\left(\mathbf{3.51} \cdot \boldsymbol{\Delta T_{core}^{(+)}} - \mathbf{1.48}\right) + \mathbf{1}\right] \cdot \boldsymbol{\Delta T_{core}^{(+)}} \end{aligned} \tag{3}$$

Fiala's control equation for the sweating rate in g/min is given by:

$$\begin{aligned} \boldsymbol{Sw} = \left[\mathbf{0.65} \cdot \boldsymbol{tanh}\left(\mathbf{0.82} \cdot \boldsymbol{\Delta T_{sk,mean}^{(+,-)}} - \mathbf{0.47}\right) + \mathbf{1.15}\right] \cdot \boldsymbol{\Delta T_{sk,mean}^{(+,-)}} \\ + \left[\mathbf{5.6} \cdot \boldsymbol{tanh}\left(\mathbf{3.14} \cdot \boldsymbol{\Delta T_{core}^{(+)}} - \mathbf{1.83}\right) + \mathbf{6.41}\right] \cdot \boldsymbol{\Delta T_{core}^{(+)}} \end{aligned} \tag{4}$$

Fiala's control equation for the cutaneous vasoconstriction, dimensionless, is given by:

$$\begin{aligned} \boldsymbol{Cs} = \mathbf{35} \cdot \left[\boldsymbol{tanh}\left(\mathbf{0.29} \cdot \boldsymbol{\Delta T_{sk,mean}^{(-)}} + \mathbf{1.11}\right) - \mathbf{1}\right] \cdot \boldsymbol{\Delta T_{sk,mean}^{(-)}} - \mathbf{7.7} \cdot \boldsymbol{\Delta T_{core}^{(-)}} \\ + \mathbf{3} \cdot \boldsymbol{\Delta T_{sk,mean}^{(-)}} \cdot \frac{\boldsymbol{\partial T_{sk,mean}}}{\boldsymbol{\partial t}}^{(-)} \end{aligned} \tag{5}$$

Fiala's control equation for the shivering response in W is given by:

$$\begin{aligned} \boldsymbol{Sh} = \mathbf{10} \cdot \left[\boldsymbol{tanh}\left(\mathbf{0.51} \cdot \boldsymbol{\Delta T_{sk,mean}^{(-)}} + \mathbf{4.19}\right) - \mathbf{1}\right] \cdot \boldsymbol{\Delta T_{sk,mean}^{(-)}} - \mathbf{27.5} \cdot \boldsymbol{\Delta T_{core}^{(-,+)}} - \mathbf{28.2} \\ + \mathbf{1.9} \cdot \boldsymbol{\Delta T_{sk,mean}^{(-)}} \cdot \frac{\boldsymbol{\partial T_{sk,mean}}}{\boldsymbol{\partial t}}^{(-)} \end{aligned} \tag{6}$$

## 3. Methods

### 3.1. Used datasets

Dataset 0 was assembled to validate the body core and skin temperatures predicted by the updated Gagge's two-node model and does not include any thermal sensation and/or thermal comfort vote, which are instead part of the other datasets described below. It includes data coming from 5 different experiments carried out by different research teams [30–33]. In the first experiment (Condition 0-1) 3 subjects were exposed to warm step-change exposures from 28.5°C to 37.5°C and back to 28.5°C [34]. In the second experiment (Condition 0-2) 3 subjects were exposed to cold step-change exposures from 29°C to 22°C and back to 29°C [30]. In the third experiment (Condition 0-3) 3 subjects were exposed to an air temperature of 12°C for 90 minutes followed by a sudden change to 28°C [31]. In the fourth experiment (Condition 0-4) 8 subjects were exposed to an air temperature of -10°C for 180 minutes followed by a sudden change to 21.7°C and the metabolic rate was alternately varied between 1.2 and 3 met [32]. Finally, in the fifth experiment (Condition 0-5) 11 subjects were exposed to step-changes in metabolic rates from 2.2 met to 3.5 met and finally to 1 met [33].

Table 1. Details of the experimental conditions included in Dataset 0. The data are used to validate the updated Gagge's two-node model.

| | $\mathbf{T_a}$ (°C) | $\mathbf{T_r}$ (°C) | **RH** (%) | **V** (m/s) | **clo** | **met** |
|---|---|---|---|---|---|---|
| Condition 0-1 [34] | 28.5-37.5-28.5 | 28.5-37.5-28.5 | 40-33-41 | 0.1 | 0.1 | 1 |
| Condition 0-2 [30] | 29-22-29 | 29-22-29 | 44-39-41 | 0.1 | 0.1 | 1 |
| Condition 0-3 [31] | 12-28 | 12-28 | 45 | 0.2 | 0.1 | 1 |
| Condition 0-4 [32] | -10-21.7 | -10-21.7 | 81-59 | 0.15 | 1.1 | 1.2-3 |
| Condition 0-5 [33] | 30 | 30 | 30 | 0.2 | 0.1 | 2.2-3.5-1 |

Dataset I is used to validate the updated Fiala's DTS model and is made of experimental data collected at Kansas State University [35]. This is one of the very first laboratory experiment investigating cyclical temperature fluctuations. As part of the experiment, 12 students were exposed to 2 different cyclical temperature fluctuations, with each variation having an overall duration of 3 hours (Condition I-1 and I-2 in Figure 4). The study was conducted in summer and was addressing cooling and warming temperature transients in warm conditions. Thermal sensation was monitored every 7.5 minutes.

Table 2. Details of the experimental conditions included in Dataset I. The data are used to validate the updated Fiala's DTS model.

| | $\frac{\partial T_a}{\partial t}_{mean}$ (°C/h) | $\mathbf{T_{a_{mean}}}$ (°C) | $\mathbf{T_r}$ (°C) | **RH** (%) | **V** (m/s) | **clo** | **met** |
|---|---|---|---|---|---|---|---|
| Condition I-1 [35] | ±10.9 | 27 | 25.6 | 45 | 0.14 | 0.7 | 1 |
| Condition I-2 [35] | ±5 | 27.4 | 25.6 | 45 | 0.14 | 0.7 | 1 |

Dataset II is used to derive the updated Fiala's DTS and Fanger's DPD models and consists of experimental data collected at the University of Sydney [36]. Among the literature of thermal comfort studies investigating cyclical temperature variations, this is the laboratory experiment employing the greatest number of participants exposed to the highest rates of temperature change (up to 30°C/h). As part of the experiment, 56 students were exposed to 6 different cyclical temperature fluctuations (Conditions II-2 to II-7 in Figure 5), with each variation having an overall duration of 2 hours. The study was conducted in summer and was addressing cooling and warming temperature transients in warm conditions. Thermal sensation and thermal acceptability were monitored every 5 minutes.

Table 3. Details of the experimental conditions included in Dataset II. The data are used to derive the updated Fiala's DTS and Fanger's DPD models.

| | $\frac{\partial T_a}{\partial t}_{mean}$ (°C/h) | $\frac{\partial T_r}{\partial t}_{mean}$ (°C/h) | **RH** (%) | **V** (m/s) | **clo** | **met** |
|---|---|---|---|---|---|---|
| Condition II-2 [36] | ±8.8 | ±8.8 | 72 to 86 | up to 0.12 | 0.5 | 1 |
| Condition II-3 [36] | ±13.4 | ±13.4 | 65 to 94 | up to 0.12 | 0.5 | 1 |
| Condition II-4 [36] | ±10.2 | ±10.2 | 70 to 94 | up to 0.12 | 0.5 | 1 |
| Condition II-5 [36] | ±10.3 | ±10.3 | 68 to 82 | up to 0.12 | 0.5 | 1 |
| Condition II-6 [36] | ±10.7 | ±10.7 | 66 to 86 | up to 0.12 | 0.5 | 1 |
| Condition II-7 [36] | ±11.3 | ±11.3 | 64 to 98 | up to 0.12 | 0.5 | 1 |

Dataset III is used to derive the updated Fiala's DTS model and includes experimental data collected at Chongqing University [37,38]. This is one of the most recent laboratory experiment investigating step-change variations, both cool-neutral-cool and warm-neutral-warm transients. As part of the experiment, 12 students were exposed to 3 different cool-neutral-cool variations (Condition III-1: 12-22-12°C, Condition III-2: 15-22-15°C and Condition III-3: 17-22-17°C) in winter and 3 different warm-neutral-warm variations (Condition III-4: 32-25-32°C, Condition III-5: 30-25-30°C and Condition III-6: 28-25-28°C) in summer. Each experiment lasted for 2 hours. Following the step-change transition, thermal sensation and thermal comfort were monitored every 2 minutes.

Table 4. Details of the experimental conditions included in Dataset III. The data are used to derive the updated Fiala's DTS model.

| | $T_a$ (°C) | $T_r$ (°C) | **RH** (%) | **V** (m/s) | **clo** | **met** |
|---|---|---|---|---|---|---|
| Condition III-1 [37] | 12-22-12 | 12-22-12 | 57-44-57 | 0.07-0.01-0.07 | 1.17 | 1 |
| Condition III-2 [37] | 15-22-15 | 15-22-15 | 58-51-58 | 0.03-0-0.03 | 1.17 | 1 |
| Condition III-3 [37] | 17-22-17 | 17-22-17 | 54-49-54 | 0.06-0-0.06 | 1.17 | 1 |
| Condition III-4 [38] | 32-25-32 | 32-25-32 | 59-58-59 | 0.1 | 0.5 | 1 |
| Condition III-5 [38] | 30-25-30 | 30-25-30 | 59-58-59 | 0.1 | 0.5 | 1 |
| Condition III-6 [38] | 28-25-28 | 28-25-28 | 61-61-61 | 0.1 | 0.5 | 1 |

Dataset IV was specifically assembled to validate the updated Fiala's DTS model under dynamic conditions characterized by significant changes in metabolic rates. The dataset includes data coming from 4 different experiments carried out by different research teams [39–42]. In the first experiment (Condition IV-1), 11 subjects alternatively rested for 15 minutes (1 met) and walked slowly (1.5 met). At the same time, they were exposed to cyclical temperature variations at rates of ±18°C/h over a period of 2 hours and their thermal sensation was recorded every 5 minutes [39]. In the second experiment (Condition IV-2), the thermal sensation of 10 subjects was recorded during a work/rest sequence at an air temperature of 10°C. For the first hour of the experiment the subjects exercised on a bicycle (2.6 met) followed by an hour of recovery during which the subjects seated quietly (1 met) [40]. In the third experiment (Condition IV-3), 6 students pedalled on a bicycle (3.6 met) for 90 minutes after resting for 30 minutes (1 met) at an air temperature of 24°C. Their thermal sensation was surveyed each 15 minutes [41]. In the third and fourth experiments (Conditions IV-4 and IV-5), 20 students alternately seated (1 met) and walked at 0.9 m/s (2.0 met) and 1.2 m/s (2.6 met) for 30 minutes at two different air temperatures of 20 and 25°C. Their thermal sensation was recorded each 1 to 5 minutes [42].

Table 5. Details of the experimental conditions included in Dataset IV. The data are used to validate the updated Fiala's DTS model.

| | $T_a$ (°C) | $T_r$ (°C) | **RH** (%) | **V** (m/s) | **clo** | **met** |
|---|---|---|---|---|---|---|
| Condition IV-1 [39] | $\frac{\partial T_a}{\partial t}_{mean}$ =±18°C/h | $\frac{\partial T_a}{\partial t}_{mean}$ =±18°C/h | 50 | 0.25 | 0.7 | 1-1.5 |
| Condition IV-2 [40] | 10 | 10 | 52 | 0.1 | 1.2 | 2.6-1 |
| Condition IV-3 [41] | 24 | 24 | 45 | 0.15 | 0.6 | 3.6-1 |
| Condition IV-4 [42] | 20 | 20 | 53 | 0.1 | 0.85 | 1-2-2.6 |
| Condition IV-5 [42] | 25 | 25 | 53 | 0.1 | 0.85 | 1-2-2.6 |

### 3.2. Performance metric

The root-mean-square-error (RMSE) is used to measure the predictive accuracy of the updated models against the original ones.

$$\boldsymbol{RMSE} = \sqrt{\frac{\sum(\boldsymbol{OV} - \boldsymbol{PV})^2}{\boldsymbol{n}}} \tag{7}$$

where $OV$ is the observed value, $PV$ is the predicted value and $n$ is the number of data points.

## 4. Updated models

### 4.1. Gagge's two-node model

From the review of Section 2.1 we can conclude that, despite its simple representation of the human body, Gagge's two-node model is mildly accurate to be used for practical applications in the built environment where environmental conditions are usually near the neutrality and activity levels are mostly lower than 3.5 met. However, activities in the built environments can be sometimes characterized by abrupt changes in metabolic rates, especially in residential settings where occupants engage in activities other than sedentary ones. Thus, we have decided to extent the predictive capabilities of Gagge's two-node model by substituting its simple linear, temperature-based active system model with Fiala's non-linear, temperature-based active system model, which has been reviewed in Section 2.3.

### 4.2. Fiala's DTS model

Once having determined the static comfort part, Fiala derived the dynamic component of human thermal sensation by linear regression using the following rearranged equation:

$$\boldsymbol{Y} = \left[\boldsymbol{tanh^{-1}}\left(\frac{\boldsymbol{DTS}}{\boldsymbol{3}}\right) - \boldsymbol{a} \cdot \boldsymbol{\Delta T_{sk,mean}} - \boldsymbol{g}\right] \cdot (\boldsymbol{1} + \boldsymbol{g}) = \boldsymbol{b} \cdot \frac{\boldsymbol{\partial T_{sk,mean}}}{\boldsymbol{\partial t}} \tag{8}$$

The linear regression was run using a limited set of experimental data coming from only two exposures to sudden step-changes in air temperature: 28-18-28°C and 28-48-28°C [29]. Additional experimental data from cyclical temperature variations were then used to validate the model for transient conditions. In Figure 4, observed thermal sensation votes (TSV) are compared with Fiala's predicted DTS values for two exposures to cyclical temperature fluctuations [35]. Fiala's predictions (in cyan in Figure 4) use the updated Gagge's 2-node model coupled with Fiala's DTS model. The predicted DTS values agree reasonably well for the slower sinusoidal changes of air temperature ($\frac{\partial T_a}{\partial t} = 5\ K/h$ for Condition I-2 in Figure 4) but the model is not able to follow faster fluctuations of air temperature ($\frac{\partial T_a}{\partial t} = 10.9\ K/h$ for Condition I-1 in Figure 4). Given these limitations, we have decided to update Fiala's $b$ coefficient by using additional experimental data coming from both the cyclical conditions of Dataset II [36] and the step-change conditions of Dataset III

[37,38], which have been illustrated in Section 3.1. The linear regression procedure to obtain $b$ is the same as the one used by Fiala but the body core and skin temperatures are simulated using the updated Gagge's 2-node model described in Section 4.1.

By looking at the relationship between $Y$ and $\frac{\partial T_{sk,mean}}{\partial t}$ in Figure 1 we can see that the dynamic component of thermal sensation strongly depends on the rate of change of the skin temperature, however it does not grow indefinitely for high values of $\frac{\partial T_{sk,mean}}{\partial t}$; but rather reaches a positive and negative asymptote. Thus, we model this asymptotic behaviour using the classical hyperbolic tangent and, thus, we apply regression analysis to the linearized equation $Y = b \cdot tanh\left(\frac{\partial T_{sk,mean}}{\partial t}\right)$ instead of the form $Y = b \cdot \frac{\partial T_{sk,mean}}{\partial t}$ used in Equation 8. The resulting linear model for cooling gradients has a coefficient of determination $\mathrm{R}^2$ equal to $0.728$, hence our predictor $tanh\left(\frac{\partial T_{sk,mean}}{\partial t}\right)$ explains about 73% of the variability of our dependent variable Y. The $F - ratio$ is equal to $369.5$ and the p-value associated with the model as a whole is very small, $p < 7.56e^{-41}$, which means that the regression model is a good fit of the data. The resulting linear model for warming gradients has a coefficient of determination $\mathrm{R}^2$ equal to $0.552$, an $F - ratio$ equal to $167.3$ and a small p-value associated with the model as a whole, $p < 1.90e^{-25}$. We have checked that the key assumptions of linear regression (normality, homoscedasticity and no autocorrelation of the residual errors) are met. The resulting updated DTS model has the form:

$$\boldsymbol{DTS} = 3 \cdot \boldsymbol{tanh}\left[\boldsymbol{a} \cdot \boldsymbol{\Delta T_{sk,mean}} + \boldsymbol{g} + \left[\boldsymbol{b} \cdot \boldsymbol{tanh}\left(\frac{\boldsymbol{\partial T_{sk,mean}}}{\boldsymbol{\partial t}}\right)\right] \cdot \frac{\mathbf{1}}{(\mathbf{1} + \boldsymbol{g})}\right] \qquad 9$$

where the coefficient b is equal to $0.3412$ for cooling gradients $\frac{\partial T_{sk,mean}}{\partial t}^{(-)}$ and $0.2755$ for warming gradients $\frac{\partial T_{sk,mean}}{\partial t}^{(+)}$.

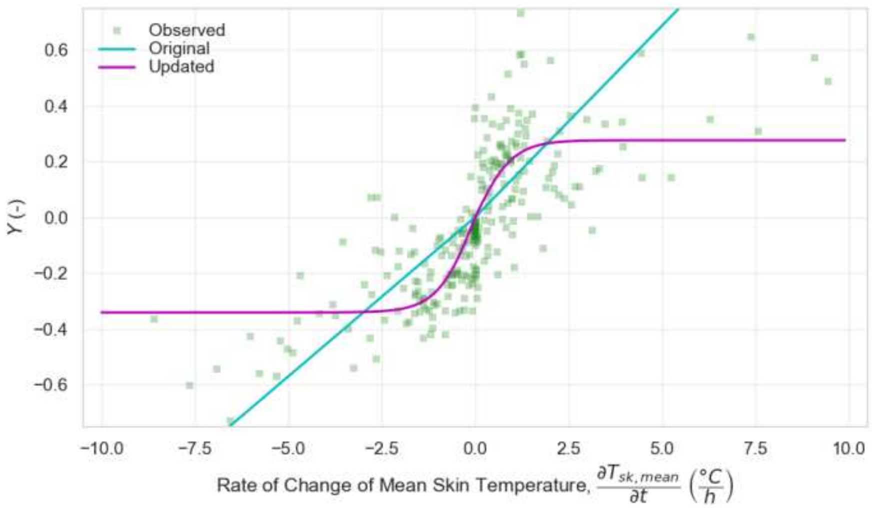


Figure 1. The term Y as a function of $\frac{\partial T_{sk,mean}}{\partial t}$. Observed data are from Dataset II [36] and Dataset III [37,38].

### 4.3. DPD model

Fanger's well-known non-linear relationship between $PMV$ and $PPD$ is derived from steady-state laboratory experiments involving 1300 subjects and is given by:

$$\boldsymbol{PPD} = \mathbf{1} - \mathbf{0.95} \cdot \boldsymbol{e}^{(-0.03353 \cdot PMV^4 - 0.2179 \cdot PMV^2)} \qquad 10$$

We derive a new dynamic version of Fanger's static PPD index by using the new Equations **Erreur ! Source du renvoi introuvable.**. The reason behind this modelling approach is twofold: the parameter $a$ accounts for the fact that the dynamic thermal perception horizontally shifts subjects' neutral conditions (at which maximum comfort is felt) towards warm thermal sensations during warming transients and cold thermal sensations during cooling transients. This is due to the warming and cooling overshoots perceived during warming and cooling transients respectively. At the same time, a vertical thermal comfort shift expressed by the parameter $b$ accounts for the alliesthesial effect: in warm conditions cooling transients elicit pleasure and, thus, increased satisfaction, while warming transients elicit displeasure and, thus, decreased satisfaction. The opposite is true for cold conditions. For the literature on the phenomenon of thermal alliesthesia the reader is referred to the works of Cabanac [43], Attia [44], Zhang [25–27], Parkinson [45] and Vellei & Le Dréau [46].

The data used to derive the new dynamic $PPD$ relation comes from the warm conditions of Dataset II since too few data of Dataset II is related to cold conditions [36]. In Dataset II, the observed percentage of dissatisfied subjects, *observed* $PD$, is interpreted from a binary thermal acceptability scale and is defined as the ratio of thermal unacceptability votes to total votes. Fanger's PPD index is derived using a different definition for the percentage of dissatisfied subjects, which is the percentage of people voting above warm or below cool (≥2 or ≤-2) on the 7-point ASHRAE thermal sensation scale. This method of derivation of $PPD$ is suitable under steady-state conditions. However, under dynamic conditions, warm and cold thermal sensations can be associated with satisfaction/pleasure if positive alliesthesia is elicited, hence Fanger's derivation of the $PPD$ index is suitable to predict thermal comfort only under steady-state conditions.

To obtain the unknown parameters $a$ and $b$ of Equation 11 we use the Nelder-Mead Algorithm (as implemented in the python function *scipy.optimize.minimize*) to minimize the $RMSE$ for both cooling and warming transients under warm conditions. The resulting $a$ and $b$ parameters for cooling gradients are equal to $-0.2151$ and $-0.0251$, while for the warming gradients are equal to $-0.5424$ and $-0.0679$. These coefficients are valid for warm exposures since they are both derived from the warm conditions of Dataset II. In cold conditions, it is assumed that cooling and warming overshoots have the same magnitude than in warm conditions. Thus, the coefficient $a$ is the same as derived above. Based on the alliesthesial effect which states that warming gradients are pleasurable in cold conditions but unpleasant in warm conditions and, on the contrary, cooling gradients are pleasurable in warm conditions but unpleasant in cold conditions, it is assumed that the coefficient $b$ for cold conditions has the opposite sign than the coefficient derived above for warm conditions.

$$\boldsymbol{DPD} = \mathbf{1} - \mathbf{0.95} \cdot \boldsymbol{e}^{\left(-0.03353 \cdot \left(TSV + a \cdot tanh\left[\frac{\partial T_{sk,mean}}{\partial t}\right]\right)^{4} - 0.2179 \cdot \left(TSV + a \cdot tanh\left[\frac{\partial T_{sk,mean}}{\partial t}\right]\right)^{2}\right)} + \boldsymbol{b} \cdot \boldsymbol{tanh}\left[\frac{\partial T_{sk,mean}}{\partial t}\right] \qquad 11$$

where:

- in warm and cold conditions, the coefficient $a$ is equal to $-0.2151$ for cooling gradients $\frac{\partial T_{sk,mean}}{\partial t}^{(-)}$ and $-0.5424$ for warming gradients $\frac{\partial T_{sk,mean}}{\partial t}^{(+)}$,
- in warm conditions, the coefficient b is equal to $-0.0251$ for cooling gradients $\frac{\partial T_{sk,mean}}{\partial t}^{(-)}$ and $-0.0679$ for warming gradients $\frac{\partial T_{sk,mean}}{\partial t}^{(+)}$, while in cold conditions

the opposite is true, the coefficient b is equal to $+0.0251$ for cooling gradients $\frac{\partial T_{sk,mean}}{\partial t}^{(-)}$ and $+0.0679$ for warming gradients $\frac{\partial T_{sk,mean}}{\partial t}^{(+)}$.

The novel DPD model is plotted in Figure 2 for warm conditions (left) and cold conditions (right).

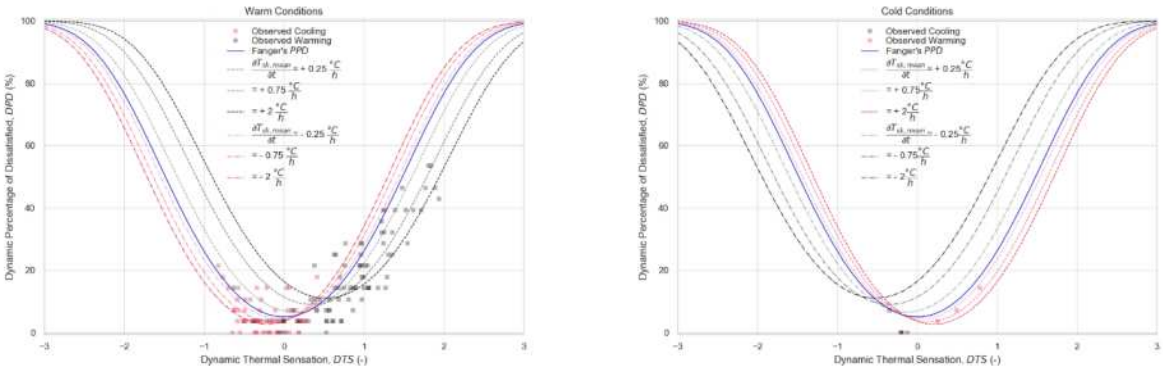


Figure 2. Updated Fanger's PPD relation for warm conditions (left) and cold conditions (right). The observed data comes from Dataset II [36].

## 5. Results

### 5.1. Skin and body core temperatures

In this Section, we show the performances in terms of RMSE of the updated Gagge's two-node model against the original ones for predicting body core and mean skin temperatures. From Figure 3 we can see the significant contribution of Fiala's active system in improving the prediction of the body core temperatures. However, there is not such improvement for the mean skin temperatures, except for the very cold exposure of condition 0-4.

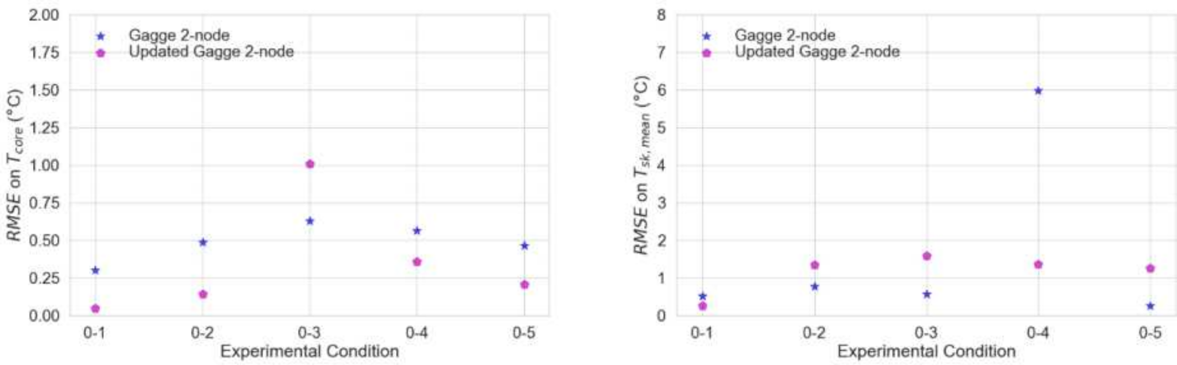


Figure 3. RMSE of the updated Gagge's two-node model against the original one for the different experimental conditions of Dataset 0.

### 5.2. Thermal sensation votes

In this Section, we show the performances in terms of RMSE of the updated Fiala's DTS model against the original one. Fanger's PMV model is also included for comparison.

<u>Sedentary activity level</u>

From Figure 6 we can see that for the cyclical temperature variations of Dataset I and II and the step-change conditions of Dataset III, the updated Fiala's DTS plus the Gagge's two-node model give the best results, generally performing better than Fanger's PMV model, with the difference more accentuated for the more dynamic conditions.

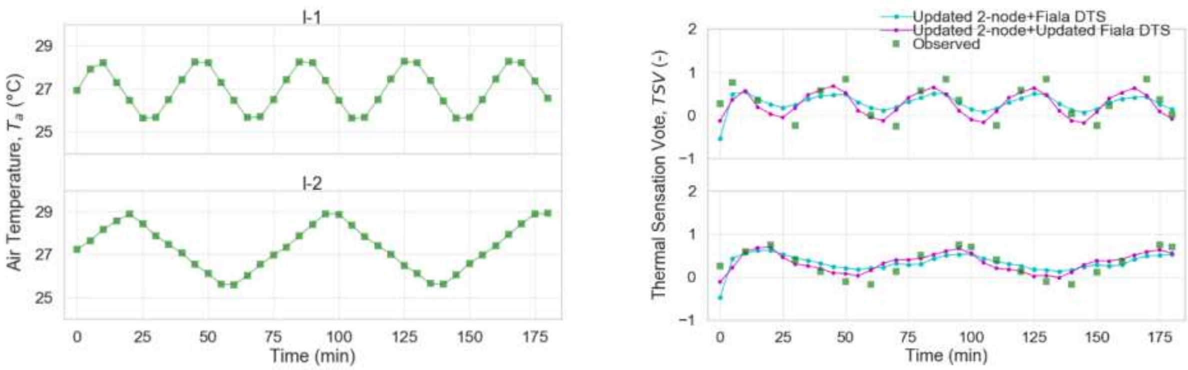


Figure 4. Air temperature ($T_a$, left) and thermal sensation ($TSV$, right) for the 2 cyclical temperature variations (Conditions 1 and 2) of Dataset I [35]. Observed data are shown in green.

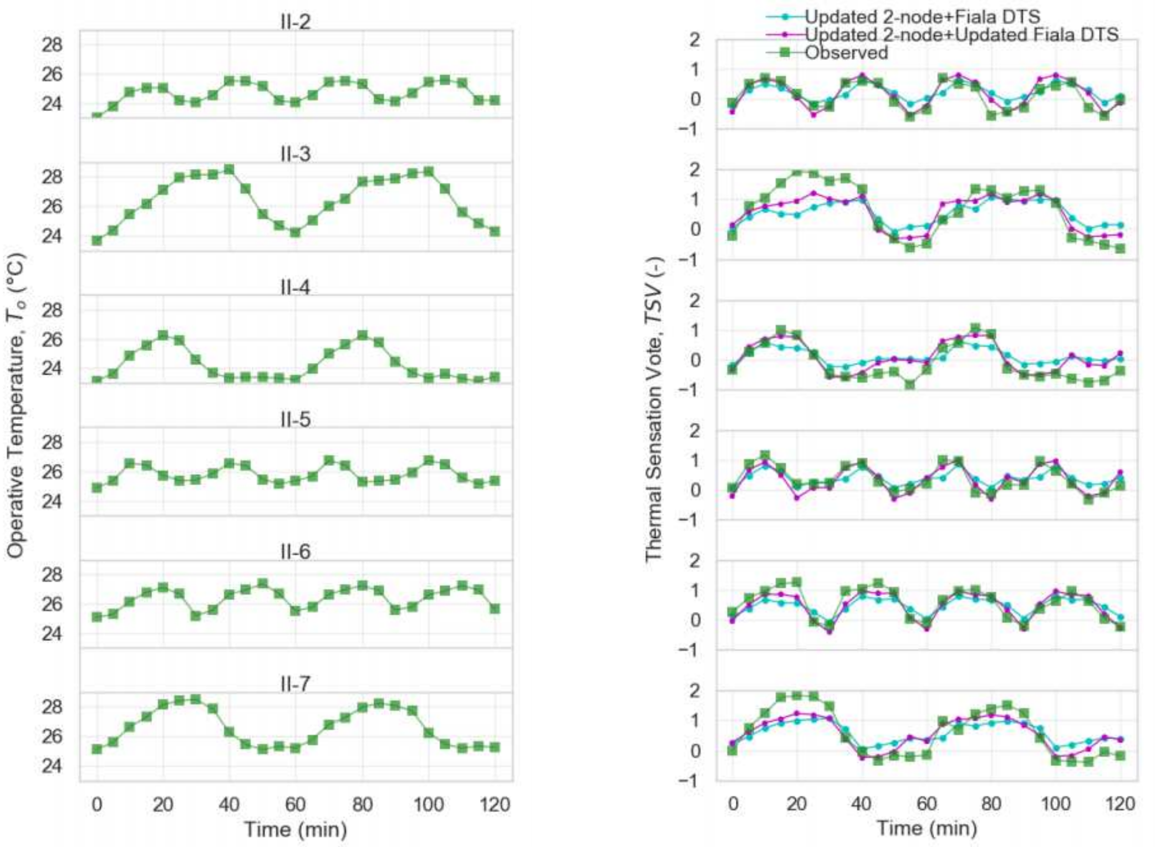


Figure 5. Operative temperature ($T_o$, left) and thermal sensation ($TSV$, right) for the 6 cyclical temperature variations (Conditions 2-7) of Dataset II [36]. Observed data are shown in green.

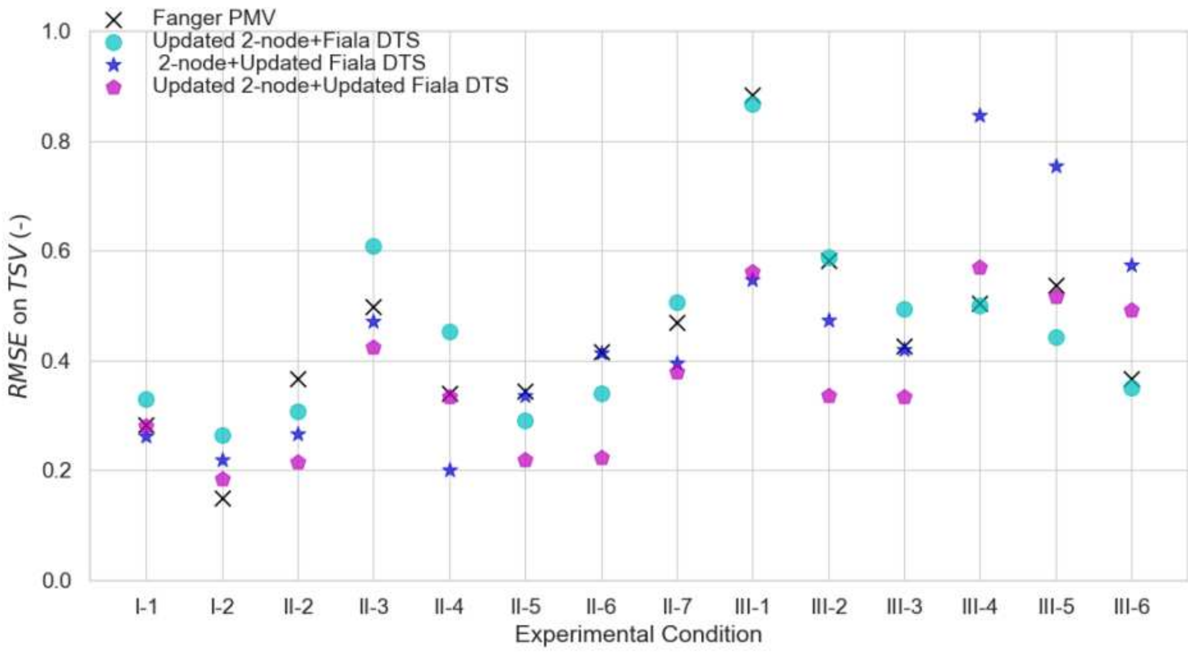


Figure 6. RMSE on TSV of the different tested models for the different experimental conditions of Dataset I (cyclical conditions), II (cyclical conditions) and III (step-change conditions).

Transient work

From Figure 7 we can see that the updated Gagge's two-node model gives better results than the original one in the majority of the studied conditions, showing how determinant is the role of the Fiala's active system for conditions of transient work. Gagge's two-node model also performs better than Fanger's PMV model. We can further see that the predictions of Fiala's updated DTS model are similar than those of the original one. In fact, during transient work the dynamic thermal sensation is dominated by the body core temperature rather than by the mean skin temperature. Finally, by comparing Figure 6 and Figure 7, we can observe that the performances during transient work are generally worse than during sedentary conditions.

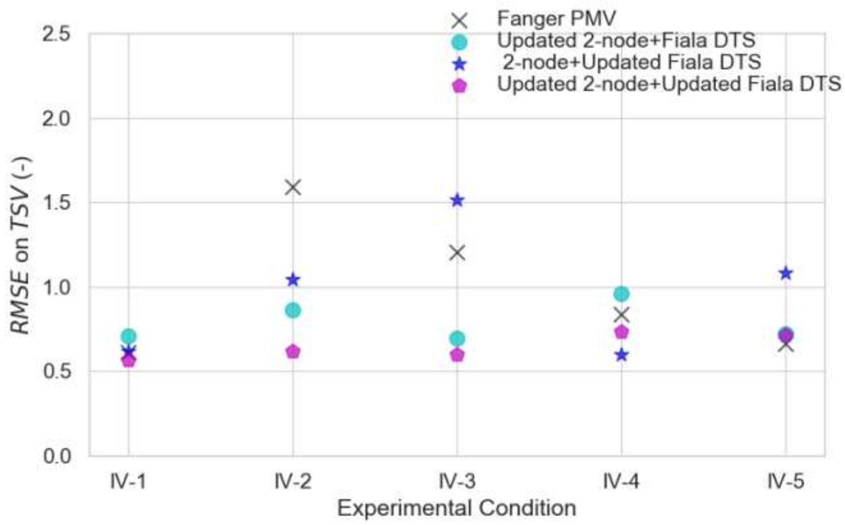


Figure 7. RMSE on TSV of the different tested models for the different experimental conditions of Dataset IV.

### 5.3. Percentage of Dissatisfied Occupants

In this Section, we show the performances in terms of RMSE of the updated Fanger's PPD (named DPD) against the original one. From Figure 8 we can see that the updated model is particularly important for improving the prediction during the most dynamic cyclical conditions II-3 and II-7 of Database II.

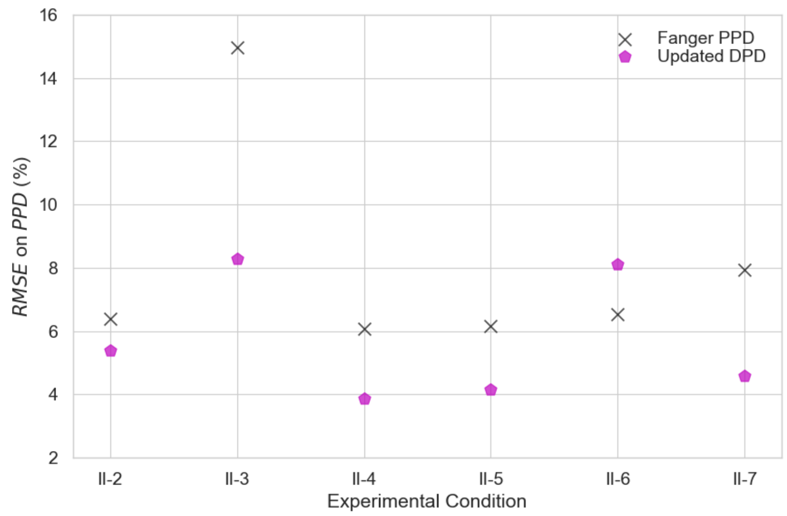


Figure 8. RMSE on PPD of the different tested models for the different experimental conditions of Dataset II.

## 6. Conclusions

In this paper, we describe, evaluate and provide a new simple tool for predicting dynamic thermal comfort under uniform conditions. This tool is based on previous well-known and esteemed works: Gagge's 2-node model, Fiala's DTS model and Fanger's PPD model, which we have updated using recent knowledge and new empirical data. Gagge's 2-node model has been updated using Fiala's empirical control equations for sweating, shivering, and cutaneous vasomotion. The dynamic component of Fiala's DTS model has been updated using new data from both cyclical and step-change thermal conditions. Finally, we have used a new framework and new data from cyclical thermal conditions to update the form of the traditional Fanger's PPD model into a new dynamic index. We show that our updated models have better performances than the original ones and also outperform Fanger's model, especially for very dynamic conditions far from the neutrality. The simplicity and low computational cost of the proposed tool are important advantages over more-complex and more computationally expensive multi-segment and multi-node thermo-physiological models.

### Acknowledgements

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### Supplementary materials

The models coded in Python are available to download at [https://gitlab.univ-lr.fr/jledreau/dynamic-thermal-comfort](https://gitlab.univ-lr.fr/jledreau/dynamic-thermal-comfort).

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# Carbon dioxide and its effect on occupant cognitive performance: A literature review

**Asit Kumar Mishra[1], Stefano Schiavon[2], Pawel Wargocki[3], and Kwok Wai Tham[4]**

[1] Berkeley Education Alliance for Research in Singapore, Singapore, asit.mishra@bears-berkeley.sg;
[2] Center for the Built Environment, University of California, Berkeley, USA, schiavon@berkeley.edu;
[3] International Centre for Indoor Environment and Energy, Technical University of Denmark, Kgs. Lyngby, Denmark, paw@byg.dtu.dk;
[4] Department of Building, National University of Singapore, Singapore, bdgtkw@nus.edu.sg

**Abstract:** Building ventilation standards use indoor carbon dioxide ($CO_2$) levels as a proxy for air quality, acknowledging that at typical indoor levels, $CO_2$ itself is not a pollutant. By 2100, outdoor $CO_2$ levels may reach 900 ppm. With current ventilation standards, that would nearly double the levels of chronic, indoor $CO_2$ exposure, raising concerns for its potential effect on occupants. In the last 15 years, an effort to gain this understanding, particularly regarding cognitive performance, has been made by 11 studies. They focused on the effect of elevated $CO_2$ while minimizing exposure to other indoor pollutants. Five of the studies found an effect of $CO_2$ exposure on performance and six studies did not. Four studies found an effect on cognitive performance under 2000 ppm exposure. But three of these four studies used the same proprietary, closed-source tool to measure cognitive performance. Physiological effects – like blood pressure, heart rate changes – were found only at exposures over 2500 ppm and were not always associated with cognitive decrements. These discrepancies could have been due to differences in measures used and individual differences in response to $CO_2$. Future works should adopt a more in-depth and holistic approach.

**Keywords:** carbon dioxide; building ventilation; climate change; hypercapnia; cognitive effects

## 1. Indoor air quality, occupants, and carbon dioxide

Indoor air quality influences occupants' health and performance (Seppänen et al., 1999; Tham, 2016; Wyon, 2004). From as early as the 18th century, importance has been placed on building ventilation in order to keep indoor $CO_2$ and human bio-effluent concentrations under certain limits (A. Persily, 2015). But from the 18th to the 21st century, ventilation standards have used $CO_2$ level as an easy, proxy measure of other contaminants in the air, particularly bioeffluents. Indoor generated contaminant concentrations correlate to the difference between indoor and outdoor $CO_2$ levels. Correlations are strongest for bioeffluents and weaker for building/furnishing emitted ones (Apte et al., 2000). $CO_2$ concentration of 1,000 ppm have been linked with bioeffluents' concentration which would be considered as unpleasant to an un-adapted visitor (A. K. Persily, 2015). From the perspective of human health, the Occupational Safety and Health Administration (OSHA) marks a transitional exposure limit of 5,000 ppm (time weighted average, over an 8-hour work day, 40 working hours a week) and a short-term exposure limit of 30,000 ppm (time weighted average over 15 minutes) (Law et al., 2010).

It is reasonable to presume that most of the past research endeavours have looked at how the mixture of $CO_2$ and bioeffluents have impacted on the perception and performance of building occupants. Until the end of the last century, there was no impetus to examine the effects of just $CO_2$ in buildings. Recently, there has been a growing interest in the direct effects of $CO_2$ on occupant cognitive performance. This changed focus stems partially from the rising atmospheric $CO_2$ levels. By the next century, the worst-case scenarios predict outdoor $CO_2$ levels breaching the 900 ppm mark (IPCC, 2009). If effects on occupants are proven from just $CO_2$, at these projected $CO_2$ levels, the current ventilation requirements would need to change by nearly a factor of six to ensure indoor $CO_2$ levels remain close to current values.

Over the past fifteen years, there have been 11 studies that examined the effect of elevated levels of pure $CO_2$ on human cognitive performance. These studies mostly used $CO_2$ levels under the OSHA limit of 5000 ppm. All of them also eliminated the confounding effect of other indoor pollutants by keeping a high enough ventilation level while dosing pure $CO_2$ into the controlled chambers where the studies took place. These studies have conflicting results. Five of them showed a cognitive impact from elevated levels of pure $CO_2$. Consequently, the question of whether or not we need to change future ventilation standards remains open as of now (Fisk et al., 2019). It is useful for further investigations in this direction to proceed with an overview of these works. We attempt to provide this overview with the current article. We do not examine studies that looked at elevated levels of $CO_2$, due to low ventilation, that came with elevation in other indoor pollutant levels as well. We also do not consider such studies (Vercruyssen et al., 2007) that looked at the impact of high concentrations (> 2 %) of $CO_2$ on cognition. We are primarily concerned here with levels relevant for building ventilation. Similarly, we have avoided discussions related to exposures in specialized environments such as submarines (Schaefer et al., 1963) or space flights (Hughson et al., 2016). The scope of this investigation has been focused on results related to cognition from the aforementioned works. In addition to an overview of the said 11 works, we also try to provide some background into the physiological origins and impact of $CO_2$. We believe that such background information may help us understand the aforementioned study results.

## 2. $CO_2$ in the human body: a brief introduction

Carbon dioxide is a byproduct of cellular metabolism and is always present in our bodies. It originates from the mitochondria of cells and, due to the concentration gradient, diffuses from the cells in the bloodstream. $CO_2$ is transported in our bloodstream primarily as bicarbonate ions, with partial pressure of $CO_2$ in venous blood being close to 6 kPa (Higgins, 2008). Once the blood reaches the lungs, it diffuses across the alveolar membrane and is exhaled. Because of the high solubility of $CO_2$ in bodily fluids, the difference in its partial pressure across venous blood, alveolar space, and arterial blood is quite small and these values are highly correlated (Barten and Wang, 1994).

$CO_2$ has several important roles in the human body. Partial pressure of $CO_2$ in alveolar air regulates respiration (Cormack et al., 1957; Hill and Flack, 1908); it is the most important chemical stimulus affecting breathing (Bainton et al., 1978). $CO_2$ also aids regulation of cerebral blood flow (Laffey and Kavanagh, 1999) and cerebral blood flow, in turn, is related to mental effort during task performance (Nishihara et al., 2014).

### 2.1. How much $CO_2$ is too much?

Due to individual differences, a single value cannot be used to characterize a safe $CO_2$ exposure level for inhalation. In asymptomatic individuals, partial pressure of $CO_2$ in blood (PaCO2) ranged between 5.6 and 8.6 kPa (Permentier et al., 2017), and as mentioned earlier, this value correlates well with $CO_2$ concentration in alveolar space. Tolerance to increases in body $CO_2$ levels reduces with age (Permentier et al., 2017), the elderly may be subjectively less sensitive to $CO_2$ – in terms of panic related affects (Griez et al., 2007). Looking from the perspective of respiratory failure, Type I respiratory failure is about declining oxygen levels in blood, with normal of low PaCO2, while Type II respiratory failure is when PaCO2 rises over 6.0 kPa, with or without hypoxaemia (i.e. low blood oxygen levels) (Elliott and Ghosh, 2018).

### 2.2. Human body coping with elevated $CO_2$ levels

Our body has a significant ability to store up $CO_2$ - up to 120 litres of gaseous $CO_2$ (Adolph et al., 1929; Seed et al., 1970) - that comes out to the $CO_2$ contained in about 260 minutes of breathing, assuming we breathe out close to 7.5 liters of air every minute. When the exposure is in terms of seconds to a few minutes, alveolar and blood $CO_2$ stores are involved; over 20-60 minutes, skeletal muscle and viscera come into play; over several weeks of a new, steady-state $CO_2$ level, the bone $CO_2$ stores are affected (Seed et al., 1970). Assuming that exposure was not long enough to develop a new steady state, $CO_2$ elimination is almost immediate after being removed from a $CO_2$ rich atmosphere, as observed from measurements of PaCO2 (Stupfel, 1974). Chronic exposure to elevated $CO_2$ raises PaCO2 and lowers blood pH but these are compensated over a period of a few days or 2-3 weeks as body moves to a new steady level without much increase of PaCO2 (Guais et al., 2011; Seed et al., 1970). Respiratory acclimatization to $CO_2$ during chronic exposures (>1 % concentration) showed an initial increase in respiratory rate followed by a slow decline back to normal, along with a continual increase in tidal volume (Schaefer et al., 1963). During cases of intermittent exposure, however, these compensatory mechanisms may not get enough time to be activated (Guais et al., 2011).

## 3. Physiological effects of exposure to elevated levels of $CO_2$

While there is no dearth in the literature investigating the impact of $CO_2$ on the human body, the majority of studies have used exposures to $CO_2$ concentrations of 1 % or over. Such levels are nearly impossible to come across in normal indoor conditions and typically occur in sealed environments (like submarines, space stations) or in industries with strong CO2 sources (like brewing). The reasoning behind this choice was that noticeable physiological effects had only been noted at high concentrations. Similarly, studies that investigated the impact on cognitive performance due to $CO_2$ also chose the option of inducing physiological impacts and then observing any cognitive effect. While these levels of $CO_2$ may not be relevant for building ventilation, the identifiable physiological impacts may be informative in terms of how the human body responds to an increased level of $CO_2$.

Visuomotor performance may start to get affected by $CO_2$ levels at 1.2 %, although these effects may not impede functionality of the person (Manzey and Lorenz, 1998). Chronic exposure to 2% $CO_2$ across a time span of days is likely to lead to headaches, while at 2.5%, stereoacuity reduces as does the ability to detect motion (Guais et al., 2011). Figure 1 provides a quick summary of physiological impacts observed when human beings were breathing in air with 1 % or greater $CO_2$ level, this condition is named hypercapnia.

From Figure 1, it is apparent that hypercapnia is liable to affect multiple bodily systems. The one that has the most obvious relation with cognition would be the brain and central nervous system (CNS). Hypercapnia induces cerebral vasodilation and increases blood flow to the brain. However, increased blood flow can lead to raised intracranial pressure, which may cause headaches at inhalation concentrations of $CO_2$ over 1.2% (Sliwka et al., 1996). At high concentrations, $CO_2$ starts to act as a CNS depressant. At breathing concentrations of 5 %, $CO_2$ already starts reducing cerebral oxygen metabolism rate (Xu et al., 2011).

The other bodily system that is widely affected by variations of bodily $CO_2$ concentrations is the cardiorespiratory system. End-tidal $CO_2$ (ETCO2) is the concentration level of $CO_2$ that is measured at the end of an exhaled breath. ETCO2 changes are one of the fastest responses to changes in breathing (Burton et al., 2006). ETCO2 closely reflects changes in PaCO2 and thus, body $CO_2$ levels (McSwain, 2010; Young et al., 1991). While it may not have an obvious influence on cognitive performance, increased heart rate, increased blood pressure, and laboured breathing (due to factors like reduced diaphragm contractility, increased pulmonary vascular resistance, and increased tidal volume) may likely impact task performance.

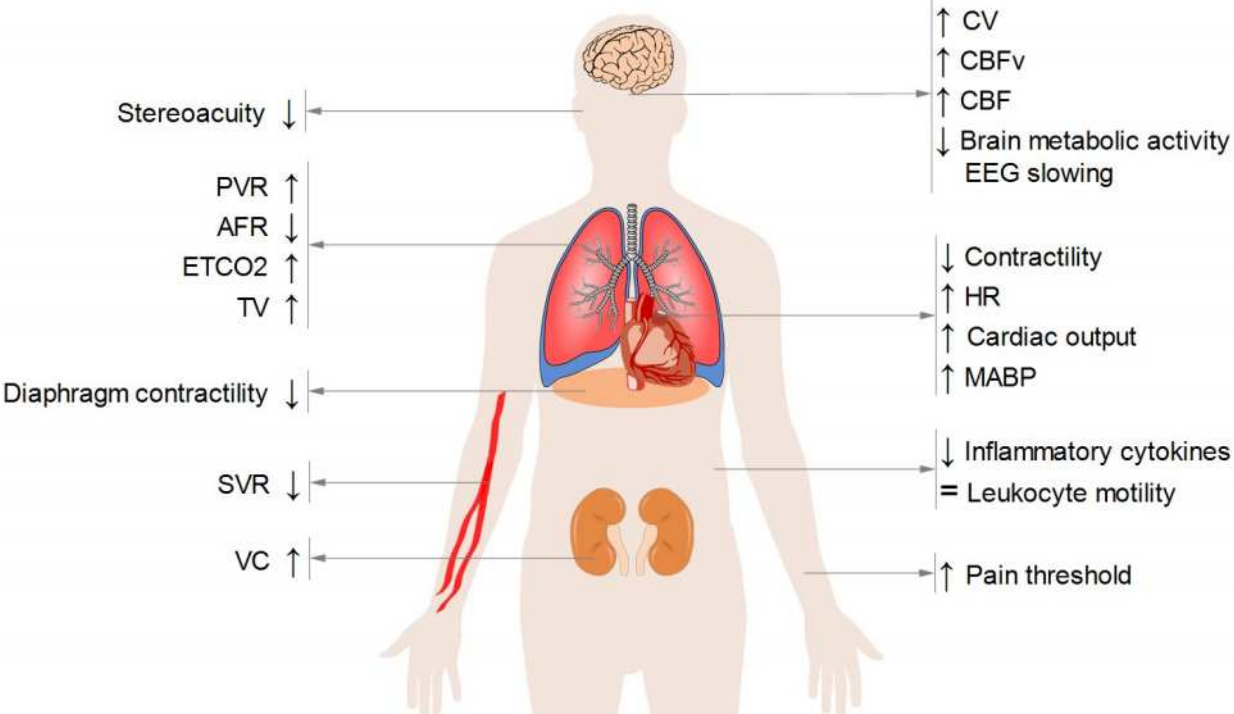


Figure 1. Summary of effects of hypercapnia on human physiology. The image is inspired from Barnes et al. (2018). ↑ indicates rise, ↓ indicates reduction, = indicates no change. Abbreviations: CV - cerebral vasodilation; CBFv - cerebral blood flow velocity; CBF - cerebral blood flow; EEG - electroencephalogram; HR - heart rate; VC - vasoconstriction; PVR - pulmonary vascular resistance; SVR - systemic vascular resistance; MABP - mean arterial blood pressure; AFR - alveolar fluid resorption; TV- tidal volume, ETCO2 - end tidal $CO_2$

## 4. Cognitive effects of exposure to $CO_2$

Eleven studies, conducted over the past 15 years, examined the effects of elevated levels of pure $CO_2$ on cognitive performance are summarized in Table 1. All of them used high ventilation levels to deal with other indoor pollutants, while dosing pure $CO_2$ to reach elevated levels. All of them, except one, used within-subjects designs. All the exposures considered, except one, were under the OSHA specified safety limit of 5000 ppm. Thus, these studies managed to explore a domain of $CO_2$ exposure that has been traditionally little explored. Participants were mostly students and/or office workers. Three works though had specialized populations - submariners (Rodeheffer et al., 2018), astronaut trainees (Scully et al., 2019), and pilots (Allen et al., 2018) - though the studies themselves were conducted in normal climate chamber set-up. The number of participants varied between 5 and 31 per exposure. A reasonably wide range of age groups have also been covered - mean age between 21 and 45 years - representing a broad fraction of workforce. Studies have been mostly carried out in the USA and Europe, except for one study in Japan. While studies have generally tried to balance participants in terms of sex, the three studies that had specialized populations were biased in favour of men. Participants were as often paid as they were not. Exposure duration varied between 50 and 250 minutes except for the one study involving office workers which had a duration covering an entire eight-hour work-day.

Table 1. Summary of studies investigating the impact of elevated pure $CO_2$ levels on cognitive performance

| | **$CO_2$ levels (ppm)** | **Exposure duration (min)** | **Participant mean age (years)** | **Number participants (Paid/No)[M:F]** | **Participant background** | **Study location** |
|---|---|---|---|---|---|---|
| Kajtar et al., 2006 | 600, 1500, 2500, 5000 | 140 | 22.5 | 10 (?) [5:5] | Students | Hungary |
| | 600, 1500, 3000, 4000 | 140 @1500, 4000; 210 @600, 3000 | 21.3 | 10 (?) [4:6] | | |
| Satish et al., 2012 | 600, 1000, 2500 | 150 | 25.5 | 22 (?) [10:12] | Students | California |
| Allen et al., 2016 | 550, 945, 1400 | 480 (lunch break ~45) | 41 | 24 (Paid) [10:14] | Office workers | New York |
| Zhang et al., 2016 | 500, 5000 | 150 | 25 | 10 (Paid) [5:5] | Students | Denmark |
| Zhang et al., 2017 | 435, 1080, 3000 | 255 | 23 | 25 (Paid) [10:15] | Students | Denmark |
| Liu et al., 2017 | 380, 3000 (@ 35 ºC) | 180 | 24.8 | 12 (Paid)[6:6] | Students | Denmark |
| Rodeheffer et al., 2018 | 600, 2500, 15000 | 150 | 30 | 36*(No)[36:0] | Submariners | Connecticut |
| Allen et al., 2018 | 700, 1500, 2500 | 180 | 45 | 30 (No)[30:0] | Commercial airline pilots | Florida |
| Snow et al., 2019 | 830, 2700 | ~48 | 22.5 | 31 (Paid) [?] | Students, university employees | England |
| Scully et al., 2019 | 600,1200, 2500,5000 | 180 | 38.8 | 22 (No)[14:8] | Astronaut trainees | Texas |
| Chikamoto and Mimura, 2019 | 600, 1500, 3500, 5000 (with mask) | 105 | (?) | 5(?)[5:0] | University students | Japan |

*A between subjects design, 12 participants per exposure.
(?) has been used where the corresponding information is not available from the particular work

Figure 2 represents a mapping between the studies and the different measures utilized by them. The measures have been classified under three headings: cognitive tasks, subjective feedback, and physiological measures. Recent studies have been more prolific in examining physiological markers, bringing in measures like EEG and near infrared spectrometry to analyse brain activity. One group (Liu et al., 2017; Zhang et al., 2017, 2016) has consistently cast the widest “physiological net”, trying to evaluate cardiorespiratory parameters, in addition to salivary markers for stress. Few studies have considered measuring skin temperature even though it can be obtained with relative ease and in a less invasive manner. This may be because the sessions did not change with respect to the thermal environment or, the experimenters did not believe altered $CO_2$ levels would affect body's thermoregulation.

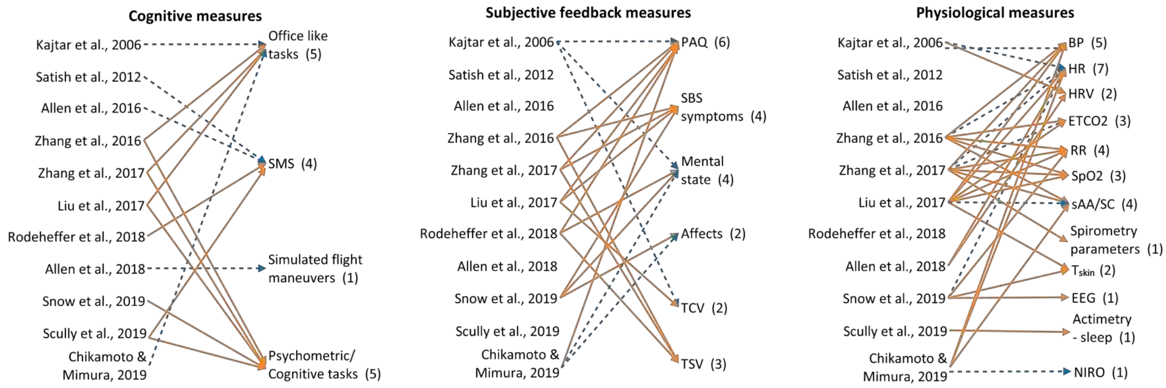


Figure 2. A mapping between studies and measures adopted by each of them. When significant effects were found for a certain measure, with respect to control exposure, the connection has been presented as a dotted line. Abbreviations: BP - blood pressure; EEG - electroencephalogram; ETCO2 - end-tidal $CO_2$; HR - heart rate; HRV - heart rate variability; NIRO - near-infrared spectrometry; PAQ - perceived air quality; RR - respiratory rate; sAA - salivary alpha-amylase; SBS - sick building syndrome; SC - salivary cortisol; SMS - strategic management simulations; SpO2 - blood oxygen saturation; TCV - thermal comfort feedback; $T_{skin}$ - skin temperature; TSV - thermal sensation feedback

Only one work considered obtaining an objective measure of last night's sleep quality from their participants using a wearable device with an actimeter (Scully et al., 2019). As discussed by the same authors, participant's last night sleep quality is likely to have played a role in their findings. Since sleep quality has an intimate relation with cognitive performance, it would be useful if more future studies could obtain such objective measures of sleep quality. At the same time, since the procedure is invasive, there are logistic barriers to its implementation.

Subjective measures generally covered perception of air quality while some of the studies also evaluated thermal sensation and comfort. Building related symptoms (e.g., headaches, difficulty breathing, skin/throat dryness or itchiness) were also collected in four studies, while another four studies queried about mental state (e.g., sleepiness, alertness, clarity of thought, feeling of mental load, etc.). Affects were only queried by a couple of recent studies in form of positive and negative affect schedule (PANAS) (Snow et al., 2019) and feeling of worthlessness (Chikamoto and Mimura, 2019). It would be interesting to have future studies using measures of affect that assess arousal and pleasure, in addition to positive and negative affect. Since $CO_2$ inhalation at concentrations of over 5% are known to trigger anxiety symptoms (Garner et al., 2011), future works would be prudent to investigate if long-term inhalation of much lower levels of $CO_2$ inhalation may have any similar effects.

Four measures were used to ascertain cognitive performance: standard psychometric tasks (e.g., Stroop test, Tsai-Partington test, digit span memory test), office-like tasks (e.g., proofreading, typing, arithmetic tasks), the strategic management simulation (SMS) task, and flight manoeuvres. The last task is relevant to only one study and one specific population. SMS has been used by four works and the rest of the studies have used some form of combination of psychometric tasks and office-like tasks. SMS was developed as a measure of executives functioning in the 'real' world, described by its developers to be sensitive to even the slightest decrements in human performance because of its challenging nature (Streufert et al., 1995, 1988). Psychometric tests were developed to measure a broad range of mental characteristics and competencies and have been widely used in psychological research, though mostly aimed at detecting serious compromises in cognitive functions caused by injury, disease, addiction etc. (Hammond, 2006). Office-like tasks have the advantage of being representative of work done in an office, but they often tend to be simplistic, modular tasks, unable to capture the complexity of present office work. Additional aspects that may guide the decision on the nature of cognitive tasks could be the cost of implementation and access to raw, performance data.

Figure 3 presents the effects found by the different studies. Significant effects, in red, have been classified according to the measure. Exposures that did not show any significant effect, for any of the measures, have been marked with a blue 'x'. Even going with the worst-case scenario regarding $CO_2$ emissions, by the turn of this century, a building that abides by current ventilation regulations should not have indoor $CO_2$ levels beyond 2000 ppm, assuming a difference between indoors and outdoors of around 700 ppm, as per current requirements and outdoor levels at 900 ppm. So, we propose that from the perspective of indoor ventilation, only levels under 2000 ppm are of concern.

All significant effects observed, under 2000 ppm exposure, related to cognitive performance. Within this range, there were five exposures with significant difference and three without. All noticed physiological effects occurred at over 2,500 ppm. This deserves more attention, possibly from a different domain of investigators, since, traditionally, it has been believed that you require $CO_2$ inhalation at 10,000 ppm or more to produce notable physiological effects. It could also be that the changes noted, though statistically significant, may not carry operational significance. Four of the studies that did find physiological effects at exposures of over 2,500 ppm did not find associated cognitive decrements while two studies did.

Apart from the work involving pilots, studies that have noted an effect on cognitive performance for exposures under 2000 ppm used SMS. Two of these works even noted effects at 900-1000 ppm of $CO_2$, levels that are commonly found in buildings currently. The SMS tasks do not fit the mould of standard psychometric tasks or office like tasks. As described by the creators, they are challenging on cognitive faculties and can be stressful (Streufert et al., 1995). The one study that applied both SMS and standard psychometric tests found a reduced performance at 1,200 ppm for SMS but not for the psychometric tasks (Scully et al., 2019). However, as the world evolves towards an economy of more knowledge-based workers and stressful workspaces, the pertinence of SMS may not be entirely denied. It remains to be seen if stress, in combination with $CO_2$ exposure, may contribute to declines in performance.

The other two studies that noted effect on cognitive performance but did not employ SMS, used office like tasks and noted them at $CO_2$ levels over 3000 ppm (Chikamoto and Mimura, 2019; Kajtar et al., 2006). These two studies used small populations (n= 5 and 10, respectively). The findings from Kajtar et al. (2006) were also unique in that their participants perceived the air quality to be compromised with rising levels of pure $CO_2$. This is an unexpected and unexplained result since $CO_2$, at these levels, is not known to trigger olfactory sensations.

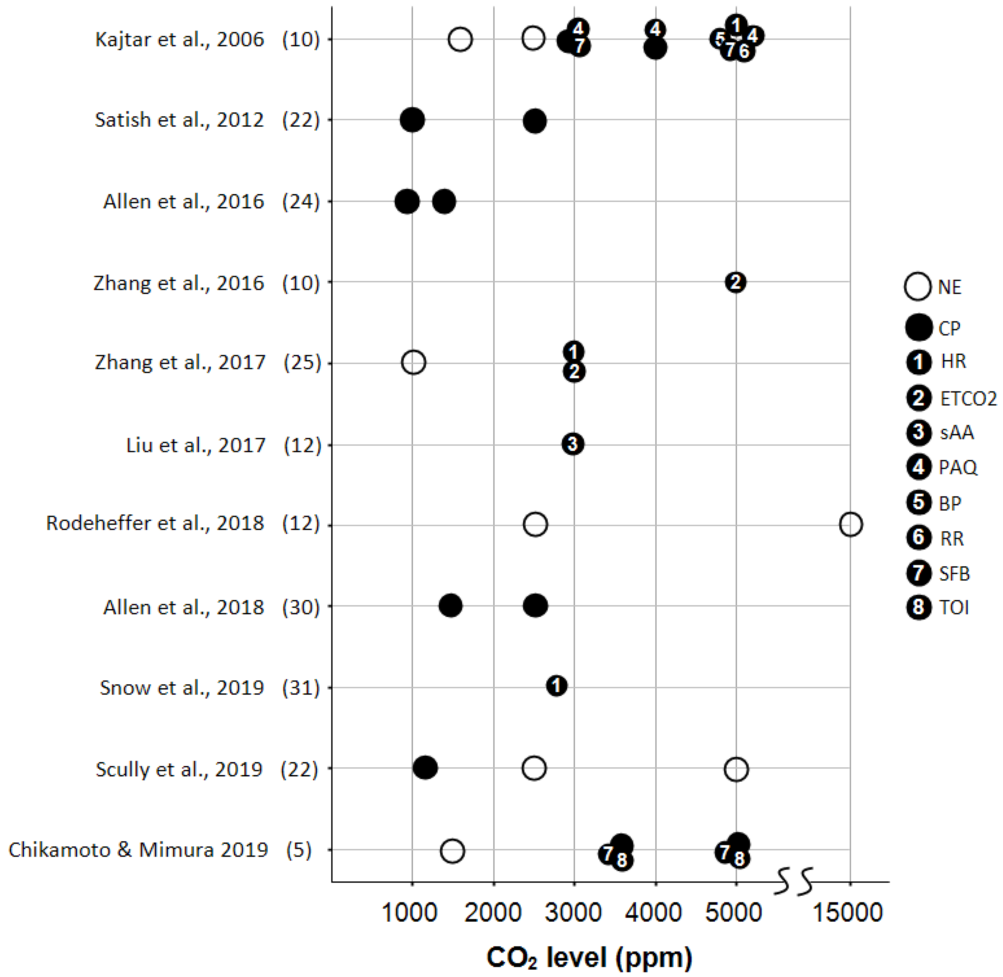


Figure 3. A summary on the effects found by the studies. Significant effects, as compared to the study's respective control exposures (between 400 and 850 ppm), have been given in red. For a certain exposure, only measures for which significant effects were found have been provided in red. When no measures showed a significant effect, a blue 'x' has been used. Each study's population size is reported in a bracket next to the study. Abbreviations: BP - blood pressure; CP- cognitive performance; ETCO2 - end tidal $CO_2$; HR - heart rate; NE- No effects; PAQ - perceived air quality; RR - respiratory rate; sAA - salivary alpha amylase; SFB - subjective feedback (on tiredness, affects etc.); TOI - tissue oxygenation index.

Other than the studies that used SMS, there was also the study that tested performance in flight manoeuvres and detected compromised performance at sub 2000 ppm levels (Allen et al., 2018). This was the test of a real world task, being performed by well-practiced professionals. The evidence from this work is, in a sense, more reliable than the evidence based on SMS tasks. However, we should point out here that the distinctions in performance were found by the flight inspectors but not by the on-board flight computer. The study also did not find any relation between $CO_2$ exposure and HRV.

The background of participants may also have played a role in the findings. Two studies that used SMS and did not notice a dose-dependent effect of elevated $CO_2$ levels on performance had participants who were highly trained individuals who deal with stressful situations (Rodeheffer et al., 2018; Scully et al., 2019). It could be that their background made them immune to the demands of SMS. Another confounding factor, noted by one of the studies, is the impact of overnight sleep on performance (Scully et al., 2019). Unfortunately, this is an area that has not received enough attention so far and hopefully is considered and assessed in future works.

Duration of exposure is another critical aspect that needs to be considered by future studies. At least two studies that noted a performance decrement associated with elevated levels of $CO_2$ also indicated performance decrement with exposure length (Allen et al., 2018; Kajtar et al., 2006). The longest exposure studied so far was a full work day (eight hours) (Allen et al., 2016). The problem with exposure to elevated indoor $CO_2$ levels is that it is chronic but intermittent. As has been observed from medical literature, compensatory mechanisms that are activated by the human body to chronic $CO_2$ exposure may not help in the future indoor exposure scenarios that we are concerned with, where exposure is intermittent and not continual (Guais et al., 2011). How best to replicate the effects of such chronic, intermittent exposure on performance and physiological markers would be of interest and cerebration for future work. Subjects participating in the discussed experiments were generally healthy and information was not provided regarding their lung capacity/respiratory parameters. As it is likely that people with respiratory problems have more troubles in dealing with $CO_2$ than others, having information on the participants' respiratory health in future studies would be pragmatic.

Individual characteristics may also have contributed to specific findings in certain studies. Participants in previous studies were generally healthy. No information was provided regarding their lung capacity/respiration. It is highly likely that people with respiratory issues will be more susceptible to effects of $CO_2$. Hypercapnia increases cerebral blood flow, which in turn may cause headaches, thus possibly accounting for the decrement in cognitive performance. However, the studies that noted a cognitive decrement have not provided any evidence of such a mechanism in action. An example of how individual physiological characteristics may serve as a confounder is that changes in cerebral blood flow related to hypercapnia, as found for normotensive individuals, may be absent for hypertensive individuals (Harper and Glass, 1965). Similarly, sympathetic nervous system activity can also attenuate hypercapnia induced increase in cerebral blood flow (Jordan et al., 2000).

## 5. Instead of a conclusion

Investigations into effects of $CO_2$, at typical indoor levels, on cognitive faculties is pertinent and timely given the rising atmospheric $CO_2$ levels. The results can have serious implications for building ventilation energy requirements, possibly changing them by an order of magnitude. Findings from studies so far indicate the following:

- The evidence on cognitive impact of just $CO_2$, as of now, remains inconclusive.
- The topic requires more in-depth investigations, focusing on levels relevant to building ventilation, that is < 2000 ppm of $CO_2$.
- More recent studies have been more prolific in adopting markers to check for physiological effects.
- Any physiological effects noted in studies so far occurred at $CO_2$ levels ≥2500 ppm.
- Not many studies have looked at how $CO_2$ exposure may have impacted participant mood, leaving this as an important gap.
- Future works will need to focus on occupant demographics (background, training, education, age, health etc.), their sleep quality in days during the studies, exposure duration, and choice of the cognitive performance measure.

There were a couple of conspicuous limitations of this review. While presenting an overview of the studies examining impact of $CO_2$ on cognitive performance and the physiological consequences of $CO_2$, we were not able to better correlate these two areas. Second, we did not attempt a meta-analysis of the data from the studies since they employed different measures and exposure levels were different, among other contrasts across the studies.

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## Glossary

| | |
|---|---|
| AFR | alveolar fluid resorption |
| BP | blood pressure |
| CBF | cerebral blood flow |
| CBFv | cerebral blood flow velocity |
| CP | cognitive performance |
| CV | cerebral vasodilation |
| EEG | electroencephalogram |
| ETCO2 | end tidal $CO_2$ |
| HR | heart rate |
| HRV | heart rate variability |
| Hypercapnia | increase in body's $CO_2$ beyond normal levels |
| Hypocapnia | reduction in body's $CO_2$ below normal levels |
| Hypoxameia | Reduced body oxygen levels |
| MABP | mean arterial blood pressure |
| NIRO | near infrared spectrometry |
| PaCO2 | partial pressure of $CO_2$ in arterial blood |
| PAQ | air quality perception |
| PVR | pulmonary vascular resistance |
| RR | respiratory rate |
| sAA | salivary alpha amylase |
| SBS | sick building syndrome |
| SC | salivary cortisol |
| SFB | subjective feedback |
| SMS | strategic management simulations |
| SpO2 | blood oxygen saturation |

| | |
|---|---|
| SVR | systemic vascular resistance |
| TCV | thermal comfort feedback |
| TOI | tissue oxygenation level |
| Tskin | skin temperature |
| TSV | thermal sensation feedback |
| TV | tidal volume |
| VC | vasoconstriction |

# Causes and effects of partial cooling during sleep

**Noriko Umemiya[1], Yuhan Chen[1] and Ikuna Fujimoto[1]**

[1] Graduate School of Engineering, Osaka City University, 3-3-138, Sugimoto, Sumiyoshi-ku, Osaka City, Japan, umemiyanor@osaka-cu.(ac.jp)

**Abstract:** Causes and effects of partial cooling use during sleep were surveyed during 616 nights based on responses of 142 Osaka apartment residents. 137 nights of partial cooling use and 209 nights of full-time cooling use were compared. Results revealed the following. 1) The thermal environment of the outside air was not related. 2) Heat and cold tolerance of the respondents were not related, but easy perspiration and poor circulation caused partial cooling. 3) Partial cooling users had less stress, lower income, stronger environmental consciousness and habits of more frequent clothing control. 4) Dwelling units of partial cooling users were less sunny, more efficient in cooling, stronger in thermal insulation, less condensed, and lower on living floors. 5) Bedrooms of partial cooling users had better views, better thermal insulation, and better ventilation, but less glare, less polluted outside air, less annoyance from solar heat and less anxiety about crime. 6) The bedroom humidity ratios were higher; the humidity sensation and perspiration sensation were higher in partial cooling dwelling units. 7) The total sleep quality score and the sleepiness score of morning awakening were better for partial cooling users. No differences were found between sleep maintenance scores, although partial cooling users awakened more frequently during sleep than full-time cooling users did.

**Keywords:** Partial cooling, Sleep Quality, Thermal comfort, Bedroom

## 1. Background and Purposes

Air conditioners are sometimes not used throughout the night but are instead used partially to aid sleep in summer. Sakane et al. (2013) reported for apartments in an urban area of Osaka that only 31.5% of residents used air conditioners throughout the night, 27.9% used them partially, and 38.6% did not use them. Discomfort caused by over-cooling and anxiety about cooling bills might cause their use.

This study investigates the partial use of cooling during sleep. Thermal control use during sleep was recorded. The thermal environment was measured. Then sleep quality was assessed using questionnaire sheets. Attributes of the dwellings and occupants were also surveyed. Thorough use and partial use were compared among 1) occupant attributes, 2) dwelling attributes, 3) setting temperatures and air volumes, 5) sleep clothing and bed clothing, 6) sleeping style, 7) bedroom thermal environments, 8) thermal sensations in bedrooms, and 9) sleep quality.

## 2. Methods

Surveys were conducted in an urban area of Osaka for 36 apartments in 2014, 27 apartments in 2015, 23 apartments in 2016 (Nakayama et al, 2016), and 56 apartments in 2017 (Umemiya and Yamagata et al, 2019). Surveys continued for a week for each apartment.

Air temperatures were recorded at 10 min intervals, humidity was read by the occupants before and after sleeping. The participants recorded the use of air conditioners, electric fans, and natural ventilation by window opening at intervals of 30 min. Also, bedroom occupancy and time of sleep were recorded.

Respondents reported sleep quality by OSA inventory scales (Yamamoto et al, 1999), thermal sensations, and sleeping styles when awake in the morning.

Figure 1 presents the total number of measurements for each day for the four years. Daily outdoor temperatures are also shown. Measurements were distributed evenly in summer. Data for nights with 'much stress', involving 'very bad health', with bad sleep by non-thermal reasons, or with babies under two years old were excluded from 760 nights for 153 apartments. Therefore, 622 nights for 142 apartments were used for evaluation.

Figure 2 portrays a distribution of thermal control use patterns during sleep. Nights when air conditioners were used, electric fans were not used, and windows were closed all night were 25.5%. Nights when air conditioners were used, electric fans were not used, and windows were closed all night were 25.5%. Nights when air conditioners and electric fans were not used and windows were open all night were 14.2%. Nights when air conditioners were used partially, electric fans were not used all night, and windows were closed for the whole night were 12.2%. Nights when air conditioners and electric fans were not used and windows were closed all night were 8.2%. Nights when air conditioners were not used, electric fans were used, and windows were opened all night were 7.9%. Nights when air conditioners were used all night (A) were 37.7%. Nights when air conditioners were used partially (P) were 24.7%. Nights when air conditioners were not used were 37.7%.

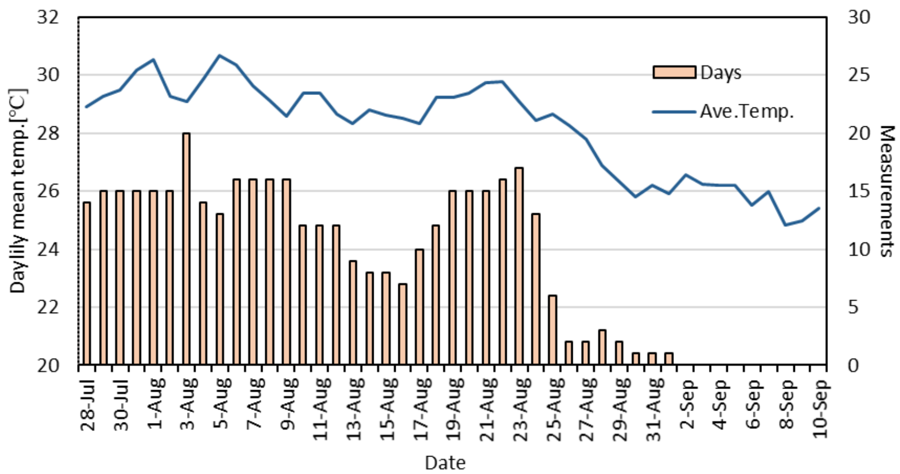



Figure 1. Daily number of measurements and daily mean outdoor temperature for 4 years

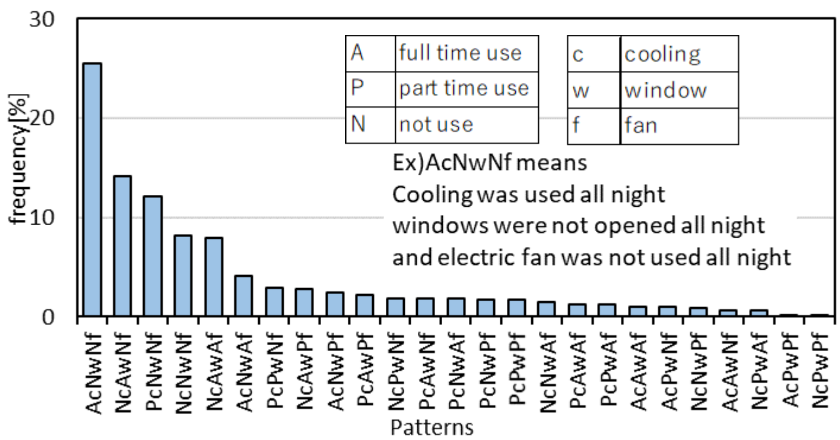



Figure 2. Distribution of thermal control use patterns

## 3. Participants

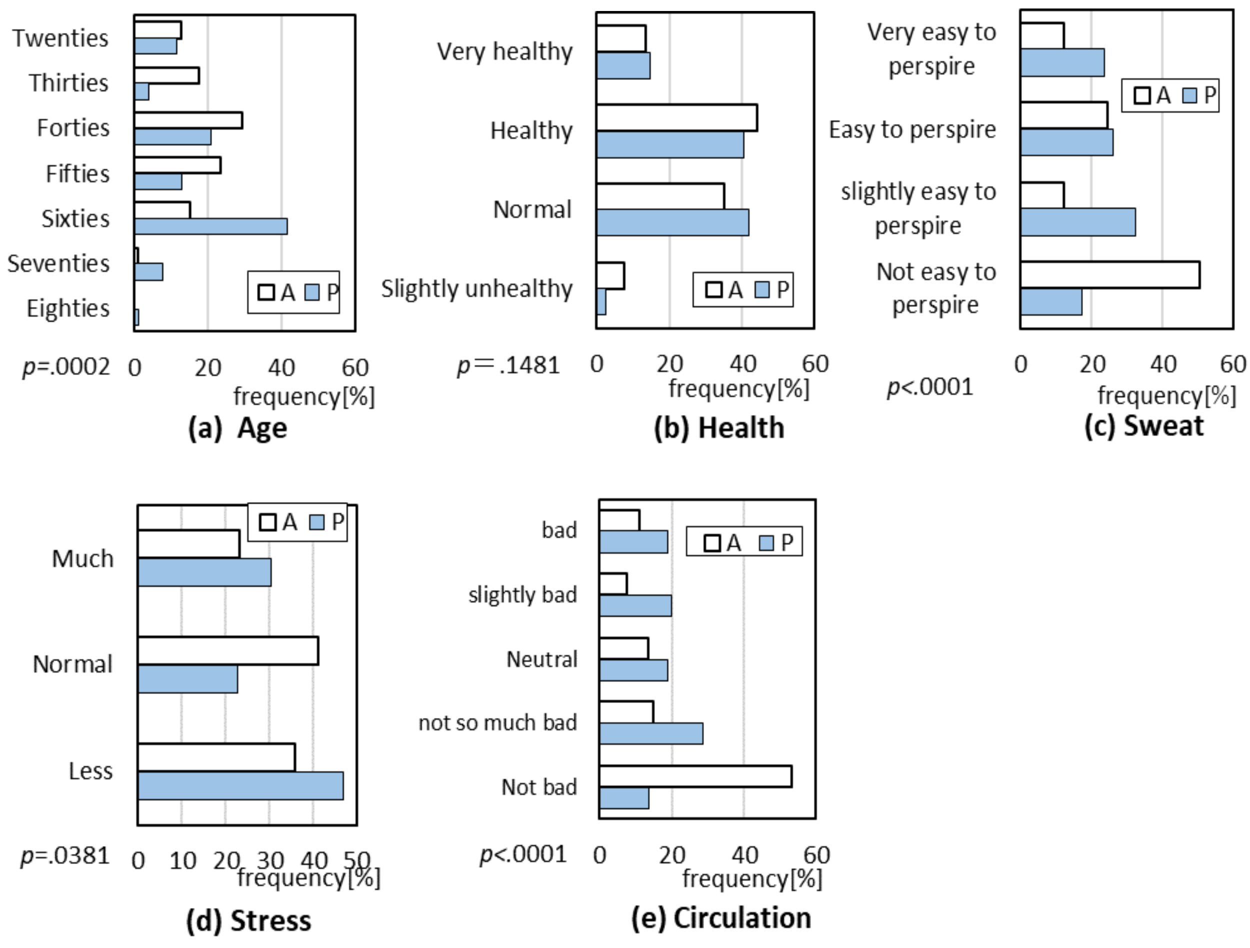
Figure 3 presents distribution of age, health, sweat, stress and circulation of participants. To difference was found by sex. Averages and standard deviations of age of A and P were 46.0±11.3 and 49.9±14.3; the *t*-test *p*-value was 0.0002. P was dominant for homemakers. A was the dominant response given by unemployed participants.

'Not easy to perspire' was dominant in A and 'slightly easy to perspire' was dominant in P ($p$<0.0001). 'Not bad circulation' was dominant in A and 'not so much bad circulation' was dominant in P ($p$<0.0001). No difference was found in heat tolerance or cold tolerance between A and P.

Moreover, no difference was found in health between A and P. More stress was reported among A than among P ($p$=0.0381).

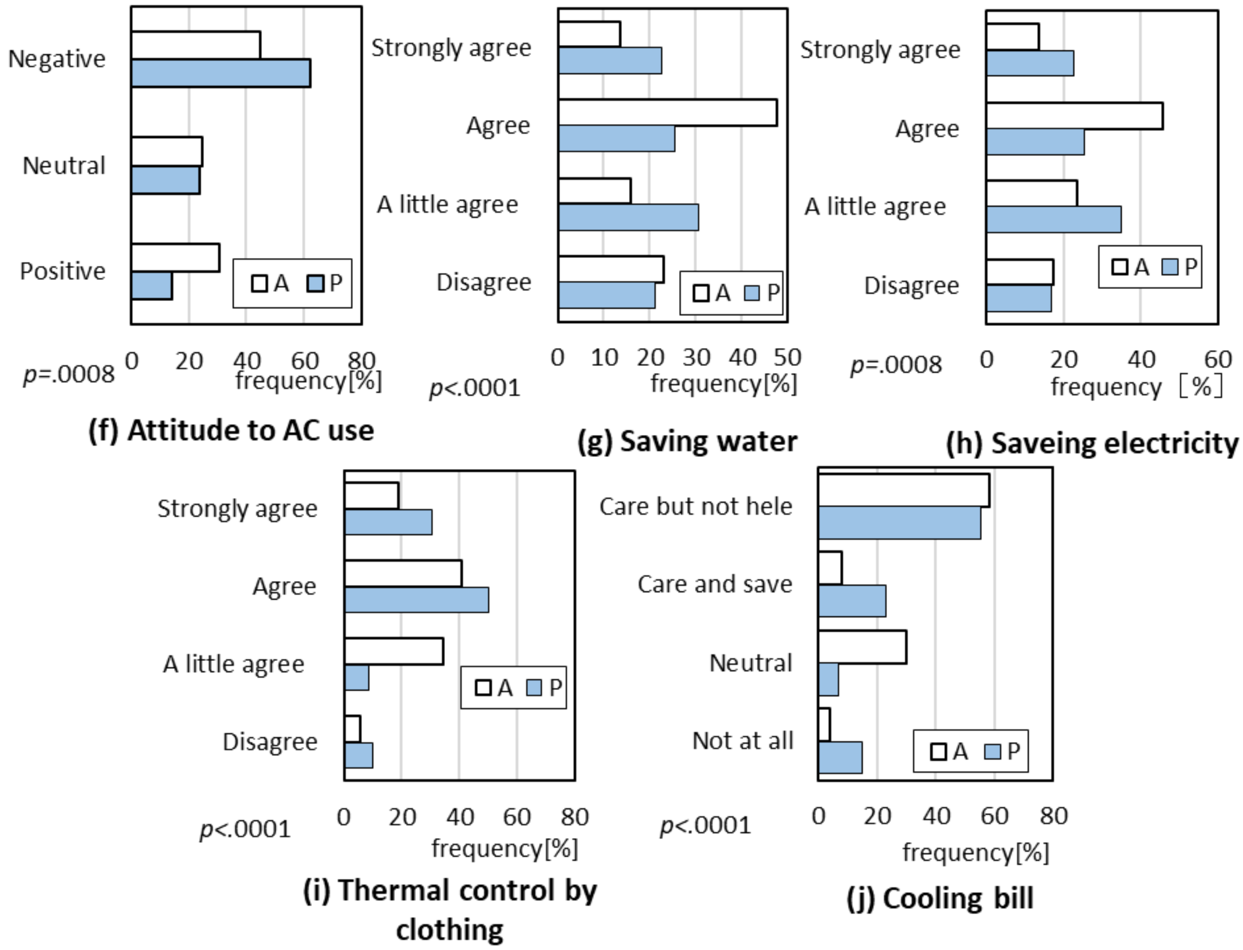
Figure 4 shows awareness and habits of participants. Of A respondents, 30.8% were positive for air conditioner use, whereas 14.1% of P were positive ($p$=0.0008). P reported less habits devoted to saving water and saving electricity ($p$<0.0001), although P had reported more habits devoted to thermal control by clothing or bed clothing ($p$<0.0001).

More than half of A and P were 'anxious about the electric bill in the cooling season but thought air conditioners are necessary'. However, 29.8% of A thought 'the bill was not so high', whereas 23.0 of P 'saved air conditioner use'. P was more anxious about the electric bill than A ($p$<0.0001). The mean family income WS 4,744 thousand yen for A and 3,418 thousand yen for P ($p$=0.0159).




A: full time use P: part time use

Figure 3 Distribution of age, health, sweat, stress circulation of participants




A: full time use P: part time use

Figure 4 Awareness and habits of participants

## 4. Apartment and Bedroom Attributes

Mean living areas were 62.0 m$^2$ for A and 60.3 m$^2$ for P ($p$=0.19). The mean height of the building story was 5.88 for A and 5.14 for P ($p$=0.0412). The mean number of household members was 2.33 for A and 2.36 for P. No significant difference was found ($p$=0.3496).

Figure 5 portrays the distribution of apartment attributes. The thermal insulation performance level was thought to conform to the standards of energy saving code of the year of construction. The standards had been changed in 1992 and 1999, so the thermal insulation levels were classified into three groups, before 1992, 1992–1998, and after 1999. There were more P for new apartment buildings ($p$<0.0001). The year of construction had a stronger relation with the difference between A and P than attributes of the subjects. It can be said that the thermal environment can be maintained better with partial air conditioner use if the thermal insulation level was better.

Solar heat was less of a nuisance ($p$<0.0001), sunlight was less glaring ($p$<0.0001), condensation was less ($p$=0.0003), sunshine was less ($p$=0.002), and cooling was more effective ($p$=0.0344) for apartments of P. No difference was found in the ventilation or molding between apartments A and P.

Figure 6 shows the distribution of bedroom attributes. The bedrooms of P had clearer outdoor air ($p$<0.0001), more effective cooling ($p$<0.0001), better view ($p$=0.0051), less sunshine ($p$=0.0096), less bothersome solar heat ($p$=0.0195), and humidity and smells were less of a nuisance ($p$<0.0001), but crime was more noticeable ($p$=0.0012).

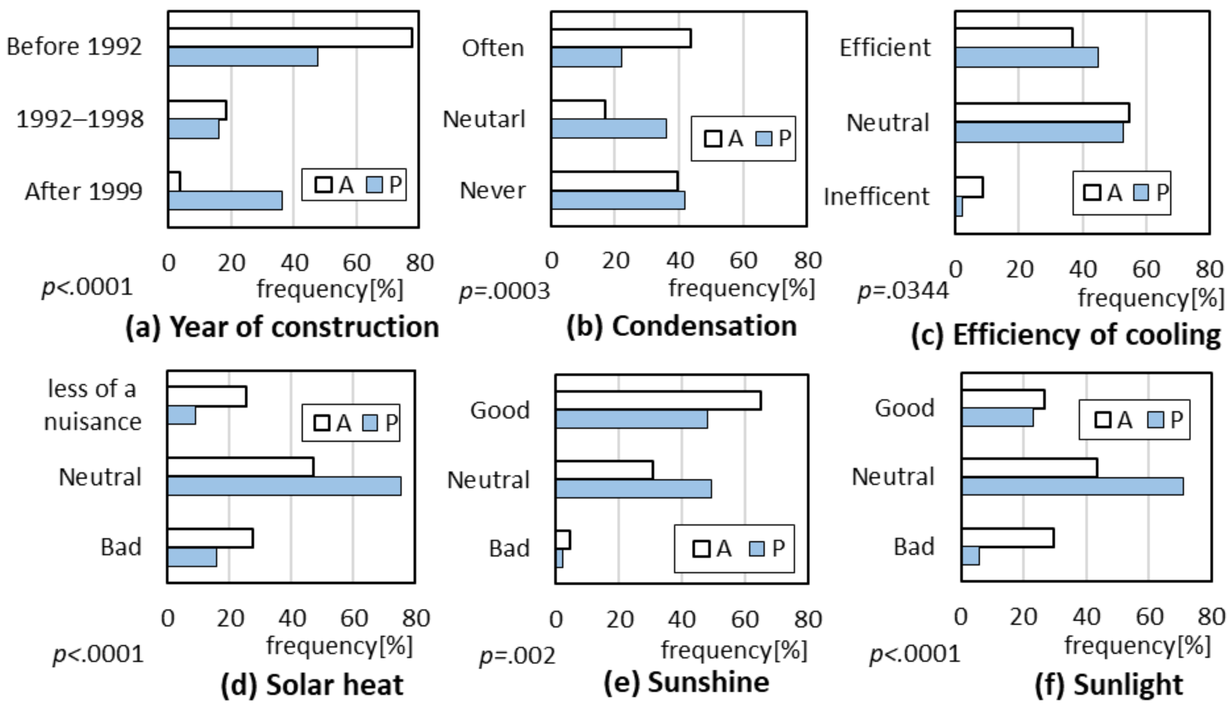



Figure 5 Distribution of apartment attributes

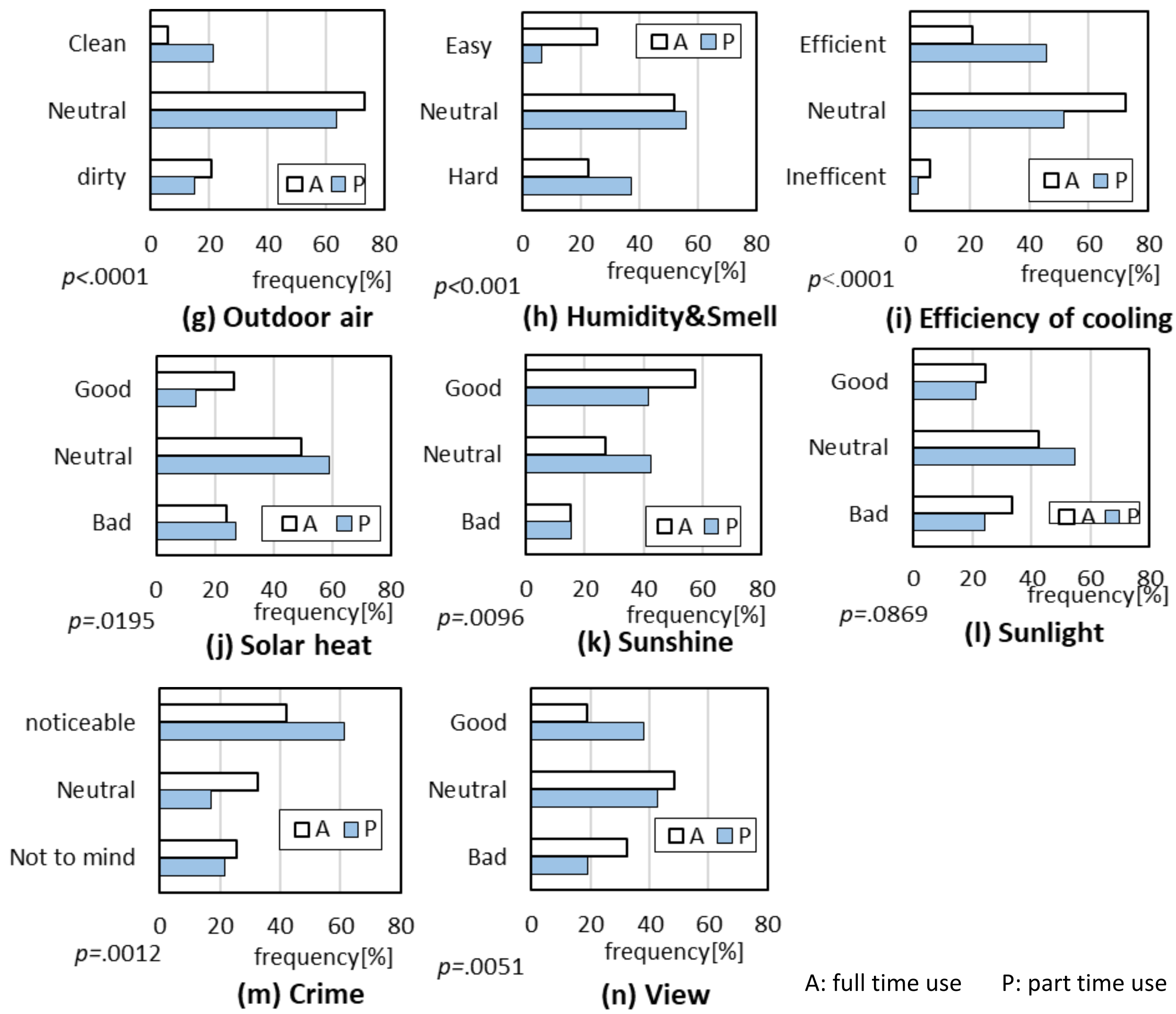



Figure 6 Distribution of Bedroom attributes

## 5. Thermal Environment

### 5.1. Outdoor thermal environment

Weather observatory data were used as outdoor thermal environment data. Mean air temperatures were 27.4°C for A and 27.6°C for P; no difference was found ($p$= .2282). Mean relative humidity was 77.0% for A and 78.0% for P; no difference was found ($p$=0.973). The humidity was marginally different ($p$=0.0503) between 17.7 g/kg of A and 18.0 g/kg of P. It can be said that the outdoor environment had little effect on selecting A and B.

### 5.2. Bedroom thermal environment

#### 5.2.1. Use of air conditioner timers

Figure 7 presents bedding and putting quilt when sleeping. Figure 8 portrays the sleepwear, air volume setting and the place to sleep. Respondents reported that 61.2% turned off air conditioners by timer, 18.0% turned them off manually, 7.2% turned them off manually after turning them on manually after turning them off by timer, 4.3% turned them on manually, 1.4% turned them off before the timer turned them off, 0.7% turned them off manually after turning them on manually. The mean timer setting was 3.6 hr: 21.5% were set to 3 hr, 18.3% were set to one hour or five hours.

No difference between A and P was found in the setting temperatures of air conditioners. Air volume settings differed between A and P ($p$=0.023). 'Weak' was dominant in P, where 'strong' and 'medium' were dominant in A.

Bed covers were lighter for P than for A ($p$=0.0002), 'took off bed covers unconsciously' were more in P than in A ($p$=0.0002). Futon on the floor was 83.1% and dominant for P ($p$=0.0037). Sets of half sleeves and half pants were dominant for P, where sets of half sleeves and long pants were dominant for A as sleep clothing ($p$=0.0034). Cooling sheets were used 18.1% of A and 40.8% of P ($p$<0.0001). It can be said that P controlled the thermal environment more intensively.

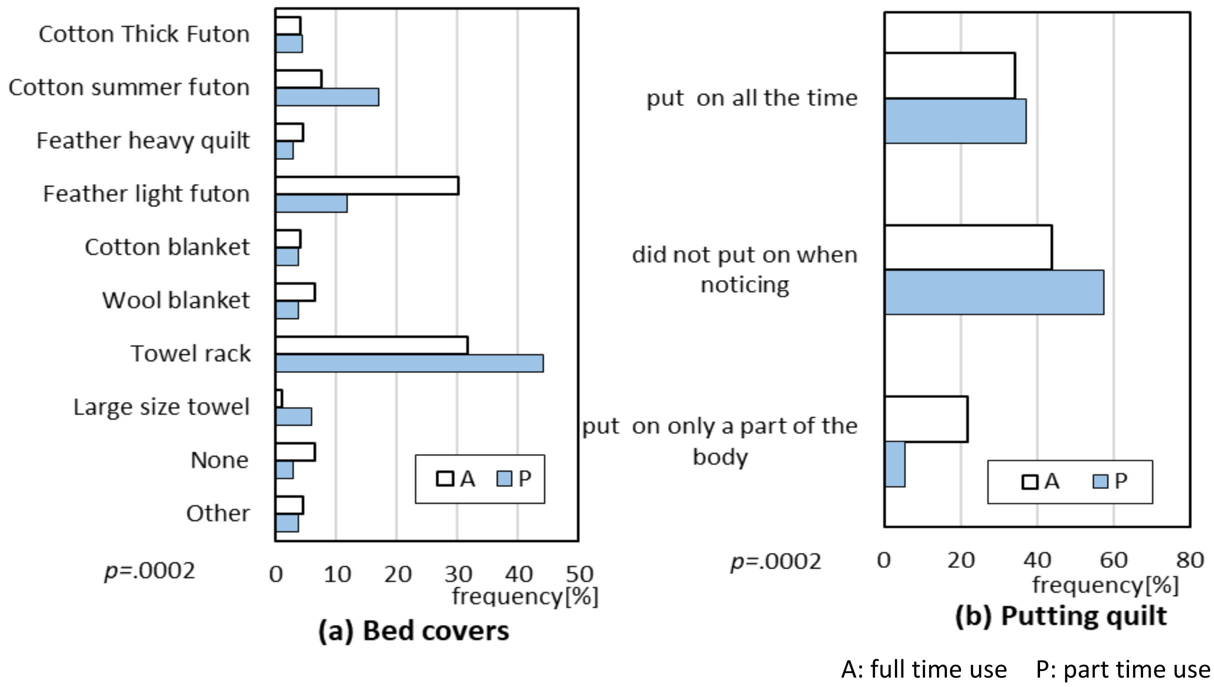
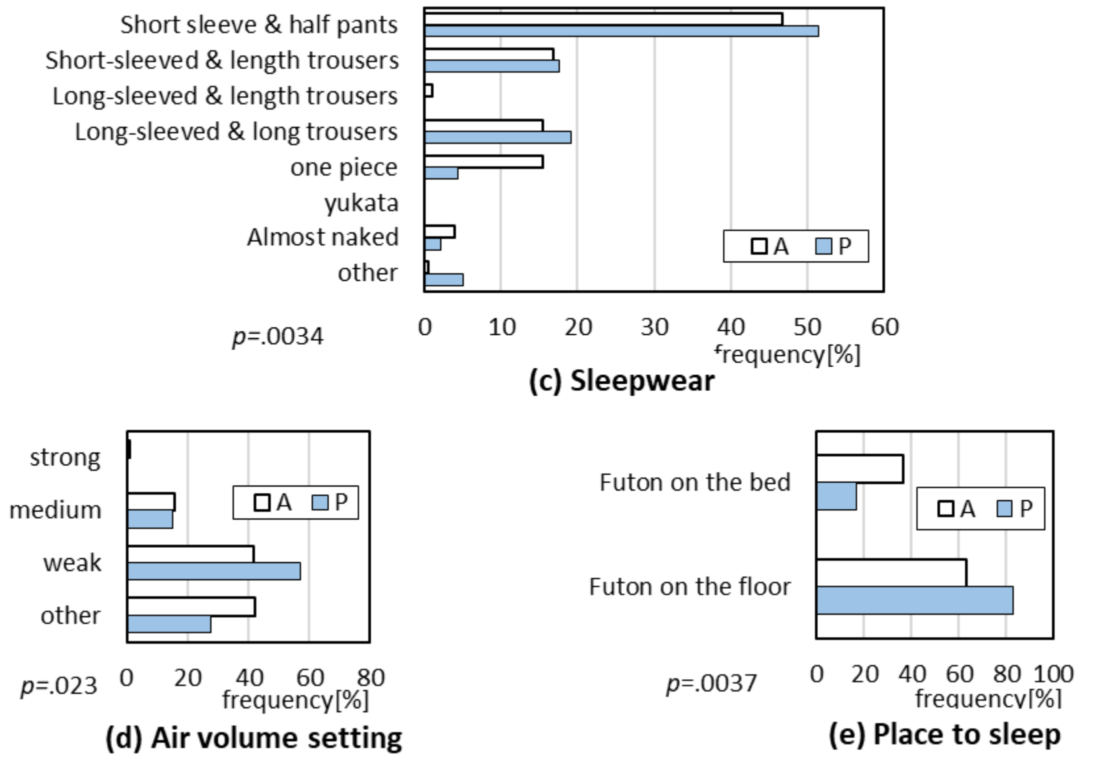



Figure 7 Bedding and sleep habits




A: full time use P: part time use

Figure 8 Sleepwear and sleep habits

The mean numbers of occupants in the bedrooms were 1.84 for A and 1.51 for P. Bedrooms with more occupants might need air conditioners.

### 5.2.2. Bedroom thermal environment

The bedroom mean temperature for nights was 26.6°C for A and 28.1°C for P ($p$<0.0001). No difference was found in relative humidity between A and P, but the humidity ratios were 13.9 g/kg for A and 15.1 g/kg for P ($p$<0.0001). Indoor WBGT were 23.9°C for A and 25.1°C for P ($p$<0.0001).

## 6. Thermal Sensation and Sleep Quality

### 6.1. Thermal sensation

Figure 9 shows distribution of thermal sensation. Thermal sensation was evaluated as hotter in P than in A ($p$=0.0199). However, no difference was found in thermal comfort or acceptability between A and P ($p$=0.180, 0.216). Humidity sensation was more humid in P than in A ($p$=0.0021). Perspiration sensation was much greater in P than in A. These results accorded with the fact that humidity was higher in P than in A.

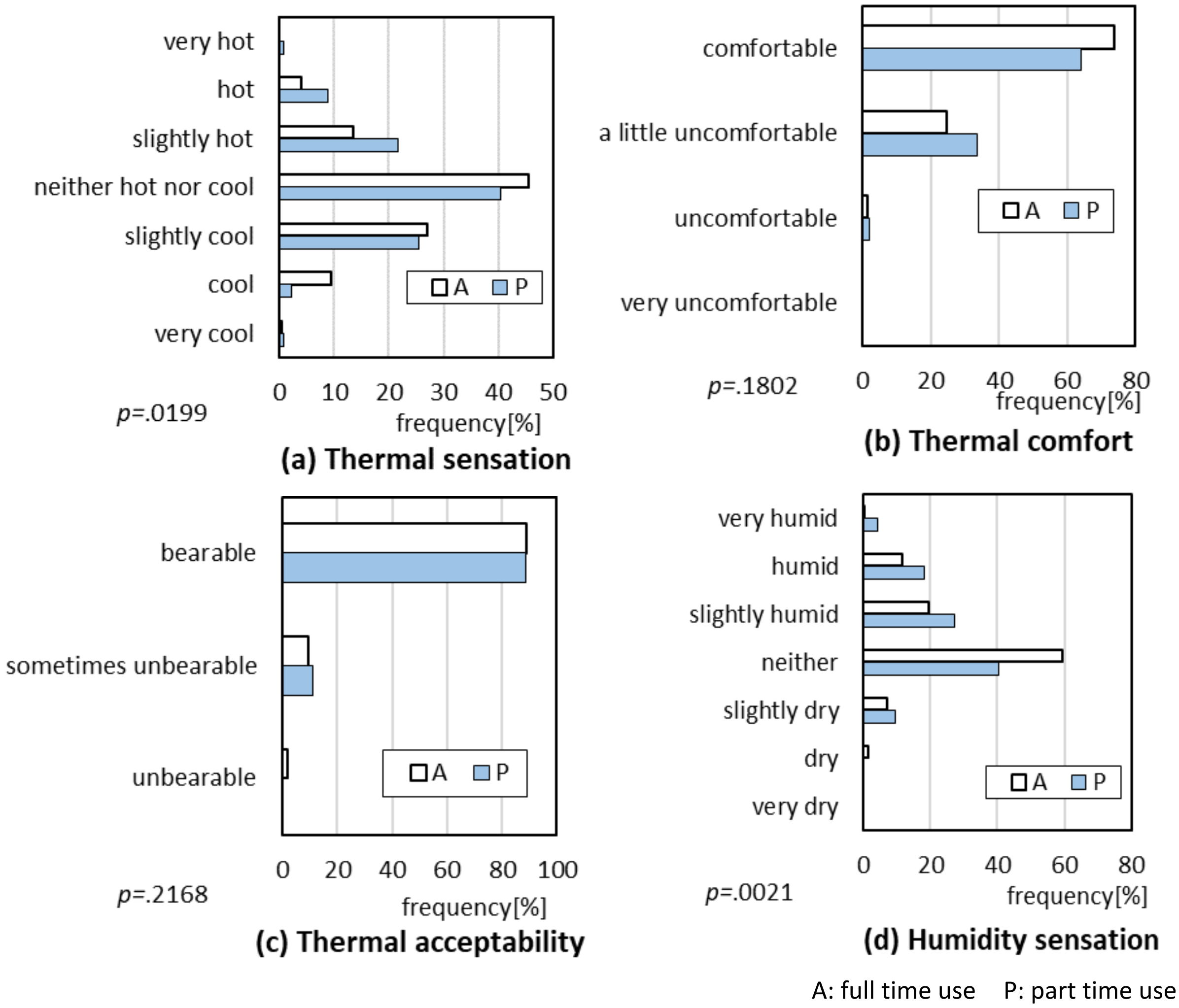



Figure 9 Distribution of thermal sensation, comfort, acceptability and humidity sensation

### 6.2. Sleep quality

Figure 10 shows sleep quality scores by OSA sleep inventory. OSA Sleep quality scores are calculated from answers to 15 five-point scale questions about sleep when awaking. 15 scales are classified into five factors, sleepiness when awaking (S), sleep introduction and maintenance (M), dreaming (D), recovery from fatigue by sleep (F), and length of sleeping time (T). The total sleep quality score is the mean of five factor scores. Higher OSA scores mean better sleep.

The total sleep quality score was 50.0 for A and 51.1 for P ($p$=0.111). The S-score was 50.2 for A and 52.1 for P ($p$=0.041). No difference was found in M-scores between A and P. The mean waking time during sleep was 0.63±0.83 for A and 0.91±1.03 for P. It can be said that partial cooling causes more waking time in P than in A, but the difference is not so large as to cause the difference in sleep introduction and maintenance score between A and P.

No difference was found in D-scores between A and P. The F-scores and T-scores were slightly higher in P than in A ($p$=0.156 and 0.152). It can be said that subjective sleep quality difference between A and P is not so large, but scores tend to be evaluated higher in P than in A, especially in sleepiness when waking score.

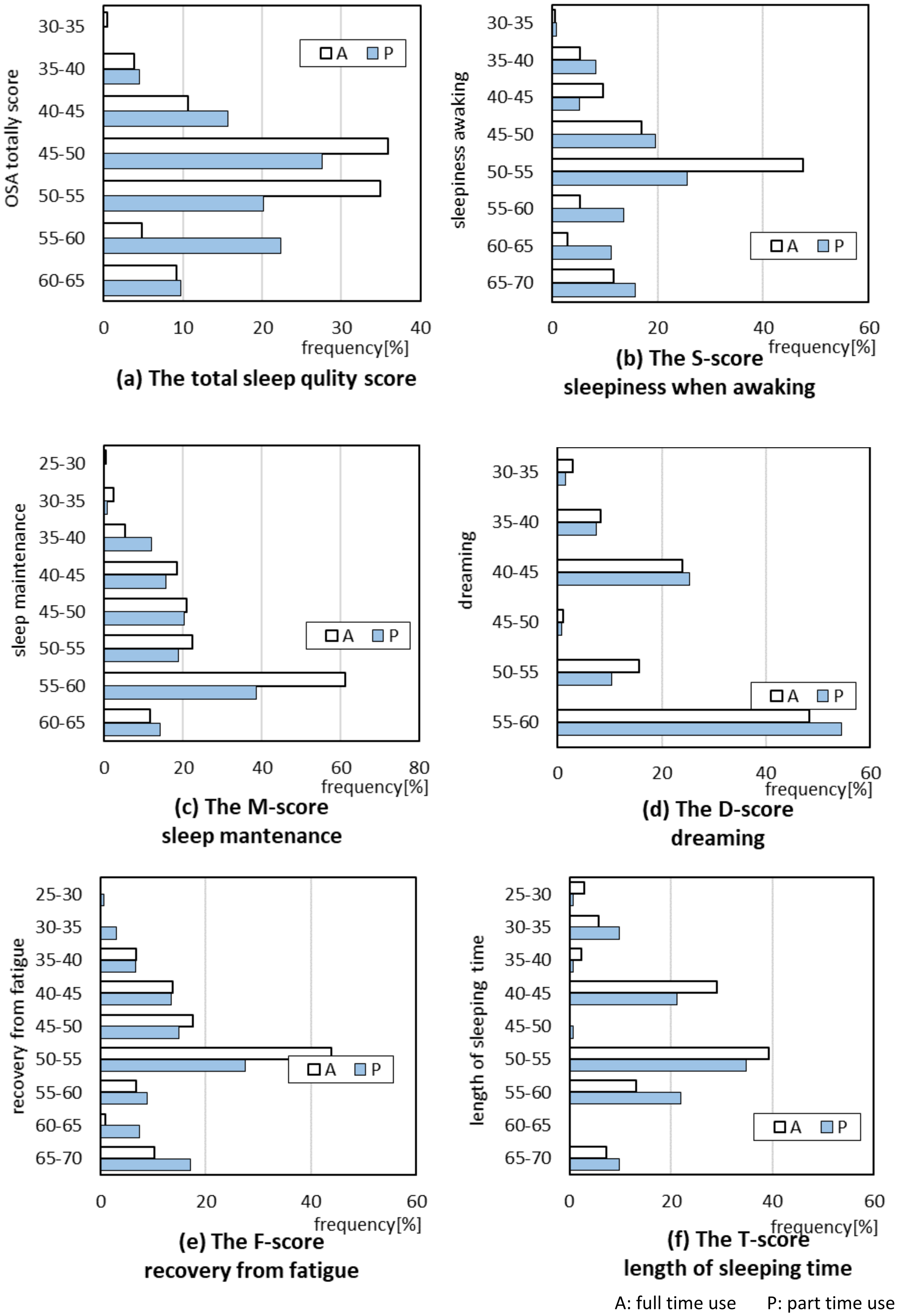



Figure 10 Sleep quality scores

## 7. Conclusions

Thermal environment and subjective evaluation for 137 nights reported by 23 respondents of partial cooling use and 209 nights reported by 33 respondents of full-time cooling use were compared.

As causes of partial cooling, followings were revealed. 1) The thermal environment of the outside air was not related to how air conditioners were used during sleep. 2) Heat and cold tolerance of the respondents were not related to the cooling use, but easy perspiration and poor circulation caused partial cooling. 3) Partial cooling users had less stress, lower income, stronger environmental consciousness and habits of more frequent clothing and bed quilt control. 4) Dwelling units of partial cooling users were less sunny, more efficient in cooling, stronger in thermal insulation, less condensed, and lower on living floors. 5) Bedrooms of partial cooling users had better views, better thermal insulation, and better ventilation, but less glare, less polluted outside air, less annoyance from solar heat and less anxiety about crime.

As effects of partial cooling, followings were revealed. 6) The bedroom absolute humidity ratios were higher; the humidity sensation and perspiration sensation were higher in partial cooling dwelling units. 7) The total sleep quality score and the sleepiness score of morning awakening were higher for partial cooling users. But no differences were found between sleep maintenance scores of partial cooling users and full-time cooling users, although partial cooling users awakened more frequently during sleep than full-time cooling users did.

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# Snuggies at work: Case study examples of thermal [dis]comfort, behaviors, and environmental satisfaction in the workplace

**Julia K. Day[1], Zakora Moore[1], and Shelby Ruiz[1]**

[1] Washington State University, USA; julia_day@wsu.edu
Integrated Design + Construction Laboratory: PO Box 645815, Pullman, WA, 99164

**Abstract:** This paper discusses findings from a large mixed methods study in the U.S. Differences between the climate type and thermal/visual satisfaction were explored through qualitative and quantitative methods. Multiple statistical tests were run to determine if there was a difference between a buildings' climate type and occupants' thermal or visual satisfaction. Climate types were grouped into three categories: hot and humid, mixed-marine, and cold or very cold. One-way ANOVA tests were run between climate categories and satisfaction scales. There was no significant difference found between the visual satisfaction scales and climate type. However, there was a statistically significant difference found among the three climate types and the thermal satisfaction scale responses. People in the mixed-marine climate type category were less satisfied with their thermal conditions than occupants in the other two climate type categories. Occupants' reported satisfaction levels remained positive, despite the significant differences found between climate types and reported temperature differences. Follow up interview responses alluded to the importance of adapting one's own behaviour and playing a more active role to achieve thermal comfort as beneficial to building energy use outcomes. Interviews also uncovered interesting findings surrounding thermal comfort, including dress code, cultural expectations, communication styles and adaptive behaviours.

**Keywords:** Thermal comfort, adaptive opportunities, occupant comfort

## 1. Introduction

As technologies advance, an increasing number of high-performance buildings are emerging. However, these sustainable, energy-conserving buildings oftentimes garner their efficiency by providing little control to their inhabitants. This lack of control, as well as a lack of understanding about systems, may lead to thermal discomfort for building occupants. This discomfort may prompt occupants to interact with the building through unorthodox strategies that compromise the energy saving goals of high-performance buildings. For example, occupants may tape over diffusers or place popsicles on top of thermostats to thwart setpoints and energy saving goals (Day and O'Brien, 2017). On the other hand, occupants may also suffer in silence or take adaptive actions to maintain comfort. These examples demonstrate occupant actions reported in the study reported herein. In fact, the title of this paper is not entirely snarky; it represents an genuine finding of this research in which occupants used "work snuggies" to maintain thermal comfort near drafty windows.

As individuals continue to spend the majority of their time indoors, designers are moving to prioritize comfort, health, and productivity within these spaces (Deng and Chen, 2018). To achieve these lofty goals, it is important to clearly define and understand how designers can approach the great challenge of providing occupant comfort. To better understand thermal comfort, beyond technical guidelines and definitions, this study offers insights from survey results and in-depth conversations with building occupants of high-performance buildings in a variety of climate types.

In particular, this paper discusses findings from a large mixed methods study in the United States. Differences between the climate type and thermal/visual satisfaction were explored through qualitative and quantitative data collection methods (i.e. surveys and interviews). The hypothesis and primary research question results have been reported elsewhere, (Day, 2014; Day and Gunderson, 2015). However, one of the research questions, not yet been disseminated, lead to interesting findings directly related to thermal comfort. As such, the following research question is discussed as the primary focus of this paper*: Is there a difference between climate type and thermal satisfaction or visual satisfaction?*

The first section of this paper includes a brief explanation and definition of thermal comfort, an overview of various high-performance building design considerations as related to thermal comfort, factors that influence occupants' thermal comfort, and occupant interactions with the building to maintain thermal comfort. This literature review provides the foundation in which to discuss the study methodology. This section is then followed by the results and discussion sections, which tie the literature review directly to the results.

## 2. Literature review: Defining thermal comfort

Thermal comfort is a meaningful aspect of encompassing occupant satisfaction. Thermal comfort represents an occupant's overall satisfaction of their indoor environment. While the there are many predictive standards for designing for thermal comfort, designers and engineers must also acknowledge that people (and their perceptions of thermal comfort) is complex (Nicol and Humphreys, 2002; Schellen et al, 2013).

One of the factors that affects both building design and occupant comfort relates directly to climate. In the U.S., ASHRAE has designated eight distinct climate zones: hot-humid, mixed-humid, hot-dry, mixed-dry, cold, very cold, subarctic, and marine, which are all defined based on heating degree days, average temperatures, and precipitation levels (Baechler, 2015). Variable climatic conditions, building orientation, building envelope strategies and more can all impact indoor thermal conditions.

When assessing indoor environments, ISO 7730 and ASHRAE Standard 55 are the two most utilized units of measurements for thermal comfort throughout Europe, as well as North America and Asia, respectfully (Engineers, 2017; ISO, 2015). Both standards have been thoroughly developed and operate based on heat-balance methods referred to as predicted mean vote (PMV) and predicted percentage dissatisfied (PPD) (Parkinson et al, 2019).

Since much of this research project was conducted in the United States, ASHRAE standards, guidelines, and definitions were referenced in the following literature review. According to ASHRAE Standard 55, to achieve thermal comfort, at least 80% of a building's occupants must be satisfied, as to not exceed a percentage of people dissatisfied (PPD) of 20% (Aryal and Becerik-Gerber, 2018).

In addition to ASHRAE thermal comfort surveys and tools, thermal comfort can also be assessed by proxy through Indoor environmental quality (IEQ) surveys and post-occupancy evaluations. One study, conducted by Frontczak et al (2012), found that occupants more highly valued their thermal comfort over air quality, acoustic environment, and visual comfort (Frontczak et al, 2012).

Rapid and innovative progress in technology can also aid in a better understanding how thermal comfort can be measured more accurately and precisely. For instance, a simulation study in Monte Carlo found that low-cost pervasive monitoring technologies such as SAMBA, the tested IEQ monitoring system, may potentially improve the industry's response to and understanding of, indoor environmental quality issues (Parkinson et al, 2019). Another recent development, the thermal heat balance model (ATHB), permits the prediction of thermal sensation and thermal comfort votes at great magnitudes (Schweiker and Wagner, 2015). Other studies have used thermal cameras and measurements of actual skin temperature to help identify opportunities for increased thermal comfort in buildings (e.g., Cheng et al, 2017).

The way in which we measure thermal comfort is rapidly changing, but through the literature, occupants consistently value their thermal comfort, regardless of how it is measured.

**2.1. High-performance buildings and energy efficiency**

HVAC systems are commonly responsible for 43% of energy consumption in U.S. buildings (Aryal and Becerik-Gerber, 2018). Many standards have become increasingly aggressive in terms of building energy codes and design expectations of mechanical systems and strategies for high-performance buildings (O'Brien and Gunay, 2014). Although some mechanical systems aim to lessen overall energy consumption, depending on how they are utilized, energy use and associated costs may *increase* if not properly commissioned or understood.

Building systems often waste energy when running controls that do not suit their users (Bordass et al, 1993). During extreme seasons, mechanisms such as air-conditioners serve as the dominant measures for heating and cooling indoor air temperatures, but there are typically 23.2% of windows partly ajar when these mechanisms are in use (Liu et al, 2012). Conflicting methods, such as simultaneous heating and cooling, can contribute to wasted energy in buildings.

There are a few passive and mixed-mode systems frequently used in high-performance buildings that can great affect both comfort and energy use. Daylighting and natural ventilation are two of the most implemented forms of passive systems.

Good daylighting can increase workers' performance and speed; it may also decrease mistakes, accidents, and absenteeism (Ries et al, 2006). This promotes both visual and non-visual biological effects of occupants (van Bommel, 2006). To control daylight, blinds are the typical shading mechanism. In Newsham's (1994) findings, manually operable window blinds improved thermal comfort, as opposed to no shading device.

Other control options in naturally ventilated buildings include central heating, doors, curtains, heaters, and hot air blowers, which are all key in achieved needed air movement that is heavily influenced by outdoor airflow (Daghigh et al, 2008a; de Dear and Brager, 2002).

Mixed-mode systems, that integrate both mechanical and passive systems, primarily revolve around providing the occupant with enough adaptive opportunities, or personal control of environmental conditions (Brager et al, 2004b). Buildings that operate on mixed-mode systems have become a favoured method in the recent years as they provide equal use of both manual and automatic systems, specifically, through the use of natural ventilation combined with mechanical cooling (Ackerly and Brager, 2013; Brager et al, 2011). Commonly, this approach to space conditioning obtains natural ventilation through either manually or automatically controlled operable windows that allow for proper air circulation as well as improved thermal comfort (Brager et al, 2004a). According to Cole et al, operable windows are growing to be a prerequisite of a North American green building regardless of its type, size, or complexity (Cole and Brown, 2009).

A popular approach to mixed-mode operable windows is the implementation of signalling systems, which operates based on notifying and advising the occupant for when best to utilize their manual controls to make their environment more thermally comfortable. However, signalling controls also have drawbacks, as it is difficult to program the human factor of an occupant desiring either fresh air or air circulation (Ackerly and Brager, 2013).

Ultimately, to achieve optimal thermal comfort and energy efficiency in a high-performance building, control designs and human-building interfaces must be carefully taken into account for both automatic and manual systems (Bordass et al, 1993). A building's design heavily influences the total occupant experience and interior environment, and comfort may vary widely, depending on the type of building. Thoughtful design must consider a building's passive, active, and human interface as a connected system that will promote comfort and energy efficiency (Bordass et al, 1993). However, a known barrier in achieving optimal energy efficiency in any given office building is the comfort of the occupant.

Behaviors of occupants can both positively and negatively impact a building's energy use whether it is during regularly occupied hours or even when they are not present (Day and Gunderson, 2015). Thermally and visually comfortable occupants are less inclined to engage in energy-intensive actions (O'Brien et al, 2019).

### 2.2. Factors contributing to occupants' thermal comfort

An occupant's thermal comfort is critical as it can impact their satisfaction with their environment, their health, as well as their productivity (Aryal and Becerik-Gerber, 2018). Thermal comfort is multifarious in nature and impacted by demographics, culture, biology, and more. In terms of environmental factors, sufficient air movement, humidity levels and ventilation are all critical for maintaining thermal comfort (Daghigh et al, 2008a).

Age greatly influences the thermal comfort of an occupant. Aging, unsurprisingly, produces negative effects on performance and thermal sensation. Schellen et al (2010) that the elderly population had a 5-20% lower performance score than the young adults, and a the thermal sensation assessment was also 0.5 units lower in the elderly. In general, the elderly population is more likely to have progressed diseases and lessened overall activity, and as such, concern must be given when adjusting thermal environments for senior populations (Anderzhon, 2012; Ashe et al, 2009). Additionally, when seeking post occupancy data from elderly individuals, attention to the questions asked and metrics evaluated must be given for variants in skin sensation, and thermal preferences (Anderzhon, 2007).

Culture (both office or company-based, as well as geographically speaking) heavily influences an occupant's expectations of their thermal and visual comfort. In reference to office buildings, the common layout of shared spaces versus personal spaces forces each occupant into similar, un-personalized conditions that tend to be unsatisfactory for everyone involved (Day and O'Brien, 2017). In addition, it has been found that occupants may choose to remain uncomfortable and not alter their thermal conditions out of concern for anyone else's comfort. Holistically, cultural disparities founded on habituation and expectation, can contribute to psychological adaptations, which often alters thermal perceptions (Brager and de Dear, 1997; Liu et al, 2012).

A reoccurring finding is that both gender and health have an influence on an occupants' perception of comfort, although great debate occurs over the significance and reality of such influences (Choi and Yeom, 2019; Davoodi et al, 2017; Karjalainen, 2012). In most cases, females express their thermal dissatisfaction more regularly than males, and are also more receptive to temperature deviations from neutral states (Jacquot et al, 2014). Several studies have discovered a correlation between females and sensitivity to cooler extremities and distal skin regions that encompass hands, forearms, and upper arms, which serve as significant thresholds for overall thermal sensation (Jacquot et al, 2014; Schellen et al, 2012; Schellen et al, 2010). Karjalainen (2007) found significant differences between the genders in preferences of thermal comfort and frequency of interaction with thermostats, as well as females reporting lower satisfaction rates due to unideal temperatures, being either too hot or too cold (Karjalainen and Koistinen, 2007). This finding is supported specifically by Schellen et al. (2012), who found female participants were less satisfied and less comfortable than their male counterparts, but also that skin temperature of their hands significantly influenced their whole bodies' thermal sensation more than it did for the men (Schellen et al, 2012). On the other hand, Zhao et al. (2017) posits that thermal comfort is based more on individual preference than gender or age, and that individuals are likely to develop thermal preferences that are consistent over time (Zhao et al, 2017). Disagreements on thermal comfort and biology continue, as interest in understanding the complexity of the subject in academia grows.

When confronted with thermal discomfort, occupants may approach this issue in several ways, including not only physical solutions, but various psychological coping mechanisms such as tolerance or ignorance (O'Brien and Gunay, 2014).

**2.3. Occupant interactions with their building & comfort provisioning**

A series of factors determine when, how, and to what extent an occupant may choose to interact with their building. Details, such as location and ease of a building's control interfaces, greatly impact the frequency of use by occupants. Features that are too complex -- either passive, mechanical, or mixed-mode -- may overwhelm the occupant and discourage use (Bordass et al, 1993; Galasiu and Veitch, 2006; O'Brien and Gunay, 2014). The concept of usability is well documented in Ponce et al.'s study where usability is viewed as a measurement that can improve the use of devices or interfaces when considering a series of factors, like display and flexibility (Ponce et al, 2018).

Also, to further interact with their environment effectively, occupants must be knowledgeable of the high-performance building that they inhabit, as well as the controls allotted to them (Day, 2015; Day and Heschong, 2016; Orr, 1993). Most occupants are unaware and easily confused with the logistics on how their building or space may operate, and adequate training is often found to assist in the disconnect between an occupant and their building, as well as significantly boost occupant satisfaction rates (Day and Gunderson, 2015).

Although much of today's automation systems are refined with the intent to improve both comfort and energy efficiency, their implementation often runs the risk of establishing a perceived lesser sense of control for occupants, leading to diminished satisfaction (O'Brien and Gunay, 2014). Occupants tend to rank the importance of comfort factors based on what dissatisfies them the most (Galasiu and Veitch, 2006).

When occupants have little to no influence on the conditions of their environment, they condition themselves to their environment. Clothing adjustment serves as one of the main methods in which occupants adapt their behaviours in search of thermal comfort. The measurement of resistance provided by clothing to sensible heat transfer is expressed in the unit CLO (Brager and de Dear, 1997). Clothing plays a major role in defining human microclimate, which is responsible for administering feelings of comfort as well as peak productivity (Sahta et al, 2014).

All of the factors briefly described the literature review above provide a foundation in which to discuss the methodology and results of this study.

## 3. Methodology

The methodology implemented for this research was a three-phase sequential explanatory mixed method study. Both online surveys and interviews were used to discover how occupants understood how to use their building controls.

Specifically, in the first phase of the study, open-ended interviews were conducted with experts in the field. In the second phase, an online survey was sent to occupants in high performance office buildings. In the final, third phase of the study interviews were conducted to further understand responses from the survey. Initially, quantitative and qualitative data were collected from 56 high performance buildings. Of these, 53 of the buildings were in the U.S., was in Canada, and two in Europe. The majority of the data analyses reported in this paper emerged from the survey responses (*n*=118) and interviews (*n*=41) (Day and Gunderson, 2015). The following section includes a brief discussion of sampling selection method used for this research, as well as limitations related to the sample.

### 3.1. Sampling technique

Initially, the researchers set a goal to randomly select a sample from a stratified selection of high-performance buildings from all eight ASHRAE climate zones to minimize threats to external validity. First, all of the buildings compiled for the high-performance building database were stratified by climate zone, and a weighted sample was randomly selected to comprise the sampling frame. After buildings were initially randomly selected from each stratum, the researcher began to contact building representatives for study participation. However, it was quickly realized that this method was too ambitious for a single un-funded researcher. Therefore, the sampling technique shifted from a climate stratified random sample to a purposive sampling technique. The building design, overall square footage and climate zone became additional variables to compare individual responses. Full details of the sampling strategy shift, and further limitations, are reported in Day and Gunderson (2015).

### 3.2. Research Question

The overarching hypothesis for this study was that if occupants had received training or education on how to use their building controls (e.g., window blinds, lighting controls), then they would be more satisfied than individuals who had not received any training or did not understand how to use their building controls. As previously discussed, the hypothesis and primary research question results have been reported elsewhere, in Day and Gunderson (2015). The following research question is the primary focus of this paper*: Is there a difference between climate type and thermal satisfaction or visual satisfaction?* Results are presented below.

## 4. Results

To best answer the focal research question and to determine if a difference existed between climate type and thermal and/or visual satisfaction, a Pearson chi-square test was run between the existing climate zones against the recoded satisfaction variable that grouped responses into "mostly satisfied" or "mostly dissatisfied." No significant differences were found between climate type and the overall satisfaction variable, so the satisfaction responses were broken up by the satisfaction questions were (a) thermal, or (b) visual. This created two new summated scale variables that could then be tested inferentially against climate types. For climate types, since there were some categories with very low response rates (i.e. climate zones 7 and 8), the ASHRAE climate zones were regrouped and recoded into a new climate type variable (independent variable) for analysis, which grouped like climate zones together to increase the sample size for each category.

Decreasing the number of categories, and increasing the number of cases within each category, improved the statistical validity of the tests conducted. The three categories were (a) hot and humid (1A, 3A), (b) mixed marine (4C), and (c) cold and very cold (5B, 7, 8). Although climate zones 5B, 7 and 8 differ slightly, their individual group mean responses were nearly the same for the thermal and visual satisfaction responses, therefore, it was determined they could be combined into one "cold and very cold" group. Since the skewness was normal for both variables, an ANOVA test was run between the recoded climate type variable and the thermal summated satisfaction scale and the visual summated satisfaction scale (dependent variables) to test the difference between climate types and satisfaction. Tukey Post Hoc HSD tests were also conducted to investigate where the differences existed since the overall *F* (ANOVA) was significant ($p \leq .001$). A statistically significant difference was not found among the three levels of climate types and visual satisfaction responses. However, a statistically significant difference was found among the three levels of climate types and thermal satisfaction responses, $F$ (2, 115) = 10.584, $p \leq .001$. Figure 1 shows the mean score for the hot and humid climate (5.38), the mean value for the mixed marine climate (4.02), and the mean value for the cold and very cold climate (4.22).

Post hoc Tukey HSD tests indicated that the mixed marine group and hot and humid group differed significantly in their thermal satisfaction assessments with a large effect size ($p < .05$, d = 1.23). Likewise, there were also significant mean differences amongst the hot and humid group and the cold and very cold group with a large effect size ($p < .05$, d = 1.02). If Cohen's *d* is greater than 1, then the difference between the two-group means is larger than one standard deviation (Cohen, 1988).

This finding warranted further analysis, so climate data were gathered for the time periods when the surveys were taken for the "mixed marine "climate type buildings. The "hot and humid" climate data were also investigated since the most significant difference was found between those two groups. Historical climate data were pulled for each location during the dates the survey was taken for each building from http://www.wunderground.com. Even though the surveys were taken at different times of the year, the average outdoor dry-bulb temperatures for the periods when each of the surveys were taken were still fairly similar for each building (WeatherUnderground, 2013). See Figure 2.

*One-way ANOVA and Tukey Post Hoc Tests for climate type * thermal & visual satisfaction*

| | | N | Mean | Std. Deviation | Std. Error | 95% Confidence Interval for Mean: Lower Bound | 95% Confidence Interval for Mean: Upper Bound | Min. | Max. |
|---|---|---|---|---|---|---|---|---|---|
| *Environmental Satisfaction (thermal)* | hot and humid | 20 | 5.38 | 1.071 | .240 | 4.87 | 5.88 | 4 | 7 |
| | mixed marine | 62 | 4.02 | 1.147 | .146 | 3.73 | 4.32 | 2 | 7 |
| | cold and very cold | 36 | 4.22 | 1.198 | .200 | 3.82 | 4.63 | 1 | 6 |
| | Total | 118 | 4.31 | 1.241 | .114 | 4.09 | 4.54 | 1 | 7 |
| *Environmental Satisfaction (visual)* | hot and humid | 20 | 5.22 | 1.311 | .293 | 4.61 | 5.83 | 2 | 7 |
| | mixed marine | 62 | 5.32 | 1.346 | .171 | 4.97 | 5.66 | 1 | 7 |
| | cold and very cold | 36 | 5.84 | 1.500 | .250 | 5.33 | 6.35 | 2 | 7 |
| | Total | 118 | 5.46 | 1.400 | .129 | 5.20 | 5.71 | 1 | 7 |

*ANOVA*

| | | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|---|
| *Environmental Satisfaction (thermal)* | Between Groups | 28.025 | 2 | 14.012 | 10.584 | .001* |
| | Within Groups | 152.248 | 115 | 1.324 | | |
| | Total | 180.273 | 117 | | | |
| *Environmental Satisfaction (visual)* | Between Groups | 7.603 | 2 | 3.802 | 1.971 | .144 |
| | Within Groups | 221.781 | 115 | 1.929 | | |
| | Total | 229.385 | 117 | | | |

Figure 1: One-way ANOVA and Tukey Post Hoc Tests for climate type x thermal & visual satisfaction

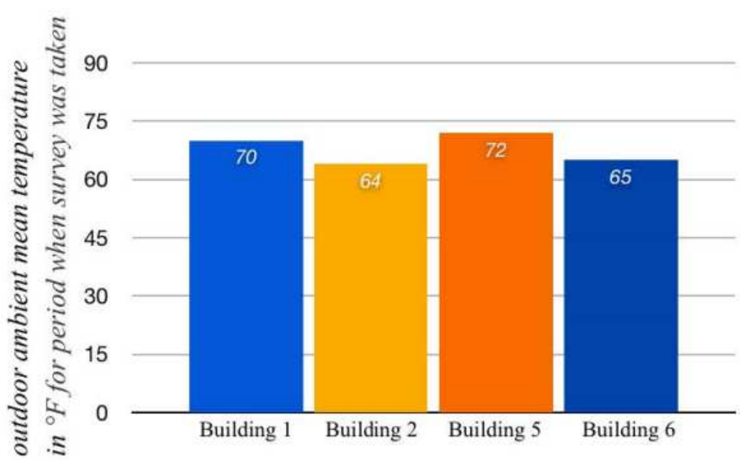


Figure 2: Mean temperatures for Buildings 1,2,5, & 6 during the respective survey period.

Follow-up interviews were not conducted for Building 5 or 6, but they were done for Buildings 1 and 2. The results from both the descriptive statistics for thermal satisfaction and the ANOVA analyses were reinforced by the interview comments. People in Building 1 most frequently reported they were too cold in the building.

When one occupant was asked what they disliked about their building, the response was, *"I think the only thing is we cannot figure out the louvers that are above our windows and for some reason the one right above my desk is bent or got stuck open or something and it opens at totally different times than all the others."*

Another occupant from the same building said, "*I think people enjoy the ability to open the windows, but I know that there are some complaints with the louvers for venting the $CO_2$, particularly from people that are seated close to the exterior perimeter. It creates that suction, the vacuum…So they get cold when that happens – you know, their desk space. So, I would tell you there are a few ladies in the office that have blankets and snuggies at their desk."*

The comments surrounding the natural ventilation can be further explained by the building strategies (automatic louvers) used in Building 1, which were evident in both the interview responses and through the document analysis. The louvers automatically opened based on $CO_2$ levels and previously programmed temperature setpoints. Figure 3 illustrates section views of the automated louvers for natural ventilation for Building 1. (Note: the image cannot be properly cited without identifying the building, so it should be noted that these drawings were taken and modified from Building 1's tenant improvement manual, which was collected during the qualitative phase). While occupants in Building 1 liked the ability to open windows, there were some occupant complaints about being too cold, which aligned with the results found in the quantitative phase. Alternatively, in Building 2, the occupants were encouraged to interact with the natural ventilation system to suit their thermal comfort needs while maintaining the energy efficiency of systems. The statement below describes the innovative system and controls used in the net zero building.

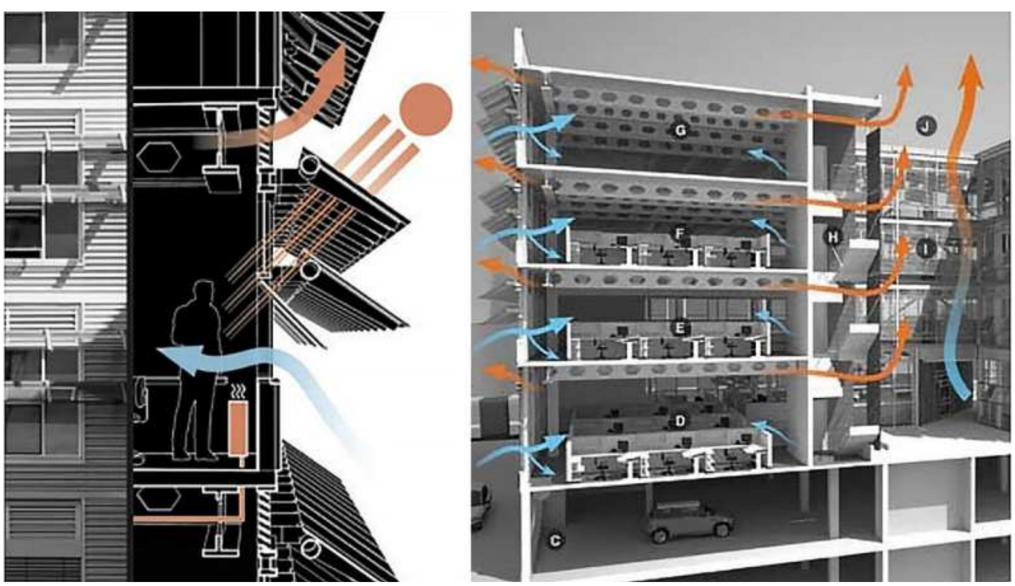

Figure 3. Section of natural ventilation louver strategy in Building 1.

*"We have a completely open system. So, you can do it remotely or you could be anywhere in the building and just walk over and say: Hey, it's too hot in the room or too cold or I want to turn on the lights or off lights or whatever. It is a touch panel and is at two places in the middle of this building… There's also an autonomous part of the building where it sort of acts on setpoints like normal building automation systems, but we also have an adaptive predictive element in it so that it looks at trends. We know that it's going to be cold January 15th, and we have last year and the year before and the year before that's data, and we can look at how the building was used, by how many people, and that weather regime. And we have a lot of meteorological sensors, solar sensors, ETO sensors, all kinds of different things that tell us how to make the building more comfortable."* The individuals in this building reported high satisfaction responses for the thermal comfort questions.

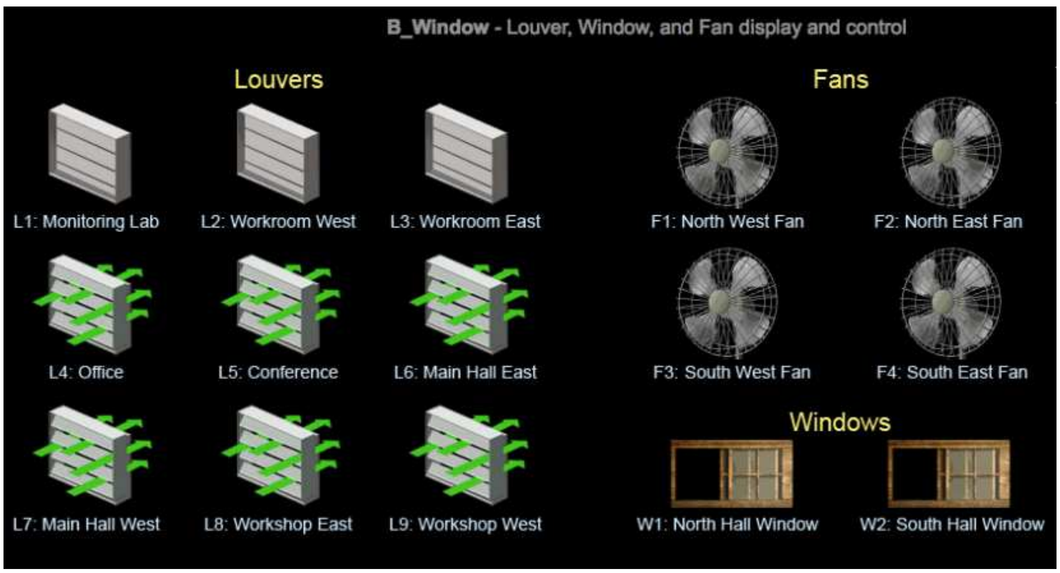

Figure 4. Screen Shot of Energy and Control Panel Dashboard for Building 2.

Figure 4 shows a screenshot of the interactive control system the occupant mentioned in their statement. If an occupant was too hot or cold, they could log into the system on their computer or cell phone and simply click on the picture of whichever louver, fan or window they wanted to manipulate. The results introduced in this section are further discussed in the section below.

## 5. Discussion

Multiple statistical tests were run to determine if there was a difference between a buildings' climate type and thermal or visual satisfaction. To increase the number of cases for statistical testing, all climate types were grouped into three categories: hot and humid, mixed marine, and cold or very cold. One-Way ANOVA tests were run between the recoded climate type categories and both the summated visual and thermal satisfaction scales. There was no significant difference found between the visual satisfaction scales and climate type. However, there was a statistically significant difference found among the three climate types and the thermal satisfaction scale responses. Overall, people in the mixed marine climate type category were less satisfied with their thermal conditions than those in the hot and humid and the cold and very cold climate types.

This significant difference in satisfaction appraisals for thermal comfort is particularly interesting, especially since the average outdoor temperatures were relatively similar for all the building locations when the survey was taken. The following graphic was developed to demonstrate and overlay where the average temperatures for some of the study buildings fell when compared to standardized thermal comfort ranges (see Figure 5). The national differences in temperature ranges were pulled from when this study took place in 2013.

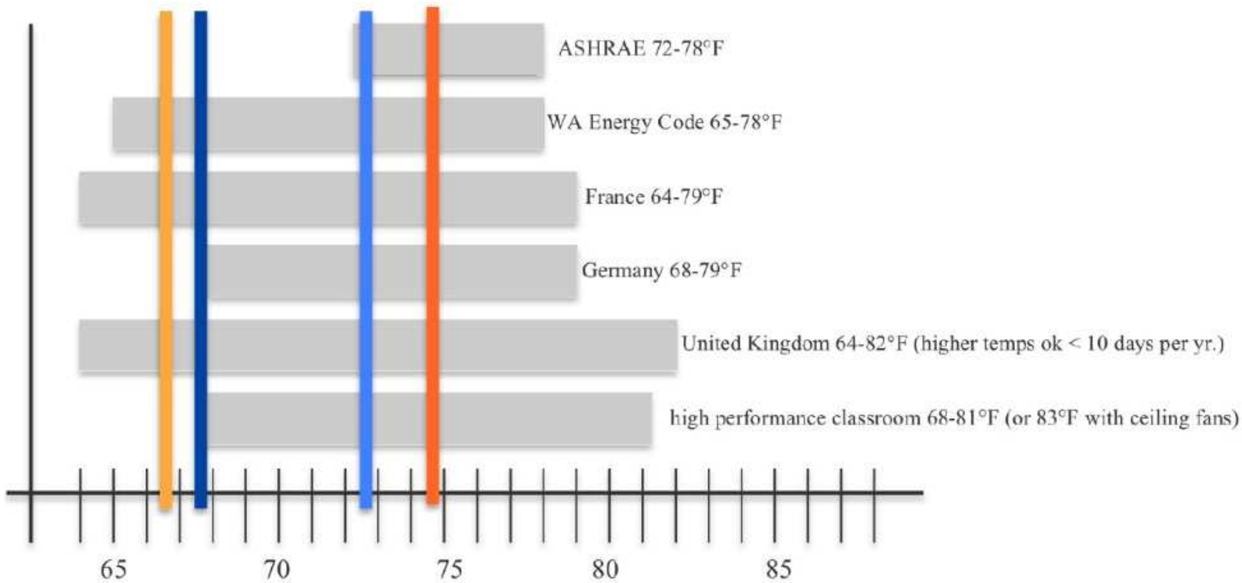


Figure 5. Occupant expectations for indoor thermal comfort compared to mean ambient outdoor temperatures for study buildings.

Buildings 2 and 3 were categorized in the hot and humid category, and they had the lowest and highest average daily temperatures, yet, occupants were more satisfied than they were in Buildings 1 and 6. Obviously, these temperatures are for the outdoor averages and interior temperatures were not measured. However, although the coloured bars in Figure 5 represent outdoor temperatures, it is important to note that all of these buildings were implementing natural and passive ventilation strategies at the time of the study. None of the outdoor average temperatures fell within the prescribed ASHRAE thermal comfort range, except for Building 5. However, all the temperatures did fall within an acceptable thermal comfort range in France and the United Kingdom. As seen in the literature, the thermal comfort standards and ranges are broader in many European countries when compared to the U.S (Barlow and Fiala, 2007). Additionally, many authors have implicated that people in high-performance buildings need to expand their notion of thermal comfort if energy savings are to be realized (Cole et al, 2008; de Dear and Brager, 2002; Halawa and van Hoof, 2012; Indraganti et al, 2014).

One reason for the discrepancy in thermal satisfaction ratings may have to do with the building strategies that were used in certain climates. A large majority of the survey respondents in the mixed marine climate occupied a building with an automated natural ventilation system with louvers that would automatically open and close. It was revealed during the interviews that the occupants were often too cold when the louvers would open, and it was frustrating to them that they could not open or close the louvers manually. In addition, the way in which the interior space was arranged may have also contributed to thermal discomfort. The open office workstations were situated around the perimeter of the building, so when the louvers would open for natural ventilation, air would blow directly on the occupants. This additional air velocity likely contributed to lower thermal comfort appraisals.

Another reason for the significant differences between thermal satisfaction in the buildings in the hot and humid climate and those in the mixed marine climate may be attributed to the level of control the occupants had over their environment. After studying the building plans and photographs, an interesting fact was discovered. The majority of occupants surveyed in the mixed marine climate were in highly automated buildings, where little occupant interaction was required unless an occupant wanted to override a setting. Alternatively, the building occupants in the hot and humid climates had more control in terms of how much they could manipulate the building. Even though many of the building systems were still automated, a free-standing energy kiosk, and an easy-to-use computer interface, allowed occupants to turn on and off lights, open and close windows, turn on and off fans, and open and close ventilation louvers all from their personal computer or phone.

The literature suggested that people with more access to personal control over their environment have a wider range of perceived thermal comfort (Day et al, 2012; Day and O'Brien, 2017; Hellwig, 2015; Luo et al, 2014). This may be the case for this study as well. Even though Building 2 had the lowest mean outdoor temperature when compared to all of the other buildings, the reported thermal satisfaction was the highest. This idea of “perceived” comfort also emerged during an interview with one of the occupants from Building 2. It was clear the building occupants understood that the building temperatures would shift more frequently and more dramatically in their office building than they might in a conventional office building. In this case, the occupants’ expectations for thermal comfort were different, which led many of the occupants to the conclusion that if they were too hot, then they could open a window, or if they were too cold, then they could put on a sweater. This notion of adapting one’s behaviours and environment for thermal comfort is something that is beneficial to energy use in high-performance buildings (Barlow and Fiala, 2007). Similar themes emerged in the interviews for other buildings.

*“It is far more comfortable for me to work here than our last building, which we used to call “the pit.” It was kind of in a very dark dingy corner with a vent blasting at you. So, it was definitely uncomfortable. I don’t know if my experience was typical, but I definitely enjoy more control and also the fact that we are able to control our comfort… you get into conversations with your co-workers more often about it [comfort], which is really good.”*

Once occupants understand the need to play a more active role in their thermal comfort, and that the building will not always be between 72°F and 78°F, then they will be able to make adjustments as needed.

These issues such as types of building strategies used, occupants’ adjacency to natural ventilation/openings, level of control, perception of comfort and adaptive comfort behaviours all may account for the lower satisfaction appraisals of thermal conditions in the mixed marine climate type. However, a key limitation of this study is that the interior temperatures were not actually measured for any of the buildings in this study; these conclusions are being drawn from the existing literature, the mean average outdoor temperatures during the time of the survey for each building, and the occupant responses.

Even though there was a significant difference found between climate types and reported environmental satisfaction, all mean satisfaction values were still fairly positive in nature. On a Likert scale from (1 to 7), where one represented least satisfied and seven represented most satisfied, the lowest reported mean satisfaction rating was 4.02, and the highest was 5.38, which both fall within the neutral to satisfied range.

It is also important to note that a significant difference was found between gender and satisfaction, as males were more satisfied with their indoor environment (all IEQ factors) than females. The differences in satisfaction between males and females cannot necessarily be explained by this study. However, as previously mentioned, the literature suggests that females are typically less satisfied with thermal comfort than males (Karjalainen and Koistinen, 2007). The majority of the sample in this study (both male and female) were still "mostly satisfied" with their environment, but females were less satisfied than males in the thermal assessment.

## 6. Conclusion

Ultimately, there was no significant difference found between the visual satisfaction scales and climate type. However, there were statistically significant differences found among the three climate categories and the thermal satisfaction scale responses. People in the mixed-marine climate type category were less satisfied with their thermal conditions than occupants in the other two climate type categories. Occupants' reported satisfaction levels remained positive, despite the significant differences found between climate types and reported temperature differences. Follow up interview responses alluded to the importance of adapting one's own behaviour and playing a more active role to achieve thermal comfort (e.g. wearing a "work snuggie") as beneficial to building energy use outcomes. Interviews also uncovered interesting findings surrounding thermal comfort, including dress code, cultural expectations, communication styles and adaptive behaviours.

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# Thermally Activated Furniture: Learnings from Thermal Mannequin and Human Subjects.

**Rajan Rawal*, Vishnu Vardhan, Yash Shukla, Arjun Desai**

Centre for Advanced Research in Building Science and Energy (CARBSE), CRDF, CEPT University, Kasturbhai Lalbhai Campus, Ahmedabad – 380009, India; rajanrawal@cept.ac.in

**Abstract:** This study investigates the effectiveness of Thermally Activated Furniture (TAF) in controlled indoor office environment set up conditions. The TAF included radiantly cooled low-height vertical partitions placed on the front and to the side of a workstation. The study presents the results of two experiments: the first was conducted using a heated thermal mannequin and the second with help of human subjects. Both experiments were conducted in sequence, using the same experimental facility, referred as the Thermal Comfort Chamber (TCC). The Overall and Local Skin Temperature as well as Heat Flux of the thermal mannequin have been presented. The 22 human subjects were surveyed for their Thermal Acceptance, Sensation, Comfort, and Preference. 16 combinations of TCC Air Temperature and TAF Surface Temperature were investigated for the thermal mannequin and 10 combinations for the human subjects. The Mannequin PMV was compared with the Human AMV. The Cooling Thermal Power of the setup was calculated for all the cases of the Thermal Mannequin study. The results from the two experiments were found to be mutually consistent and indicative of the fact that the TAF operation was effective in providing comfort at indoor air temperatures of up to 28°C.

**Keywords:** PCS; Radiant Cooling; Thermal Mannequin; Human Subjects.

## 1 Introduction

Our planet is warming at a pace faster than ever while the energy intensity of buildings does not help reverse the trend. The energy consumption by buildings is responsible for over 27% of the global greenhouse emissions and is expected to rise in the coming times (Nejat, Jomehzadeh, Taheri, Gohari, & Muhd, 2015). As per the estimate of the Sustainable Development Scenario 2010-2030 by IEA, the developing and Sub-Saharan nations will have a 100% access to electricity, which currently stands at 86% and 45% respectively (IEA, 2019). With the increase in the availability of electricity, it is natural for the population to resort to more sophisticated and energy-intensive thermal conditioning devices – studies predict a sharp increase in the demand for air conditioners and the consequent emissions in the developing nations, specifically India (Rawal & Shukla, 2014). Studies also predict a steep increase in the cooling demand of the planet, especially the global south (“India Cooling Action Plan,” 2018; International Energy Agency (IEA), 2018). The current scenario obviates the adoption of technologies and approaches which reduce the greenhouse emissions while not compromising on the provision of affordable thermal comfort to the masses.

### 1.1 The Personal Approach for Cooling

One of the emerging approaches which show promise on the aspects of energy-effectiveness and provision of comfort is the Personal Thermal Comfort approach. Personal Comfort Systems (PCS) principally operate as per the adage of *Unicuique suum* – “to each his own”, i.e. the occupants are in control of their immediate thermal ambience and can adjust it as per their preferred sensation or perception of comfort.

The conventional 'whole-volume' conditioning approach targets at conditioning the entire built volume at a single, comfortable thermal set-point at a time. On the contrary, the PCS approach targets at creating a localized conditioned zone around an occupant's body or desk as per her/his perception of comfort while keeping the surroundings relatively under-conditioned. The reasoning behind this approach is that the occupants remain stationed at a fixed spot for a prolonged time period during a majority of the daily tasks and spend a relatively insignificant amount of time in transitory movement and indoor commute, specifically in a workplace setting. This allows the dominantly unoccupied, 'surrounding' zones to be maintained at a temperature which is, (a) marginally higher than the comfortable temperature, in a cooling-dominated environment, or (b) marginally lower than the comfortable temperature, in a heating-dominated environment. The relatively uncomfortable temperature of the surroundings can be maintained by any mode of indoor ventilation ranging from natural ventilation to conventional HVAC operation at an elevated or relaxed set-point.

The PCS approach limits the size of the conditioned zone from the entire built volume to an occupant's immediate ambience (such as a cubicle space, in a workplace setting) – this enables a reduction in the overall electrical energy consumption. Studies by (Godithi et al., 2019; Kalaimani, Jain, Keshav, & Rosenberg, 2018; Zhang, Arens, Taub, et al., 2015) have shown that the PCS approach consumes a reduced amount of energy than the conventional whole-volume conditioning approach. The PCS approach also helps maintain more acceptable thermal ambiences - studies by (Greenberger, Strasser, Cummings, & Dunham, 1989; Kim et al., 2019; Samani, Rasid, & Sofian, 2015) have shown that PCS devices, in addition to increasing the occupants' thermal acceptability, improve the workplace productivity. Particularly, the PCS utilising the radiant mode of heat transfer have been found to offer more comfort to the occupants at the same environmental conditions in comparison to other PCS (Karmann, Schiavon, & Bauman, 2017; Lehrer, 2017).

## 1.2 Basis of the Study

PCS can be categorised on the basis of their mode of heat transfer, type of device, mode of operation, etc. Multiple literature reviews by (Godithi et al., 2019; Warthmann, Wölki, Metzmacher, & van Treeck, 2018; Zhang, Arens, & Zhai, 2015) studying the topic have shown that the most commonly used PCS devices utilise convection as a mode of heat transfer and incorporate devices such as Round Movable Panels (Melikov, Krejciríková, Kaczmarczyk, Duszyk, & Sakoi, 2013), Desk-mounted Devices (Bauman, Carter, Baughman, & Arens, 1998), Seat-embedded Devices (Arens et al., 1998), Garment-embedded Devices (Barwood, Davey, House, & Tipton, 2009), Fans (Arens et al., 1998), etc. There have been a few studies on PCS devices such as Radiant Heating/Cooling Panels (He, Li, He, & He, 2017; Melikov et al., 2013; Watanabe, Melikov, & Knudsen, 2010), Radiant Foot-warmers (Oi, Yanagi, Tabat, & Tochihar, 2011), Heated/Cooled Seats (Brooks & Parsons, 1999; Pasut, Zhang, Arens, Kaam, & Zhai, 2013), etc., which use Conduction and Radiation as the mode of heat transfer; however, the number of these studies is more limited than the ones focussing on convection-based devices.

The literature review also informs that PCS devices have been studied using one of the following four research methods:

i. Field studies
ii. Laboratory studies with human subjects
iii. Laboratory studies with thermal mannequins
iv. Simulation studies

However, there have been no singular studies, which have incorporated the results from laboratory studies on both human subjects and thermal mannequins. There also is a lack of studies which account for both comfort and energy vis-à-vis PCS. The literature review by Karmann et al. assess if radiant systems provided better, equal, or lower thermal comfort than all-air systems – this study also indicated that there is a lack of studies on the topic (Karmann et al., 2017). Thermal mannequins offer the ability to test various indoor environmental conditions and derive the response of an average respondent, while human subjects add the dimension of subjectivity to the study.

### 1.3 Structure of this paper

This study analyses the effect of a Thermally Activated Furniture (TAF) on a thermal mannequin and human subjects in varied indoor thermal conditions. The TAF consists of radiant cooling panels placed as desktop partitions which can be maintained at varied radiant panel surface temperatures ($T_{surf}$). The experiments on both, the thermal mannequin, and the human subjects, were conducted in controlled conditions of the Thermal Comfort Chamber (TCC) at three Air Temperature ($T_{air}$) conditions of 26, 28, and 30°C, $T_{surf}$ between 18 and 30°C, and a constant RH of 50%. Please refer Table 2 for further details.

The following narrative describes the experimental setup used for the two experiments and lays out the rationale of study cases. It mentions about the thermal mannequin – its make, measurement protocols, mode of operation, thermal energy consumption, and the monitored parameters of Overall (O) and Local (L) $T_{skin}$, O and L Heat Flux, Predicted Mean Vote (PMV). For the human subjects, it mentions about their generic characteristics, clothing type, survey protocol, and the subjective votes of Acceptance, Preference, Comfort, and Sensation or Actual Mean Vote (AMV). The discussion delves into the results for each of these parameters including the comparison of the mannequin's PMV with the human subjects' AMV, and the Cooling Thermal Power (CTP) for the thermal mannequin study.

The study concludes with a summary of the concurrence of the results for the two research methods, the extent of energy savings with respect to the pre-defined baseline, and the scope of further research on the topic.

## 2 Instrumentation and Methodology

The study methodology can be broadly categorized into two sections: Thermal Mannequin Study, and Human Subjects Study. Both the studies were conducted in the TCC and involved the usage of the same TAF setup, its sensing and controlling system, energy and environment monitoring system.

### 2.1 TCC and TAF

The TCC is located on the basement floor of the Net Zero Energy Building at the Centre for Advanced Research in Building Science and Energy (CARBSE), CEPT University, in the hot and dry city of Ahmedabad, India (Rawal et al., 2019). The layout of the chamber, as shown in Figure 1, is representative of a typical office layout and has internal dimensions of 5.5×4.5×3.2 m. The west wall of the TCC faces the ambient air while being completely shaded throughout the year, the north and east walls face conditioned zones within the basement, and the south wall is adjacent to the fill-up earth. The four walls have a U-value of 0.12 $W/m^2K$ each, while the ceiling and floor have a U-value of 0.21 $W/m^2$ each. The TCC includes one window each on the north and west walls. The north-side one is an internal window with a conditioned zone adjacent to it. . The west window, although exposed to the outdoor air, does not receive any direct solar radiation at any time of the year. The two windows are made out of double-glazed units (DGU), with AIS-Ecosense Exceed Clear vision glass of 6 mm thickness. The glass is Low - E, with a VLT (Visual Light Transmission) of 0.39 and SHGC (Solar Heat Gain Coefficient) of 0.29, along with a 12mm air gap between the two glass layers, amounting to a U-value of 1.7 W/m$^2$K.

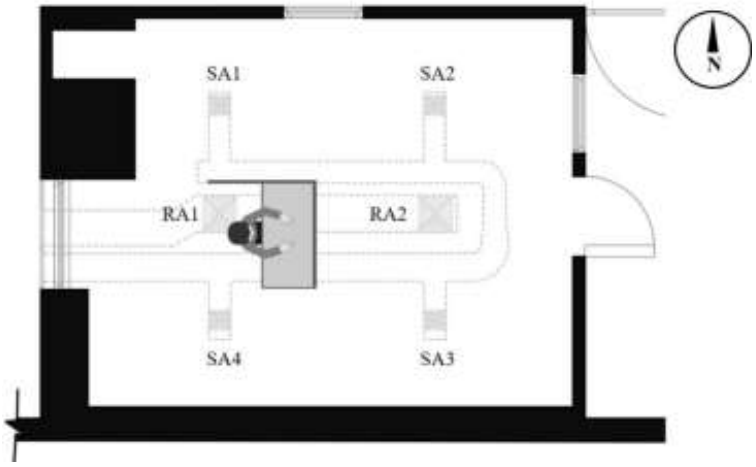


Figure 1. TCC layout.

The TCC is capable of maintaining indoor $T_{air}$ between 15 and 42°C with an accuracy of ±0.3°C and RH in the range of 16-95% with an accuracy of ±2%. Four Supply Air (SA) diffusers and two Return Air (RA) diffusers, as shown in Figure 1 maintain the indoor environmental conditions. Each of the SA diffusers supplies an air volume of 254.85 m$^3$/h. The TCC maintains homogeneous indoor thermal conditions with the maximum difference between the temperature of its air and its indoor surfaces (walls, ceiling, floor) less than ±0.3°C.

The TCC included a centrally placed workstation with a desktop (0.6×1.2 m), placed at 0.75 m from the ground. The desktop was made out of ply-board and laminate and had a 1.2×1.2 m cooling radiant panel at the front and left side of the desktop each. This setup is termed as the TAF and is shown in Figure 2. These radiant cooling panels were made out of expanded polygraphite and cooled through the embedded cross-linked polyethylene pipes which carried chilled water. The chilled water was supplied through a chilled water circuit, as shown in Figure 2. The amount of chilled water supplied to the radiant panels from the chiller was regulated using an actuator-controlled three-way modulating control valve installed on the return side, and it was measured using an analog water flow meter installed on the supply side. All the components of the chilled water circuit were ultimately connected to the Building Management System (BMS), which controlled the $T_{surf}$ of the Radiant Panels and the $T_{air}$ of the TCC.

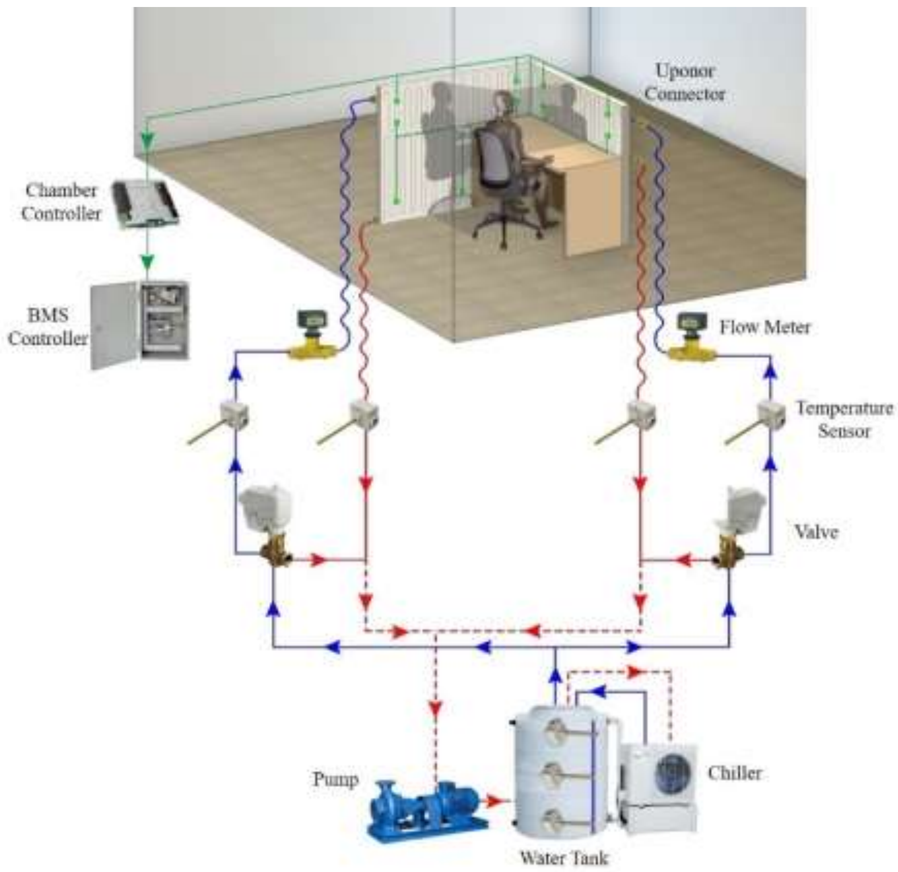


Figure 2. TAF, TCC, and the chilled water circuit.

The $T_{surf}$ of the TCC walls, ceiling, floor, and Radiant Panels, as well as the $T_{air}$ across various points close to the seated mannequin and occupant was measured using the same type of Resistance Temperature Detector (RTD) sensors. The desk-level air velocity and air supply flow rate were measured to ensure a homogeneous thermal environment and no stratification within the TCC. Table 1 includes the details of all the instruments used in the chilled water circuit as well as in the measurement of indoor environmental variables.

Table 1. Instrumentation details.

| Component | Type | Details |
|---|---|---|
| Chiller | Neslab ThermoFlex 900 | **Fluid Temperature Output:** 5 to 40°C<br>**Cooling Capacity:** 300 to 1300 W |
| Flow Meter | FTB503 – CK | **Measurement Range:** $3.15\times10^{-6}$ to $3.15\times10^{-5}$ $m^3$/sec<br>**Fluid Temperature Range:** -268 to 232°C<br>**Accuracy:** ±1% |
| Three-way Control Valve | VC 7931 | **Supply Voltage:** 24 V<br>**Control Signal:** Nominal 0/2 to 10 Vdc<br>**Input Impedance:** 47.5 kΩ<br>**Nominal Stroke Timing:** 120 sec at 60 Hz<br>**Fluid Temperature Range:** 0 to 65°C |
| Desk-Level Air Velocity Meter | Testo 480 | **Range:** 0.6 to 50 m/s (Ø 16 mm), 0.1 to 15 m/s (Ø 100 mm)<br>**Resolution:** 0.1 m/s (Ø 16 mm), 0.01 m/s (Ø 100 mm) |

| | | |
|---|---|---|
| Ambient Air-flow Meter | Accubalance Air Hood 8380 | **Range:** 0.01 to 1.18 $m^3/s$<br>**Accuracy:** ±3%<br>**Resolution:** $4.71\times10^{-4}$ $m^3/s$ (1 CFM) |
| Air Temperature Sensors | Band 5 - DIN 1/10 | **Accuracy:** ±0.3°C |
| Surface Temperature Sensors | Band 5 - DIN 1/10 | **Accuracy:** ±0.3°C |

## 2.2 Study Cases

The two experiments were conducted at various permutations of the radiant panel $T_{surf}$ and the indoor $T_{air}$. The indoor $T_{air}$ was varied between 26, 28, and 30°C, since an average Indian acclimatised to hot-dry conditions would begin to require cooling when the ambient temperature exceeds ~26°C (Manu, Shukla, Rawal, Thomas, & de Dear, 2016). The choice of the radiant panel $T_{surf}$ was governed by the following two drivers:

i. There should not be any condensation on the radiant panels, thus the $T_{surf}$ should remain higher than the Dew Point Temperature. For an added degree of caution, $T_{surf}$ should be kept 2°C higher than the Dew Point Temperature.
ii. The difference between the ambient $T_{air}$ and the radiant panel $T_{surf}$ should remain less than 10°C in order to avoid discomfort due to thermal asymmetry (ASHRAE-55, 2013).

The above two drivers allowed the establishment of a range of $T_{surf}$ for each $T_{air}$ condition, with each $T_{surf}$ separated by 2°C. The mannequin experiments were conducted prior to human subject experiments. The mannequin experiment results determined the number of cases for the experiments with human subjects. The mannequin experiment results indicated that the effect of the radiant panel was the most prominent when its $T_{surf}$ was lower than the $T_{air}$ by 6 and 8°C. Therefore, the human subject experiments were conducted for a reduced number of cases. The reference case was established by ensuring the PMV to be neutral without the operation of Radiant Panels. To determine the neutral PMV at given clothing insulation, metabolic rate, and ambient thermal conditions, Centre for Built Environment Thermal Comfort Tool (Hoyt et al., 2017) was used. The variables of air speed, RH, metabolic rate, and clothing insulation of the TCC-mannequin setup were input in the tool and it was operated in PMV mode. The PMV was found to be neutral (0) at $T_{air}$=25.5°C, which was chosen as the baseline $T_{air}$ case for both the studies.

Table 2 includes all the cases studied and presented in this study.

Table 2. Cases studied.

| TCC $T_{air}$ (°C) | TAF $T_{surf}$ (°C) | |
|---|---|---|
| | **Thermal Mannequin Study** | **Human Subjects Study** |
| 25.5 (Baseline) | 25.5 | 25.5 |
| 26 | 26, 24, 22, 20, 18 | 26, 20, 18 |
| 28 | 28, 26, 24, 22, 20 | 28, 22, 20 |
| 30 | 30, 28, 26, 24, 22 | 30, 24, 22 |

### 2.3 Thermal Mannequin Study

The thermal mannequin generated its own heat, mimicking the metabolic processes of a human, using high-conductivity wire arrays beneath the skin, with the $T_{skin}$ dependent on the electric current supplied. It was designed after a typical Asian female and was dressed in an Indian summer attire of cotton kurta, pyjama, and standard inner-wears with no socks. The clothing insulation of the mannequin was experimentally obtained by comparing its heat flux with and without clothes and was found to be 0.612 clo. Since the mannequin was represented to be involved in a sedentary office activity, its metabolic rate was specified as 1.1 MET.

In order to study the effect of the TAF $T_{surf}$ and TCC $T_{air}$ on the mannequin, the TCC-TAF setup was first stabilized at the defined temperatures by overnight operation, with the mannequin already seated within the TCC. Figure 3 shows the various temperatures within the TCC, indicating stabilisation. The mannequin was then operated until the $T_{skin}$ and Heat Flux readings were stabilized – this typically took ~2 hours, but for enhanced assurance, the L/O $T_{skin}$, L/O Heat Flux, and PMV readings were taken after a 4-hour stabilisation period.

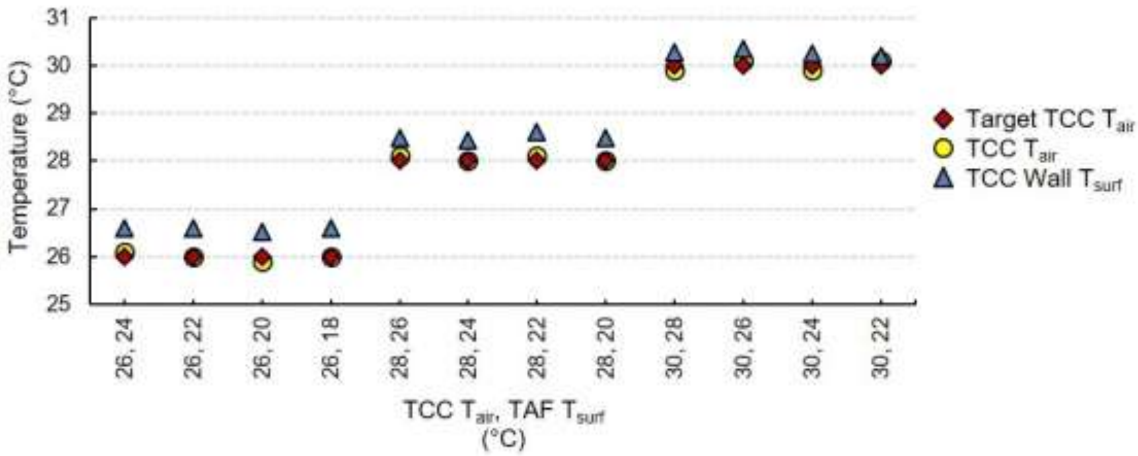


Figure 3. Variation of target $T_{air}$ in the TCC, near TAF, along with the TAF and TCC wall $T_{surf}$.

The thermal mannequin study also accounted for the variation in the CTP required for the TCC-TAF operation; it is the thermal power consumed by the chiller in cooling the chilled water to maintain the TAF $T_{surf}$ added to the power consumed by the AHU to maintain the TCC $T_{air}$. In order to calculate the same, the inlet/outlet temperature and the inlet flow rate of (a) the conditioned air supplied to the TCC from the Air Handling Unit (AHU), and (b) the chilled water supplied to the TAF, were measured using the instruments described in section 1.

### 2.4 Human Subject Study

The human subject study involved 22 (11 male, 11 female) subjects belonging to the age group of 21-45 years, and a common salary background (middle-income group). It was ensured that the subjects had been living in the city of Ahmedabad for at least 2 years and were acclimatised to the local climate. Each subject participated in 10 experiments, and each experiment lasted for 80 minutes, therefore the total survey duration was for more than 293 hours during the summer season. The TCC $T_{air}$ or TAF $T_{surf}$ setpoints sequence were chosen in a randomized manner to avoid any influence in subjective responses due to a perception bias.

The subjects were instructed to dress in Indian summer clothing. For men, the recommended attire included half/full-sleeved shirt and light trousers; for women, it included half/full-sleeved shirt with light trousers, *Saree*, or a Punjabi Suit Ensemble (*Kurta*: half/full-sleeved knee-length shirt, *Salwar*: loose harem pants, *Churidar*: light trousers).

The TCC-TAF setup was preconditioned and stabilized at a single combination of TAF $T_{surf}$ and TCC $T_{air}$ before the arrival of the subjects. They were given a period of 15 minutes before entering the TCC so that their metabolic rate could stabilize. Each experiment involved the entry of a single subject who was made to sit on a cushioned chair with back support in the centre of the TCC, as shown in Figure 1. A researcher was perennially present in the TCC to monitor the subject's behaviour and offer him/her any assistance throughout the experiment.

Upon the subject's entry in the TCC, he/she had to undergo: (a) 15-minutes of acclimatisation, (b) 30 minutes of sedentary activity while seated, (c) 5 minutes of break (for walking, stretching, standing, or drinking water), and (d) 30 minutes of sedentary activity while being seated, in the respective order. During a total of these 80 minutes, the subject was supposed to respond to questions on his/her overall Thermal Acceptability, Thermal Sensation, Thermal Comfort, Thermal Preference, Air Quality Acceptability, Air Movement Acceptability, and Air Movement Preference. The survey was filled 9 times throughout the 80 minutes. Figure 4.a shows the timing of each of the nine survey questionnaires and Figure 4.b shows the screenshots of the survey questions. It must be noted that although the surveys included questions on all these parameters, this study does not include the results or discussion for the Air-related parameters to maintain brevity and relevance to the topic.

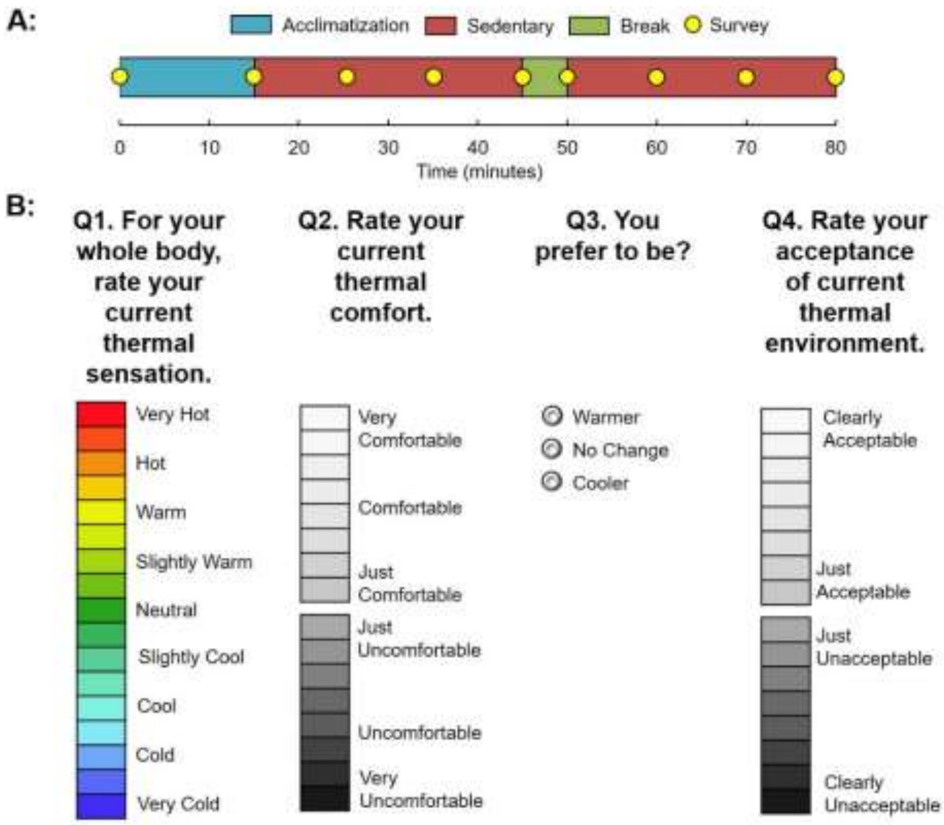

Figure 4.a. Survey schedule, and b. survey questions.

## 3 Results and Discussion

As mentioned before, the results include the O/L $T_{skin}$, O/L HF, and O PMV for the thermal mannequin, along with the individual responses of thermal acceptability, sensation, comfort, and preference for the human subjects. The results also include the CTP of the TCC-TAF setup for the mannequin study.

### 3.1 Skin Temperature and Heat Flux

Figure 5 shows the variation of O $T_{skin}$ and HF for the thermal mannequin for the 15 cases along with the baseline (25.5, 25.5) case. The X-axis shows the TCC $T_{air}$ and the TAF $T_{surf}$. For the cases when the TAF was not in operation, TAF $T_{surf}$ was maintained at the same temperature as the TCC $T_{air}$. The figure shows, as the TCC $T_{air}$ was increased from the baseline by 0.5°C to 26°C without the panels in operation, the O $T_{skin}$ of the mannequin increased by 0.1°C and the O HF from the mannequin decreased by 2.5 W. Subsequently, reducing the TAF $T_{surf}$ at a fixed TCC $T_{air}$ of 26°C, resulted in a decrease in the O $T_{skin}$ by ~0.1°C, and increase in O HF by ~1 W, per 2°C decrease in the TAF $T_{surf}$. Increasing the TCC $T_{air}$ by 2°C caused a more significant change in the O $T_{skin}$ and O HF than a 2°C change in the TAF $T_{surf}$. Without the TAF in operation, a 2°C increase in the TCC $T_{air}$ (from case 26,26 to 28,28 to 30,30) was found to elevate the O $T_{skin}$ by 0.4°C and O HF by ~8 W.

The results indicate that the O $T_{skin}$ was found to increase and O HF found to decrease with the increase in TCC $T_{air}$ as well as the TAF $T_{surf}$ – implying warmer ambient conditions lead to higher $T_{skin}$ and lower HF. The TAF operation resulted in an identical change in the O $T_{skin}$ and O HF of the thermal mannequin, irrespective of the TCC $T_{air}$; also, a 2°C reduction in TCC $T_{air}$ was found to affect the O $T_{skin}$ and O HF of the thermal mannequin by up to four times in comparison to a 2°C reduction in TAF $T_{surf}$ at either of the three $T_{air}$ conditions.

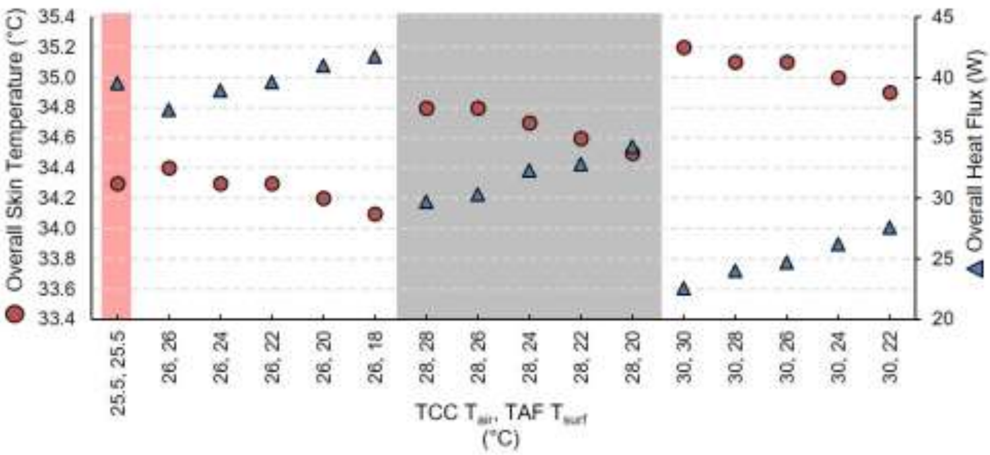


Figure 5. Overall $T_{skin}$ (°C) and HF (W) for the mannequin.

The O $T_{skin}$ and O HF, as shown in the previous figure, were averaged over the entire mannequin skin surface area of 1.69 $m^2$. The thermal mannequin was divided into 22 body parts by the manufacturer, which were - crown, head, left chest, right chest, left back, right back, left upper arm, right upper arm, left forearm, right forearm, left hand, right hand, pelvis, buttocks, left front thigh, right front thigh, left rear thigh, right rear thigh, left foreleg, right foreleg, left foot, and right foot. The thermal mannequin allowed the measurement of local (L) parameters of $T_{skin}$ and HF for each of these body parts. The variation in local $T_{skin}$ has been shown to influence the L and O Thermal Comfort; Zhang et al. studied the effect of PCS on local body parts (Zhang et al., 2010). They found that at $T_{air}$=28°C and 30°C, the L $T_{skin}$ of cheek, foot, and finger reduced by 1-2°C due to PCS operation. This reduction in $T_{skin}$ also resulted in an improvement in the L Thermal Comfort by ~1 vote (at 28°C) and ~2 votes (at 30°C).

Figure 6 shows the average, maximum, and minimum values of L $T_{skin}$ and L HF for the 22 body parts for all the TCC $T_{air}$ - TAF $T_{surf}$ cases, except the baseline case. As seen from the previous figure, the warmest ambient condition (TCC $T_{air}$ = 30°C, TAF $T_{surf}$ = 30°C) resulted in the highest O $T_{skin}$ and lowest O HF, and vice versa for the coolest ambient condition (TCC $T_{air}$ = 26°C, TAF $T_{surf}$ = 18°C) – the local parameters reflected the same. The combination of highest L $T_{skin}$ and lowest L HF for all the body parts was attained at TCC $T_{air}$ = 30°C, TAF $T_{surf}$ = 30°C, while the combination of lowest L $T_{skin}$ and highest L HF for all the body parts was attained at TCC $T_{air}$ = 26°C, TAF $T_{surf}$ = 18°C. The left and right feet and hands were among the body parts with the lowest L $T_{skin}$ and highest L HF, while the pelvis, along with the front and rear thighs had the highest L $T_{skin}$ and lowest L HF.

The difference between the maximum and minimum values of the local parameters indicates their variability when subjected to the 15 TCC $T_{air}$ - TAF $T_{surf}$ combinations. It was found that the body parts closer to the torso – the ones with higher fat content and therefore thermal mass, exhibited the least variation in their L $T_{skin}$ and L HF, while the body parts farther away from the torso exhibited the highest variation. For instance, the L $T_{skin}$ of the left and right hands varied between 32.62-34.67°C and 33.11-34.65°C, exhibiting a variation of 2.05°C and 1.54°C respectively, whereas, the L $T_{skin}$ of the pelvis and buttocks varied between 35.07-35.68°C and 34.90-35.48°C, exhibiting a variation of 0.61°C and 0.58°C respectively. Since L $T_{skin}$ and L HF are inversely proportional, the hands were therefore found to have a higher L HF than the pelvis or buttocks.

It must also be noted that the minimum L $T_{skin}$ of the left hand was lower than that of the right hand by 0.49°C – the left parts of the body were found to be consistently colder than their right counterparts. This was because, in the TAF setup, the radiant panels were placed in the front and to the left of the thermal mannequin, absorbing more heat from the left side of the body than the right due to its view factor. This difference is not reflected in the 'maximum' readings of L $T_{skin}$ and L HF since that case accounts for TCC $T_{air}$ = 30°C, TAF $T_{surf}$ = 30°C, i.e., no radiant panel in operation and no asymmetry in heat absorption.

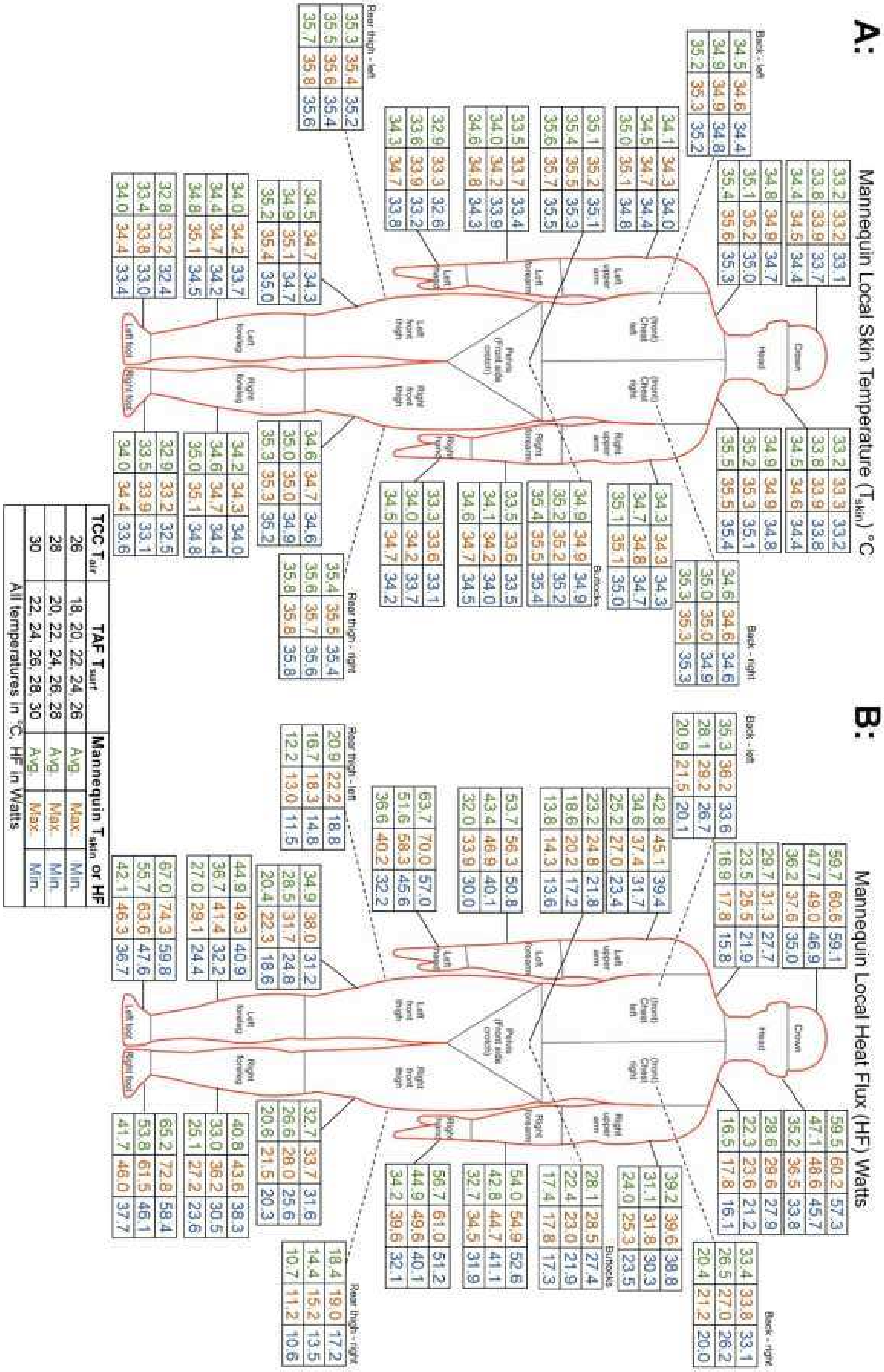


Figure 6. Average, Maximum, and Minimum values of local a. $T_{skin}$ (°C), and b. HF (W) for the mannequin.

## 3.2 Subjective Responses

The human subjects indicated their responses to the questionnaires shown in Figure 4.b. The responses shown in this paper include the subjects' responses to their O Thermal Acceptability, O Thermal Sensation, O Thermal Comfort, and O Thermal Preference, as shown in Figure 7.

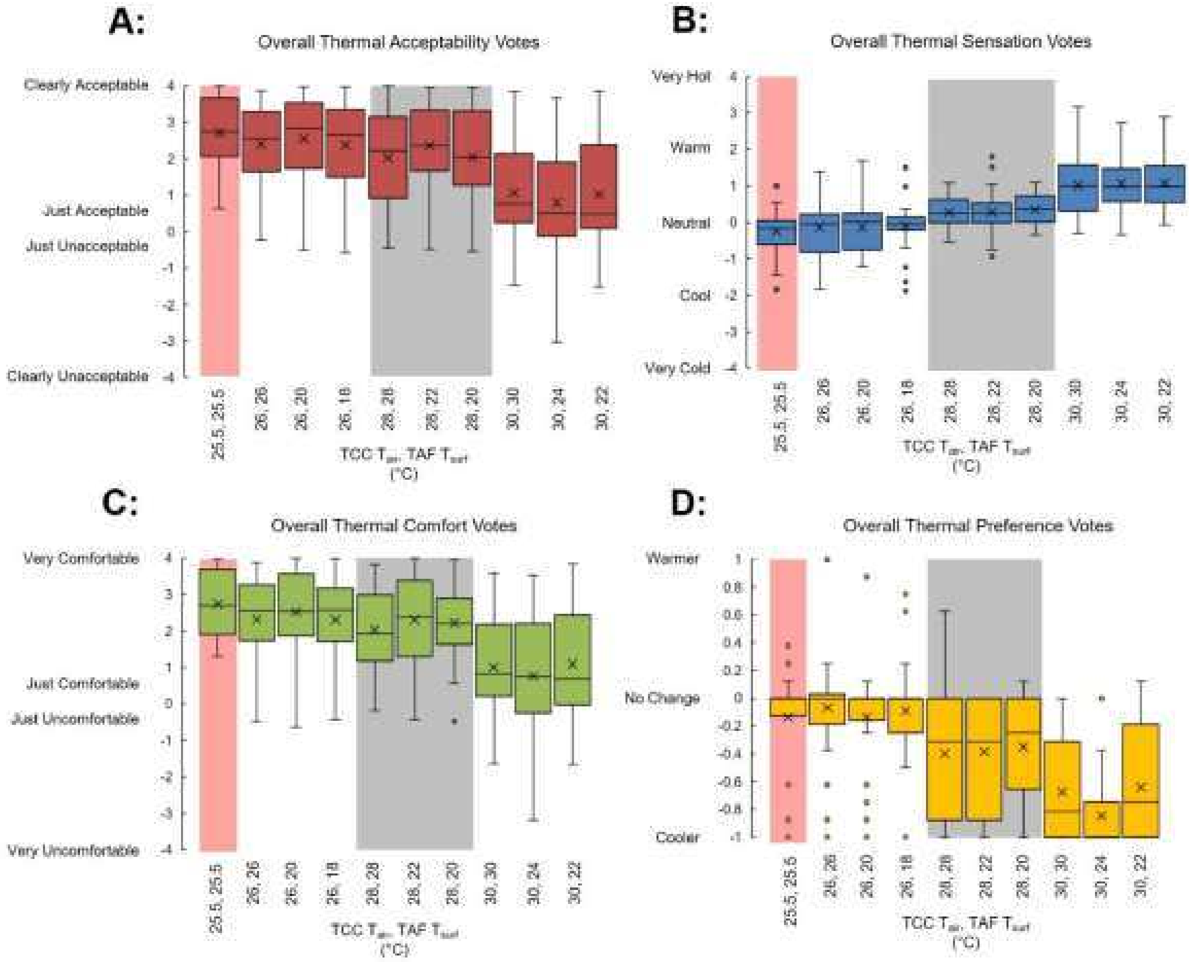


Figure 7. Overall Thermal a. Acceptability, b. Sensation, c. Comfort, and d. Preference, as indicated by human subjects.

The average O Thermal Acceptability was found to be the highest for the reference case (TCC $T_{air}$ = 25.5°C, TAF $T_{surf}$ = 25.5°C) and found to reduce marginally when the TCC $T_{air}$ was increased by 0.5°C (TCC $T_{air}$ = 26°C, TAF $T_{surf}$ = 26°C), as shown in Figure 7.a. As a general trend, a reduction in TCC $T_{air}$ resulted in a decrement in the average acceptability. This decrease was negligible (less than 0.5 acceptability votes) when TCC $T_{air}$ was changed from 26 to 28°C, but it varied by more than 1 acceptability votes when TCC $T_{air}$ was changed from 28 to 30°C. The subjects found the condition TCC $T_{air}$ = 30°C, TAF $T_{surf}$ = 24°C the most unacceptable, even more than the warmest condition of TCC $T_{air}$ = 30°C, TAF $T_{surf}$ = 30°C. The subjects' mean acceptability for the cases TCC $T_{air}$ = 30°C, TAF $T_{surf}$ = 30°C and TCC $T_{air}$ = 30°C, TAF $T_{surf}$ = 22°C was 1.06 and 1.02 respectively. However, a two-tailed t-test revealed that there is no significance between the subjects' acceptability votes and TAF $T_{surf}$ reduced below the prevalent $T_{air}$ ($p > 0.1$ in t-test). This is indicative of the fact that the TAF cooling might not be contributing enough to bring a change in the subjects' thermal acceptability. However, it is important to note that even at the warmest ambient conditions, some of the subjects found their thermal ambience acceptable even without any TAF operation.

Thermal sensation is indicative of how warm or cool did the subjects feel, irrespective of thermal comfort/discomfort – this is shown in Figure 7.b. The subjects' average thermal sensation remained close to neutral for all the cases with TCC $T_{air}$ = 26°C and 28°C, including the baseline case. The spread of the subjective responses was the narrowest for the baseline case, indicating a more prevalently accepted neutral thermal sensation. There was an increase in the average thermal sensation towards the warmer side by < 0.5 sensation votes as the TCC $T_{air}$ was increased from 28°C to 30°C. At TCC $T_{air}$ = 30°C, the TAF operation was found to reduce the thermal sensation in isolated cases by a negligible margin.

Every heating or cooling technology attempts to ensure that the human subject is comfortable with his/her thermal ambience. His/her thermal comfort votes can convey differently from the thermal sensation votes as he/she might associate a warmer-than-neutral or cooler-than-neutral sensation with optimum thermal comfort. For instance, most of the tropically acclimatised individuals associate a cooler-than-neutral sensation with the 'very comfortable' state. Figure 7.c shows the variation of subjects' overall thermal comfort responses for this study. The subjects were most comfortable at the reference condition. At TCC $T_{air}$ = 26°C, the subjects' thermal comfort responses were in the range of 2.4-2.5 comfort votes. As the TCC $T_{air}$ was increased to 28°C without the TAF in operation, the average comfort vote was found to reduce by < 0.5 votes. Operation of TAF at $T_{sur}$ = 20°C and 22°C resulted in an increase in the average comfort vote by < 0.5 votes. At TCC $T_{air}$ = 30°C, without the TAF in operation, the average thermal comfort vote was 'just comfortable', while there were a few subjects who marked themselves as uncomfortable. At TCC $T_{air}$ = 30°C, the subjects were more 'uncomfortable' with the TAF $T_{surf}$ = 24°C, than with no TAF in operation. Additionally, the subjects' average comfort votes for the case of TCC $T_{air}$ = 30°C, TAF $T_{surf}$ = 24°C was 0.2 votes higher (more comfortable) than the case TCC $T_{air}$ = 30°C, TAF $T_{surf}$ = 30°C.

Figure 7.d shows the variation of subjects' thermal preference for all the studied cases. The results re-establish the trends from the three previous figures. Additionally, it shows that some of the subjects preferred a warmer sensation after a prolonged exposure to TCC $T_{air}$ = 26°C but this cannot be attributed to the TAF operation, since 'those few' subjects preferred a warm sensation even without the TAF in operation for the case TCC $T_{air}$ = 30°C, TAF $T_{surf}$ = 24°C, and TCC $T_{air}$ = 25.5°C, TAF $T_{surf}$ = 25.5°C.

Figure 7 established that the TAF operation at temperatures of "$T_{air}$ - 8°C" contributed to the subjects attaining comfortable conditions at TCC $T_{air}$ of 26 and 28°C. The same can be ascertained using the Predicted Mean Vote (PMV) calculated for the thermal mannequin using the Equivalent Temperature method within the mannequin software, as done by Tanabe et al. (Tanabe & Arens, 1994). PMV is plotted on the Thermal Sensation Scale, therefore the human subject's Thermal Sensation votes can be superimposed and considered as the AMV – the Actual Mean Vote.

Figure 8 shows the comparison of the Human-AMV and Mannequin-PMV on the Sensation Scale, with the 'comfortable' sensation marked by a band of -0.5 to +0.5 Sensation Votes. The figure reiterates the inferences of Figure 7.b for the Human Subjects and shows that the Mannequin-PMV was the closest to the neutral for the reference case (25.5, 25.5). As the TCC $T_{air}$ was increased to 26°C without the TAF in operation, the PMV was found to rise marginally above neutral while remaining in the comfort band. The PMV stayed within the comfort band for all the cases at TCC $T_{air}$=26°C, going marginally below the neutral sensation at TAF $T_{surf}$ = 18, 20°C. At TCC $T_{air}$=28°C, the PMV was found to be uncomfortable and "slightly warm", which reduced with the TAF operation – operating the TAF at $T_{surf}$ = 20°C reduced the PMV to lie within the comfortable band. All the cases at TCC $T_{air}$ = 30°C resulted in a consistently uncomfortable PMV, although the TAF operation at $T_{surf}$ = 22°C reduced the PMV by ~0.5 votes.

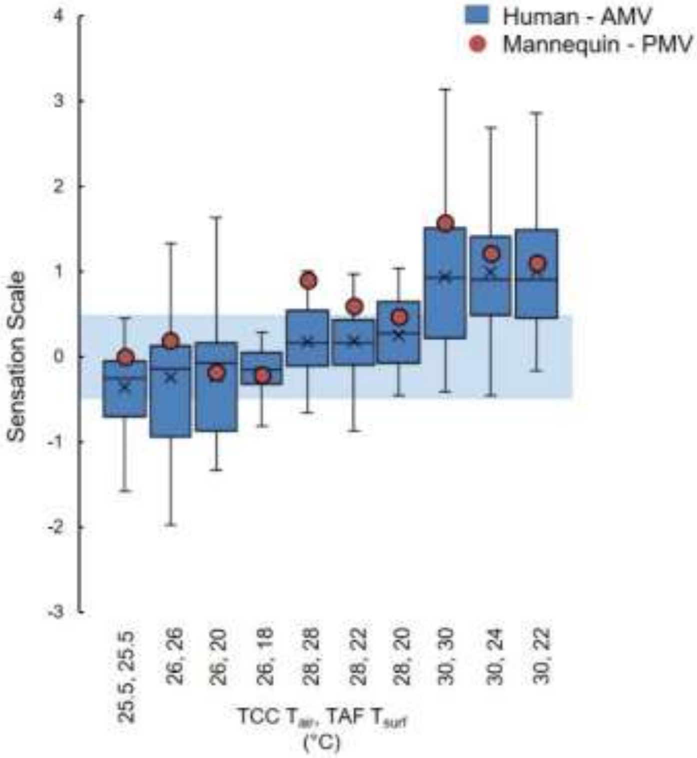


Figure 8. Human-AMV and Mannequin-PMV.

The Mannequin-PMV trend showed steady decrement from the No-TAF cases to the cases when the TAF was used at the lowest $T_{surf}$ at that TCC $T_{air}$. This trend is not evident in the Human-AMV results as the average AMV was found to remain near-constant for each TCC $T_{air}$ setpoint, irrespective of the TAF $T_{surf}$. A comparison between the AMV and PMV shows that the mannequin exaggerated the thermal sensation on the warmer side compared to the human subjects. The mannequin sensation was closest to the human sensation at the peak TAF operation, while the difference between the two was the highest when the TAF was not in operation.

### 3.3 Cooling Thermal Power (CTP)

The thermal mannequin study was conducted in the TCC, located in the city of Ahmedabad with a hot and dry climate. The experiments were conducted between the summer months of March and July 2018, when the peak outdoor $T_{air}$ remained in the range of 30-45°C and RH consistently below 30%. The TCC $T_{air}$ was maintained by the cooled air from the Air Handling Unit (AHU) and the TAF $T_{surf}$ was maintained by the cooled water supplied by the chiller; their individual CTP was calculated, as described in section 1.

Figure 9 shows the variation of the CTP for the AHU (Air) and the TAF (water). For the cases when the TAF was not in operation, the water CTP was zero, while it was highest when the TAF $T_{surf}$ was the lowest for each $T_{air}$. The air CTP was the highest for the baseline case ($T_{air}$ = 25.5°C) at 864.4 W, and it was found to reduce with the increase in the indoor $T_{air}$ setpoint – since, as the TCC $T_{air}$ setpoints were moved closer to the outdoor $T_{air}$, the AHU had to exert a reduced amount of power in maintaining the desired temperature.

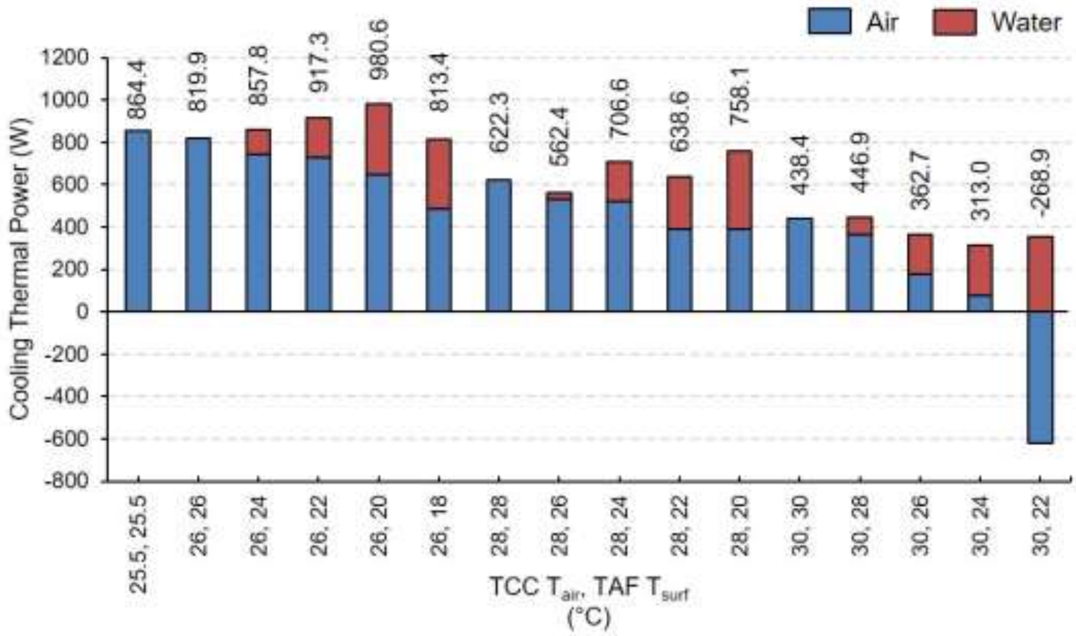


Figure 9. Cooling Thermal Power of the TCC-TAF setup for the mannequin study.

The air CTP was also found to reduce as the TAF $T_{surf}$ was reduced, but this change was not as drastic as when the TCC $T_{air}$ was varied. The air CTP gradually decreased with the reduction in the TCC $T_{surf}$ too and was found to be negative for the case TCC $T_{air}$ = 30°C, TAF $T_{surf}$ = 22°C – this was because of the cooling action of the TAF. A negative air CTP implies that in order to supply $T_{air}$ = 30°C to the TCC, the return air (with a temperature of < 30°C due to the interaction with TAF at $T_{surf}$ = 22°C) had to be heated by the AHU. The thermal power required for this heating has been accounted as negative CTP.

At TCC $T_{air}$ = 26°C, the total CTP was found to marginally increase with the TAF operation between $T_{surf}$ = 24 to 20°C, while it reduced significantly at $T_{surf}$ = 18°C due to the cooling of supply air due to the action of TAF. At TCC $T_{air}$ = 28°C, although there was a steady reduction in the air CTP, the air-TAF interaction was not significant enough to reduce the overall CTP. At TCC $T_{air}$ = 30°C, maintaining the $T_{air}$ required the least amount of CTP and the air-TAF interaction brought the overall CTP further down. However, the magnitude of Thermal Power consumed for the last case (TCC $T_{air}$ = 26°C, TAF $T_{surf}$ = 30°C) exceeds the baseline by 82.5 W.

It is important to note that CTP is representative of the total energy consumed in the cooling process and it does not directly yield the energy savings. The future studies on the topic can compare and contrast between the CTP of the Mannequin-TCC setup and the electrical energy consumption of the human subject-TCC setup.

## 4 Conclusion

The study successfully presents the results from 16 cases of the Thermal Mannequin study and 10 cases of the Human Subject study conducted in the Thermal Comfort Chamber (TCC). The Overall Skin Temperature ($T_{skin}$) and Heat Flux (HF) were found to vary by ~0.1°C and ~1 W with every 2°C decrease in the TAF Surface Temperature ($T_{surf}$) at a given TCC Air Temperature ($T_{air}$). Changing the TCC $T_{air}$ by 2°C had a more prominent effect on the two variables – the $T_{skin}$ and HF varied by 0.4°C and ~8 W respectively. The Local $T_{skin}$ and HF for the 22 body parts was found to be different for the left and right body parts due to the left-side position of the panels. The local variables for the body parts closer to the torso had the least variation, while the body parts farthest from the torso had the highest.

The human subjects voted to have a near-neutral thermal sensation for the cases of TCC $T_{air}$ = 26 and 28°C, while the TAF operation was not found to bring any difference in their thermal sensation at any TCC $T_{air}$. The TAF operation marginally improved the subjects' thermal comfort responses as well as their thermal preference. At TCC $T_{air}$ = 30°C, a majority of the subjects preferred a cooler sensation, and the TAF operation did not affect their thermal comfort or preference. The Human-AMV and Mannequin-PMV results were mutually consistent at the lowest TAF $T_{surf}$ conditions, while at no TAF operation, they varied by up to 0.7 sensation votes. The total Cooling Thermal Power (CTP) of the TCC-TAF setup was found to reduce primarily due to the reduction in the effort of AHU in cooling the resupply air – the trend of TAF chilled water CTP variation was the same for each $T_{air}$ condition. The cooled surface of the TAF helped reduce the internal loads of the TCC and therefore reduced the overall CTP.

To summarise, the TCC-TAF setup was effective in maintaining the comfort conditions below $T_{air}$ = 28°C. The cooling effect of TAF was more evident for the Thermal Mannequin than for the Human Subjects. The thermal sensation of the mannequin and the human subject was found to be similar. The reduction in overall CTP was due to the reduction in air-CTP due to the effect of the TAF-induced cooling, however, there was a negligible reduction in the water-CTP by changing the $T_{air}$ setpoint. Since the TAF setup lies in the range of TRL 3-4, it has not yet reached the level of a use-ready product. Future works can involve a modified TAF setup with occupant-controlled setpoint and study the effect of perceived control.

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# Measurement of the convective and radiative heat transfer coefficient for the clothed human body through thermal manikin experiment

**Shan Gao[1], Ryozo Ooka[2], and Wonseok Oh[1]**

[1] Graduate School of Engineering, Department of Architecture, The University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan;
[2] Institute of Industrial Science, The University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan

**Abstract:** To predict thermal comfort, many human thermoregulation models have been developed. The convective and radiative transfer coefficients are required as input data for these models. However, most studies on the heat transfer coefficient have been conducted using naked thermal manikins. The purpose of this study was to confirm the effects of airspeed and wind direction on the convective and radiative heat transfer coefficients using a clothed manikin. Hence, a clothed manikin with a fixed surface temperature was placed in a wind tunnel with airspeed ranging from 0.25 m/s to 1.4 m/s. Sitting and standing postures were adopted, and the manikin was set to face three wind directions—upwind, downwind, and crosswind. The results are as follows: (1) The convective heat transfer coefficient of the clothed manikin was larger than that of the naked manikin, for both sitting and standing postures; (2) The convective heat transfer coefficient differed with the type of clothing; (3) The whole-body convective heat transfer coefficient caused by crosswind was the least recorded in the standing position for both naked and clothed manikins; (4) The convective heat transfer coefficient of clothed and naked manikins increased with airspeed.
**Keywords:** convective heat transfer coefficient, radiative heat transfer coefficient, clothing, thermal comfort

## 1. Introduction

A goal for thermal comfort research is to develop comprehensive models of human thermoregulation that can predict thermal comfort level (de Dear *et al.*, 1997). To develop these models, there is a strong need for empirical data, such as convective and radiative heat transfer coefficients. In recent years, experiments and numerical simulations using thermal manikins and computational thermal manikins have been conducted, and various convective and radiative heat transfer coefficients calculation methods have been proposed (Ichihara *et al.*, 1997; Oh and Kato, 2018). However, most of the studies have been conducted on the naked thermal manikins, studies on the convective and radiative heat transfer coefficients for the clothed human body are very few. Therefore, data about the clothing heat transfer coefficient is not enough.

In previous studies, the clothing heat transfer coefficient has been approximated by multiplying the naked body heat transfer coefficient by the clothing area factor (Tanabe *et al.*, 2002; Ogulata, Tugrul, 2007). However, not only does the increase in the area due to the uneven surface of clothing causes a larger clothing heat transfer coefficient, but other factors such as the features of the clothing surface material also affect the heat transfer coefficient. Therefore, in order to evaluate the human thermal comfort level much more accurately, it is necessary to calculate the heat transfer coefficient of the clothing surface directly.

Oguro et al. measured the convective heat transfer coefficient for the clothed human body under airspeeds of 0.2–5 m/s using a thermal manikin (Oguro *et al.*, 2002). Oliveir et al. measured the convective heat transfer coefficient of extremely thick clothing under wind speed conditions of 0–10 m/s (Oliveira, Gaspar and Quintela, 2006). However, in these studies, only one clothing ensemble was investigated. Whether the convective heat transfer coefficient for the clothed human body differs with clothing material has not been verified. Besides, the radiative heat transfer coefficient for the clothed human body has not been discussed. With the development of material engineering, clothing materials have become very diversified. For example, waterproof moisture permeable materials and raised fabric are used for windbreakers, fleece coats, raincoats, etc.. Therefore, it is important to clarify the characteristics of the convective and radiative heat transfer coefficients for clothing made of such new materials.

The present research set up experiments in a wind tunnel to measure the convective and radiative heat transfer coefficients for the clothed human body under various airspeeds and wind directions using a clothed thermal manikin.

## 2. Methods

### 2.1. Clothing ensembles

In this study, three sets of clothing ensembles were selected (Table 1). The underwear (bra and panty) and shoes utilized in each experiment were the same. The material of the underwear was 100 % cotton. The material of the shoes was 100 % cotton for the upper, rubber for the sole. The basic insulation $I_{cl}$ is separately 0.8 clo, 1.0 clo, and 0.8 clo for Ensemble 1, Ensemble 2, and Ensemble 3 under an airspeed of 0.25 m/s in standing posture (Table 1).

Table 1 Information for all tested clothing ensembles.

| | | |
|---|---|---|
|  |  |  |
| Shirt: 100 % cotton<br>Trousers: 100 % polyester | Windbreaker jacket, the outer material, 100 % nylon, the inner material (mesh), 100 % polyester<br>Shirt: 100 % cotton<br>Trousers: 100 % nylon | Shirt: Breathable fiber, 100 % polyester<br>Trousers: Breathable fiber, 100 % polyester |
| E1 | E2 | E3 |

### 2.2. Experimental settings

The thermal manikin (height: 1.66 m, standing, 1.21 m, sitting; skin surface area: 1.48 m$^2$) used in this research has the shape of a female body, with 16 independent body segments.

The skin area of each body segment of the manikin is designed according to the actual human body. The surface temperature of the thermal manikin was controlled to 33 °C, and the sensible heat loss from the thermal manikin was recorded by Manikin® software. The thermal manikin was situated to sitting and standing postures because they are the most common in indoor environments. For the sitting posture, the manikin was seated on a mesh chair to minimize the impact on the airflow and radiation heat exchange around the manikin. For the standing posture, the manikin was suspended to the ceiling with a rope. For both postures, the feet of manikin was elevated 5 cm from the floor to eliminate conductive heat loss. All the thermal manikin experiments followed the ISO standard—ISO 14505(ISO 14505-2, 2006).

Figure 1 shows a diagram of the temperature stratification wind tunnel (16.5 m × 2.2 m × 1.8 m) located in Institute of Industrial Science, the University of Tokyo. Airspeeds of 0.25 m/s, 0.75 m/s, 1.1 m/s, and 1.4 m/s were reproduced, which are in the range of expected indoor wind speeds. The thermal manikin was rotated between three positions such that the wind flowed from the front side, backside, and right side of the manikin. The air temperature in the wind tunnel cannot be precisely controlled. However, the natural temperature in the wind tunnel was stable during the measurement of each clothing ensemble. The temperature condition for the experiments is shown in Table 2.

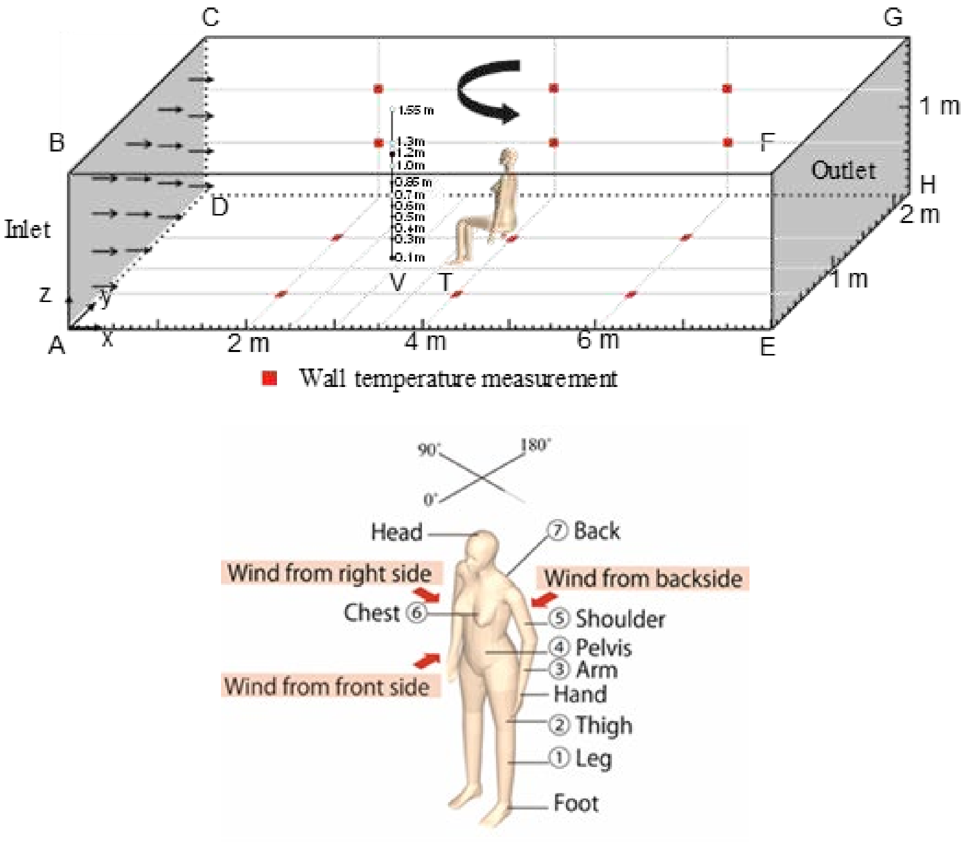



Figure 1 Diagram of the wind tunnel and the thermal manikin.

Table 2 Air temperature and wall temperature during the experiment

| | |
|---|---|
| Air temperature | Sit: 27.5 °C<br>Stand: nude, 27.1 °C, E1, 25.8 °C; E2, 25.3 °C; E3, 25.7 °C; |
| Wall temperature | Sit: 27.5 °C |

| |
|---|
| Stand: nude, 27.0 °C, E1, 26.0 °C; E2, 25.4 °C; E3, 25.7 °C; |

## 2.3. Measurements

All the temperatures in this study were measured with T-type thermocouples recording over 10 min at 10-s intervals and averaged. Concerning the wall temperature, six measurement points were set at each wall, and the values for each measurement point were averaged (Figure 1). The air temperature measured 0.5 m before the manikin at heights of each segment of the thermal manikin during sitting and standing postures (Table 3). The detailed information for the measurement points for the wall temperature and the air temperature was described in the previous study (Gao, Ooka and Oh, 2019a).

Table 3. Heights of measurement points (Temperature and velocity)

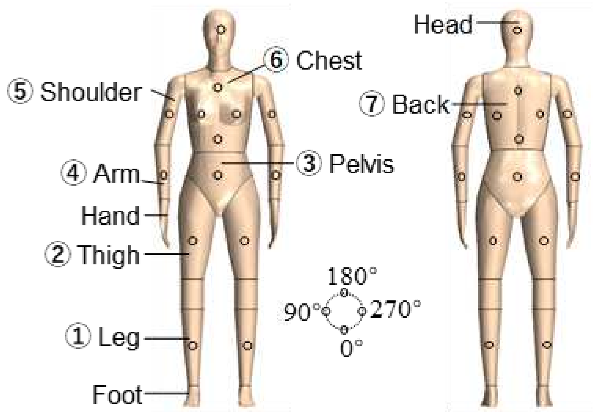
| *i* | Segment (*i*) | Sitting posture (m) | Standing posture (m) |
|---|---|---|---|
| 10 | Head | 1.2 | 1.55 |
| 9 | Back | 0.85 | 1.25 |
| 8 | Chest | 0.85 | 1.25 |
| 7 L / 7 R | Left shoulder / Right shoulder | 0.85 | 1.3 |
| 6 L / 6 R | Left arm / Right arm | 0.6 | 1.0 |
| 5 | Pelvis | 0.6 | 1.0 |
| 4 L / 4 R | Left hand / Right hand | 0.4 | 0.7 |
| 3 L / 3 R | Left thigh / Right thigh | 0.5 | 0.7 |
| 2 L / 2 R | Left leg / Right leg | 0.3 | 0.3 |
| 1 L / 1 R | Left foot / Right foot | 0.1 | 0.1 |

Note: For the body segments which have left and right side, for example, the leg and the hand, the segment number *i* for the right and left side are the same.

Temperature measurement points on the thermal manikin and clothing surface are shown in Figure 2. Although the thermal manikin can output skin surface temperatures, they were still recorded to verify whether the skin temperature reached the target value. On the back and chest, there were four temperature measurement points respectively. And they were uniformly distributed. On the hands, there was one temperature measurement point on the palm and back respectively. On other body segments, there were four temperature measurement points with 90° intervals on each body segment. Each thermocouple was welded onto a 0.1 mm-thick copper disk with a diameter of 6 mm shown in Figure 3 (Mcguffin *et al.*, 2002). The self-made thermocouples were attached to each thermal manikin segment with non-woven tape carefully. All these efforts made the thermocouple contact well with the clothing surface and attained a fast response.

Airspeeds were measured with a single-sensor miniature wire probe calibrated just before the experiment. The detailed information for the measurement points and results for the airspeed was described in the previous study (Gao, Ooka and Oh, 2019a).

All the equipment utilized in this study is shown in Table 3.




| Segment | 0° | 90° | 180° | 270° |
|---|---|---|---|---|
| Head | ○ | ○ | ○ | ○ |
| ⑦ Back | | ○× 4 | | |
| ⑥ Chest | | ○× 4 | | |
| ⑤ Shoulder (L.,R.) | ○ | ○ | ○ | ○ |
| ④ Arm (L.,R.) | ○ | ○ | ○ | ○ |
| Hand (L.,R.) | | ○ | | ○ |
| ③ Pelvis | ○ | ○ | ○ | ○ |
| ② Thigh (L.,R.) | ○ | ○ | ○ | ○ |
| ① Leg (L.,R.) | ○ | ○ | ○ | ○ |
| Foot (L.,R.) | ○ | ○ | ○ | ○ |

Thermal manikin surface: on chest and back, measurement points uniformly distributed; on hands, one measurement point on the palm and the back of hands respectively; on other segments, 0°, 90°, 180°, and 270° in the circumferential direction.

Clothing surface: as the hands and head were not covered with clothing, there were no clothing surface temperature measurement points. The positions of the measurement points on other segments were the same as the naked manikin surface.

Figure 2 Temperature measurement points distribution on the thermal manikin surface and the clothing surface.

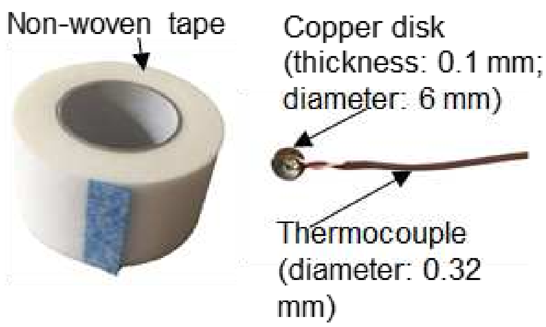



Figure 3 The non-woven tape and the self-made thermocouple

Table 4 Instruments in this research.

| Measurement | Instrument | Valid range | Accuracy |
|---|---|---|---|
| Thermal manikin | 16-part thermal manikin by PT Tech | | |
| Air temperature<br>Wall temperature<br>Clothing (skin) surface temperature | T-type thermocouple | −40–125 °C | ±0.5 °C |
| Airspeed | Single hot-wire probe (Dantec Dynamics 55P11) | 0.05–500 m/s | Depending on the quality of the calibration |
| Data logger | Graphtec GL800 | | |

## 2.4 Calculation

Sensible heat loss of the clothed human body flows from the skin surface to the surrounding environment through the following path: (1) from the skin surface to the outer clothing surface through the clothing, and (2) from the outer clothing surface to the immediate surroundings shown in Figure 4 (ASHRAE, 2017). The sensible hear loss was divided into convective heat loss and radiative heat loss (Equation (1)).

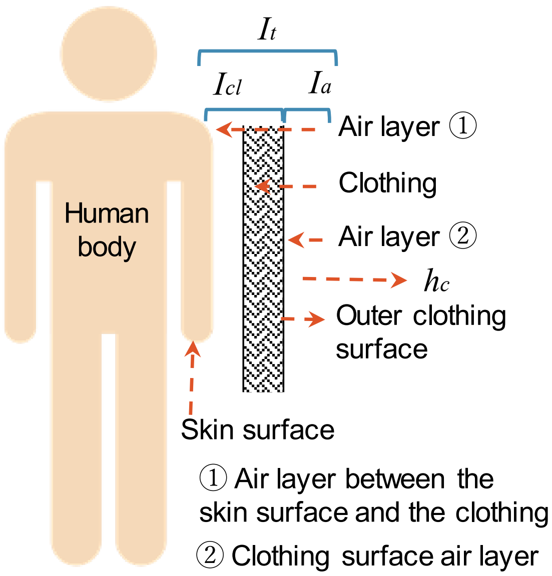



Figure 4 Schematic for the human body and the clothing

$$q_{t,i} = q_{c,i} + q_{r,i} \tag{1}$$

where, $q_{t,i}$ is sensible heat loss through the surface of the clothed manikin segment $i$, $q_{c,i}$ is convective heat loss through the surface of the clothed manikin segment $i$, and $q_{r,i}$ is radiative heat loss through the surface of the clothed manikin segment $i$.

$q_{t,i}$ can be recorded by the Manikin® software. $q_{r,i}$ was calculated with Equation (2) based on the measured mean wall temperature $t_r$ and clothing surface temperature $t_{cl,i}$. The emissivity of the naked manikin, the clothed manikin, and the wall was respectively 0.95, 0.95, and 0.9.

$$q_r = \sigma \varepsilon f_{eff}[(t_{cl,i} + 273.15)^4 - (t_r + 273.15)^4] \tag{2}$$

where, $\sigma$ is Stefan-Boltzmann constant, $5.67 \times 10^{-8}\, \mathrm{W/(m^2 \cdot K^4)}$, $\varepsilon$ is the average emissivity of the body surface, $f_{eff}$ is effective radiation area factor for each body segment.

Therefore, the convective heat transfer coefficient and radiative heat transfer coefficient for the clothed manikin can respectively be calculated with Equation (3) and Equation (4).

$$h_{c,i} = \frac{q_{t,i} - q_{r,i}}{(t_{cl,i} - t_a)} \tag{3}$$

and

$$h_{r,i} = \sigma\varepsilon f_{eff}\left[\left(t_{cl,i} + 273.15\right)^2 + \left(t_{r,i} + 273.15\right)^2\right]\left[\left(t_{cl,i} + 273.15\right) + \left(t_r + 273.15\right)\right] \tag{4}$$

where, $h_{c,i}$ and $h_{r,i}$ are respectively convective and radiative heat transfer coefficient for clothed manikin segment $i$, $t_a$ is the air temperature, and $t_r$ is the weighted average temperature of the wall surfaces. The weighted average temperature of the wall surfaces is calculated with Equation (5).

$$t_r = \frac{\sum_{j=1}^{6} S_j \cdot t_{w,j}}{\sum_{j=1}^{6} S_j} \tag{5}$$

where, $S_j$ and $t_{w,j}$ are respectively the area and the temperature for each wall $j$.
In each clothing condition, shoes were the same; in addition, the head and hands were not covered by clothing (Table 1). Therefore, the clothing heat transfer coefficients for the shoes, head, and the hands were not included when calculating the average clothing heat transfer coefficient. Namely, only leg (left and right), thigh (left and right), arm (left and right), pelvis, shoulder (left and right), chest, and back were taken into consideration when calculating the average heat transfer coefficient (Figure 4). The whole-body convective and radiative heat transfer coefficients were calculated with Equation (6) and Equation (7).

$$h_c = \sum_{i=1}^{7} h_{c,i} \cdot \alpha_i \tag{6}$$

$$h_r = \sum_{i=1}^{7} h_{r,i} \cdot \alpha_i \tag{7}$$

where, $\alpha_i$ is the ratio of the surface area of each segment to the total naked manikin surface area.

The clothing insulation for each clothing segment was calculated with Equation (8), and the whole-body clothing insulation was calculated with Equation (9).

$$I_{cl,i} = \frac{t_{s,i} - t_{cl,i}}{q_{t,i}} \tag{8}$$

$$\frac{1}{I_{cl}} = \sum_{i=1}^{7} \frac{\alpha_i}{I_{cl,i}} \tag{9}$$

where, $I_{cl,i}$ is the clothing insulation for clothed manikin segment $i$, $t_{s,i}$ is the surface temperature for the naked manikin segment $i$, $I_{cl}$ is whole-body clothing insulation for the clothed manikin.

## 3. Results

### 3.1. Whole-body convective heat transfer coefficient

Figure 5 shows the whole-body convective heat transfer coefficients for clothed manikin and naked manikin for sitting and standing postures. As in this part, we aimed at comparing the convective heat transfer coefficients of different clothing ensembles, the whole-body convective heat transfer coefficients for various wind directions were averaged.

The convective heat transfer coefficients for the clothed manikin were larger than those of naked manikin. This is consistent with the results of other studies (Danielsson, 1992; Oguro *et al.*, 2002). In the low wind speed range (0.25 m/s), the whole-body convective heat transfer coefficients for Ensemble 1, Ensemble 2, Ensemble 3, and naked manikin were almost the same. This indicates that, in the low wind speed range, the convective heat transfer coefficient for naked manikin can be used as the clothing convective heat transfer coefficient. At other airspeeds, the convective heat transfer coefficient for Ensemble 3 was the largest. This is because Ensemble 3 was made of a material with good air permeability, and the convective heat loss due to the intrusion of air was large.

The convective heat transfer coefficient for the clothed manikin and naked manikin both increased with airspeed. The difference between the convective heat transfer coefficient for the clothed manikin and the naked manikin tended to increase with the airspeed. In the standing posture, the increase in the convective heat transfer coefficient due to clothing was large.

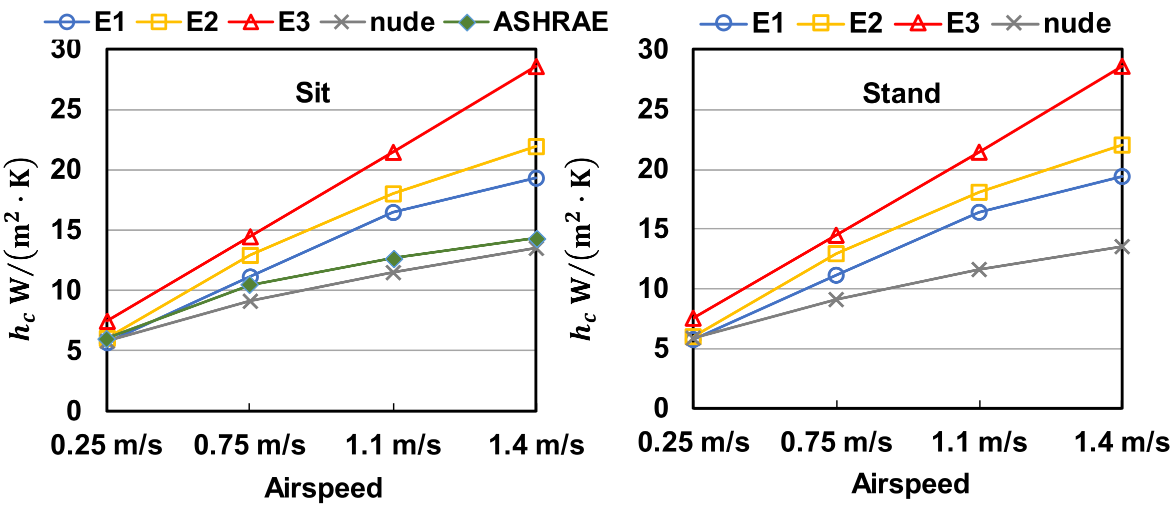



Figure 5 Comparison of whole-body convective heat transfer coefficients for clothed manikin and naked manikin for sitting and standing posture (mean value of three wind directions, E1, Ensemble 1, E2, Ensemble 2, E3, Ensemble 3)

Figure 6 shows the whole-body convective heat transfer coefficients for the clothed manikin and the naked manikin due to different wind directions in the sitting posture. For the naked manikin, the difference between convective heat transfer coefficients caused by various wind directions was relatively small. When the wind blew from the right side of the manikin, the body area facing wind was smaller. Therefore, the convective heat transfer coefficient caused by the crosswind was assumed to be smaller. However, in the sitting posture, some of the body segments were shielded from each other and weaken the influence of the wind direction.

For the clothed manikin, as there was an air layer between the manikin surface and the clothing, the convective heat transfer coefficient was much more susceptible to the wind. The results for the clothed manikin showed that the convective heat transfer coefficients for E1 and E3 due to wind from the right side of the manikin were slightly smaller than those for other wind directions (Figure 6).

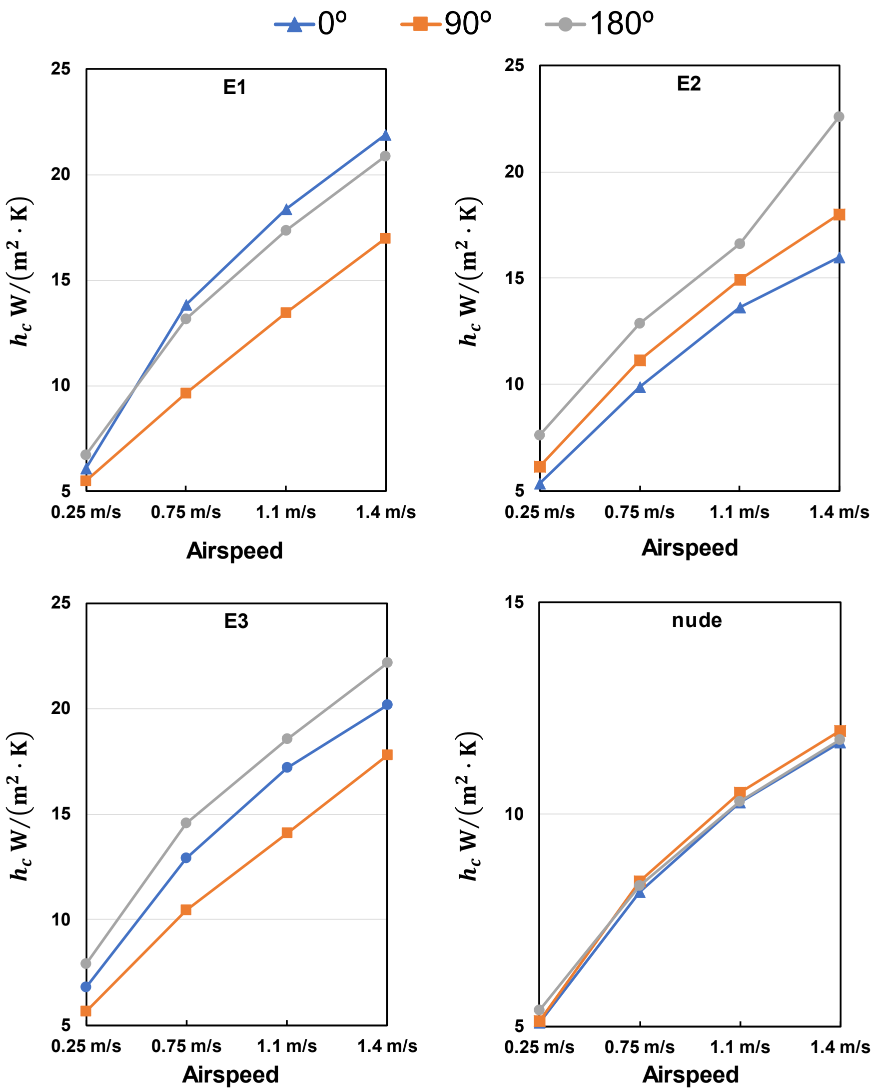



Figure 6 Comparison of the convective heat transfer coefficient for the clothed manikin and the naked manikin due to different wind directions (Sitting)

Figure 7 shows the convective heat transfer coefficient for the clothed manikin and the naked manikin due to different wind directions in standing posture. The convective heat transfer coefficient caused by the wind from the right side of the manikin was the smallest both for the clothed manikin and the naked manikin. The reason is that the smaller surface area faced the wind.

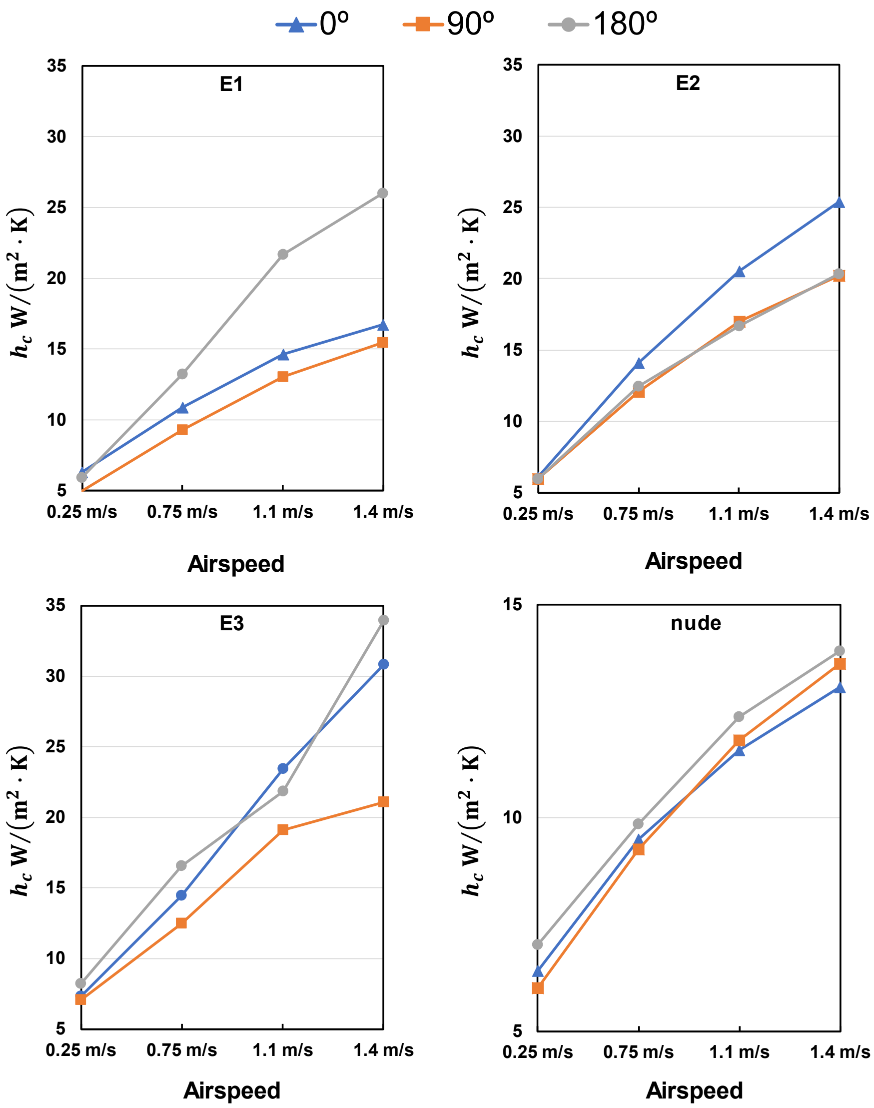



Figure 7 Comparison of the convective heat transfer coefficient for the clothed manikin and the naked manikin due to different wind directions (Standing)

### 3.2. Convective heat transfer coefficient for the different body segments

Figure 8 shows the convective heat transfer coefficients for each segment of the clothed and the naked manikin under various airspeeds. The results for the head, the hands, and the feet are not shown here. As already seen in the whole-body result, in the low wind speed range, there was no significant difference in the convective heat transfer coefficient for the clothed manikin and the naked manikin.

In both sitting and standing posture, there was a large difference between the convective heat transfer coefficient for the clothed manikin and the naked manikin at the pelvis and leg. This is partly because the air layer for the leg and the pelvis between the manikin surface and the clothing was thick. The air layer was thinned by the airflow, which resulted in more convective heat loss. The convective heat transfer coefficient for the shoulder of different clothing ensembles showed little difference.

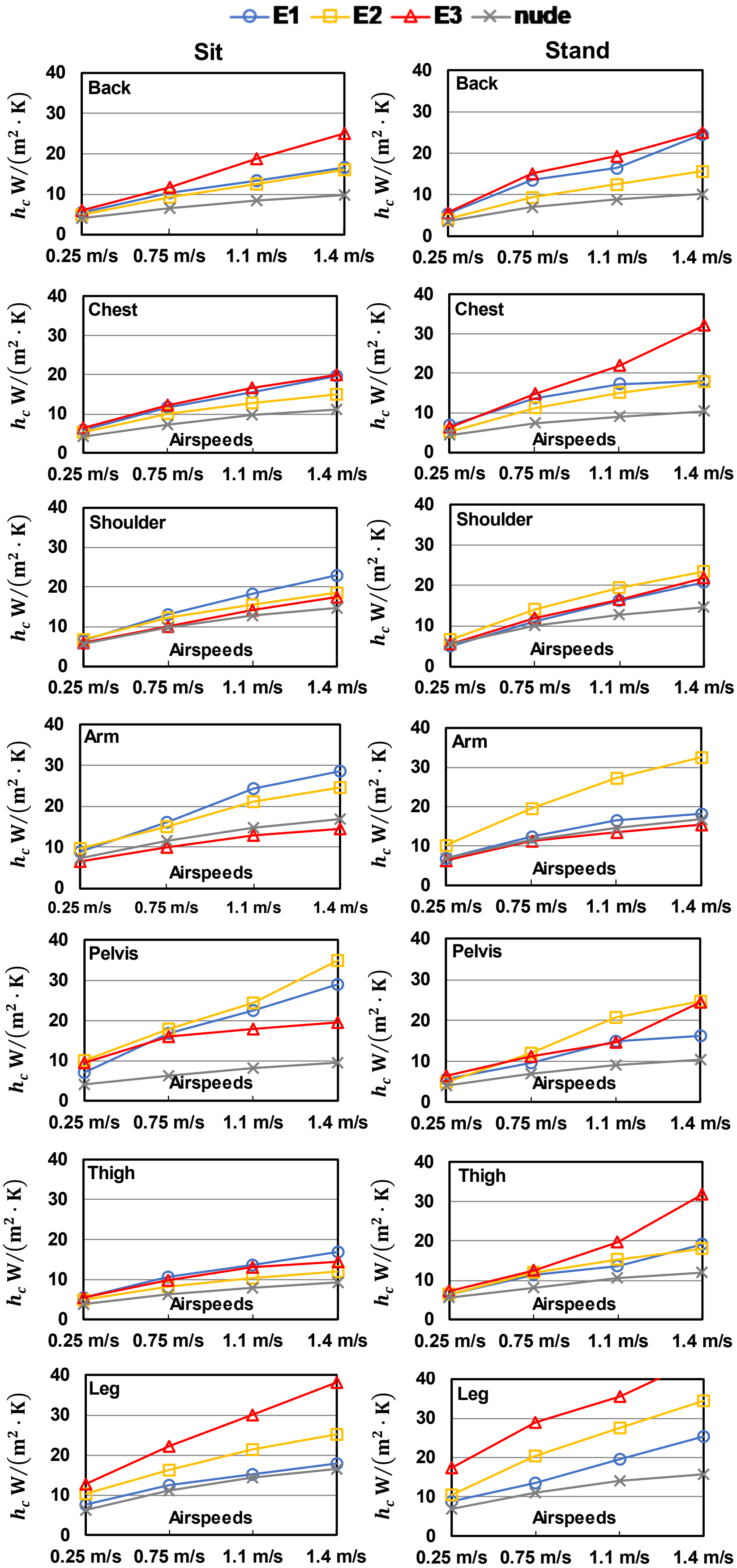



Figure 8 Convective heat transfer coefficients for each body segment for the clothed manikin and the naked manikin (except the head, hands, and feet)

### 3.3. Whole-body radiative heat transfer coefficient

Figure 9 shows that the radiative heat transfer coefficients for different clothing ensembles were almost the same. The reason is that the difference between surface temperatures for different clothing ensembles were small (Figure 10). In addition, the radiative heat transfer coefficient didn't change with airspeed. In the previous study, we concluded that the radiative heat transfer coefficient for the standing thermal manikin was larger than the sitting thermal manikin because the standing thermal manikin has a larger view factor (Gao, Ooka and Oh, 2019b). This result was consistent with the clothed manikin in this study. As it is shown in Figure 9, for all the clothing ensembles, the radiative heat transfer coefficient for the standing posture was larger.

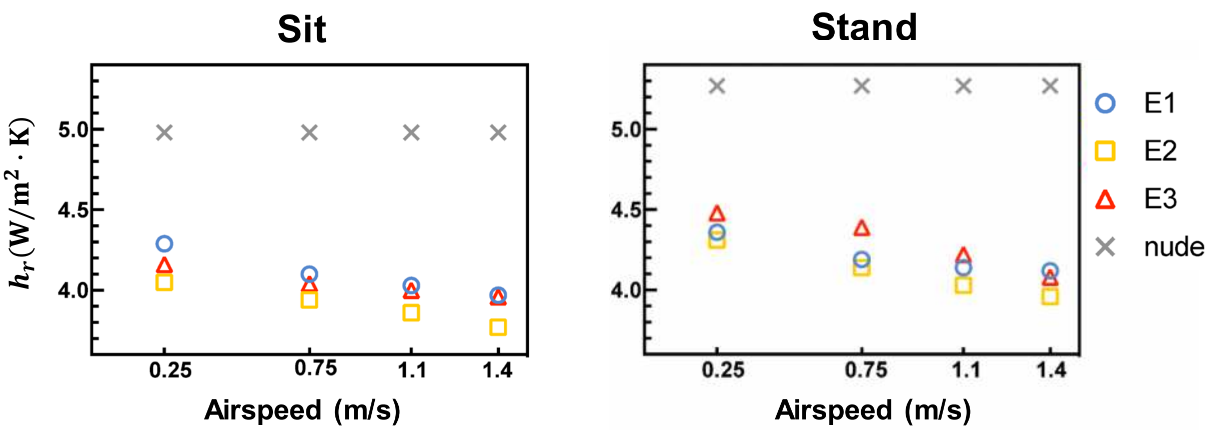



Figure 9 Comparison of whole-body radiative heat transfer coefficient for the naked manikin and clothed manikin in sitting and standing postures

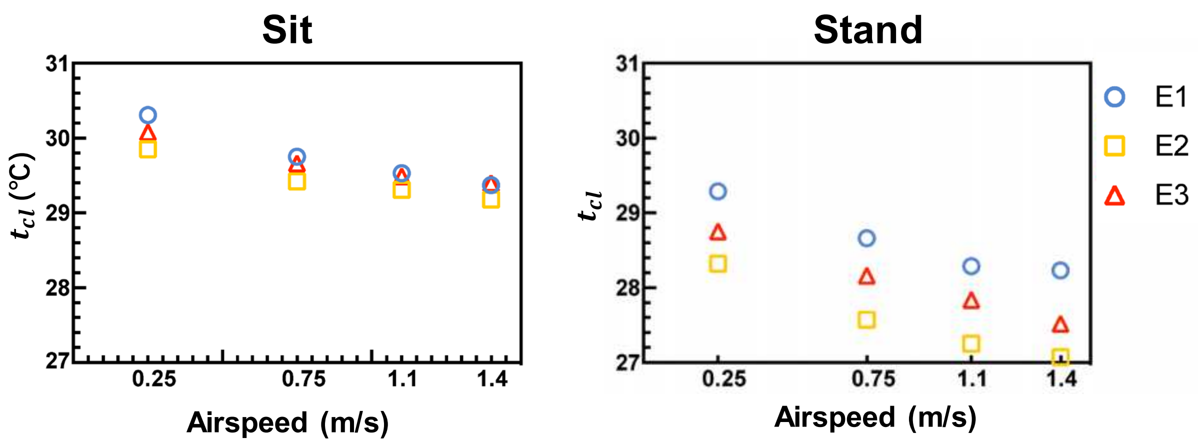



Figure 10 Comparison of whole-body clothing surface temperature for the clothed manikin in sitting and standing postures

### 3.4. Radiative heat transfer coefficient for different body segments

Figure 11 shows the radiative heat transfer coefficient for each body segment. Only results in sitting posture under an airspeed of 1.4 m/s were shown here. The radiative heat transfer coefficient for the clothed manikin was smaller than that of naked manikin at each body segment. The reason is that the temperature for the clothing surface was lower than the naked manikin surface. Hence, the radiative heat loss from the clothing surface was less than the naked manikin.

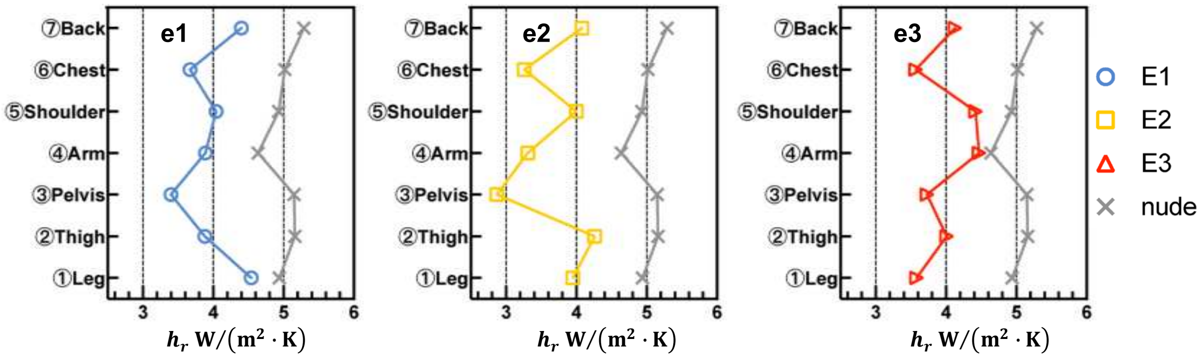



Figure 11 Radiative heat transfer coefficient for each body segment of different clothing ensembles in sitting posture under an airspeed of 1.4 m/s

## 4. Discussion

The objective of this study was to verify whether the convective and radiative heat transfer coefficients vary with different clothing ensembles. The first discussion is concerned with the convective heat transfer coefficient. Three clothing ensembles were measured, and the whole-body convective heat transfer coefficient for E3 was the largest. This partly because the material of E3 had good air permeability, and the wind caused larger convective heat loss. The convective heat transfer coefficient for E1 and E2 also showed a slight difference. For the convective heat transfer coefficient for each body segment, there was a difference between various clothing ensembles. Since the convective heat transfer coefficient tended to be different depending on the different clothing ensembles, it is necessary to measure much more clothing ensembles. When looking at the results of the radiative heat transfer coefficient, the radiative heat transfer coefficients for different clothing ensembles were almost the same

In some thermal comfort index predictions, such as the PMV model and the two-node model, the clothing heat transfer coefficient was assumed by multiplying the naked body heat transfer coefficient by the clothing area factor. Namely, the clothing heat transfer coefficients for different clothing ensembles were considered the same if the clothing area factors were the same. Therefore, it is necessary to clarify how the difference in the clothing heat transfer coefficient measured in this study affects thermal comfort index prediction in the future.

## 5. Conclusion

Convective and radiative heat transfer coefficients for the nude manikin and the clothed manikin in three kinds of clothing ensembles were measured through wind tunnel experiments. The main conclusions arising from this study are as follows:

(1) The convective heat transfer coefficients for the measured clothing ensembles were different and larger than the naked manikin.
(2) The difference in convective heat transfer coefficient for the clothed and naked manikin was small at low airspeed range.
(3) The radiative heat transfer coefficients for the measured clothing ensembles were slightly different and smaller than the naked manikin.

(4) The heat transfer coefficient for each clothed manikin segment was different. Furthermore, at the same body segment, the convective heat transfer coefficient for different clothing ensembles were different.

## Nomenclature

Variables

$h_{c,i}$: convective heat transfer coefficient for clothed manikin segment $i$, $\mathrm{W/(m^2 \cdot K)}$

$h_{r,i}$: radiative heat transfer coefficient for clothed manikin segment $i$, $\mathrm{W/(m^2 \cdot K)}$

$h_c$: whole-body convective heat transfer coefficient for clothed manikin, $\mathrm{W/(m^2 \cdot K)}$

$h_r$: whole-body radiative heat transfer coefficient for clothed manikin, $\mathrm{W/(m^2 \cdot K)}$

$I_{cl,i}$: the basic insulation for clothed manikin segment $i$, *clo*

$I_{cl}$: whole-body basic insulation for the clothed manikin, *clo*

$I_t$: whole-body total insulation for the clothed manikin, *clo*

$I_a$: whole-body air insulation for the clothed manikin, *clo*

$q_{t,i}$: sensible heat loss through the surface of the clothed manikin segment $i$, $\mathrm{W/m^2}$

$q_{c,i}$: convective heat loss through the surface of the clothed manikin segment $i$, $\mathrm{W/m^2}$

$q_{r,i}$: radiative heat loss through the surface of the clothed manikin segment $i$, $\mathrm{W/m^2}$

$t_{cl,i}$: clothing surface temperature of manikin segment $i$, °C

$t_{s,i}$: skin surface temperature for the clothed manikin segment $i$, °C

$t_a$: the air temperature, °C

$t_r$: the weighted average temperature of the wall surfaces, °C

$S_j$: the area for each wall $j$, $\mathrm{m^2}$

$t_{w,j}$: the temperature for each wall $j$, °C

$\alpha_i$: the ratio of the surface area of each part to the total naked manikin surface area, dimensionless

$\sigma$: Stefan-Boltzmann constant, $5.67 \times 10^{-8}\,\mathrm{W/(m^2 \cdot K^4)}$

$\varepsilon$: average emissivity of the body surface, dimensionless

$f_{eff}$: effective radiation area factor for each body segment, dimensionless

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# Advances to ASHRAE Standard 55 to encourage more effective building practice

**Edward Arens[1], David Heinzerling[2], Shichao Liu[3], Gwelen Paliaga[4], Abhijeet Pande[4], Stefano Schiavon[1], Yongchao Zhai[5], Hui Zhang[1]**

[1]*Center for the Built Environment, University of California Berkeley, CA*

[2]*Taylor Engineering, Alameda CA*

[3]*Worcester Polytechnic Institute, Worcester MA*

[4]*TRC Companies, Inc. Lowell MA*

[5]*Xi'an University of Architecture and Technology, Xi'an China*

**Abstract:** ASHRAE Standard 55 has been evolving in recent years to encourage more sustainable building designs and operational practices. A series of changes address issues for which past design practice has been deficient or overly constrained. Some of the changes were enabled by findings from field studies of comfort and energy-efficiency, and others by new developments in the design- and building-management professions. The changes have been influencing practice and spurring follow-on research.

The Standard now addresses effects of elevated air movement, solar gain on the occupant, and draft at the ankles, each with several impacts on energy-efficient design and operation. It also addresses the most important source of discomfort in modern buildings, the large inter- and intra-personal variability in thermal comfort requirements, by classifying the occupants' personal control and adaptive options in a form that can be used in building rating systems. In order to facilitate design, new computer tools extend the use of the standard toward direct use in designers' workflow. The standard also includes provisions for monitoring and evaluating buildings in operation. This paper summarizes these developments and their underlying research, and attempts to look ahead.

**Keywords:** Standards, thermal comfort, building energy efficiency, design

## 1. Introduction

Since WW2, the miracle of air-conditioning has transformed the world and eased constraints on building designers. Sealed glass buildings with deep floor plates became common worldwide, many highly exposed to solar gain. Traditional window shading and cooling measures such as operable windows and ceiling fans went away. In commercial buildings, open-plan multi-occupant spaces became dominant in offices, classrooms, etc; mostly with central thermostatic control. In both cold- and warm-climate residential buildings, the norm became sealed envelopes in which AC and its temperature thermostat was the first recourse to comfort.

Indoor environmental standards reflected the engineering practice underlying this evolution –a focus on Ta, Tr, and RH, since they are the outputs of HVAC systems. Indices and models such as PMV/PPD established rational design practice. The ideal indoor climate was 'Cool, dry, and still'. 'Climatic design' based on outdoor-indoor interactions went out of fashion, (persisting a bit longer in the UK and its ex-colonies, and in the residential sector).

Like a genie released from a bottle, the miracle had significant downsides. The new AC-based building designs demanded a lot of energy. After originating and taking over in energy-rich developed-countries, the air-conditioned methods and 'international' building styles spread rapidly in the developing world, creating a potentially gigantic energy demand.

There was an energy shock in the 70's, stirring up a reaction that attempted to revive traditional climate-responsive design methods, but it gained little traction with the mainstream. The principal achievements were in energy simulation models, and standards for tighter envelopes and more efficient equipment. Michael Humphreys and Fergus Nichol were making fundamental contributions addressing the adaptive behavior of occupants, but at the time these were not taken up in practice or in indoor environmental standards.

An important milestone in the early 80's was Larry Berglund's and Fred Rohles' idea for an ASHRAE project to measure the success of its comfort standards in the field. This grew into a series of well-instrumented studies (RPs 462, 702, 821, 921) that generated significant amounts of detailed data on comfort and associated environmental conditions. ASHRAE then funded a project to examine adaptation (RP 884) which was carried out by deDear and Brager (deDear and Brager, 1998). This project assembled a database of the previous field studies, allowing them to quantify that there was a difference between comfort responses from air-conditioned (AC) and naturally ventilated (NV) buildings with operable windows, and to create an adaptive model that Standard 55 adopted in 2004.

The adaptive model was highly restricted in the standard (applicable only in non-cooled spaces) but it raised a surprising level of interest internationally, particularly among architects, for whom it broadened their design options beyond that of the sealed box. It permitted another look at NV design with operable windows, and mixed-mode designs. The causes for the observed adaptive differences were largely hypothetical, but many people began looking into it.

During this time, it became clear that there were major energy savings from allowing the interior setpoint range to widen. Every 1C extension at indoor air temperature setpoint toward the warm side saves 5 to 10% of a building's total HVAC energy, depending on the HVAC systems involved. These numbers have been found in both simulations and field studies, commercial and residential buildings, temperate (Hoyt et al. 2014) and tropical climates (Sekhar 1995, Rim et al 2015, Duarte et al. 2019).

It made sense to consider the energy implications of designs and operating approaches that were regulated by the standard, and to critically review barriers that the standard was imposing on promising practice.

In the following, we present some of the changes to the standard made since the adaptive model. We also present significant research underlying the standard changes, and tools to enable their use in practice. They are presented in no particular order:

- Elevated indoor air movement in building design and operation—2009, 2015.
- Model of solar gain on occupants for use in design of fenestration and solar control—2016.
- Thermal control classification for rating personal comfort systems and accommodating individual occupants' variable thermal requirements, for design, certification, and operation—2020.
- Smaller items: seasonal clothing insulation model—2013, thermal stratification limit—2014, draft at ankles—2017.
- New supporting research data: A) expanded comfort database--2018, B) clothing database--2018, 2020, C) research on the comfort and energy effects of reducing VAV minimum flowrates.
- New official thermal-comfort computer tool for designers—2017.
- Methods for measuring and evaluating comfort in operating buildings; plus best-practice guides—2010-2013.
- Providing comfort in transient spaces—in process.

These 12 developments are handled in different ways in the standard. They raise some interesting issues about the various roles of standards in encouraging best practice design and operation.

**2. Air movement considerations**

The most efficient solutions to adaptive comfort in neutral-to-warm environments involve cooling the occupant with air movement. In earlier standards its use was restricted to temperatures above 26C, and individual occupant control was mandatory. For most HVAC design situations, the draft risk model was the only design consideration. Fountain (1991) was the first to attempt to explicitly balance the positive cooling contributions of air movement with the negative draft concerns.

In 2004 and 2007 respectively Toftum and Arens et al. used the ASHRAE RP 884 comfort database to learn that occupants preferred higher levels of air movement than expected, even down into the 'slightly cool' sensation zone, and that this phenomenon applied in both AC and NV buildings. This led to a reexamination of how air movement was being dealt with in the standard, and how to encourage it as an integral part of environmental control throughout the seasons of year. A new approach was first adopted in the 2010 standard.

The sensible and evaporative cooling effect of air movement are now evaluated using the Standard Effective Temperature model (SET) (Gagge and Fobelets 1986). This generates the equal-comfort curves in Figure 1, which are applied over the full width of any given comfort zone. The figure contains an important feature—subzones based on access to air speed control. They are based on an empirical temperature dependence observed in Comfort Database 1, in which imposed air movement was seen to become acceptable above 22.5C. The

Standard imposes a maximum (0.8m/s) for imposed air speed, but no maximum for group control. It also has simplified the previous draft risk provisions. The new air-movement approach applies to both air-conditioned and naturally-ventilated building types, and is integrated into the CBE/ASHRAE Thermal Comfort Tool described later.

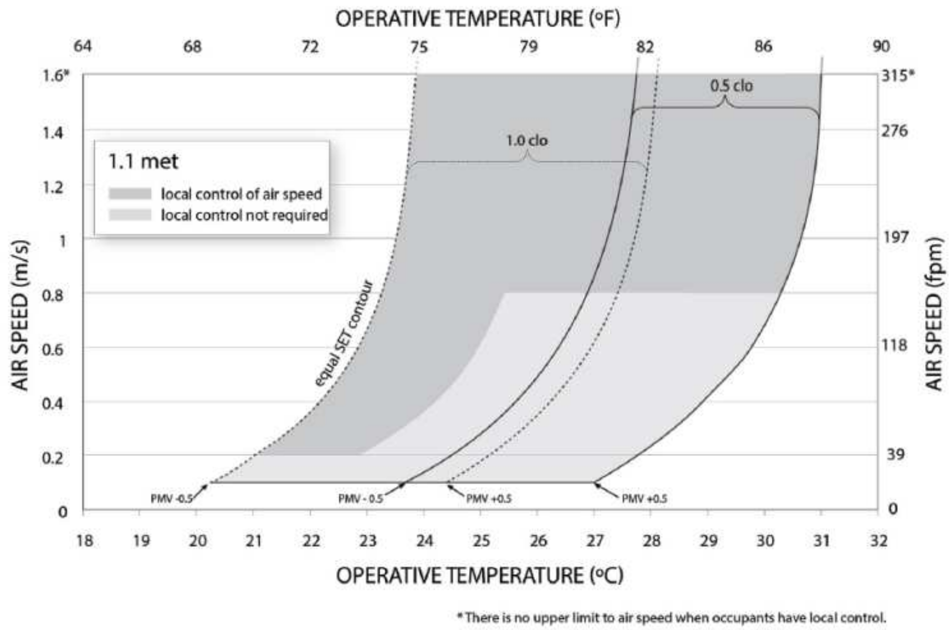


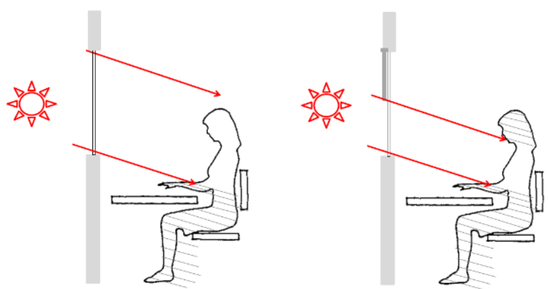

Figure 1. Acceptable ranges of operative temperature $t_o$ and average air speed $V_a$ for the 1.0 and 0.5 clo comfort zones, at humidity ratio 0.010

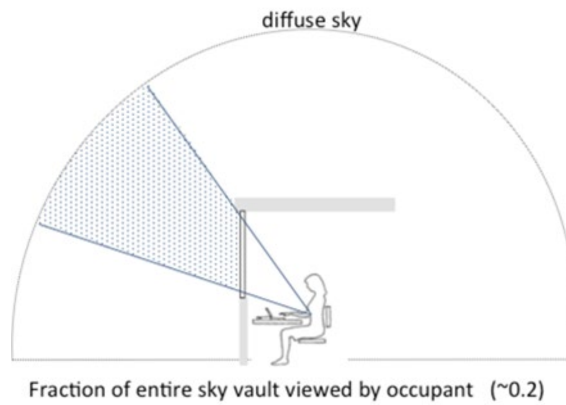
The new air speed provisions have attracted a great deal of interest, with much new research underway on how to create effective air movement within rooms. Huang et al. 2014, Gao et al. 2017, Zhai et al. 2017, Lipcynska 2018, are just a selection of papers examining design issues related to room fans. The integration of fan speed control with HVAC temperature setpoints is only just beginning, but products are now in the market.

### 3. Solar control.

Solar radiation on working occupants indoors almost always results in discomfort. In addition, most low-energy design strategies cannot succeed in inappropriately shaded buildings. In spite of their comfort and energy drawbacks, highly glazed unshaded buildings have become the norm. Up until 2017, indoor solar radiation was not addressed in any thermal comfort standard. It was as if engineers had no role at all in dealing with the problem. An addendum containing new performance- and prescriptive compliance approaches was added to Standard 55 in 2017 (Arens et al 2018). Direct- and diffuse shortwave gains on occupants are now evaluated in order to predict the amount of HVAC cooling required to offset them, and to prod both architects and engineers to become more engaged in shading design. The prediction is done using the ‘SolarCal’ model (Arens et al 2015), which is also incorporated in the CBE/ASHRAE Thermal Comfort Tool.

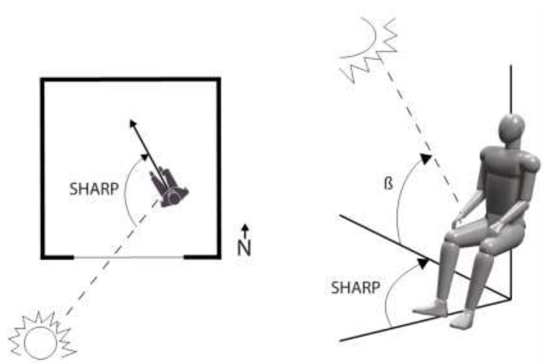
The model is simplified to require only inputs that designers can realistically provide at an early design stage.  It uses minimal geometrical definition of interior architecture and workstation furnishings, defining them in terms of occupant-centric variables new to the standard. These are: the posture and orientation of the representative occupant relative to the sun, and the extent of the person’s body area exposed to direct sun and the diffuse sky vault.  The shortwave gain is added into the standard’s PMV prediction as additional mean radiant temperature.






a) Fraction of body exposed to sun (not including the body’s self-shading)

b) Fraction of entire sky vault viewed by occupant (~0.2 in this example)




c) Solar horizontal angle relative to the front of the person (SHARP) and solar altitude *β*

Figure 2.  Occupant-centric components of the solar model

Recently software developers have modified the SolarCal model to read in output from Radiance and EnergyPlus, allowing the model to predict annual solar comfort effects and facilitating its adoption within current architectural workflow (Zani et al. 2018).

## 4. Thermal Environmental Control Classification

Addendum C to the 2017 Standard assigns credit to the degree of individual comfort control available to the occupants (adopted February 2020). Based on evidence that achieving high rates of thermal satisfaction requires individual control (Karmann et al. 2018), a five-level 'thermal environmental control' classification scheme now rates the degree of control available to occupants. The degree of control is quantified by the number of options made available by the building and its management to individual occupants. Options include personal comfort systems, group control of ceiling fans and thermostats, etc. Their eligibility in the Standard is determined by their comfort-correcting power as measured in degrees temperature (Zhang et al. 2015a). .

The definition of 'corrective power' in the standard is: 'the ability of a PCS system expressed in degrees (°C, °F) to "correct" thermal conditions toward the comfort zone, measured as the difference between two operative temperatures at which equal thermal sensation is achieved - one a temperature in the comfort zone with no PCS, and one with PCS in use, with all other environmental factors held constant.'

The new classification approach is aimed at building rating systems, such as LEED and WELL, and by real-estate managers. Each of these are now rating the quality of office environments in operation as well as design. Basing an environmental control classification on the availability of occupant control options is a promising new approach in comfort standards, encouraging designs and practice that have lower dissatisfaction percentages and higher energy-efficiency. The classification is summarized in Tables 1 and 2; the first describing the numbers of control measures per classification level, and the second the criteria for accepting PCS devices as control measures. There are numerous papers describing the performance of the compliant types of PCS devices, (Luo et al. 2018, Zhang et al. 2015b, Pasut et al. 2015, Kim et al. 2019), in addition to fans as described previously.

Table 1: Thermal Environmental Control Classification Levels (from Std 55-2017).

| Comfort Control Classification Level | Control Measure(s) for Environmental Factors Required to Achieve Level | Informative Examples Meeting Comfort Control Classification Levels |
|---|---|---|
| 1 | Each occupant is provided two or more control measures for their personal environment | • Private office with a ceiling fan and an occupant-adjustable thermostat<br>• Shared office with a desktop fan and foot warmer for each occupant |
| 2 | Each occupant is provided one control measure for their personal environment | • Private office with an occupant-adjustable thermostat<br>• Shared office with a desktop fan for each occupant |

| | | |
|---|---|---|
| 3 | The room or *thermal zone* provides multi-occupant control of at least two control measures in their shared environment. | • Shared office with an occupant adjustable thermostat and ceiling fan control |
| 4 | The room or *thermal zone* provides multi-occupant control of one control measure in their shared environment. | • Shared office with an occupant adjustable thermostat |
| 5 | No occupant control of any environmental factors | • Shared or private office with an unadjustable thermostat or no thermostat |

Table 2: Prescriptively Compliant Personal Comfort Systems (from Std 55-2017)

| Description | Requirements |
|---|---|
| Cooling | |
| Desk fan aimed at head/face/upper body | Capable of providing air speed at the occupant's head/face/upper body within range of 0.36 – 0.8 m/s (70.9 – 157.5 fpm) |
| Cooled chair | Capable of extracting 20 watts from the body |
| Heating | |
| Footwarmer | Capable of adding 6 W to the body |
| Heated chair | Capable of adding 14 W to the body |

This new classification is a different approach from the ISO PMV-based classification system in which narrow temperature deadbands are rated as providing superior environments (ISO 2005, CEN 2007). Conforming to the higher classification levels in these systems is highly energy-intensive. Of equal concern, examination of the two ASHRAE comfort databases and individual field studies show that the higher classification levels do not actually improve occupant comfort (Li et al., 2019, Lipczynska et al., 2018). Narrow room temperature control basically cannot solve the wide interpersonal variation in occupants' thermal comfort requirements. In addition, research consistently points to deficiencies in the predictive value of PMV and PPD, the measures underlying the ISO classification system.

## 5. Smaller elements

5.1. **A clothing insulation model** was added in 2015 to give designers a standard way of incorporating seasonal clothing behavioral changes in their designs. Clothing insulation on a given day is based on outdoor air temperature at 6 AM (Figure 3). The model is based on analyses of the ASHRAE databased of thermal comfort field studies (Schiavon and Lee, 2013, 2014).

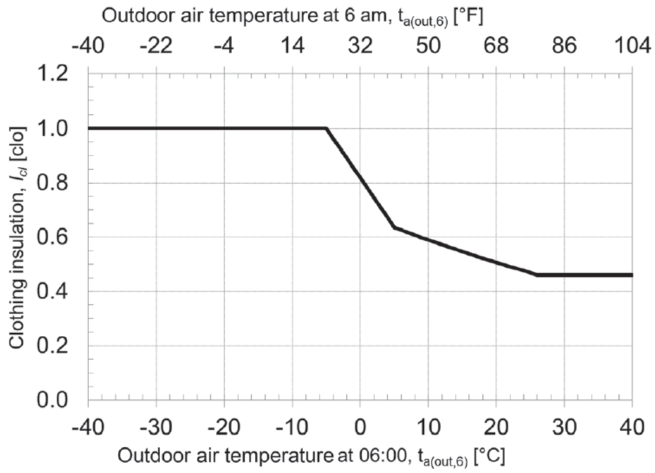


Figure 3. Clothing insulation as a function of outdoor air temperature

5.2. **The vertical thermal stratification** limit was in 2014 clarified to be 4K for standing and 3K for seated occupants. The original limit of 3 K between head and ankle had been applied in another standard to standing occupants, resulting in a 2K effective limit when seated. This was found to be adversely impacting the design and operation of displacement ventilation (DV) and underfloor air distribution (UFAD) systems (Bauman et al 2010).

5.3. **Ankle draft risk model**, approved and published as Addendum A in 2017. Draft, or unwanted local cooling caused by air movement, is a major issue for both DV and UFAD system manufacturers and designers (Melikov et al., 2005). Occupied floor area, mechanical system sizing, and energy use depend are all impacted. Since the exposure is at feet and ankles, the traditional Draft Risk model (Fanger et al., 1988) based on upper body dorsal exposure did not apply. A new model predicts percentage dissatisfied with ankle draft as a function of whole body thermal sensation and air speed at the ankles (Figure 4), (Liu et al., 2016, Schiavon et al., 2016).

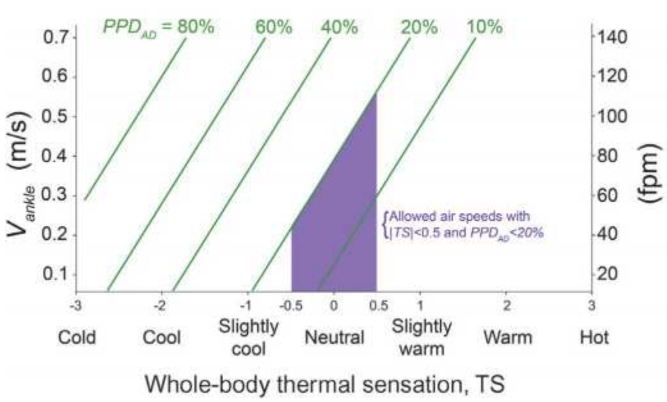


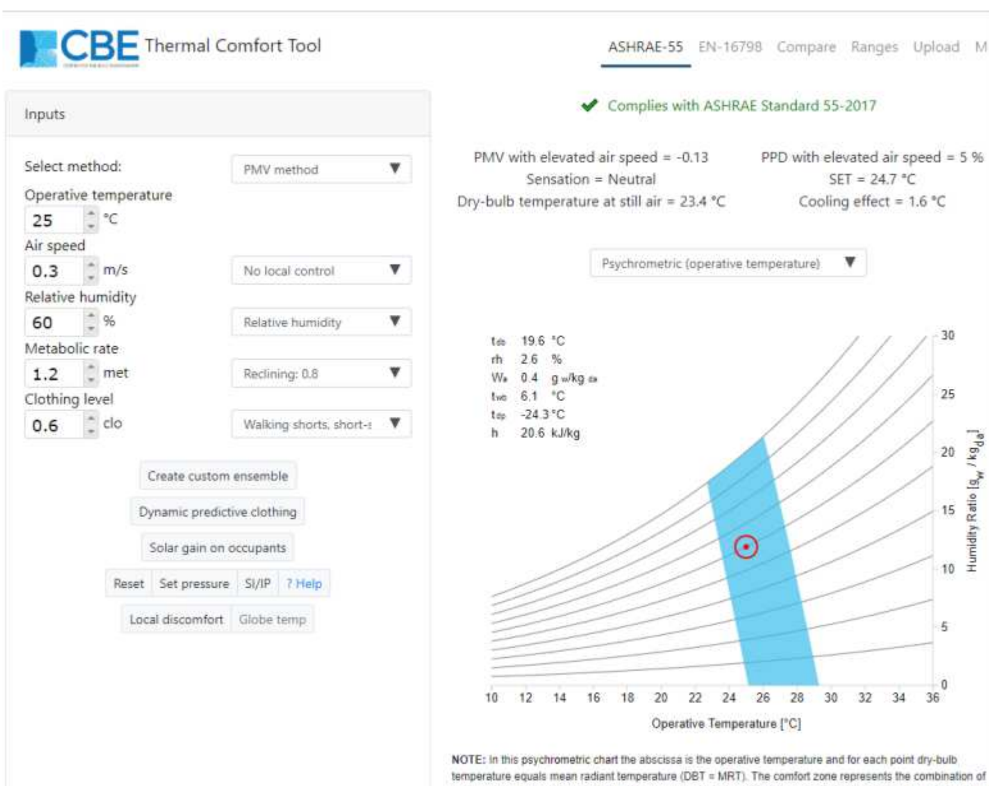

Figure 4: Air speed limits at 0.1 m (4 in.) above the floor as a function of whole-body thermal sensation and the predicted percentage of dissatisfied with ankle draft ($PPD_{AD}$)

In the model, the whole-body thermal sensation is approximated using PMV with the input air temperature and speed averaged over two heights, and not three as in the rest of the standard. The two heights are 0.6 m and 1.1 m for seated occupants and 1.1 m and 1.7 m for standing occupants.

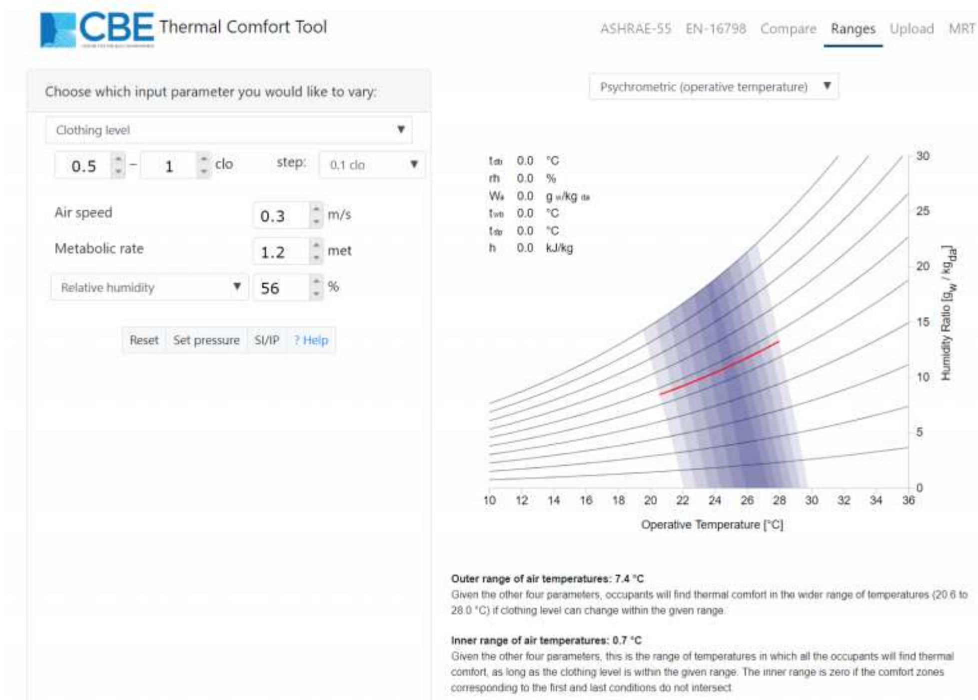
This type of draft risk might also occur in perimeter zones in which there are large glazed areas that are relatively cool. An architecture firm has developed an open web tool that incorporates this ankle draft risk model. [https://www.payette.com/glazing-and-winter-comfort-tool/](https://www.payette.com/glazing-and-winter-comfort-tool/)

## 6. ASHRAE/CBE Thermal Comfort Tool

The CBE Thermal Comfort Tool is a free web-based application that allows building designers and other practitioners to perform thermal comfort calculations (Schiavon et al. 2014, Hoyt et al. 2019). It complies with the ASHRAE Standard 55 and the European Standards EN-15251. It was launched in 2017 as the official tool for ASHRAE, with upgrades in 2019. The tool has been used by over 48,000 unique users, with 94,000 sessions per year from users around the world. At this point, the largest number of users are from the US (25% of total), Brazil, and the UK. [https://comfort.cbe.berkeley.edu/](https://comfort.cbe.berkeley.edu/) .




a)




b)

Figure 5: a) main screen, b) comparison screen showing comfort zones for a range of clothing

The tool incorporates the: PMV model for determining a representative occupant's thermal sensation in still air, the SET model for determining the cooling effect of air movement, the adaptive model for non-air conditioned buildings, the SolarCal model for solar gain on people, the dynamic predictive clothing model, and several local discomfort models (radiant temperature asymmetry, draft, ankle draft, vertical air temperature difference, and floor surface temperature).

The CBE thermal comfort tool serves many uses. One can compare various design scenarios, assess the effect of the variation of one of the variables (for example air speed) on the thermal comfort range, calculate the major thermal comfort indices for a large set of measured or simulated data; and accurately model the mean radiant temperature in a room.

The Thermal Comfort Tool has been integrated with EnergyPlus and Radiance to obtain more detailed input values needed for time-series calculations, and to integrate it into modern design workflow (Zani et al., 2018).

## 7. Standard-55-oriented research data

### 7.1. ASHRAE Global Thermal Comfort Database II

The original Global Thermal Comfort Database created in 1998 served to develop the Standard 55 adaptive model, the elevated air movement model, and the climate-based clothing model.

It was also extensively used to study analytic and adaptation models across climatic zones and cultures. Since many additional field studies have been completed since 1998, funding was secured from ASHRAE in 2015 to support the collection and consolidation of all available datasets. Completed in 2019, the ASHRAE Global Thermal Comfort Database II contains data from 43 research projects, all voluntarily donated (Foldvary et al, 2019). The database is 6x larger, and the number of represented countries increased to 23. The dataset is accompanied by software tools for visually exploring and analyzing the data. A large number of analytical studies have been done with the data within the first year since the publication of the data.

One of these (Parkinson et al 2020) evaluated the adaptive model and found that people in all types of buildings (AC, MM, NV) adapt to the *indoor* thermal environment. This is a breakthrough because it suggests, among other things, that adaptive models can be applied to any type of building. Other studies have used the new database to examine the effectiveness of existing comfort indices (Cheung et al, 2019).

The new database is openly accessible at: http://www.comfortdatabase.com/ (Parkinson 2018). The interactive visualization tool (Pigman 2014, Cheung and Pigman 2018) is accessible at https://cbe-berkeley.shinyapps.io/comfortdatabase/ .

### 7.2. **ASHRAE databases of Non-Western and Western clothing**

The absence of non-western clothing ensembles had been a long-standing concern in the Standard 55 committee, so ASHRAE TC 2.1 sponsored a major international study of worldwide non-western clothing insulation, performed by a team led by Loughborough University (RP 1504) (Havenith et al. 2016). New standardized measurement procedures were developed to coordinate the several universities that participated in the project. Clothing insulation was quantified at the body segment level, to support advanced comfort models in the future. Vapor permeability was determined as well. When this project was completed in 2016, it was clear that the existing western clothing data in the Standard would have to raised to the same level, and that it needed to accommodate additional modern clothing trends. A second ASHRAE research project, RP 1760, is currently underway at Loughborough to fulfil that objective.

### 7.3. **Comfort and energy effects of reducing minimum airflow rates from variable-air-volume (VAV) diffusers**

ASHRAE Research Project 1515 was co-sponsored by the Standard 55 committee. It examined the impact of diffusers dumping cooled air on occupants as VAV systems throttle back under reduced loads. It found that the traditional design concern about drafts from dumping is unsupported, but also that the high minimum flow setpoints used by the industry to avoid dumping are the most probable cause of the widespread overcooling of buildings in summer (Paliaga, 2019). This is an example of research addressing the intersection of comfort and energy standards. It describes a cold comfort problem that does not occur during typical winter design-day conditions, but occurs instead during frequent periods of low occupancy in the warm season. To date, some state building energy standards have been modified to take advantage of its findings.

## 8. Evaluating comfort in operating buildings.

Standard 55 also addresses the evaluation of buildings in operation. The provisions are contained in normative and informative sections in the standard's Section 7 and Informative Appendix L. They were developed around 2011 and incorporated in the 2013 Standard, and include:

- Evaluation approaches based on 1) physical environmental measurements and models, and 2) occupant surveys, giving criteria and examples for each. There is increasing use in the industry of physical monitoring over time, and of web-based survey tools (Heinzerling 2013, Parkinson 2019).
- Exceedance metrics for comfort and acceptability as measured over time. These include the definition of exceedance-hours specified in the normative standard itself, and the definition of other measures (weighting by severity of temperature exceedance, thermal sensation exceedance, rate-of-change exceedance, and numbers of discomfort episodes) specified in the standard's informative appendices. Since 2011 there has been considerable work done on exceedance assessment in operating buildings (Borgeson and Brager, 2011, Carlucci 2013).

Table 3 gives the structure of the section's provisions. They include both physical and subjective metrics for evaluating spaces, each divided into short-term (spot) measurements, and long-term satisfaction and exceedance measurement. The intended uses of the metrics are provided as informative notes.

TABLE 3 Comfort Evaluation Approaches for Various Applications (source: ASHRAE Standard 55-2017)

| | | **Nature of Application** | |
|---|---|---|---|
| | | **Short-Term** | **Long-Term** |
| **Measurement Method** | **Occupant Surveys** | **Right-Now/Point-in-Time Survey (must survey relevant times and population):**<br>• Binning (TSENS scores) leads to % comfort exceedance during period of survey.<br>• Needs coincident temperature to extrapolate to full range of conditions<br>*(Used for research, problem diagnostics)* | **Occupant Satisfaction Survey:**<br>• Survey scores give % dissatisfied directly. ('dissatisfaction' may be interpreted to start either below -1, or below 0)<br>• Time period of interest can be specified to survey takers. |

| | | | |
|---|---|---|---|
| | | | *(Used for building management, commissioning, rating operators and real estate value, compliance with green building rating systems)* |
| | **Environmental Measurements** | **Spot Measurements, Temporary (Mobile) Sensors (must select a relevant time to measure):**<br>• Use measurements to determine PMV (Sections 5.3.1, 5.3.3)<br>• Use measurements to determine compliance with *adaptive model* (Section 5.4).<br>*(Used for real-time operation, testing and validating system performance)* | **Logging Sensors over Period of Interest, or Trend Data from Permanently Installed (BAS) Sensors:**<br>• *Exceedance hours*: sum of hours over PMV or Adaptive Model limits.<br>• Binned exceedances may be weighted by their severity.<br>• Instances of excessive rate-of-temperature change or of local thermal discomfort can be counted<br>*(Used for evaluating system and operator performance over time)* |

The primary users are facilities management and certification programs that evaluate and rate building performance over time. Such programs should ideally involve the same level of rigor as required in design standards.

To support such users, ASHRAE prepared Performance Measurement Protocols [ASHRAE 2012] for measuring indoor environmental quality, a best-practices guide presenting examples of the methods contained in Standard 55.

## 9. Looking forward: dealing with thermal comfort transitions

SSPC55 is currently discussing standards for designing and operating spaces in which comfort transients occur. Such spaces are ubiquitous and economically/environmentally important. Designing for them will ultimately require a dynamic model of comfort, enabling a kind of choreographic design for comfort sequences. For now, prescriptive measures may suffice. The new provisions would be applicable to:

1) transition zones (lobbies, stores, transit facilities)
2) interior sedentary destination zones (offices, classrooms, restaurants,)

Building *lobbies*, *retail stores*, and *transit* facilities must maintain comfort for people moving between outdoor and indoor environments. Their users' immediate and short-term comfort perceptions impact the use of such spaces, affecting their profitability. At a broader scale, transient comfort directly affects the success of public transit and non-automotive commute strategies intended to improve transportation energy-efficiency.

Transient comfort also affects the environmental control of indoor spaces in which people are primarily sedentary, such as *offices*, *restaurants*, *airport lounges*, because when people arrive in these places they must undergo a transition from a moving- to sedentary state. This must occur as rapidly as possible so the occupants do not overheat and register discomfort to the building

HVAC controller.  During the transition period, arrivees' thermal requirements may differ from those of surrounding occupants, and their efforts to change the thermostat may overcool the other occupants.  Even if there are no other occupants, the response time lag in HVAC systems is often too long for effective at comfort restoration, and the reduced temperatures persist when they are no longer needed.

For both of the above types of comfort control, there are significant energy implications.  In transitional spaces such as lobbies and stores, either heated or cooled conditioned air leaks to the outdoors, so its temperature matters.  In destination sedentary locations such as offices, rooms are being operated cooler-than-comfortable for long-term occupants, to accommodate the cooling-off of arriving occupants.

For these transient cool-downs, it turns out that air movement is the most rapid and comfortable cooling mechanism (Zhai et al., 2019a, b).  Fan air movement around the occupant is also inherently many times more energy-efficient than cooling the indoor air or surfaces. Store/lobby temperatures can therefore be higher and their leaked air does not carry as much heat.  Air cooling can be focused on the arriving occupant while sparing the already sedentary occupants from experiencing an overcooled space. In addition, fans often offer more opportunities for individual adjustment than thermostats.  The question for the Standards Committee going forward is, how may one encourage such more effective design approaches within the terms of a standard?

**10. Conclusion**

This paper has

1) described what has been happening recently in ASHRAE Standard 55, and hopefully

2) raised questions about how comfort standards might perform roles that go beyond insuring that buildings and mechanical system meet predicted extreme conditions, and instead encourage generally better design and operation.  These roles include: rewarding building designs and systems that are efficient over time, realistically rating buildings' comfort quality levels, dealing with predictable thermal transients in spaces and occupancies, and monitoring and control of existing spaces using greater input from sensors and occupants.

Standard 55 is generally considered to be a design standard but its title and scope do not actually state this.  The definitions in its *Section 4* discuss the 'representative occupant' but do not exclude simulating larger numbers of occupants, or actually measuring their comfort to appraise and control existing buildings.  There is scope for more roles for the Standard.

Standard 55's *Section 5* is entitled: 'Conditions That Provide Thermal Comfort'.  The recent addenda described in this paper related to modeling air movement, solar effects on occupants, ankle draft, and clothing, have each been added into Section 5, which at present addresses only physical environmental conditions. Psychological and physiological adaptive opportunities are not explicitly part of the section, though one could say they are indirectly embodied within the comfort ranges provided by the empirical adaptive model. The physical conditions discussed in Section 5 are steady-state, with some limits to allowable rates of change. The Section does not deal with variation in the occupant's experience while moving through space or changing activity level (e.g. walking in and sitting down), even though these are often significant parts of the indoor experience in buildings. Also, the current prevalence of summer overcooling is affecting the occupants' adaptation to the environment—how should the standard encourage an appropriate comfort zone for the season?

*Section 6* is entitled 'Design Compliance'. Recent research allows us to quantify the effectiveness of some individual adaptive opportunities (such as personal comfort systems), but devices like these are currently not considered part of the building's design or installed equipment. So they are included in in Section 6 compliance documentation as a comfort classification system. Their audience is third-party green-building rating systems. Under what circumstances could they become incorporated in design and dealt with as part of Section 5 of the standard? There are both technical and design-related issues to solve. The ceiling fan, attached to the building, is an intermediate step that should ultimately become integrated with HVAC design for more efficient and individually-responsive environments. In the future, it may be that the encouragement of efficient transient-comfort control has to begin as a quality-rating scheme within Section 6 design compliance documentation. The operable window, providing a mix of physical and psychological effects, might similarly be rewarded in a comfort classification scheme.

*Section 7* is 'Evaluation of Comfort in Existing Buildings'. The building professions have not used this section much in the past. Where they have, it has been primarily for initial commissioning, problem diagnosis, and in using the exceedence metrics in yearly simulations of predicted comfort. There is however growth and interest in 'continuous (re)commissioning', more ubiquitous sensing, obtaining occupant feedback via computer surveys and control apps, and in determining individuals' and groups comfort profiles via machine learning. Such procedures could be used for both control and comfort classification. Section 7 may perform additional roles in the future.

**11. Acknowledgment:**

The authors prepared this paper as a contribution to IEA Annex 69, *"Strategy and practice of adaptive thermal comfort in low energy buildings"*. Most of the described additions to Standard 55 address adaptive attributes of thermal comfort, in order to put them to use in designing and operating more comfortable and energy-efficient buildings.

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# Guidelines to bridge the gap between adaptive thermal comfort theory and building design and operation practice

**Runa T. Hellwig[1], Despoina Teli[2], Marcel Schweiker[3], Joon-Ho Choi[4], M.C. Jeffrey Lee[5], Rodrigo Mora[6], Rajan Rawal[7], Zhaojun Wang[8], Farah Al-Atrash[9]**

[1] Aalborg University, Department of Architecture, Design and Media Technology CREATE, Aalborg, Denmark
[2] Chalmers University of Technology, Department of Architecture and Civil Engineering, Gothenburg, Sweden
[3] Karlsruhe Institute of Technology, Building Science Group, Karlsruhe, Germany
[4] University of Southern California, School of Architecture, Los Angeles, United States of America
[5] National Taichung University of Science and Technology, Department of Interior Design, Taichung, Province Of China Taiwan
[6] British Columbia Institute of Technology, Building Science Graduate Program, Vancouver, Canada
[7] CEPT University, Centre for Advanced Studies in Building Science and Energy, Ahmedabad, India
[8] Harbin Institute of Technology, School of Architecture, Harbin, China
[9] German Jordanian University, School of Architecture and Built Environment, Amman, Jordan

**Abstract:** Adaptive thermal comfort guidelines have been developed within the work of Annex 69: “Strategy and practice of adaptive thermal comfort in low energy buildings”. The guidelines have been established based on a framework for adopting adaptive thermal comfort principles in building design and operation developed by the authors. The guidelines target building practitioners, addressing the critical interrelated role building planners, building operators and occupants play. A successful adaptive thermal comfort design, in which design for human thermal adaptation is foreseen, planned, and carefully embedded in the design and operation intent, is based on broad knowledge and understanding of the multiple quantifiable and non-quantifiable factors influencing human perception, as well as human building interaction. Adaptive building design follows a user-centric integrated design approach and therefore it is critical to consider the occupants’ and the operators’ role in buildings already in the design phase. This paper focuses on three main challenges identified earlier and how these are addressed in the guidelines, i.e. i) updating prevailing knowledge about human thermophysiology and adaptation, ii) developing a procedure for design of adaptive opportunities, and iii) providing guidance for operational planning and operation of adaptive buildings. The challenge for future research remains to assess the magnitude of how specific design decisions affect particular adaptive mechanisms.

**Keywords:** Adaptive thermal comfort, Personal control, Building energy efficiency, Climate context, Integrated Design, Occupant, Stakeholder

## 1. Introduction

Ensuring acceptable indoor temperatures with the minimum required energy use is one of the world’s challenges. The adaptive thermal comfort concept originates from the pioneering works of Webbs (1964), Auliciems (1969a, 1969b, 1981b, 1981a), Nicol and Humphreys (1973) and Humphreys (1976, 1978), who established the relationship between human thermal comfort and prevailing indoor and outdoor conditions. In contrast to the static view on thermal comfort, they define thermal comfort as a self-regulating[1] system. Their work formed the foundation for the formulation of the three adaptive principles, today known as behavioural, physiological, and psychological (de Dear et al. 1997). Since its development, numerous proofs of the adaptive thermal comfort concept were found in field studies.

Designs that apply the adaptive comfort principles by leveraging on people's natural ability to align with the outdoor climate result in more variable indoor temperatures over time, with the following benefits: 1) Avoid or reduce mechanical energy use, and help mitigate climate change, 2) enhance people's and buildings' resilience to climate change, and 3) increase thermal satisfaction of occupants, and 4) improve occupants' health and well-being (Table 1).

Table 1. Benefits from applying the adaptive principles in buildings.

| | **Performance aspect** | **Benefit** |
|---|---|---|
| **1** | Wide and sloped comfort bands dependent on the prevailing local climate, enabling relaxed set points, and reflecting thermal preferences | *Energy savings* - Avoid or reduce mechanical energy for thermal comfort |
| **2** | Wide and sloped comfort bands dependent on the prevailing local climate, enabling relaxed set points, and reflecting thermal preferences | *Resilience to climate change* - Enhance, rather than impair, physiological adaptation to the local climate, making buildings adjusted to local and enhance their supportive thermal behaviour |
| **3** | Designed, well implemented, and well-communicated adaptive opportunities and (objective and perceived) controls | *Improved usability and thermal satisfaction* - Improved operation of the building according to the design intent, improved occupants' thermal satisfaction through increased perceived control |
| **4** | Designed passively or actively regulated dynamic thermal environments that fluctuate within the adaptive comfort bands | *Health and well-being* - Improved thermal satisfaction, improved health and well-being, thermal delight |

Despite the above benefits and the considerable progress in adaptive comfort research, the manifestation of theory into design and operation practice is far from realisation. The limited examples of successfully adopted adaptive design and building operation in energy efficient building practice point to a need for developing guidance for building planners and operators[2].

For the development of the guidelines, the challenges and gaps in adopting the adaptive principles in practice were identified (Hellwig et al. 2019). The required actions to address these challenges can be summarised as follows:

- updating the understanding of human thermophysiology and supporting a better understanding of adaptation and acclimatisation

[1] This term was coined by Nicol and Humphreys (1973).

[2] In order to bridge this gap, Annex 69: "Strategy and practice of adaptive thermal comfort in low energy buildings" was established in 2015 by international thermal comfort experts under the umbrella of the International Energy Agency's (IEA) Energy in Buildings and Communities Programme (EBC). O One of the major project deliverables is a design guideline on how to use the adaptive comfort concept for lowering the energy use in buildings, including the usage of personal thermal comfort systems (EBC 2018).

- supporting a comprehensive understanding of the adaptive thermal comfort concept among practitioners: explaining the conceptual model behind the equation and the impact of contextual non-quantifiable factors
- interlinking the conceptual model of adaptive thermal comfort with building design beyond using it for determining acceptable temperature ranges
- interlinking the conceptual model of adaptive thermal comfort with operational practice in buildings
- explaining the important role of personal control and how to design for adaptive opportunities
- explaining the importance of dynamic effects in comfort with regards to design
- clarifying terminology used (building conditioning types, building classes)
- addressing the different roles of stakeholders in the process
- enabling planners to further develop their design and adapt their building design for future climate conditions
- indicating solutions for permanently or seasonally conditioned buildings

A framework was subsequently developed (Hellwig et al. 2019), which forms the basis of the guidelines. It emphasises those elements of an integrated design process[3] being most relevant for the adoption of the adaptive principles in practice: the adaptive principles, the building context, the planning and design, the operational planning and operation, and, as the end goal, the adaptive responses or actions of the occupants during building use. Although research has been focussing on office buildings the framework and guidelines apply to all building types/uses and contexts. However, there is certainly a need for well-documented use cases from diverse climates and building types/uses.

The building context (local climate, local constraints, building type/use, human context/social norms) determines the way the adaptive principles should be interpreted for a specific building project. In the planning and design phase of a building, it is the building context and the users that direct the possible passive design solutions and the active building systems (building services). Design decisions in both, passive and active design, are paramount to the potential of adaptive opportunities, as they shape which physical adaptive opportunities a building offers to its users, determine how these available opportunities are understood by users and affect the social relations among building users (e.g. small vs open-plan offices). We therefore propose a procedure for the design of adaptive opportunities, suited to climate and users, before deciding on further design parameters. Furthermore, the point to come across is the importance to tie design and operation in thermally adaptive buildings, and the importance of the human context: intended occupants, operators, managers, owners.

The guidelines report will include four main sections, as follows: After an introduction (Section 1), *Section 2* summarises the three adaptive comfort principles, i.e. physiological, behavioural and psychological adaptation supplemented with recent research findings. The section follows with a discussion on the effectiveness of the adaptive principles and on the order of activation of adaptive responses. It ends with a brief account on the development of adaptive models. *Section 3* describes the benefits from applying the adaptive principles in buildings, including energy savings, resilience to climate change, improved usability and thermal satisfaction, improved health and well-being. *Section 4* presents the developed framework for adopting the adaptive comfort principles in design and operation of buildings

[3] integrated design: often also called holistic design, whole building design, or collaborative design

(Hellwig et al. 2019). Each of the subsequent subsections includes guidelines to facilitate the integration of adaptive principles. Section 4 ends with recommendations for adopting adaptive comfort in conditioned buildings, including advice for facilitating free-running mode in building operation as often as possible and ways to integrate the use of the adaptive principles in permanently or long-season conditioned spaces. *Appendix 1* summarises information on adaptive models used in international and national standards, as well as examples of models developed by research in various locations and climates. *Appendix 2* provides checklists of parameters that can help stakeholders implement measures to ensure the availability of adaptive opportunities in buildings. *Appendix 3* is a collation of case studies with practical learnings from adaptive buildings investigated in Annex 69 Subtask C.

*In this paper*, we focus on three areas and how they are approached in the guideline: 1) Upgrading prevailing knowledge about human thermophysiology and adaptation, 2) Developing a procedure for design of adaptive opportunities, and 3) providing guidance for operational planning and operation of adaptive buildings.

## 2. Updating prevailing knowledge about human thermophysiology and adaptation

In our previous work (Hellwig et al. 2019) we identified challenges in understanding the adaptive principles and therefore difficulties of building practice to adopt and apply the concept of adaptive thermal comfort in designing buildings. New findings from neuroscience, molecular biology, health and thermal comfort research support the concept of thermal adaptation:

a) new understanding of human thermoregulation: decentralised thermoregulation principles (independent thermo-effector loops) instead of central body core temperature set-point theory (Werner 1980, 2010, Auliciems 2014, Romanovsky 2007; 2014),
b) consequently, discomfort signals come from the skin instead of coming from body core temperature deviation (Romanovsky 2014, Schlader et al. 2017),
c) positive effects of exposure to temperatures slightly outside the comfort range on health (Hanssen et al. 2015, Schrauwen and van Marken Lichtenbelt 2016, van Marken Lichtenbelt et al. 2017, Pallubinsky et al. 2017) and human adaptability/ resilience in e.g. heat waves (Auliciems 2014), and
d) the rediscovery (de Dear 2011) of the old concept of alliesthesia (Cabanac 1971) and its new interpretation as an important psycho-physiological driver for people's behaviour (Cabanac 1996) and of people's perceived control in buildings (Hellwig, 2015), and future approaches for zoning/conditioning buildings based on transient comfort perception (Parkinson et al. 2016, Zhai et al. 2019).

Figure 1 displays an integrated view on factors, mechanisms and main interrelations forming human thermal comfort perception. Factors influencing the physiological adjustments by thermoregulation determine a human body's heat balance and form the basis for steady-state thermal sensation models. They are accomplished by behavioural adaptation, psychological adaptation and acclimatisation processes (as part of physiological adaptation) and describe together thermal comfort perception in dynamically changing thermal environments.

The heat exchange mechanisms: convection, radiation, conduction and evaporation are not solely the basis to determine a human body's heat exchange balance. They also form a starting point for architectural passive design, which affords opportunities for behavioural adaptation and seasonal acclimatisation and for the choice and design of adaptive opportunities suited to the local climate and habits.

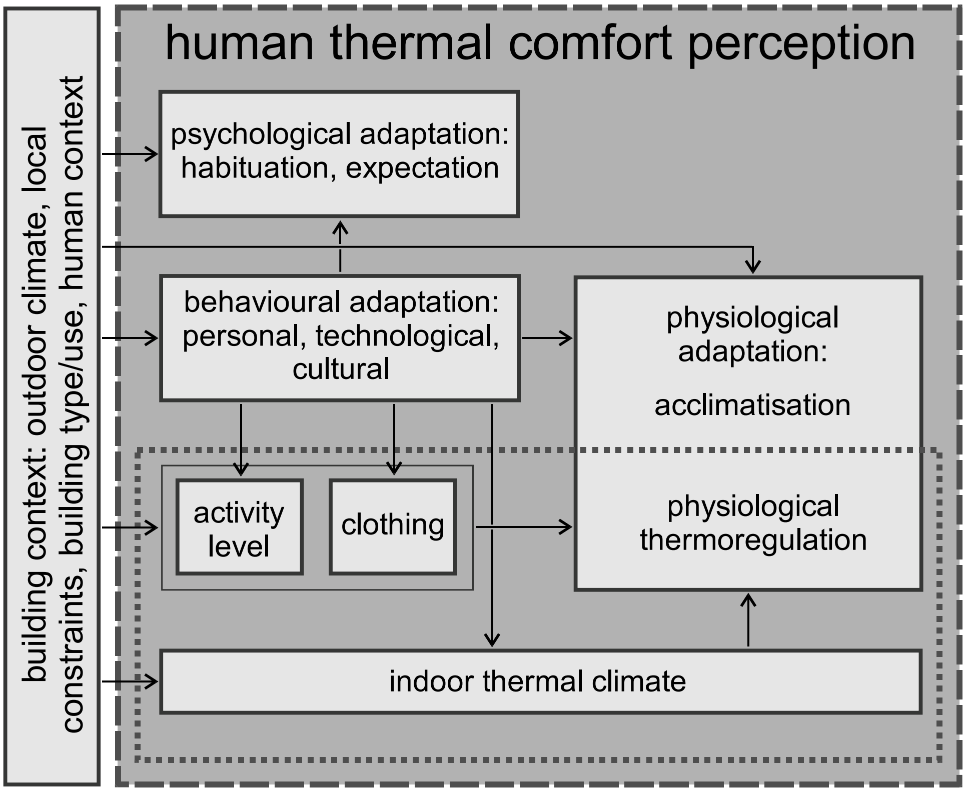


Figure 1. Integrated view on factors, mechanisms and main interrelations constituting human thermal comfort perception. Factors influencing the physiological adjustments by thermoregulation determine a human body's heat balance, and form the basis for thermal sensation models (dotted line rectangle). They are accomplished by behavioural adaptation, psychological adaptation and acclimatisation processes (as part of physiological adaptation) and describe together thermal comfort perception (dashed line rectangle) in dynamic environments.

A word on acclimatisation: A non-physiologist might start doubting when physiologists call a slowly increasing temperature, e.g. seasonal outdoor temperature change, as mild "heat strain/stress" (Taylor 2014), whether it should be "allowed" to be reflected indoors and whether it would then cause complaints. However, in everyday life such a change in outdoor temperature would be perceived as a natural change, as proven in numerous field studies, summarised in databases with data from all over the world (de Dear 1998, McCartney and Nicol, 2002, Földvary et al. 2018). However, gradual temperature changes should be separated from extreme and rapid temperature changes as e.g. in heat waves – with the two latter being the stress test whether a building's buffering and filtering capabilities are sufficient.

The human body has several strategies to detect and then respond or react to changing thermal conditions of the environment. The first response, activated autonomously, is the vasomotor response (vasodilation and vasoconstriction). The second response is behavioural thermoregulation (e.g. clothing, going to a different location, opening/closing a window). Comfort (or better discomfort) perception hereby serves as the driver to initiate behavioural adaptation before sweating or shivering, as the third thermoregulatory responses, are activated (e.g. Schlader et al. 2017, Figure 2). The psycho-physiological feedback signal to a person, i.e. whether a behavioural adjustment was successful in restoring comfort (Cabanac 1996), comes from the skin temperature at the point in time when a change in the "right" direction is detected (Romanovsky 2014). This has implications on the design of adaptive opportunities, especially of the active systems, and requires consideration when using energy-efficient low-temperature heating or low-temperature cooling systems as they tend to have a longer response time.

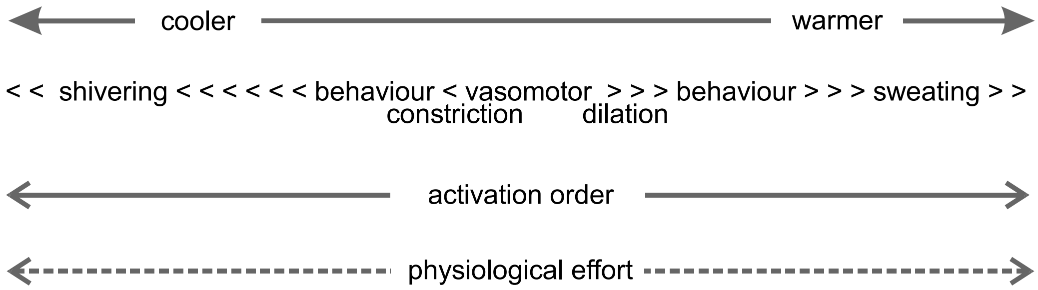


Figure 2. Hierarchy of activation of physiological autonomous (vasomotor, shivering, sweating) and behavioural body responses (simplified from Vargas and Schlader 2018, based on Schlader et al. 2017).

That behavioural thermoregulation is *activated by body signals* is a way building designers should pay careful attention to. Similar to autonomous thermoregulation, behavioural thermoregulation is a *natural biological body reaction*, and insofar it is in the building designers', planners', investors', and operators' responsibility to account for this natural and basic need for appropriate control. As physiologists have proven, behavioural thermoregulation is a basic underlying principle of ergonomics and numerous field studies have proven this to be a basic need of occupants.

While literature exists, that explains adaptive mechanisms (Humphreys and Nicol 1998, Nicol et al. 2012, Humphreys et al. 2016), identifies how to better operate buildings (Usable Building Trust, Wagner et al. 2015), or how to prepare buildings for climate change, e.g. by addressing the issue of overheating in buildings (CIBSE 2010[4], Hellwig, 2018), the above mentioned new findings contribute to better explaining results on thermal comfort evaluation from field studies (e.g. de Dear 1998, McCartney and Nicol 2002, Földvary et al. 2018) and to inform future adaptive building design and operation guidelines.

## 3. Developing a procedure for the design of adaptive opportunities

The availability of appropriate adaptive opportunities is fundamental to occupants' ability to restore thermal comfort by physiological, behavioural and psychological adaptation (see above). Adaptive opportunities and the related controls should be part of the design intent and therefore documented in the design brief to be able to further communicate the intent during the next phases to the relevant stakeholders: owner, organisational management, suppliers, control installers, facility management and occupants.

Within our framework, we have provided a table with conceivable adaptive actions from diverse climates and contexts structured according to five categories (Table 3 in Hellwig et al. 2019).

i) regulation of body internal heat generated,
ii) regulation of the rate of body heat loss,
iii) regulation of the thermal environment,

[4] As one example for guidelines on overheating avoidance by design and operation, which exist in other countries.

iv) selection of a different thermal environment, and

v) modification of one's psychological perception.

In order to enable these conceivable adaptive actions, various stakeholders in the planning and operation have to take action: the owner/investor, the building planner, the operator/facility manager, the company manager and the occupant, (**Error! Reference source not found.** in Appendix). The adaptive responses and actions of humans are defined as a *design goal* for a human-centred building design and operation. Designing buildings for adaptive comfort means to provide the necessary opportunities for occupants' adaptation. We have developed a procedure for the development of a design portfolio of adaptive opportunities, which is displayed in Figure 3.

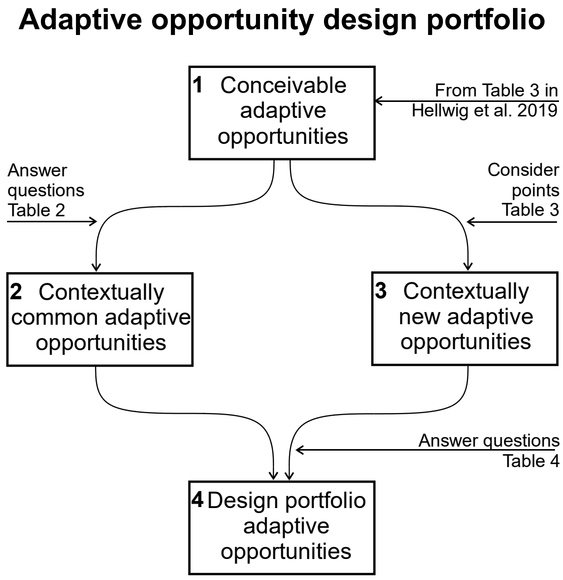


Figure 3. Procedure for development of a design portfolio of adaptive opportunities.

***Step 1:*** Starting point are all conceivable adaptive actions and responses, i.e. *conceivable adaptive opportunities* (refer to Table 3 in Hellwig et al. 2019, see summarised five categories above). These are not applicable to all situations buildings are in. Here comes the context the building is situated in into play.

***Step 2:*** By considering the specialities of the local circumstances, the conceivable adaptive opportunities are reduced to those common in the actual building's context. *Conceivable adaptive opportunities* are different in different local climates. For instance, measures such as wetting of walls or floors would be ineffective in warm and humid regions compared to hot and arid climates. Albeit some adaptive opportunities are more suited to a certain season, climate or building type, they may also be applicable in a different context depending on time of the day or occupancy. The building usage/type (e.g. residential, office, classroom etc.) may reduce the number and type of conceivable adaptive opportunities as it e.g. may not be appropriate to use a blanket when sitting in a classroom or taking off more clothes in an office environment.

Table 2 shows how these contextual factors drive design solutions and require design actions. Questions raised are exemplary and non-exhaustive. They shall support the planner in analysing the context in which the building is to be designed. After applying this procedure, planners have identified the *contextually common adaptive opportunities.*

Table 2. Contextual factors drive adaptive design solutions and require stakeholder's action. Questions raised are exemplary and not exhaustive.

| Contextual factor | | Question | Design action (responsible actor) |
|---|---|---|---|
| **Local climate** | Outdoor climate | What are the dominating factors of the climate [1)] (e.g. high/low solar radiation, distinct/not distinct seasons, hot and dry, warm and humid, cold etc.) | Identify type of basic design principles / climate adjusted design, (building planner)<br>Identify the type of adaptive need (building planner, operator) |
| | | What is the typical outdoor climate people are adapted to in this region? | Derive occupants' acceptability of indoor variability and temperature levels (building planner, operator) |
| | Season | What are the seasonal climate characteristics?[2)] | Derive the main differing seasonal design principles to be met (building planner)<br>Adjust the building operation and elements with seasonal needs (operator)<br>Allow for seasonal varying clothing of employees (organisational management) |
| | | … | … |
| **Building type/use** | Task | Which tasks and activities the occupants are expected to carry out? | Derive level and variation of activities (building planner, operator) |
| | Building use | Are there building use-related requirements which restrict certain adaptive opportunities? | Provide substitute adaptive opportunities, e.g. if a window cannot be opened in a museum with strict temperature and humidity requirements |
| | User group [5)] | Main occupants' age and health condition? | Derive ability of occupants for thermoregulation/ unconscious adaptive responses and plan accordingly (building planner, management) |
| | … | … | .. |
| **Human context/ Social norms** | Social norms[6)] | Are there adaptive opportunities which cannot be applied due to established norms? | Establish possibility/need to change norm or adjust adaptive action (building planner, operator) |
| | Indoor climate[3),4)], previous experience of users | Typical indoor climate experienced in buildings of same type?<br>Previous type of indoor climate experienced? (in case of renovation/move to new building) | If new building has different design strategy than previously: develop intense communication strategy already during design phase (building planners, operator)<br>Establish need for modification of expectations/ psychological adaptation (occupant, organisational management) and occupant education (operator, organisational management) |
| | Assumed knowledge/ common practice | Knowledge/common practice of users regarding adaptive opportunities? | Identify need for occupant education and familiarisation to new routines and adaptive strategies (operator) |
| | … | … | … |
| **Local constraints** | Pollution/noise/ UHI/ insects[7)] | Is the building site near a source? (e.g. traffic road) | Establish need to consider orientation/window opening/net protection in relation to source (building planners) and potentially special window operation schedules (operators) |
| | Security | Are there special security concerns? | Need for adjustment in design, e.g. of windows/restrictors (designer, operator) |
| | … | … | … |

***Step 3:*** However, having identified *contextually common adaptive opportunities* may not be sufficient for a contemporary portfolio a planner should have at hand. Therefore, recent or future developments listed in Table 3 should be considered. These additional criteria represent future considerations for the specific location of the building in order to prepare the building for a long-term successful operation. In sight of climate change, adaptive actions previously not used in a certain region may become desirable and appropriate in the future. However, they may be in conflict with some of the *contextually common adaptive opportunities*. Necessary measures, e.g. for energy efficiency influence the way *contextually common adaptive opportunities* are to be interpreted. New technologies and actual findings from research provide also information to derive *contextually new adaptive opportunities.*

Table 3. Considerations of recent and future developments

| **Future developments** | **Implications for adaptive opportunities** |
|---|---|
| Climate change mitigation | necessary measures are e.g. energy efficiency measures, use of renewable energy sources → need for adjusted ways of designing building which influence adaptive opportunities |
| Climate change adaptation | expected future changes of the local climate (generally increasing average temperatures, more frequent heat waves) can lead to adoption of adaptive opportunities from other climate zones |
| Increasing urbanisation | urban heat island effect, challenging certain common adaptive opportunities → need for design adjustments |
| Recent technological development of processes or products | new communication strategies, personalised comfort systems (PCS) → new types of adaptive opportunities |
| Recent research results on human perception of indoor spaces | health and well-being through experience of different temperatures → need for adjusted ways of designing building which influence adaptive opportunities |

***Step 4:*** First, the adaptive opportunities of step 2 and 3 are combined. Table 4 shows a set of questions, which support planners in accomplishing a *contemporary design portfolio of adaptive opportunities*. The choice of the *contextually new adaptive opportunities* evokes two challenges: Firstly, the critical point with introducing new behaviour options to a specific location is that all stakeholders in the building: occupants, operators and managers/owners should be provided with information about these new opportunities they are not yet familiar with. Secondly, it appears to be rather risky to rely solely on *contextually new adaptive opportunities* because not all stakeholders may be capable to uptake and embody those new ways of adaptation to the same degree. Therefore, it is strongly recommended to choose a *good mixture* of *contextually common and contextually new adaptive opportunities*, communicate them to and discuss them with all stakeholders.

Table 4. List of example questions to identify an appropriate mixture of common and new adaptive opportunities

| | |
|---|---|
| General questions | Have you implemented a variety of common adaptive opportunities which people are familiar with? |
| | Which are the most preferred contextually common adaptive opportunities in buildings in the region? |
| | When implementation of a new adaptive opportunity is planned: How are the tasks, practices, knowledge, capabilities/skills of the user group suitably and sufficiently supported? |
| | When implementation of a new adaptive opportunity is planned: What is the documented and proven acceptance of this new technology? |
| | Can an identified new adaptive opportunity replace a common one? If it is one of the most liked common adaptive opportunities, then rather keep it. |
| | Are the identified contextually new adaptive opportunities in conflict with the common adaptive opportunities? If they cannot be combined, carefully evaluate the usefulness/ necessity of the new opportunity with regards to future challenges, e.g. climate change. |
| | When implementation of a new adaptive opportunity is planned: Has the operator of the building sufficient knowledge to operate them? |
| | Are there special requirements from the operators and the operational management? |
| | … |
| New Buildings | If the company moves: Which were the most missed adaptive opportunities in the previous building? |
| | … |
| Existing buildings | If the building is renovated: Which adaptive opportunities were available in the building before renovation? Keep them, unless there were many complaints about them. |
| | If the building is renovated: Does the existing building have openable windows? Avoid replacement of previously openable windows by fixed glazing. |
| | … |

To summarise from the above: there is a large potential for behavioural thermoregulatory actions, which employ no operational energy or have a low energy use. Local climate and what people are used to (e.g. the most liked adaptive opportunities, Leaman, 2003) determine the adaptive opportunities feasible. *Since behavioural thermoregulation is deeply embedded in human thermoregulation and comes natural to people, it comes with the advantage of occupant satisfaction and engagement. There are no excuses for not designing/operating for adaptive opportunities. Constraints may exist, but they might exclude the use of adaptive opportunities only temporarily.*

## 4. Operational planning and operation of adaptive buildings

For operational planning, commissioning and operation of the building the chosen and documented design portfolio of adaptive opportunities (see previous section) is the driver to bring all measures in place, which make sure that the planned adaptive opportunities are also those available and used during the building use phase.

***Operational planning:*** During operational planning, several actors play a significant role for the effective implementation of adaptive actions (Collins et al. 2017). In case the later occupants' are known, assessing their needs at an early design and operational planning stage is helpful. At a later stage, they could then informed how they can fulfil their needs by using the building in the intended way. The adaptive opportunities identified in the design portfolio are the basis to develop operational procedures to maintain the adaptive opportunities and to inform the organisational management and the occupants about adaptive opportunities the building offers; they form the operational strategy. Such actions may include easing dress-codes if they exist, flexible working hours, maintaining different temperatures in certain zones, and maintaining functionality and accessibility of adaptive controls (e.g. openable windows, moveable blinds etc.). The result of this process may then be added to the design brief for the building. During the operational planning and based on standardised protocols (e.g. Softlandings, 2018), feedback loops between the players should be defined. They ensure that issues are identified and addressed promptly during operation. The guidelines complement with items related to adaptive thermal comfort operation.

Aside from the expected provisions for the operational planning of buildings, planning the operation of thermally adaptive buildings requires particular considerations due to the interactive nature of the building. In particular, the following provisions should be considered:

- Include in the operation and maintenance manual (see for instance BNB 2015, Wagner et al. 2015) a section on adaptive operation, including explicit sequences of operation of environmental control systems, detailed guidance on monitoring and verifying performance recurrently, and the roles, the freedom and the responsibilities of the occupants in interacting with the building. The manual should be in the local language and may be enriched with explanatory illustrations.
- Include an occupants' manual (e.g. BNB 2015) with information on what to expect from the indoor thermal environment and its systems, and simple instructions how to interact with the building. Information should include aspects of thermal comfort, indoor air quality, and other relevant environmental aspects such as lighting and noise. In addition, information should be provided in such a way, that it cannot be lost when occupants change. The manual should be in the local language and may be enriched with explanatory illustrations.
- Making provisions for the facilities manager to have a contact with the design team, especially early on during the building occupation, is essential to the full realisation of the building performance potential (e.g., CIBSE 2000). Protocols need to be established to engage designers to support and guide the tracking of building performance in line with the design and help tune the building environmental systems accordingly (initial aftercare and extended aftercare). This will in turn support the uncovering of performance anomalies by building operators, at the early stages of building occupation, and provide feedback to designers so that they can improve future designs.
- Provisions need to be made to fine tune the building environmental systems and adaptive opportunities as required during the early stages of building operation. This is common practice for all types of buildings, but is particularly critical in thermally adaptive buildings because designs include many assumptions on occupants' behaviours and interactions with the building that need to be verified (CIBSE 2000, 2009).
- A recurrent survey protocol for feedback and a protocol for the continuous performance monitoring of the building needs to be established (post occupancy evaluation, monitoring, BNB 2015). It should include the necessary types of data analysis and key performance indicators, including occupants' degree of satisfaction and levels of interactions with the building.
- To maintain occupants engaged with the good use of the building, a protocol needs to be established indicating provisions for timely response to occupants on not only their feedback on shortcomings or malfunctions, but also the performance of the

building and how their adaptive behaviours result in good environmental quality and energy savings.

- Problems arise in smaller buildings with janitors or other non-skilled facility management. For these cases with a clear lack of technical capacities inhouse, strategies will have to focus on the occupants or responsible persons from the organisation owning/renting such place. In principle, occupant-maintained spaces can include most of the measures described above, though time-constraints will make it more difficult for their implementation.
- Given that the amount of monitoring data collected may be substantial, to avoid data bottleneck, the management of data needs to be streamlined, analysed recurrently, and used effectively to produce desired performance outcomes and enable proactive operational adjustments.

***Operation:*** For building operation, occupants' perception of responsibility, knowledge of adaptive opportunities (occupant's manual), and the reduction of constraints are important aspects enhancing the implementation of an adaptive concept (Karjalainen and Koistinen, 2007). For overall satisfaction, it is supportive if an occupant – to a certain degree - feels responsible for the indoor climate at their workplace. To facilitate satisfaction of the users an appropriate complaint strategy system of the facility management of the building is desirable. This includes that complaints or feedback of users are taken seriously and comprises an appropriate feedback loop. At the same time, occupants may have to be informed about their adaptive opportunities, the effects they can expect by specific measures such as window opening and the benefits of less tight conditions with respect to energy use and health in order to manage their expectations and increase their satisfaction.

Building operation and management should try to minimise constraints to adaptive opportunities, as e.g. for windows it is important that they are accessible and operability is enabled. This requires regular checks from the facility management. Further measures already important to be considered during the design phase are for example sufficient storage space for documents, so that piles of documents on the windowsill restricting window opening can be reduced.

***Stakeholders:*** Facility managers and building operators are instrumental to implement the adaptive design principles and strategies successfully, for occupants' satisfaction and low-energy performance during the building service life. They are directly responsible for making sure that the design intent materialises.

Facility managers and building operators need to meet the following requirements to be able to implement the adaptive design intent successfully: i) to understand the adaptive principles and their role in achieving building performance targets (which outlines quite some future tasks in education and professional training); ii) to be well educated on the singularities of the building and its environmental systems; iii) to be motivated and proactive; iv) to be engaged with the occupants; v) to be well trained on the operation and management of the building environmental systems; and vi) to be properly supported by the higher management and by the building owner.

From the start of planning to beyond the commissioning, users should be involved in the decision-making processes as part of an intensive communication strategy, whenever possible. This avoids misunderstandings, minimises misconceptions and enables participation. The advantages of involving occupants are two-fold: 1) learning their thermal needs and experiences, motivating them and managing their expectations, and 2) informing them about the building. This information increases their awareness on the building environmental systems and intended environmental variability with benefits to the occupants and the environment. Most importantly, it outlines their role in controlling their own thermal environment and its impacts on building performance. Thus, a greater knowledge and understanding of building environmental features and controls can lead to a relaxation of comfort expectations, with significant implications for energy use (Brown and Cole 2008). Furthermore, research is focussing on how to engage users in the design and operation process of buildings (e.g. Martek et al. 2019, Bull and Janda 2018).

Appendix, **Error! Reference source not found.** includes sample checklist for organisational management, the operators/facility managers and the occupants, which refers to the criteria that allow the building to run in adaptive mode during the operation phase.

## 5. Conclusion

A guideline has been developed to bridge the gap between adaptive thermal comfort theory and building design and operation practice. The guideline aims to promote the adaptive thermal comfort thinking and the multiple benefits that it entails for people's health and wellbeing, as well as for energy conservation and the environment. The paper focused on three main areas addressed in the guideline. First, an update of prevalent knowledge about human thermophysiology and adaptation was summarised in an integrated chart on factors, mechanisms and main interrelations forming human thermal comfort perception. The statement of hierarchy of thermoeffectors demonstrates that designing for personal control means to design for a basic human need. It does not mean that designers have the right to remove stimuli and design for the perfect control (as it does not exist). Instead, being in a respectful dialogue with the building users about what a building design can provide (a normal predictable indoor environment including e.g. seasonal effects, Humphreys and Nicol, 1998) and being clear about their opportunities to make themselves comfortable in this environment might contribute to some clarification of expectations and contributions.

The second area addressed in the paper is the development of a procedure for the design of adaptive opportunities, which relies on to the context of the area the building is built in (climate, building type, human context/social norms, constraints) and on new technologies (personal comfort systems) or developments (e.g. climate change) which should lead to new kinds of adaptive opportunities.

Finally, the paper focuses on the role of actors, the communication of building use, function and maintenance with regard to adaptive opportunities in the operational planning and operation of adaptive buildings. Occupants' participation is encouraged already in an early design stage with the aim to learn their needs and later inform them on how to use the building in the intended way. Further aspects will be addressed, as initially stated, in the full report on guidelines by the authors of this paper (in preparation).

While these guidelines show important aspects for design and operation of buildings according to adaptive principles, it got clear that knowledge of the effect of specific design decisions on particular adaptive mechanisms is still scarce. Research on adaptive comfort continues creating so-called adaptive comfort models, which are simple regression lines between prevailing outdoor conditions and suggested indoor conditions. While being important on its own, this type of research often fails to include theoretical reasoning why regression coefficients differ between climatic or building contexts. Continuing creating solely adaptive regression models holds the potential of documenting people's adaptation to misinterpreted comfort demands (Hellwig 2018) without being able to respond to real necessities of the future, e.g. climate change mitigation or heat waves. In order to overcome such shortfall of current research activities, research needs reveal further insights into particular adaptive principles and their relationship to design and operation, as for example in advanced adaptive comfort models (e.g. the ATHB approach of Schweiker and Wagner, 2015). Research needs to systematically address and analyse particular aspects such as climatic context or building typologies and in such a way permitting causal conclusions.

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## Appendix

Table 5. Enabling adaptive opportunities for occupants: Exemplary design and operation actions by stakeholder

| Examples of adaptive opportunities | Stakeholder responsibility | | | |
|---|---|---|---|---|
| | Integrated design team | Organisational management | Operator | Occupant |
| *Adaptive opportunities available* | *Design context adjusted adaptive opportunities*<br>*Inform operation* | *Inform the design team*<br>*Facilitate use*<br>*Inform the occupants* | *Inform design and maintain context adjusted adaptive opportunities*<br>*Prepare user and operator manual* | *Take information up and use adaptive opportunities* |
| Consumption of food and hot or cool drinks | Create/design dedicated spaces | Offer hot or cool beverages as appropriate | Maintain facilities | Having hot/cold food/ beverage |
| Adjust activity level and metabolic rate | - | Allow/encourage for shifting of certain activities, siesta | | Walk around while thinking, take a siesta |
| Adjust clothing/clothing material | - | Relax dress-code | - | dress for clothing adjustment |

| | | | | |
|---|---|---|---|---|
| Use of ceiling fan and other active systems | Integrate active systems which can be adjusted by occupants | - | | |
| Use of personalised comfort systems (desk fans, warmers, etc) | - | Allow/provide PCS | | |
| Use furniture with different insulation levels | Selection of furniture ranges for different thermal experiences | Offer a variety of office chairs/furniture of different colour, sitting ergonomics, etc | Manage change requests | Make use of the offer |
| Exposure to sun/ use shading | Passive solar design, shading design | with usable shading devices | Ensure good operation and maintenance | Activate/deactiva te shading |
| Window control | Day/night-time ventila-tion design with appro-priate window design (adjustable opening width, manual/ auto-mated control, burglar- and weather-proof design); Address local constraints, e.g. pollu-tion/ noise/insects (in-sect screens, windows at appropriate building side, etc) | Choose a building with operable windows, passive and climate adjusted design | Suitability of the control settings and maintenance | Open/close window |
| Control internal heat from equipment (e.g. printers) | Design centralised printer rooms | - | Switch off heat emitting equipment if necessary (heat wave) | Print only when necessary |
| Thermostatic control | Select HVAC systems with appropriate, accessible controls | - | Ensure the controls are usable/operable | Use controls |
| Move to a cooler/warmer location | Design different microclimates/ spaces with a variety of conditions | Allow employees to select their work location | Ensure the intended design of variable indoor climates is implemented | Find a location with the preferred indoor climate |
| Resort to outdoor spaces | Design dedicated outdoor spaces with shading etc | Allow employees to extend their working environment outdoors | Maintain/clean and ensure good state | Work outside |
| … | … | … | … | … |

# Living in Extremes: Dynamic Indoor Environment and Thermal Performance of Traditional Nomadic Yurts

**Dolaana Khovalyg[1], Arnab Chatterjee[1], Wouter van Marken Lichtenbelt[2]**

[1] Thermal Engineering for the Built Environment Lab (TEBEL), École Polytechnique Fédérale de Lausanne (EPFL), Switzerland, e-mail: dolaana.khovalyg@epfl.ch

[2] Department of Nutrition and Movement Sciences, NUTRIM, Maastricht University, Maastricht, Netherlands, e-mail: markenlichtenbelt@maastrichtuniversity.nl

**Abstract:**
In modern society, we spent more than 90% of our time indoors, and almost 50% of energy in buildings goes to indoor space thermal conditioning to maintain the uniform indoor temperature in compliance with the indoor environmental standards. Thus, the indoor climate is typically tightly controlled and, typically, cold, and heat exposures are usually avoided in buildings, and the design of the indoor environment aims towards achieving thermoneutrality of occupants. However, current global climate change urges the built environment to cope with extreme outdoor conditions. Looking for inspiration for designing the sustainable and healthy built environment in modern societies in times of climate change, we studied the lifestyle of Asian nomads traditionally living in semi-natural conditions in yurts and daily exposed to temperature extremes. Temporal variation of indoor microclimate, outdoor conditions, and thermo-physical characteristics of the selected yurt was monitored for three days in January 2020. The relationship between physical parameters such as temperatures, relative humidity, air speed, and daily activities of a nomadic pastoralist is presented in this work. Measurements reveal a significant temporal and spatial variation of the indoor thermal environment. Remarkably, a pastoralist working close to the yurt goes in and out of the yurt many times during a day and is thereby exposed to frequent temperature variations of up to 50 K.

**Keywords:** yurt, nomadic lifestyle, dynamic thermal environment, temperature extremes, cold environment

## 1. Introduction

People in modern societies spend most of their time indoors in a human-made environment that affects our well-being (Klepeis, 2001). One of the main indoor environmental quality parameters is thermal comfort that is regulated by standards such as ISO 7730 (CEN, 2006), ISO 17772 (ISO, 2017), and ASHRAE 55 (ASHRAE, 2017) that usually prescribe indoor temperature settings within a certain range for mechanically and naturally conditioned buildings aiming to keep occupants thermal sensation around thermal neutral. Instead of seeking thermal neutrality of indoor environment, allowing the indoor temperature settings to drift beyond a comfortable range could promote the adaptation of people to climate change (van Marken Lichtenbelt et al, 2017). Physiological research shows that regular exposure to (mild) heat and cold not only creates resilience against extreme temperatures but on top of that also increases our metabolic health (Johnson et al, 2011; van Marken Lichtenbelt, et al, 2018).

In a quest for inspiration for how we should design healthy and sustainable buildings in times of climate change, the adaptations of nomadic people to extreme environments can be an insightful source. Mongols, living in Mongolia, and Tuvans, living in the Russian region of

Tuva neighbouring to Mongolia (Figure 1), are few of nations of Central Asia that still maintain nomadic lifestyle living in yurts throughout a year despite cold winters that can be extreme. The main dwelling of a nomadic pastoralist in Tuva is a round felt yurt shown in Figure 2. It is accustomed to the central Asian steppe as it tends to be resistant to strong winds due to its overall circular shape and an inclined aerodynamic shape of the roof. The first written description of a yurt as a dwelling, according to Humphrey (1974), was reported by Herodotus (484-424 B.C.), thus, the yurts have been in use for over 2500 years. The construction and the use of the yurt in Tuvans have not changed over the centuries making the yurt a masterpiece of nomadic civilization, and it is not losing its relevance even nowadays. In addition to the simple but effective structure of the yurt, the lifestyle of nomads is quite astonishing. Males can be out of the yurt in pastures for the entire day herding the livestock, even during the cold winter days, while females typically stay at home taking care of household chores and constantly going in-and-out the yurt. This poses a research question on what is the actual temperature that occupants of the yurts are exposed to and how often they experience significant temperature variations. Therefore, with the current scientific insights and state of the art techniques, we studied the temperature exposures and adaptations of the Tuvan nomadic pastoralists living in yurts that have not been documented before. The multi-disciplinary study encompassed physiological, health, and sociological aspects in combination with the physics of the built environment. The final goal of the study was to understand better physiological adaptation to extreme temperatures, the effect of the traditional lifestyle and housing on health and resilience to extremes, and to envisage how this knowledge can be applied to the built environment in modern societies. In total, we studied 4 yurts. The results from one yurt in greater detail are presented in this paper. Particularly, we present detailed results on the outdoor weather conditions, temporal and spatial variation of the indoor environment along over 3 monitored days (17/01-19/01) in January 2020.


Figure 1. Location of Tuva on a partial map of Eurasia (*the image adopted from* www.gettyimages.com)

Figure 2. Overview of the yurt

Figure 3. The research team with the owner of the yurt

## 2. Overview of the yurt and its occupants

The studied yurt located at 51.14682° N and 90.38989° E, at an altitude of 892 m above the sea level (Figure 4). The yurt was at the foot of the hills that surrounded it from behind (in W, S, and SE directions). The entrance to the yurt was facing the fields in a NE direction, which was slightly deviating from the common Tuvan tradition to face the entrance towards East, towards the sunrise direction.

Figure 4. Overview of the location of the yurt (the hill in the background in SE direction, and the fields in NE)

### 2.1. Description of the occupant of the yurt

The yurt was occupied by a man of 47 years old (Figure 3). His family lives in the town, and they typically visit him during the school breaks, while he goes to the town to visit his family from time to time. He lives primarily on his own in the yurt, while his relatives visit him occasionally. He owns about 100 sheep, 70 goats, 15 cows and 4 horses that he needs to pasture every day. On a typical winter day, he wakes up around 6 a.m., and, after lighting a fire in the cast iron stove and having his breakfast, he cleans the shed for sheep and cows from manure and goes to pastures from 10 o'clock till 17 o'clock. His neighbors sometimes go into his yurt during the day to put some firewood and keep the fire on when he is away, or he goes one or two times back and forth between the yurt and the pasture to put some firewood in the stove. Generally, he is quite busy with daily chores, and he has a meal twice per day and cooks only once in one or two days. He typically wears three layers of trousers (1 lightweight and 2 thick), three layers of sweaters, one T-shirt, three pairs of socks, and winter boots. When he goes outdoors, he puts on a winter jacket with or without a lamb skin-pelt vest and a winter hat, as shown in Figure 3. He wears his winter hat even when he is inside the yurt, except the time when he goes to sleep. His typical indoor clothing ensemble has a total clothing insulation value of approximately 2.0 clo.

### 2.2. Construction of the yurt and the interior design

The main elements of a typical yurt are the flexible lattice walls, long poles, and the crown, as shown in Figure 5. The studied yurt had an inside diameter of 5.7 m, and the overall height (under the crown) was 2.5 m. All in all, 81 poles of 2.3 m supported the crown in the center of the circle. The skeleton of the yurt was covered with multiple layers of materials. The innermost material was decorative, the layers in the middle were for insulating purposes and the very top layer facing outdoors was a waterproof canvas. The *walls* had 5 layers from inside to out (reflective foam insulation 3.2 mm/felt 8.5 mm/felt 4.4 mm/cloth 0.6 mm/canvas 2.2 mm), the *roof* had 6 layers (plastic 0.1 mm/canvas 1.9 mm/ felt 8.5 mm/felt 4.4 mm/cloth 0.6 mm/waterproof canvas 2.2 mm), and the *floor* had 5 layers from inside to out (carpet 3.5 mm/carpet 4.7 mm /felt 5.9 mm/ linoleum 2.3 mm/linoleum 2.4 mm). The main insulating material is the felt which is crafted using sheep wool, the average thermal conductivity of the felt is 0.077 $W/(m \cdot K)$ (Wang and Xiao, 2018), which is similar to the thermal conductivity of the cork or twice as much as of Styrofoam.

The yurt is divided into prescribed parts, as sketched in Figure 6, such as entrance (zone 0), the kitchen (zone 1), places for sleeping (zone 2, 4), and places for guests (zones 3, 4). Typically, the hosts occupy the area between the stove and the bed (zone 2). During the cold winters, young livestock such as calves and lambs can be taken inside and kept on the left side from the entrance in a temporary stall (zone 5). That was the case in the studied yurt, two calves were brought inside every evening, and taken out back to their mothers in the morning. The cast-iron stove in the center of the yurt is supposed to evenly heat the yurt in wintertime, it has a chimney which is led out through a hole in the crown. Mostly firewood and dried cattle dung are used for firing the stove, but in the studied yurt, only firewood was used.

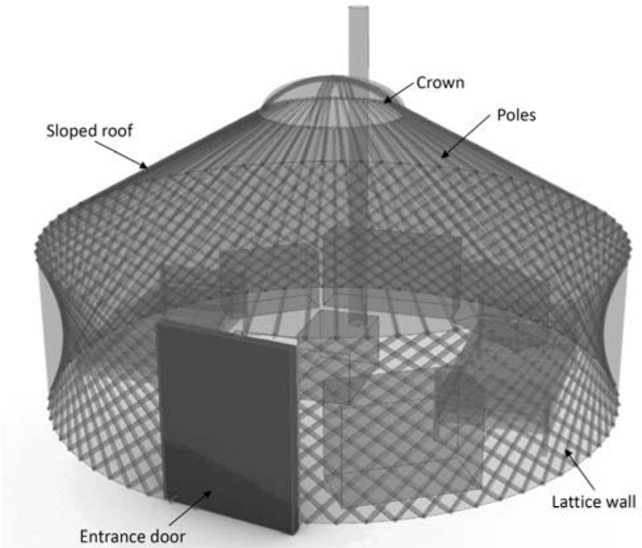


Figure 5. The overview of the structure of the yurt

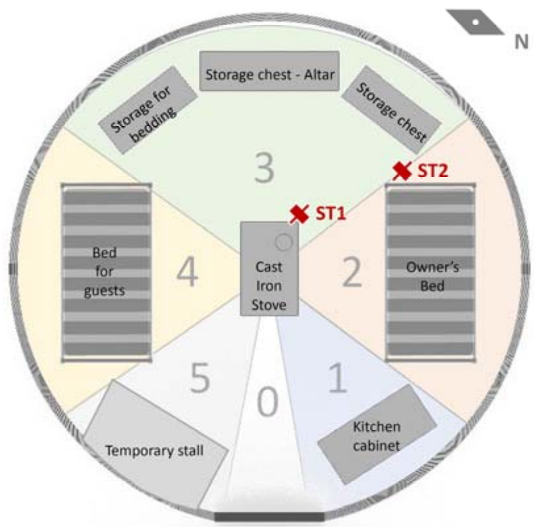


Figure 6. The layout of the furniture and the zones

## 3. The protocol of measuring environmental parameters

Thermo-physical performance of the yurts, specifically Mongolian yurts, have been studied and reported in earlier publications. The available pool of literature on the yurts has been focused mostly on two topics: (1) thermal performance characterization of existing Mongolian yurts' envelope to improve their characteristics for providing comfort and reducing heat losses and energy required for heating in wintertime (Liu et al, 2017; Xu et al, 2019; Tsovoodavaa and Kistelegdi, 2019), and (2) adaptation of the yurt design for temporary emergency shelters (Manfield, 2000; Salvalai et al, 2020). It is necessary to highlight studies from the first group such as the experimental study by Xu *et al* (2019) on the indoor thermo-hygrometric conditions of the yurt, and numerical analysis of 9 different types of traditional yurts by Tsovoodavaa and Kistelegdi (2019) in the quest of finding the optimal yurt shape in terms of energy consumption and indoor comfort. These studies looked at the dynamic variation of indoor environmental parameters; however, the yurts were studied without accounting for the actual daily use of the yurts by occupants but rather with simulating the operation of the heat source (a radiator) and the door opening. Since our study is driven by aspects of the physiology and health of the occupants, the dynamic indoor thermal conditions needed to be studied in conjunction with the daily activities of actual occupants of the yurts. Thus, our study differs from the studies on yurts performed up to date by looking at dynamic indoor environmental variation caused by the *reality of a nomadic lifestyle*, not just assumptions about it.

To characterize the temporal and spatial variation of indoor thermal environment, the following parameters were measured:

- **Outdoor weather conditions:** wind speed, wind direction, solar flux, outdoor air temperature, and relative humidity were measured using a compact mobile weather station placed outdoors next to the entrance to the yurt at the height of 2.7 m. The data was measured with a 1-minute interval.
- **Indoor thermal comfort:** air temperature (Tair), globe temperature (Tgl), airspeed (Va), relative humidity (RH), and radiant temperature asymmetry at two locations closer to the most occupied area in the yurt which is the zone 2. The first measuring point was closer to the upper right corner of the stove (ST1 in Figure 6), and the second point was closer to the bedhead of the owner's bed (ST2 in Figure 6). The overview of the stands with sensors mounted on them is illustrated in Figure 7. The stand **ST1** was placed next to the stove with air and globe temperature measurements at two levels corresponding to the hip level of a person sitting on the floor with folded legs (0.2 m) and seating on a small stool (0.6 m). Air speed, vertical and horizontal radiant temperature asymmetry were measured at 0.6 m level only. The second stand **ST2** next to the bedhead had sensors mounted at 0.9 m level corresponding to the chest level of the person sitting on the bed or the head level when a person lays on the bed. The relative humidity sensor was placed at a level of 1.1 m. All parameters were recorded each 10 sec.

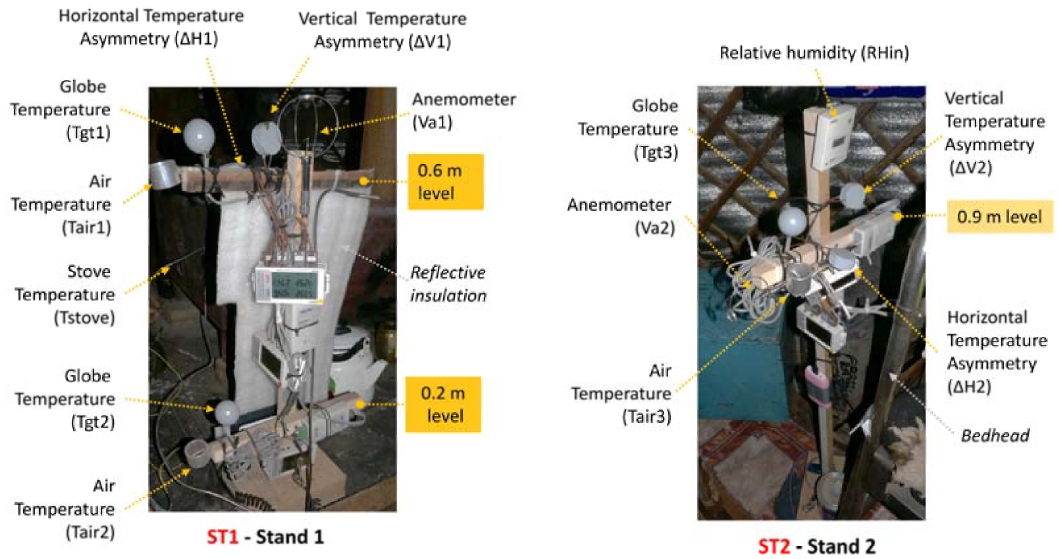


Figure 7. Overview of the stands with thermal environment measuring sensors

- **Spatial variation of the indoor temperature:** simultaneous measurements of air temperature in ten locations at 0.6 m above the floor. The sensors were placed along the circumference of the yurt about 0.6-0.7 m away from the lattice wall. The location of sensors is shown in Figure 11. The measurements were taken each 5-minute.
- **Operation of the heat source (stove)**: a high-temperature thermocouple was inserted to the stove to monitor its operation. Temperature changes inside the stove could inform when the stove was on and off. The measurements were taken each 10 sec.
- **Frequency of opening the door**: a magnetic state logger counting the number of door openings with a timestamp was installed on the door. Once the door was opened, and once the door was closed back, the state changed from 0 to 1. To account for only opening events, we excluded the closing events that always happen after the preceding change of the state.

## 4. Outdoor weather conditions

The region of Tuva has a continental climate with 4 distinct seasons and the winters lasting from November until March. The coldest month is January, with outdoor temperatures sometimes dropping as low as minus 40°C. Variation of outdoor conditions during three monitored days are plotted in Figure 8. Outdoor temperature was varying between minus 32°C during the night and minus 15°C during the day, the average temperature was minus 22°C. Relative humidity was 63-83%, with an average value of 76%. Since the monitored days were cloudy, the solar flux reached only up to 241 W/m$^{2,}$ which is quite low for the place located at relatively high altitudes. Wind speed was reaching up to 2.3 m/s, with an average of 0.2 m/s. The prevailing wind speed was from W direction, and it was below 0.5 m/s, almost 30.3% of the time. The direction for wind speeds up to 0.5 m/s was mostly W (21.8% of total measurements), NE (13.8%) and N (10%), the wind speed in the range between 0.5-1 m/s was mostly coming from the W direction (5.5% of total measurements).

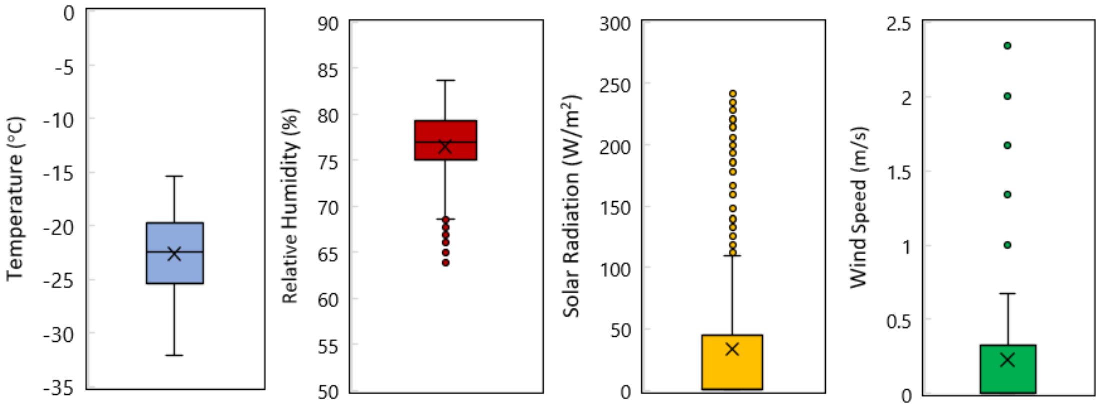


Figure 8. Outdoor weather conditions over 3 monitored days (17-19 January 2020)

## 5. Indoor thermal environment

Temporal and spatial variation of the indoor thermal environment have the utmost interest in this work; thus, the results are discussed in the following subsections.

### 5.1. Temporal variation of the indoor thermal environment

Variation of indoor conditions over three days are plotted in Figures 9-12. Indoor air temperature (Tair), globe temperature (Tgl), and operative temperature (TOP) calculated based on the measurements at two stands had a great variation, as shown in Figure 9. The greatest variation of temperature was observed very close to the stove (ST1 at 0.6 m height) – air temperature (Tair_ST1H) varied from minus 9.9°C to plus 37.9°C (mean plus 11.8°C, median plus 13.8°C), while the globe temperature (Tgl_ST1H) was varying between minus 9.9°C and plus 62.6°C (mean plus 17.0°C, median plus 17.7°C). The corresponding operative temperature (TOP_ST1) was between minus 9.9°C to plus 53.2°C (mean plus 15.5°C, median plus 16.9°C). The magnitude of the temperature variation closer to the bedhead (ST2) was smaller compared to the location ST1, and the temperature difference between the air and globe temperature was most of the time negligible. The lowest values for Tair_ST2 and Tgl_ST2 were almost the same as for the location next to the stove (minus 9.8 - minus 10°C), and the highest values were plus 40.4-40.9°C. The lowest variability of temperatures was at 0.2m in the location ST1. The air temperature was between minus 11.1°C and plus 25.4°C, and the globe temperature was between minus 10.5°C to plus 31.7°C. However, average and median values were the lowest: the average of Tair_ST1L was plus 8.1°C, and the median was plus 10.2°C; the average of Top_ST1L was plus 6.6°C, and the median was plus 8.7°C. From these measurements, we can see that the thermal environment away from the stove is more uniform and less extreme. To understand in detail the factor influencing on the indoor environment, we need to discuss the data plotted in Figure 11.

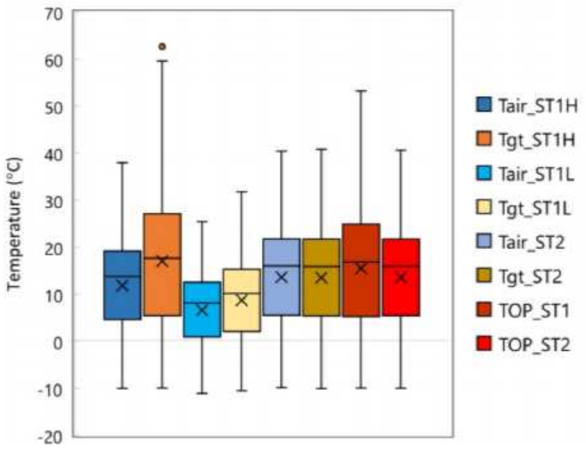


Figure 9. Variation of temperatures
(**Tgt** – globe temperature, **Tair**-air temperature,
**TOP**-operative temperature)

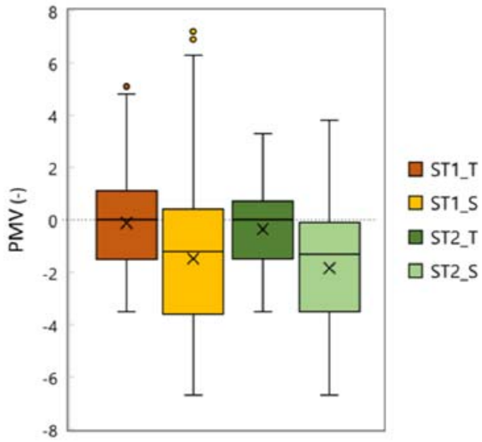


Figure 10. Variation of PMV values
(**T** – Tuvan clothing [2 clo],
**S** – standard clothing [1 clo])

The temporal variation of multiple indoor parameters is illustrated in Figure 11. The top plot illustrated variation of the temperature inside the stove (Tstove) with grey shaded regions indicating when the cooking took place. Since we could not monitor the activities inside the yurt, the cooking events (heating water, preparing the meal) were defined based on the behavior of the indoor temperature and relative humidity. Generally, indoor temperature and relative humidity had a negative correlation since firing the stove was drying the air, however, during a cooking event, the moisture content was increased due to the vaporization of water used for cooking. This can be observed in the second plot showing the variation of operative temperatures, outdoor temperature, and indoor and outdoor relative humidity. The second plot also indicates when the door was closed and open. It is obvious that firing the stove has a major effect on the indoor temperature variation. The operative temperatures follow the patterns of the stove temperature closely with the cross-correlation of 0.61 (Pearson correlation coefficient). The occupant of the yurt typically wakes up around 6 am and start firing the stove, the stove is fired from time to time during the day. In the evening, the owner fires up the stove just before going to sleep, and after that, the indoor temperature drops quite low, down to minus 10°C within 6 hours after the last firing event. The relative humidity during the day is within the range of 15-30%, and it typically reaches a maximum of about 40% when the temperature drops. From the data of the door state, we can see that the occupant of the yurt does not go outside between 11 pm and 6 a.m. During the day, the door was opened **157 times** on 17/01, **245 times** on 18/01, and **109 times** on 19/01. Since the neighbors could also enter the yurt in the absence of the owner, the actual number of ins-and-outs of the owner of the yurt can be identified by analyzing activity and outer clothing temperature tracking presented in van Marken Lichtenbelt et al. (Windsor, 2020).

The third plot from the top in Figure 11 shows the variation of PMV estimated for two clothing conditions: “S” for standard winter clothing of 1.0 clo, and “T” for the actual (Tuvan) clothing of 2.0 clo. The activity level was assumed to be the same, 1.2 met, in order to compare what would be the sensation of a person performing a light sedentary activity. First of all, we evaluated PMV values based on the measurements at ST1 location closer to the stove and ST2 location closer to the bedhead; however, the occupant typically sits in the area

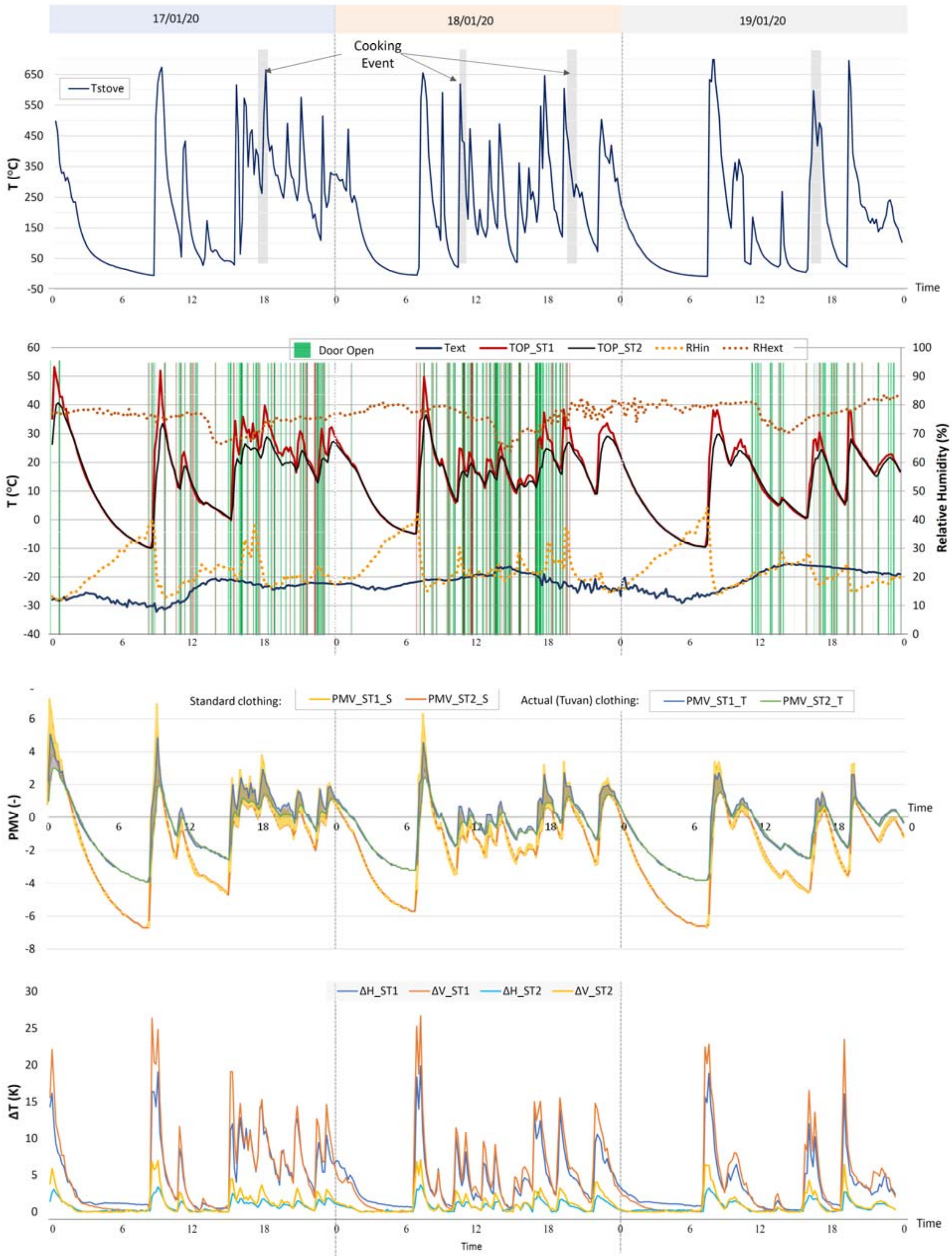


Figure 11. Temporal variation of indoor parameters over 3 monitored days. From top to bottom: (1) stove temperature (Tstove); (2) – outdoor temperature (Text), operative temperature (TOP_ST1, TOP_ST2), relative humidity (Rhin, RHout), door state; (3) – PMV for standard (1 clo) and actual (2 clo) clothing; (4) – radiant temperature asymmetry (vertical and horizontal).

between these two locations. Therefore, the shaded area between ST1 and ST2 would represent the actual sensation of a person sitting in-between. Remarkably, PMV value varies between plus 7.2-3.8 (the range of maximum values) and minus 6.7 (minimum value) for a potential occupant wearing standard clothing, while its variation between plus 5.3-3.3 and minus 3.5 for the Tuvan occupant having 2.0 clo of clothing indoors. Obviously, during the night, an occupant covers himself with duvet, and the thermal sensation most likely moved more towards slightly cold or warm rather than extremely cold as indicated on the plot. During the day when the stove is fired, it can become quite warm or even hot. The magnitude of variations is less profound for the actual occupant wearing a few layers of clothing. In general, although the variations of PMV are between hot and cold extremes, the average thermal sensation is around *neutral* (PMV=0) for the actual occupant. This is illustrated in the boxplots in Figure 10.

The bottom plot in Figure 11 shows the temporal variation of the radiant temperature asymmetry. Vertical (ΔV) and horizontal (ΔH) radiant temperature asymmetry at 0.6 m close to the stove (location ST1) was reaching 26.7 K and 19.9 K respectively during the first firing of the stove in the morning. In other words, if a person sits very close to the heat source, to the stove, the difference left and right sides of his body can experience significant temperature variation. For the location ST2, vertical and horizontal radiant asymmetry reaches 7.1 K and 3.7 K. No radiant asymmetry was observed during the night when there was no strong effect of the stove. To compare with the standardized requirements for radiant temperature asymmetry, we can assume the case of radiating stove as the “warm wall” case. Thus, to fall within the Category I and II, the temperature difference should be below 23 K (ISO, 2017). If the radiant temperature difference exceeds 23 K, but below 35K, the local discomfort falls into Category III which is not desired. In the case of the yurt, the radiant asymmetry is significant but still within the acceptable range.

The measurements of the air speed at two locations ST1 (0.6 m) and ST2 (0.9 m) showed that values did not exceed 0.2 m/s despite the high frequency of opening the door. Since there are no windows in the yurt, and there is only one opening on the top, we expect that the draught rate is very low in the yurt. Indeed, the draft rate was nearly zero for all three days. The turbulence intensity was 75.3-77.3% at ST1 location and 18.1-20.7% at ST2 location through three monitored days. High turbulence intensity at ST1 location shows the strong effect of the convective currents occurring in the near-the-stove area.

Whenever the door is opened, we could assume that an occupant goes in or out of the yurt. Thus, by calculating the difference between the outdoor air temperature and indoor temperature, the temperature difference (ΔT) the occupant could be exposed to at the moment of the door opening can be defined. The illustration of the air temperature differences between indoors and outdoors at the moment of the door opening is shown in Figure 12. Due to the spatial temperature variation indoors, as it is discussed in the next section, temperatures measured at two locations ST1 and ST2 are plotted. The most frequent ΔT was 29.4 K (6.4% times) for the location ST1 (0.2m), 35.4 K (5%) for the location ST1 (0.6m), and 38.0 K (4.6%) for the location ST2. In general, 42-46% of the observed ΔT was in the range 30-40 K.

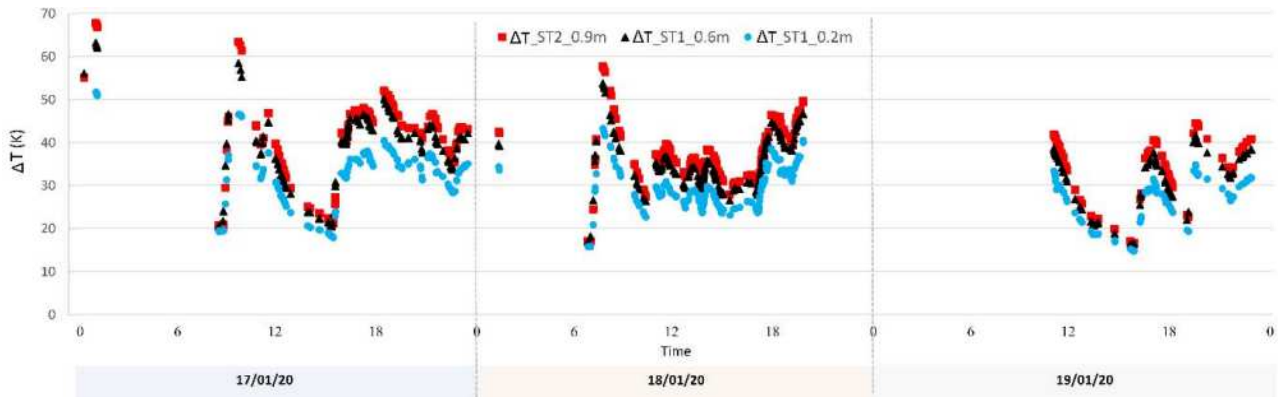

Figure 12. Temperature difference during the door opening event

### 5.2. Spatial variation of the indoor thermal environment

The spatial distribution of the indoor temperature is another dimension that was investigated in this study. Due to the circular shape of the yurt, it is supposed to be evenly heated during the winter using a central cast iron stove. To validate this hypothesis, we recorded temperatures in 10 different spots at 0.6 m height within the yurt, as shown in Figure 13. The eight sensors were placed along the circumference of the yurt about 0.6-0.7 m away from the lattice wall, while two sensors were in the middle of the yurt close to the corners of the stove. Three cases of spatial temperature variation were selected according to the distinct events during the day: (I) early in the morning before the firing the stove, (II) between the firing the stove during the day, and (III) after the stove was fired. The cross-sectional sketch of the yurt on the left of Figure 13 marks temperature points and indicates relative warmness of measurement points with regards to the coolest point indicated using the blue circle. On the right side of Figure 13, the variation of temperatures within the corresponding 2 hours long interval is shown. In the case (**I**), the spatial temperature variation is the minimum and within 1.2 K. The coldest location in the yurt was the location 4 (next to the central storage drawer), and the warmest point was the location (9) (the corner of the temporal stall for calves). Perhaps, the heat emitted from the calves made this particular location warmer compared to the other ones. In the case (**II**) which was during the daytime, the overall temperature difference reached 3.8 K. The coolest spot was between the owner's bed and the kitchen cabinet, while the warmest spots were next to the temporal stall which is quite unexpected since calves were not in the stall during the day and, thus, there were no heat sources. In the case (**III**), the warmest points were next to the stove, and the coolest spot was next to the storage drawers. The temperature difference between the coolest and the warmest location was 9.5 K. These data illustrate great variability of the indoor environment, especially right after firing the stove that was completely off before.

## 6. Summary and conclusions

This work aimed to study the spatial and temporal variation of the indoor environment inside a traditional dwelling in detail to define what is the actual variability of different environmental parameters in correlation with the daily activities of its occupants. In particular, the detailed analysis of a Tuvan yurt occupied by the mid-aged male pastoralists is presented. To characterize indoor microclimate and to establish the relationship between indoor, outdoor conditions, and daily activities of nomadic pastoralists, multiple measurements were performed over three days in January 2020. The measurements of the operative temperature showed a significant variation of the indoor thermal environment throughout a day (between minus 10$^{o}$C and plus 50$^{o}$C). Obviously, this variability was beyond the range of Categories I-III prescribed by indoor thermal comfort-related standards such as ASHRAE 55 and ISO 17772 used for the design of modern housing. Analysis of the air temperature variation reveals that an occupant of the yurt could experiences up to 50 K of the air temperature difference when he goes in and out of the yurt, but more frequently about 30-40 K. The comfort index like PMV showed that the thermal sensation of the occupant should be most of the time beyond the acceptable level; however, the actual environment was more accepted by the actual occupant of the yurt. Therefore, the PMV index might not relate the comfort as experienced in such temporary structures as yurts where occupants continually enter and leave the yurt due to their rural lifestyle. While such a significant temperature variation that we see in the yurt might not be acceptable in modern housing, this study aims to link the thermal environment variability with human physiology and related thermal adaptation. The preliminary results on the physiological data can be seen in van Marken Lichtenbelt et al. (Windsor, 2020).

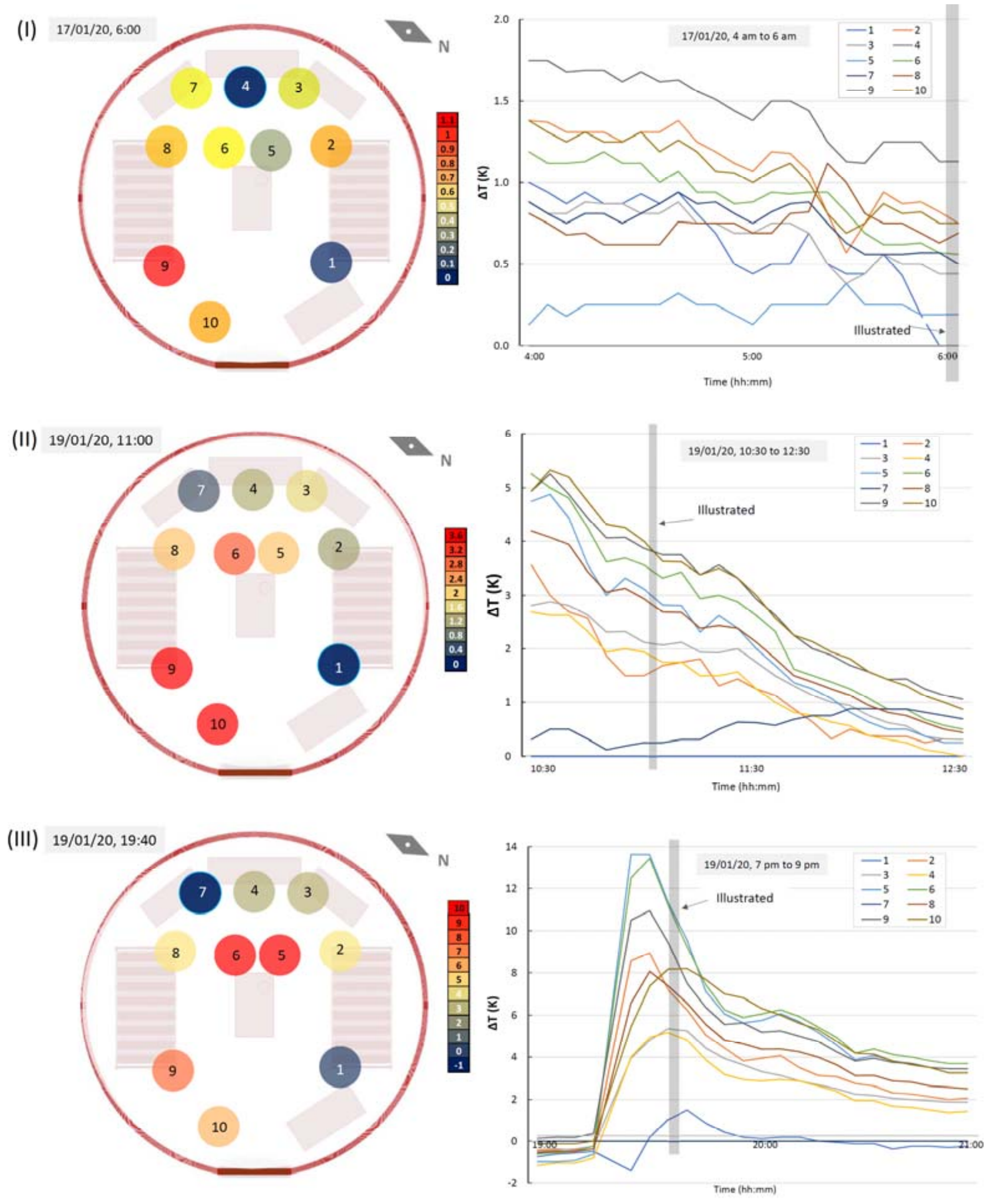


Figure 13. Spatial variation of relative indoor temperatures at 0.6m level for 3 selected times: (I) 17/01 @ 6:00, (II) 19/01 @ 11:00, (III) 19/01 @ 19:40.

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# Passive Cooling Strategies for Low Carbon Architecture

**Pablo La Roche**

***CallisonRTKL & Cal Poly Pomona University, USA. pablo.laroche@crtkl.com;***

**Abstract:** Because of how they collect, store and distribute energy, passive cooling systems provide thermal comfort using a fraction of the energy used by conventional mechanical systems, achieving thermal comfort with lower capital and operating costs. A passive cooling system reduces air temperature and provides thermal comfort by transferring heat from a building to various natural heat sinks and providing design opportunities that mechanical systems do not provide. This paper will discuss several systems and projects with passive cooling strategies in which the author has participated as a researcher, designer, or teacher. The examples are organized in three groups according to the cooling strategy: air, water, or the sky and include buildings and outdoor spaces in several warm locations of the world. All have enhanced design and comfort through the implementation of passive cooling systems, which are visible in the design.

**Keywords:** passive cooling, carbon neutral architecture, low energy, zero net carbon.

## 1. Introduction

Carbon emissions from buildings must be reduced to limit our anthropogenic effects on the planet. However, changing comfort aspirations and economic development have dramatically increased the number of mechanically cooled buildings in both residential and commercial buildings in developed and less developed countries. Rapid population growth and urbanization in less developed countries have also been accompanied by the expansion of highly vulnerable urban communities living in informal settlements, many of which are in hot climates. During extreme heat events, which are becoming more common in a warming climate, inadequate building design and expensive energy, make air conditioning prohibitive for low-income families, increasing mortality and morbidity, especially for the elderly.

## 2. Passive Cooling

Passive cooling systems transfer energy from a building to various natural heat sinks using heat flow paths that do not exist in conventional buildings. For example, a mechanically cooled building in a hot and dry climate should be well insulated to reduce heat gains so that the air conditioner can operate more efficiently using less energy. However, in a building with cooling by either night ventilation or comfort ventilation, the building should still be well insulated to reduce solar gains but should also be able to collect outdoor air to cool its thermal mass or its occupants as needed. Closing it during the daytime on very hot days keeps it cooler longer with no additional energy use. A good roof in a hot climate will also be insulated to reduce heat gains from the exterior, however a radiant roof will cool the building.

Because of how they collect, store and distribute energy, passive cooling systems provide thermal comfort using a fraction of the energy used by conventional mechanical systems, achieving thermal comfort with lower capital and operating costs. Through their simple design, they can also be built at lower costs, using local labor and resources, as well as generating income that stays in the community contributing to economic and social sustainability (McDonald and Dayer, 2018). They also provide opportunities for the occupant to establish closer connections with natural cycles and rhythms. Passive cooling systems benefit both the occupant and the planet.

Not all systems can be used in all environments and passive cooling systems are usually classified according to the heat sinks where they store energy (Givoni, 1994): ambient air (sensible or latent), upper atmosphere, water, and under surface soil. The following cooling strategies can be used together with the heat sinks:

**Comfort ventilation**: providing direct human comfort, by moving ambient air, mainly during the daytime (sensible).

**Nocturnal ventilative cooling**: opening the building to cool the structural mass of the building interior by ventilation during the night and closing the building during the daytime (sensible).

**Direct evaporative cooling**: mechanical or nonmechanical evaporative cooling of air, which is then introduced into the building (latent).

**Indirect evaporative cooling**: cooling of a building roof with evaporatively cooled fluid, so the interior space is cooled without elevation of humidity (latent).

**Radiant cooling**: transferring heat from the building to the upper atmosphere during the night hours.

**Soil cooling**: cooling the soil below its natural temperature in a given region and using it as a cooling source for a building by some type of heat transfer mechanism.

**Cooling of outdoor spaces**: cooling techniques applicable to the air of outdoor spaces adjacent to a building, usually using some sort of water evaporation or some sort of expenditure of energy.

This paper will discuss several passive cooling systems developed and tested by the author at the University of California Los Angeles, Cal Poly Pomona University and CallisonRTKL. These are organized in three groups, loosely connected with the heat sinks: a) cooling with air, b) cooling with water, and c) cooling with the sky.

## 3. Cooling with Air

The atmosphere provides a powerful medium for heat transfer, primarily through convection. Cooling by ventilation to the atmosphere is probably the simplest way to remove heat from buildings, as comfort ventilation or night ventilation. Comfort ventilation provides direct well-being by air movement through the body, evaporating sweat and cooling the skin. Night ventilation cools the thermal mass of the building with outside air. During the daytime, the cooled mass acts as a heat sink, reducing the rate of indoor temperature rise. For night ventilation to be effective the building must have enough thermal mass, outside cool air must be brought inside at specific times, and night temperatures must be low enough to cool the mass. The building must also be well shaded and insulated to reduce daytime heat gains and make the heat sink work better.

### 3.1. Smart Ventilation System

A microcomputer-controlled thermostat was developed by the author at UCLA's Department of Architecture. This intelligent control system measured both indoor and outdoor temperature and used decision-based algorithms to operate a fan and maximize indoor thermal comfort using outdoor air. The system was tested on cells above the department of architecture at UCLA. The test cells with the smart ventilation system always performed better than the test cells with a fixed infiltration rate. A higher air change rate increased the amount of cool air entering the space, lowering the temperature of the mass, also lowering the maximum temperature the next day.

Various control strategies were tested with different relationships among the variables (some rules did not use all variables), air change rates, and values for comfort low and comfort high, and are discussed in more detail in (La Roche and Milne, 2004). Multiple series confirmed that several building design considerations affect system performance: tests with shade, more mass, and higher volumes of controlled ventilation outperformed unshaded windows, less mass, and fixed ventilation rates. The rule that achieved the most hours in comfort and the lowest maximum temperatures in the experimental cell is:

If $T_o < T_i$ and $T_i > Cf_{low}$ *and* $T_i < Cf_{high}$ *then* fan ON *else* fan OFF (1)

Where:

$T_o$ = temperature outside
$T_i$ = temperature inside
$Cf_{low}$ = comfort low at 18.3°C (65°F)
$Cf_{high}$ = comfort high at 25.5°C (78°F)

The smart controller is temperature based and not time controlled, so it can adjust the ventilation rate as needed turning on the fan when exterior temperatures can provide cooling, during the day or night. Implementation of this simple system would provide free cooling when helpful and energy savings for buildings in different climates.

Smart operable shading was later added to the system. In the summer, two conditions had to be satisfied to close the shade: shading would be provided whenever the indoor temperature was above 21°C, and a black south-facing metal plate (the window was also facing south) had to be warmer than the air temperature, indicating that the window received solar radiation (Fig 1). The temperature of the test cell with the smart ventilation and smart shade was always lower than the test cell without shading or ventilation. The pink area in figure 1 shows when the shade was active while the bar charts shows the intensity of the ventilation.

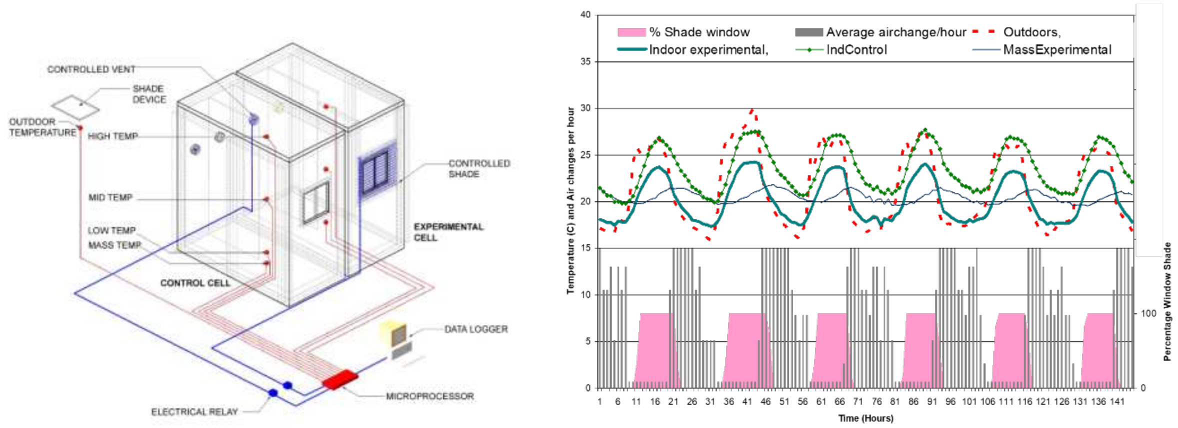


Figure 1. Smart ventilation and shade system with results of a series

### 3.2. Variable Insulation Green Roof

Further research expanded the implementation of night ventilation combining it with green roofs, first without insulation and then with a variable insulation green roof which had 10 cm of insulation, on the ceiling creating an air space between insulation and the green roof substrate. There were two openings in this ceiling, one of them with a small fan which could be turned “on” or “off” with the controller using rule (1) developed for smart ventilation. During cool summer nights, the fan is turned on, so that air circulates from the exterior into the interior and then to the plenum, cooling the thermal mass of the green roof from below. As the day gets warmer, the exterior fan is turned off while the plenum fan continues to circulate the air between the plenum and the space, transferring the heat from the space to the green roof substrate, which acts as a heat sink, keeping the space cooler for a longer period (La Roche, 2013) (La Roche, Berardi, 2014). This system was tested at the Lyle Center for Regenerative Studies at Cal Poly Pomona with positive results and then installed in a high school in Irvine, California (Fig. 2).


Figure 2. Smart ventilation and shade system with results of a series

Uninsulated and variable insulation green roofs are most effective when night temperatures are below 25°C and daytime temperatures are below 40°C, and have a daytime swing of at least 8°C. Figure 5 shows when variable insulation green roofs can be used, following the thermal mass and night ventilation zone in Givoni and Milne’s chart. Caution must be taken with uninsulated green roofs because the heat gains during very warm periods with outdoor temperatures above 40°C can exceed the savings provided.

## 4. COOLING WITH WATER

Even though their heat sink ultimately is the air, indirect and direct evaporative cooling systems are included in a separate section from the air because water is an important cooling and transport component of the system.

Evaporative cooling is the process by which the sensible heat in an air stream is exchanged for the latent heat of water droplets or wetted surfaces. The sensible temperature of the air is reduced closer to the comfort zone, with an increase in humidity. This process is adiabatic, because overall, no energy is gained or lost in the air. Furthermore, the amount of heat absorbed by the evaporation of water—its latent heat—is very high compared to other modes of heat transfer, with the potential to significantly cool the air.

## 4.1. RADIANT AND EVAPORATIVE GREEN ROOFS

Additional studies to improve performance of green roofs by the author and Dongwoo Yeom and Laura Rodriguez ( Yeom, La Roche, 2017) (Rodriguez, La Roche, 2018) (La Roche et al, 2018), investigated the cooling potential of a green roof paired with a radiant cooling system in a hot and dry environment in southern California. The green roof had pipes embedded in it, connected to a radiator inside the test cell. The radiator absorbed heat from the interior of the cell, which is then dissipated through the green roof during the irrigation (Fig. 3). Excess water not absorbed is recollected and reused. This configuration was monitored and compared with other cells in over 40 series of tests over the summers of 2015 and 2016. A ceiling with a smart fan was added and tested in the summer of 2018. The results demonstrated that this green roof performed well. The best performance occurred when the radiant system pump operated continuously, and the irrigation sprinkler operated for short intervals during the warmest time of the day between 11:30 a.m. and 4:30 p.m. This demonstrates the potential for irrigation in non-traditional ways to improve thermal comfort and reduce energy consumption in buildings, while reducing the urban heat island effect.

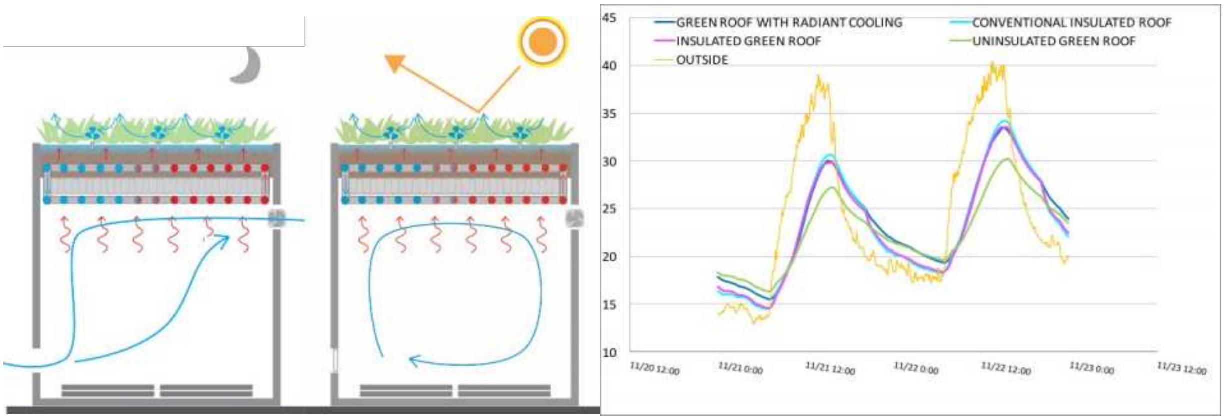


Figure 3. Performance of Radiant Evaporative System

Additional research in 2019 with Janis Liu, Nayeon Kim and Lorenzo Tayag explored improvements in performance by adding Biomorphic Micro-Cooling Devices (BMDs) that encourage evaporation by increasing the surface area of the object and/or adding surface textures for the water droplets to attach onto. By having water droplets lingering above or around the vegetation and accessible to wind, evaporative cooling is increased. Two of these devices were designed and tested based on designs from nature. The first design is based on the Stenocara gracilipes, known as the Namib Desert Beetle. The design mimics the bumps found on the back of the beetle to increase surface area and collect water droplets. The collected water displaces into small craters on the facade of the device for evaporative cooling. This prototype's pyramidical form maximizes surface area and dispersion of the water droplets falling from misters above while the surface texture increases this effect (Fig 4). The second design is modelled after the Araneae web. A fine metal mesh is used to replicate the web's design by mimicking the close-knit overlay of strands that allow for water droplets to attach onto and move along to be collected at the joints. The exposed surfaces with gaps generate more airflow throughout the object, reinforcing evaporative cooling. The plant-like structure is 3D printed with branches that resemble cactus spines. There is a larger needle with smaller barb branching outward for water to also latch onto. These branches can enhance water harvesting by encouraging water droplets to divert and collect onto the metal mesh (Fig. 4). Results in the summer of 2019 show better performance than the other test cells but this performance has not been compared with previous radiant cooling systems without the BMDs.

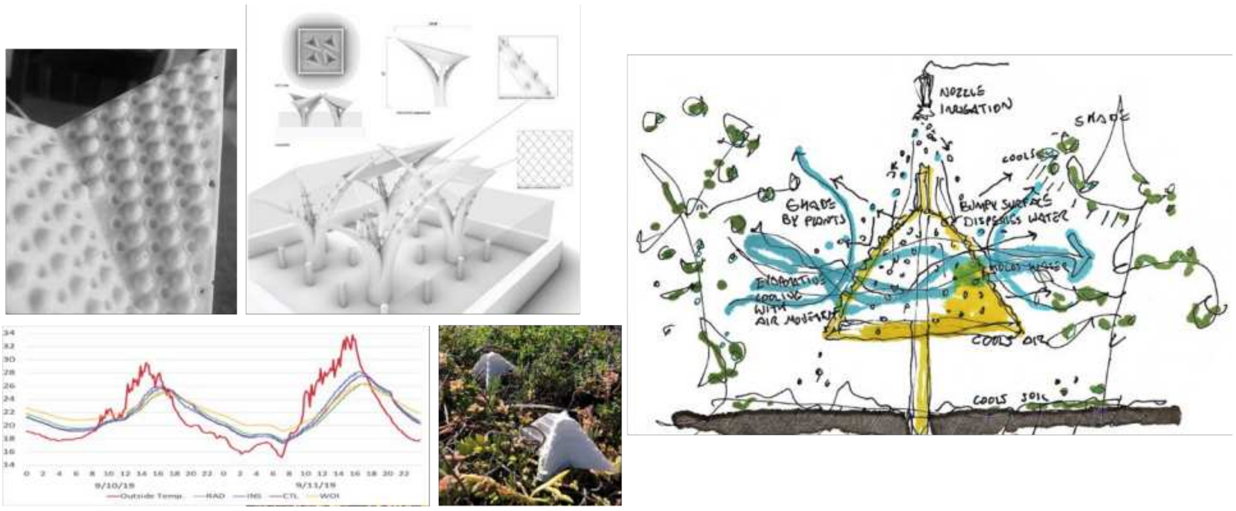

Figure 4. Design and Performance of Biomorphic Micro Cooling Devices

As all passive systems, none of the green roofs work optimally under all outdoor conditions. Figure 5 shows the applicability of the variable insulation, insulated, non-insulated, and radiant evaporative green roofs under different exterior conditions.  In all types of green roofs, the following are true for warm climates: a) The vegetation in the canopy layer improves performance by providing shade and some evaporative cooling, b) if night time temperatures are cool enough, all test cells with green roofs are more comfortable with night ventilation, c) additional thermal mass and exterior window shade also improves their performance.

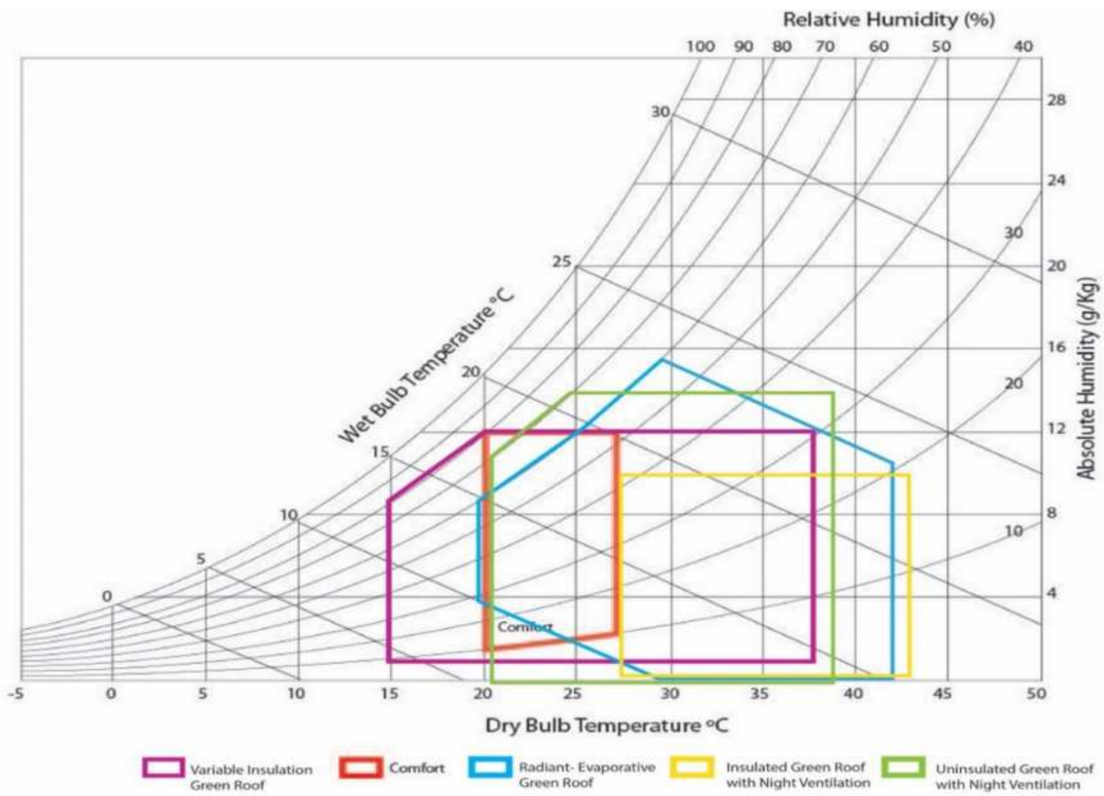


Figure 5. Applicability of different types of green roofs

### 4.2. ROOF PONDS

The author with Baruch Givoni (La Roche, Givoni, 2000) tested a roof pond system at UCLA during the summer of 1999 (Figure 6). This roof pond system consists of an insulated water tank, cooled at night, and a test cell with cooled water circulating in pipes embedded in its concrete roof. Cool water is pumped from the pond to the roof of the experimental chamber and can run either continuously or at selected hours using a timer. The shower is activated at night, cooling the pond by pumping water out of the tank and spraying it over the insulation, cooling by evaporation, convection, and radiation. During the day these insulation panels block solar gains to the water, keeping the water cool.

The indoor average dry-bulb temperature was found to correlate best with the average wet-bulb temperature and the equation to determine maximum DBT inside the test chamber was:

$$T_{mx} = WBT_{avg} + \Delta t \qquad (2)$$

Where:

$T_{mx}$ = predicted max dry bulb temperature inside the chamber on a given day

$\Delta t$ = average elevation of the indoor maximum above the outdoor average

$WBT_{avg}$ = average wet-bulb temperature for the day

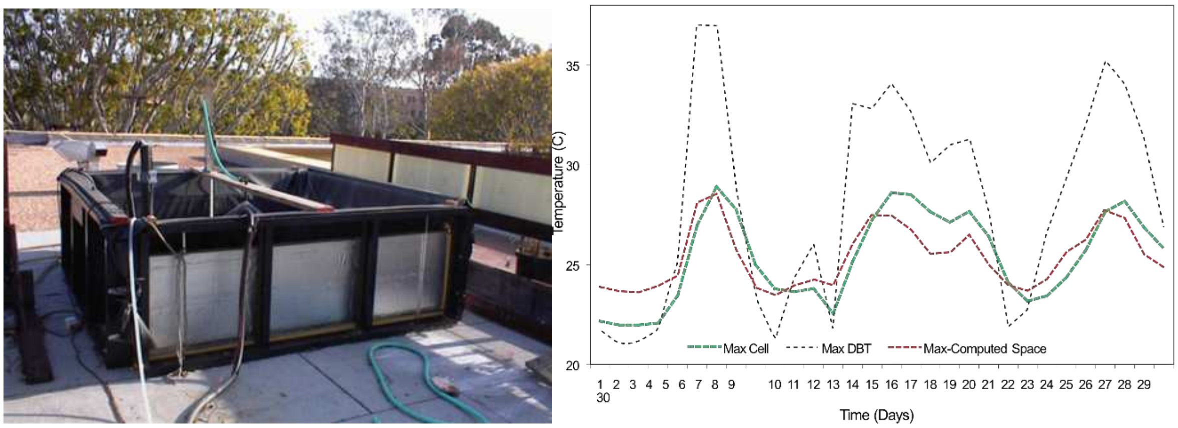


Figure 6. UCLA roof pond. Measured and predicted maximum cell temperatures (Sept 23 1999).

Later at Cal Poly Pomona University, the author developed and tested other versions of this roof pond with the water spray operated by a smart controller. Several rules were tested, the simplest one compared the temperature of a metal painted black surface facing the sky with the outside air temperature. If the temperature of the surface was lower than the air temperature the surface was radiating to the night sky and the pump is turned on. A more complex rule included the indoor temperature of the test cell and the water temperature, see controller rule (3) below.

If $T_{surf} < T_o + 2$ *and* $T_{RP} > C_{mflow}$ *and* $T_w > L_{owt}$ *then* PUMP ON (3)

where:

$T_{surf}$ = temperature of the external metal plate

$T_o$ = outdoor dry bulb temperature

$T_{RP}$ = temperature in the test cell with the roof pond

$C_{mflow}$ = lower limit of the comfort zone

$T_w$ = temperature of the water

$L_{owt}$ = lowest minimum temperature of the water.

Other roof ponds developed by the author with Cal Poly Pomona students had fins that closed during the summer day and opened at night or had fixed fins angled so that they blocked direct solar radiation during the daytime but permitted some sky exposure during the night for radiant cooling (Marnich et al, 2010). These bodies of water were tested as roof ponds but can also be located in exterior spaces such as gardens or courtyards. In this case they would cool the building with a Water to Air Heat Exchanger (WAHE). Results in all roof ponds showed that lower indoor temperatures were achieved with lower wet bulb temperatures.

### 4.3 Community Center in Tecate, Mexico.

Students from the author's Cal Poly Pomona design studio, and with feedback from Corazon, a southern California Non-Governmental Organization and local residents, designed a community center for Tecate, Mexico, 15 kilometers south of the border with the USA, in a high desert area with very hot and dry summers and cool winters. The center has been built with volunteers through Corazon and the local community. It began operating in early 2017 and is providing skills training workshops for adults, daycare facilities, meeting spaces for the community and volunteer housing.

The buildings incorporate passive cooling and heating strategies (Fig. 7) including a downdraft evaporative cool tower and a solar attic. Measurements in the downdraft evaporative cool tower demonstrated that it was able to cool the air from an outdoor temperature of 36.7 °C and a RH 24% entering the tower to 20.8 °C and 100% RH exiting at the bottom of the tower inside the space. This is a 16 °C reduction of the outlet temperature of the air with no compressor cooling.

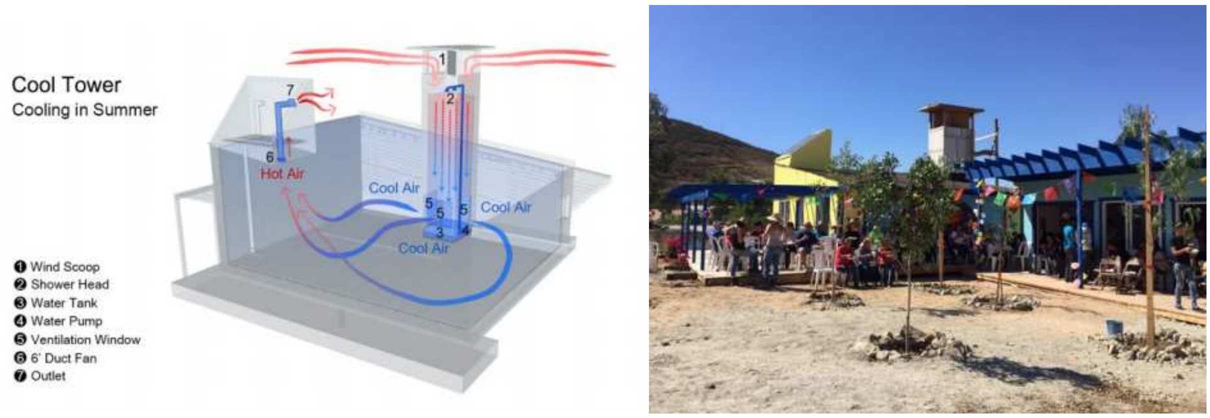


Figure 7: Cooling strategy and exterior view of the Tecate community center

Many local community members in Cerro Azul showed great interest in passive heating an cooling system after the project's construction. The goal is continue developing these systems so that they can be fabricated at the community center and sold inexpensively to the community for installation in new and existing buildings (currently none have heating or cooling). Fabrication of these systems will provide a source of income to the community while improving living conditions: true social, economic and environmental sustainability. In these communities improving cooling performance is not a matter of saving energy, it is a matter of health. At the same time, projects such as this provide students with the opportunity to do good, while learning from practice.

**4.4 Reducing energy use and improving comfort in the middle east.**

Passive cooling strategies are also proposed in projects at different scales at CallisonRTKL. In the Khiran Entertainment Complex in Kuwait, the biggest challenge was the sun and the heat with daytime summer temperatures close to 50°C and consistently above 35°C. This is a challenge in a building designed to be Kuwait's biggest state of the art cinema complex, which wants to promote transparency in the design to transmit fun, interaction of interior/exterior spaces and connectivity of the diverse entertainment activities. Inspired by a theatre setting the screen symbolises the curtain, the back wall the stage, the vast Marina the auditorium. To achieve this transparency while regulating the difficult outdoor environment the glazed atrium is protected by a large metal screen made of three-dimensional patterns that protect during the day while revealing its interior at night. Evaporative cooling was proposed to reduce outdoor temperature close to the window during the many hot and dry summer months. The combination of screens providing shading, PV, green roof elements, evaporative cooling next to the façade, misters at ground level, internal cooled slabs and AC system providing stratified cooling enables to provide transparency while reducing the cooling load, glare as low as possible (Fig 8).

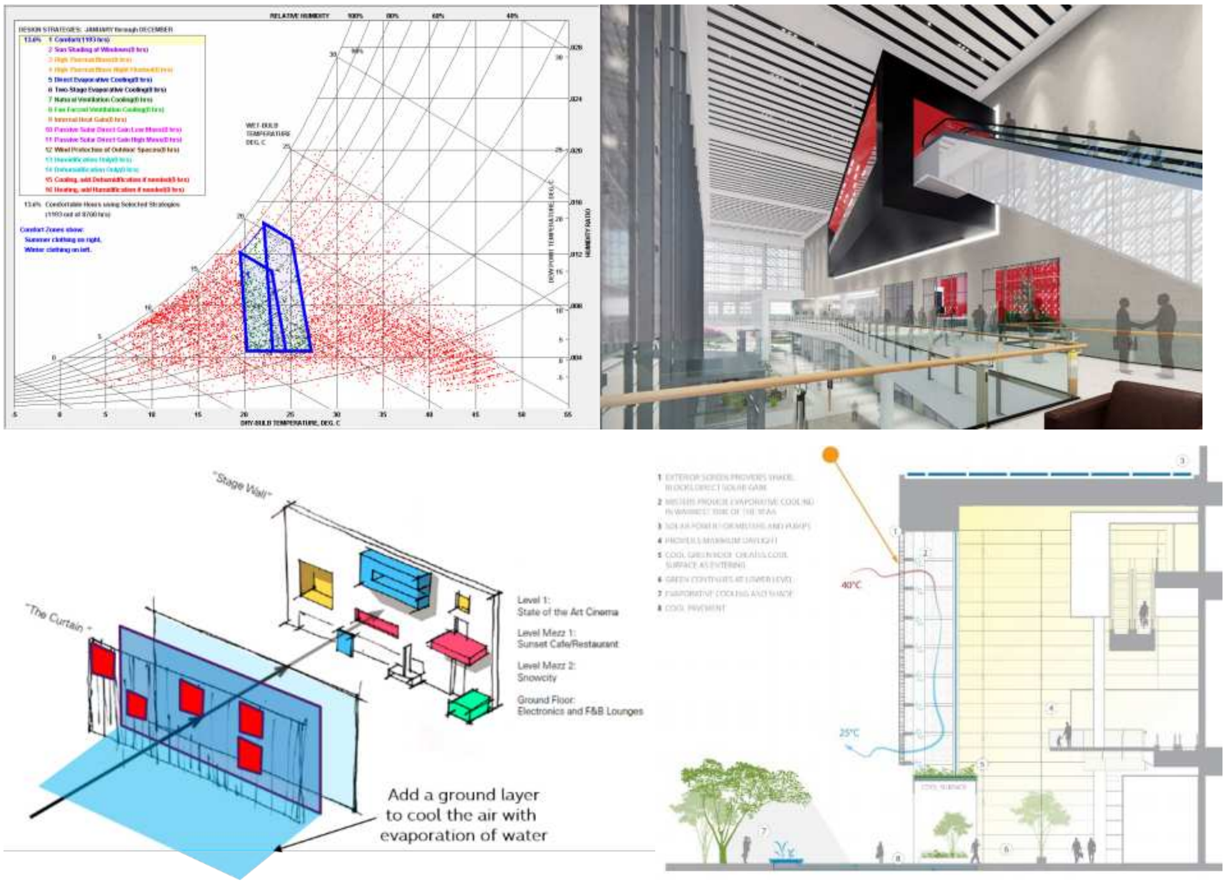


Figure 8: Khiran Entertainment Center in Kuwait

Many exterior spaces in the Middle East are mechanically air conditioned, wasting an enormous amount of energy and making a huge amount of noise, trying to achieve thermal comfort. An alternative to achieve this by combining passive strategies is proposed several outdoor spaces. These strategies modify the environmental variables that affect thermal comfort and provide cooling with little or no energy use. For example, in a series of outdoor courtyards proposed for a building in Dubai, the weather data indicates that there is a summer period from mid-April to mid-October and a mild period from mid-October to mid-April. The following passive design strategies are proposed to achieve thermal comfort: shade, air movement, water features, thermal mass, and green surfaces (Fig 9).

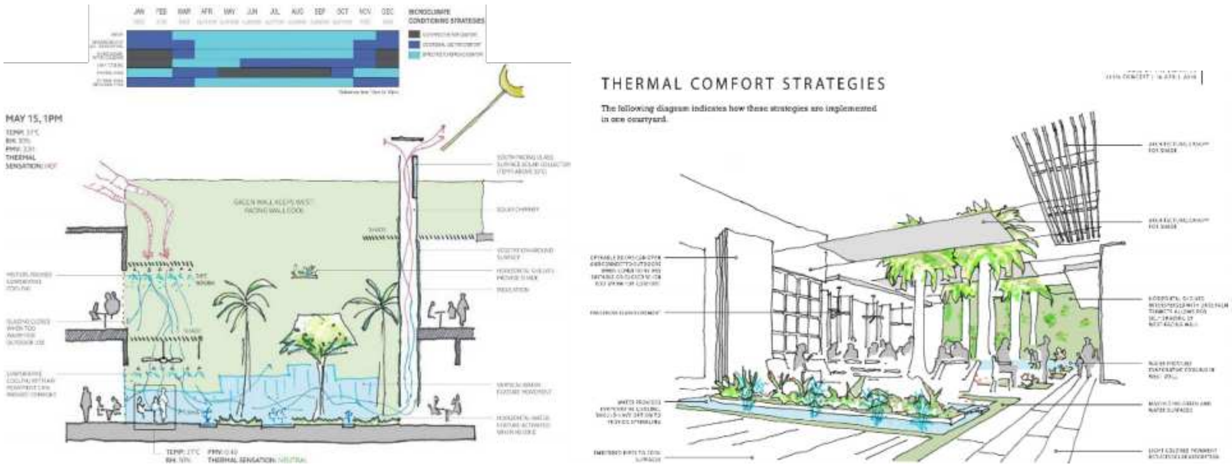


Figure 9: Strategies and courtyard design for a courtyard in the middle east

Shade is an important strategy during most of the year, improving comfort in outdoor spaces by directly reducing radiant gains to the occupants and on built surfaces. Air movement provides direct human comfort when air temperatures feel too warm, extending the comfort zone upward beyond the limit for still air. However, because above 32°C air movement is not useful for comfort, air temperature in the courtyards has to be kept below this value. Air movement can be generated with fans that move air locally which is also cooled by evaporative cooling through fountains and misters when needed. During most of the summer, and especially in the afternoon when it is warmest (but relative humidity is lower) it is possible to cool the incoming air by at least 6°C and much of the time by more than 12°C. From April to September the WBT depression is always above 12°C, and it is always possible to provide up to 12°C of cooling during this period. From Mid-October to Mid-March there is still evaporative cooling potential, above 6°C. Shaded thermal mass with night ventilation will be most effective from October to April when it is possible to cool the mass at night to a value close to the comfort zone so that the surface stays cooler during the day. The thermal mass can also be cooled with a fluid and improve thermal comfort by improving mean radiant temperature. Green walls will reduce solar radiation to the walls so that it is not later released as longer wave radiation which will negatively affect comfort. These are not complex strategies, but it is important that they are implemented correctly because their performance varies depending on specific climate variables. For example, evaporative cooling will not work on humid days.

UTCI and PMV are calculated for a person outdoor with western and non-western clothing (for PMV since UTCI assumes appropriate clothing) varying the effect of the different variables during every month of the year. The goal is to improve thermal comfort as much as possible, but especially during the shoulder periods at the beginning and end of the summer period. Figure 10 how the strategies are implemented over the year and their effect on an occupant at rest in the shade with middle eastern and with western clothing.

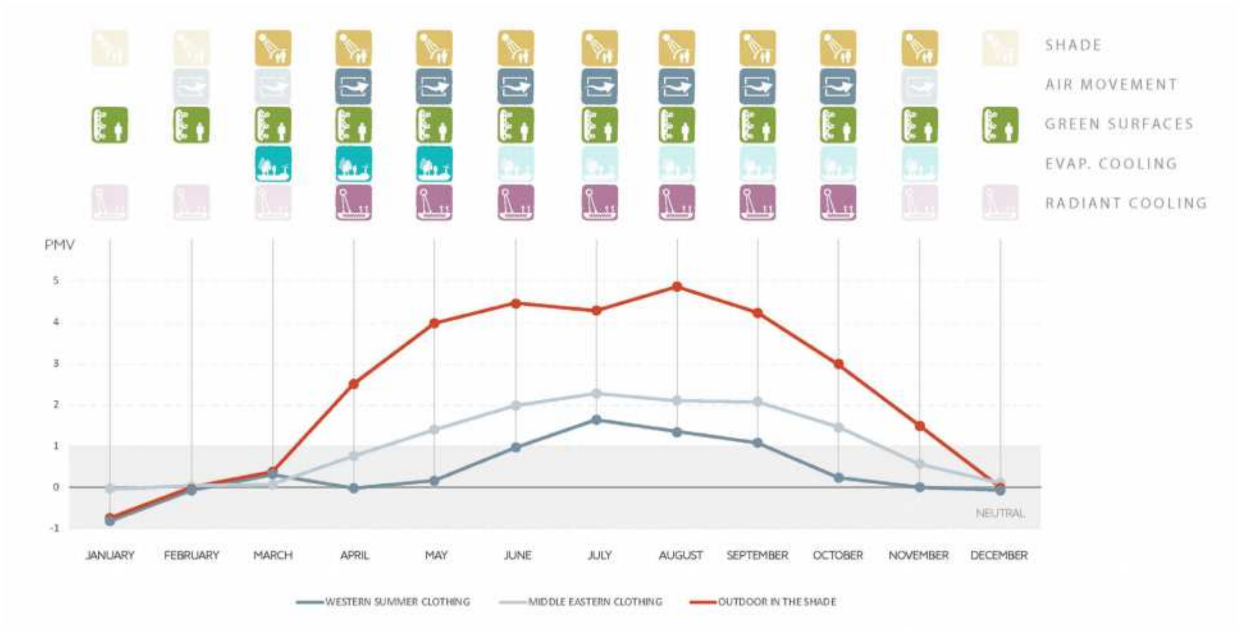


Figure 10: Implementation of passive strategies for the courtyard

For another courtyard mall in Kuwait similar strategies were proposed for the courtyards. The form of the roof also kept the hot summer air outside, shade provides solar protection and the downdraft evaporative towers provide cool air directly at the ground level where it is needed. These cool towers provide cooling, emphasizing specific areas of the outdoor spaces. Because the courtyard was larger, more cool air was needed and the towers were higher, with a larger diameter, cooling a larger volume of air. The landscape is designed to contain the cool air that enters by the towers and the areas around the tower at the lower level had additional shade and landscape features to keep the cool air inside (Fig 11).


Figure 11: Passive Strategies in a mall in Kuwait

### 4.5 IMPROVING OUTDOOR COMFORT IN A UNIVERSITY CAMPUS IN THE DESERT

For the master plan of Cal State San Bernardino's Palm Desert campus several passive design strategies were implemented to promote a liveable outdoor environment with academic vitality in which students and faculty could interact, and teaching and learning continues outside the classroom. Cooling is the overwhelming concern for designing in this hot and arid area of California. To achieve thermal comfort during this period, the following conditioning strategies are integrated in the campus masterplan: a) Minimize solar gains b) Maximize evening/night cooling rate, c) Provide evaporative cooling, d) Promote air flow, e) Building massing, f) Cool surfaces and landscape. All new buildings that are added to the master plan should include these strategies.

Minimizing solar gains. Solar gains can be reduced by increasing shade provided by trees. Increasing tree and vegetation cover lowers surface and air temperatures by providing shade and cooling through evapotranspiration.

Maximize summer evening/night cooling rate. Because of the clear desert night skies, it is possible to use the sky as a heat sink for the energy absorbed in surfaces during the daytime. Operable shade structures or systems that provide some view of the sky allow the ground below to cool to the sky at night.

Evaporative cooling can reduce outdoor air temperature, especially during summer afternoons when the Wet Bulb Temperature Depression is highest. Evaporative cooling is implemented in fountains, cool towers, or misters. Evaporative cooling systems can be located close to buildings and upwind to cool incoming wind. If structural elements such as towers are used, they can be used for wayfinding, lighting and help provide campus identity.

Promote air flow. Care has been taken in the design of the outdoor spaces, so that there is air movement as needed. Multiple wind studies have been implemented to validate some basic principles, especially the provision of an inlet and outlet to outdoor air.

Appropriate building massing. The building can help provide shade and control air flow. Understanding solar geometry and predominant wind directions can help channel shade spaces and channel wind directions as required to improve thermal comfort. An example is a test of the rotation of the courtyards. When the courtyards are located with an open side to the west most outdoor areas receive too much heat. However, if the courtyards are located with the open side to the north, they receive less solar radiation and have more summer shade because of the shading provided by buildings to the east and west.

Cool surfaces and landscape. Growing a vegetative layer of native plants on a rooftop reduces temperatures of the roof surface and the surrounding air. Installing a cool roof that significantly reflects sunlight and radiates heat away from a building reduces roof temperatures, increases the comfort of occupants, and lowers energy demand. Cool pavements on sidewalks, parking lots, and streets that remain cooler than conventional pavements by reflecting more solar energy not only cools the pavement surface and surrounding air.

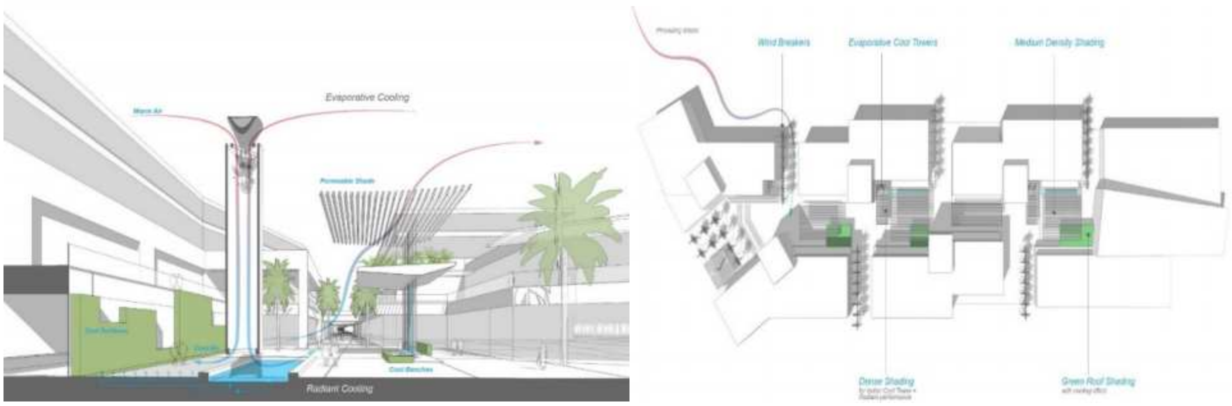


Figure 12: Passive Strategies in Master Plan of Cal State San Bernardino Palm Desert Campus

## 5. COOLING WITH THE SKY

### 5.1. RADIANT COOLING

The sky provides the ultimate continuous heat sink to maintain the Earth's thermal equilibrium. All bodies radiate and absorb energy to the sky at the same time, usually at different rates and wavelengths. Any ordinary surface that "sees" the sky loses heat by emitting longwave radiation toward the sky, a heat radiator. These radiant heat losses take place during day and night, but only at night, when there are no solar gains, are the heat losses to the sky higher than the heat gains (negative radiant gains) and the building can be cooled. A rule of thumb for a location with clear days and nights is that radiative cooling has a potential rate of about 10% of the summer radiative heating rate.

### 5.2. OPERABLE RADIANT SYSTEM FOR INFORMAL SETTLEMENTS

An option for a cooling solution in informal settlements is to provide operable radiant cooling systems. In these settlements, a common initial stage of the homes is with metal sheets in walls and roofs, replaced by brick and concrete when the family has enough financial resources. These metal roofs are very hot during the daytime but cool down quickly in the evening as they radiate energy to the night sky, acting as an effective nocturnal radiator directly above the living space. Data recorded in a house with metal walls and roofs in Maracaibo, Venezuela at a latitude of 10.5 degrees north of the equator and at sea level shows indoor daytime temperatures that are always higher than outdoor temperatures (Fig 13). Daytime conditions inside the house would improve adding insulation on the roof, but this would reduce the potential of radiant cooling during the night.

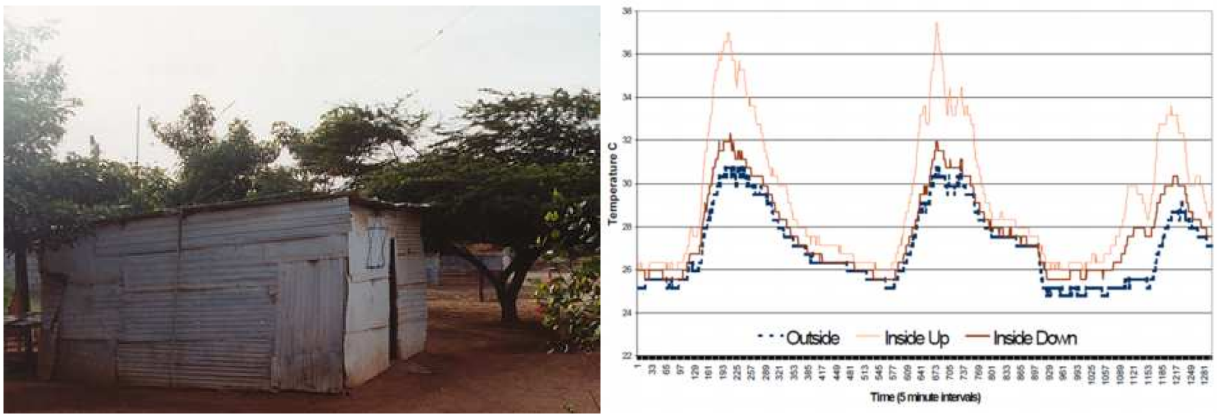


Figure 13: Informal Settlement in Maracaibo with recorded temperatures

Baruch Givoni, Carlos Gomez, and Anthony Gulish, at UCLA, developed a radiant cooling system for use in these buildings. The author conducted additional tests with variations of this system. The test cell had super insulated walls to better test the radiant system as the main source of cooling. The metal roof was painted white to Increase its emissivity, as a nocturnal radiator while reflecting solar radiation during the daytime. Below the roof were located centrally hinged, lightweight, and operable reflecting panels made of aluminium foil. During the daytime the panels were closed to form a continuous radiant barrier and reduce the heat flow into the interior. During the night, the panels were opened into a vertical position, enabling radiant and convective heat flow from the interior space to the metal ceiling, which is then cooled by longwave radiation to the sky. The rotation of the insulating ceiling panels between the closed and vertical positions was achieved by an electromechanical system designed and built by Antulio Gomez at UCLA. In a real home the panels could easily be controlled manually from the interior (e.g., by a rope). Interior operable insulation panels are not exposed to the wind and the rain, and thus can be simpler in construction, lighter, and much less expensive than external operable panels. Several series were performed with different amounts of mass in the interior. In all cases, to varying degrees, the interior conditions were much better than exterior conditions. Fig 13 shows 3 days in one of these series.

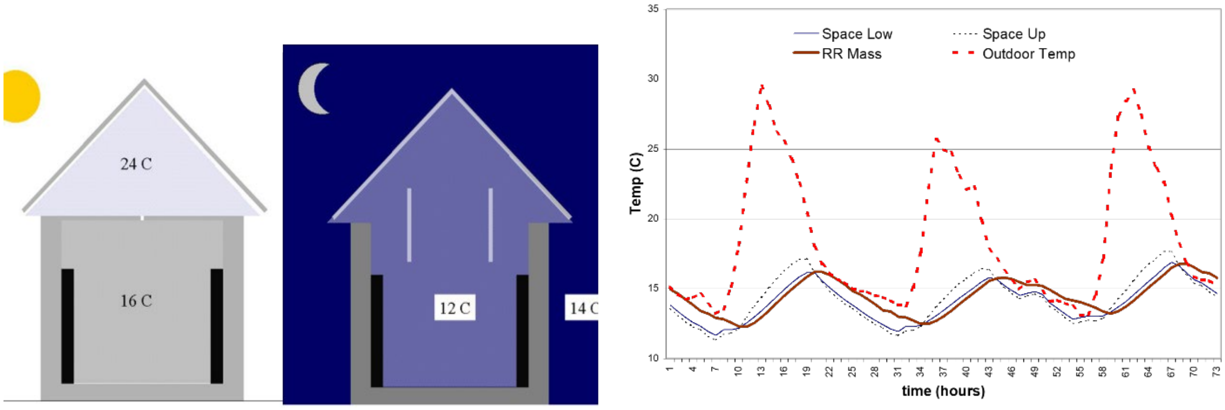


Figure 14: Radiant Cooling system designed and tested at UCLA

## 5.2. THE XYLEM

The actual architectural design can be vary considerably from these texts as long as the heat flow paths are implemented correctly. In the Xylem, designed at CallisonRTKL, a vegetated roof and water circulation for radiant cooling are included in addition to shading and natural ventilation.

As cities replace green space and vegetation with paved surfaces, “islands” of higher temperatures increase energy consumption in buildings, elevate emissions of air pollutants and greenhouse gases, compromise human health, and impair water quality, further impacting environmental conditions in these cities. A team from CallisonRTKL (J. E. Chung, P La Roche, A Ponce, N Gemigniani) proposed a concept, named after Xylem, to provide additional outdoor thermal comfort while mitigating the heat island effect. The project is named after xylem, compound tissue cells within plants and wood fibers that circulate water and nutrients upward from the roots to the leaves. Xylem cells circulate water just as this project also circulates water for radiant cooling, starting from the base, up through the structural core, and then within the conductive cladding. The Xylem improves outdoor thermal comfort by implementing a vegetated roof and water circulation for radiant cooling in addition to shading and natural ventilation. The green roofs concepts were further developed based on previous green roof research that it could actually be used for cooling. Even though it has been developed for hot and humid climates it can also be implemented in hot and dry climates. The Xylem improves outdoor thermal comfort by implementing four outdoor cooling strategies: a large canopy for shading, promoting natural ventilation, a vegetated roof for thermal mass, and water circulation for radiant cooling. The form of the Xylem maximizes shade by its large diameter at the top while its curvature and slender stem provides for air flow at the bottom (Figure 15).

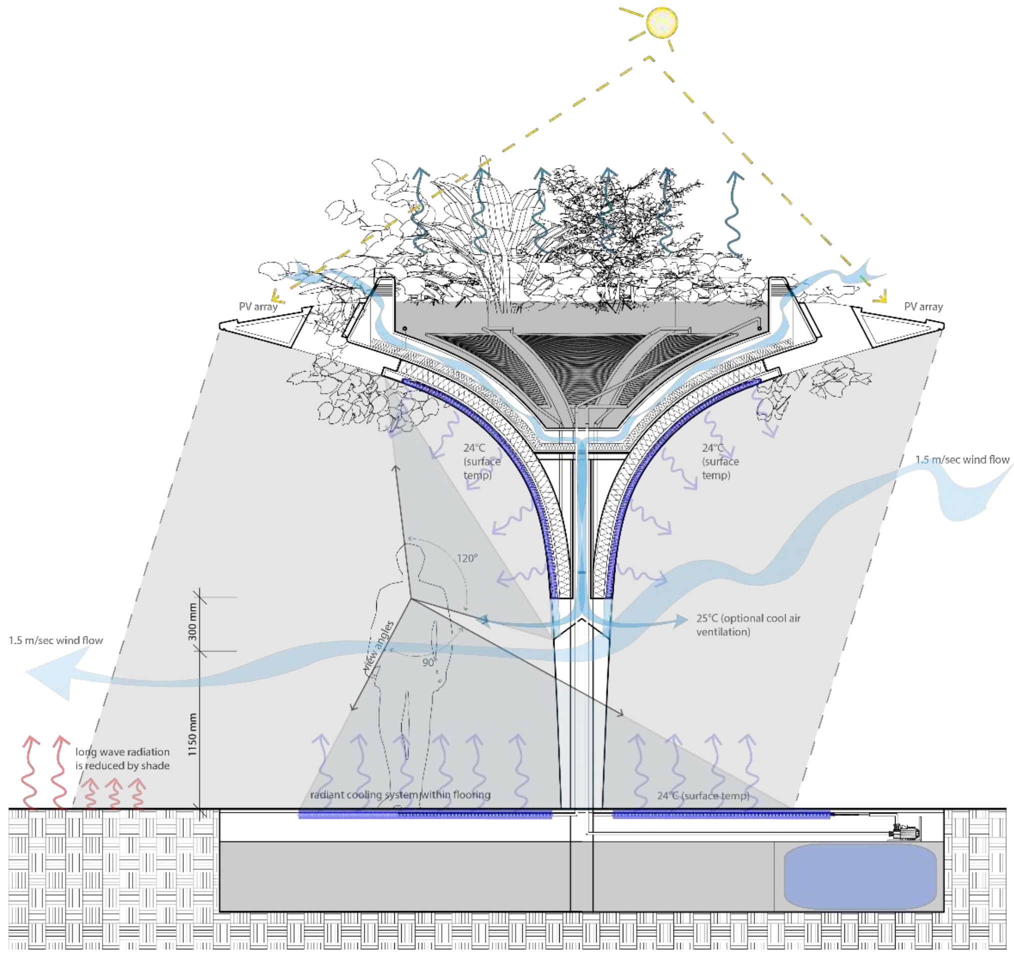


Figure 15: Design of the Xylem

A single Xylem pod provides thermal comfort at the user level, a cluster of three Xylem pods improves comfort at a larger scale and when combined as a community of clusters, the Xylem pods reduce the heat island effect, improving both outdoor and indoor conditions (Fig 16). The xylem can be used and adapted for multiple outdoor programs in different locations and cultures including plazas, markets, playgrounds, beaches, outdoor malls, community centers etc. The xylem is flexible.

Figure 16: Several Xylems together in a hypothetical location

## 6. CONCLUSION

It is important to continue developing new versions of passive cooling systems and improving performance of established systems using the new technologies and materials that are now available. It is necessary to design architecture that will continue using appropriate paths to harness energy flows, creating buildings that are simpler to operate and more resilient.
It is also necessary to understand and reinforce the connection between passive cooling strategies and thermal comfort. These passive strategies use heat flow paths to promote cooling and improve thermal comfort by radiation and air movement in addition to reducing the air temperature.

In an ever-warming world passive cooling systems are an important part of the process to design comfortable low carbon buildings that are connected with the environment around them.

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# Impact of urban albedo on microclimate and thermal comfort over a heat wave event in London

**Agnese Salvati[1] and Maria Kolokotroni[1]**

[1] Institute of Energy Futures, Brunel University London, UK
agnese.salvati@brunel.ac.uk;
maria.kolokotroni@brunel.ac.uk

**Abstract:** This work investigates the potential of increasing the surface albedo of roads and buildings' facades for mitigating thermal stress in London over heatwave events. The results are based on microclimate simulations with ENVImet (V4.4.3), validated using air temperature and radiation data (incoming and reflected) measured in a case study area of London. The comparison shows that ENVImet can accurately estimate the reflections within urban canyons in most cases and slightly overestimates the peak air temperature in urban canyons. The validated model is used to assess the impact of surface albedo on the Physiological Equivalent Temperature (PET) at the street level, considering the meteorological conditions of the heat wave on 29th June 2019. The results show that, at London's latitude, increasing the albedo of facades has a negligible impact on the thermal environment at the street level. Conversely, reducing the reflectivity of facades and increasing the reflectivity of roads reduces the hours of extreme heat stress and lowers the PET values during the hottest hours of the day. This result can be explained by the impact of facades' albedo on the multiple reflection of solar radiation within urban canyons.

**Keywords:** Urban Albedo; reflective materials; outdoor thermal comfort; heat waves; urban microclimate

## 1. Introduction

Urban environments play a crucial role in the challenges posed by the current climate crisis. Since the unfortunately famous heat wave of 2003, which caused thousands of deaths in Europe (Public Health England, 2019), the health risks associated with heatwaves have become clear, especially in cities.

In cities, the risks posed by higher global temperatures and by the increase in frequency, severity, and duration of heat waves are amplified by local urban climate phenomena such as the heat island effect (Li and Bou-Zeid, 2013; Founda *et al.*, 2015). Furthermore, urban population is growing all over the world (World Bank, 2014), increasing the number of inhabitants exposed to heat-related health risks at any latitude (Inostroza, Palme and De La Barrera, 2016). For this reason, mitigation and adaptation strategies play an important role in improving the thermal response of urban environments and reducing the population exposure under extreme weather events. This is particular relevant in urban areas with high building density and scarce vegetation, which experience the maximum UHI intensity (Kolokotroni and Giridharan, 2008; Lemonsu *et al.*, 2015; Salvati *et al.*, 2019).

One cause of the heat island effect is the ability of urban fabrics to absorb and store heat during daytime, due to the thermal and optical properties of materials and the urban surface geometry that causes multiple reflections of solar radiation (Yang and Li, 2015; Oke *et al.*, 2017). The use of green infrastructures and high albedo materials can contribute to mitigate the UHI by reducing solar absorption and heat storage (Santamouris, 2014; Alchapar, Cotrim and Correa, 2017; Gunawardena, Wells and Kershaw, 2017; Giridharan and

Emmanuel, 2018; Imran *et al.*, 2018). Green infrastructure helps retaining water in the urban environment and dissipating heat through the evaporation process. Surface albedo, which is defined as the ratio of the shortwave radiation reflected by a surface to the shortwave radiation reaching that surface, can contribute to lower urban surface temperatures by reflecting more of the incoming ration toward the sky.

However, in an urban context, the ratio of solar radiation reflected toward the sky depends on both the surface albedo of materials and the geometry of urban canyons. For this reason, the concept of urban albedo was introduced. The urban albedo (UA) is defined as the ratio of the outgoing to the incoming shortwave radiation at the upper edge of the urban canopy layer (Yang and Li, 2015). UA is different from surface albedo since its value depends on both the photometric properties of materials (i.e. surface albedo) and the geometry of the urban surface. In fact, in an urban fabric the incoming radiation undergoes multiple reflections between urban surfaces (facades and roads) and, at every incidence, a portion is absorbed by the incident surface while another portion is reflected towards other urban surfaces. For this reason, the effectiveness of high albedo materials in improving outdoor thermal comfort in complex urban geometries is still under investigation and it may vary depending on urban geometry (Yang *et al.*, 2016) and latitude (i.e. solar altitude).

Many studies indicated a positive impact of increasing the reflectivity of roads on UHI intensity and outdoor thermal comfort (Wang and Akbari, 2016; Salata *et al.*, 2017; Santamouris *et al.*, 2018). Conversely, some studies highlighted that the use of high reflective materials may have a negative impact on summer thermal comfort (Erell, Pearlmutter and Boneh, 2012; Alchapar and Correa, 2016), due to the increase of reflections within urban canyons and the consequent increase of mean radiant temperatures. Furthermore, Nazarian et al. (Nazarian *et al.*, 2019) showed that high reflective walls can increase the building energy use in high-density urban areas in Singapore, due to the increase of solar radiation transmitted into the neighbouring buildings.

This study investigates the potential of high albedo materials for facades and pavements for mitigating heat stress over a heatwave event at London latitude (lat 51.5º N). A real residential area is used as a case study. Different scenarios are investigated and their impact on the street level air, mean radiant and surface temperatures, and physiological equivalent temperature (Hoppe, 1999) is discussed. The analysis is based on microclimate simulations using the ENVImet program.

## 2. Methods

This study is based on microclimate simulations using the software ENVImet (V4.4.3), validated with air temperature and solar radiation data measured in a residential area of London. ENVImet is a microclimate simulator able to calculate high-resolution spatial and temporal distribution of microclimate variables within an urban domain (Bruse and Fleer, 1998; Huttner and Bruse, 2009).The accuracy of ENVI-met estimations of air temperature and reflections within urban canyon is assessed comparing the modelled microclimate outputs with the measured data.

The impact of materials reflectivity of facades and roads on outdoor thermal comfort is assessed in terms of hourly PET changes under heatwave conditions.

### 2.1. Air temperature and radiation measurements

An area of approximately 100m by 100m in a London borough is used as case study for this analysis. The area has typical characteristics of residential neighbourhoods in London, with low rise terraced houses cladded with bricks and plaster (Figure 1).

An air temperature sensor was installed in a radiation screen at 5m height on a lamppost in the case study area (Figure 1 c). A bluetooth temperature, humidity and dew point sensor beacon and data logger is used with temperature resolution of 0.1ºC and accuracy of 0.3ºC, with maximum 0.4ºC at -10ºC to +75ºC.

Spot measurements of the incoming and reflected solar radiation in different points within the canyons of the study area were performed on the 23rd of May 2019, under clear sky conditions (Figure 1 a, b and d). An albedometer composed of two pyranometers pointing one upward and the other one downward was used to measure the incoming radiation from the upper hemisphere and the reflected radiation from the lower hemisphere at three levels within canyons: at the street level (1.2m height), at the 2nd floor level (5m height) and at the eaves level (10m height). A cherry picker was used to carry out the measurements at the different heights (figure 1 b and d).

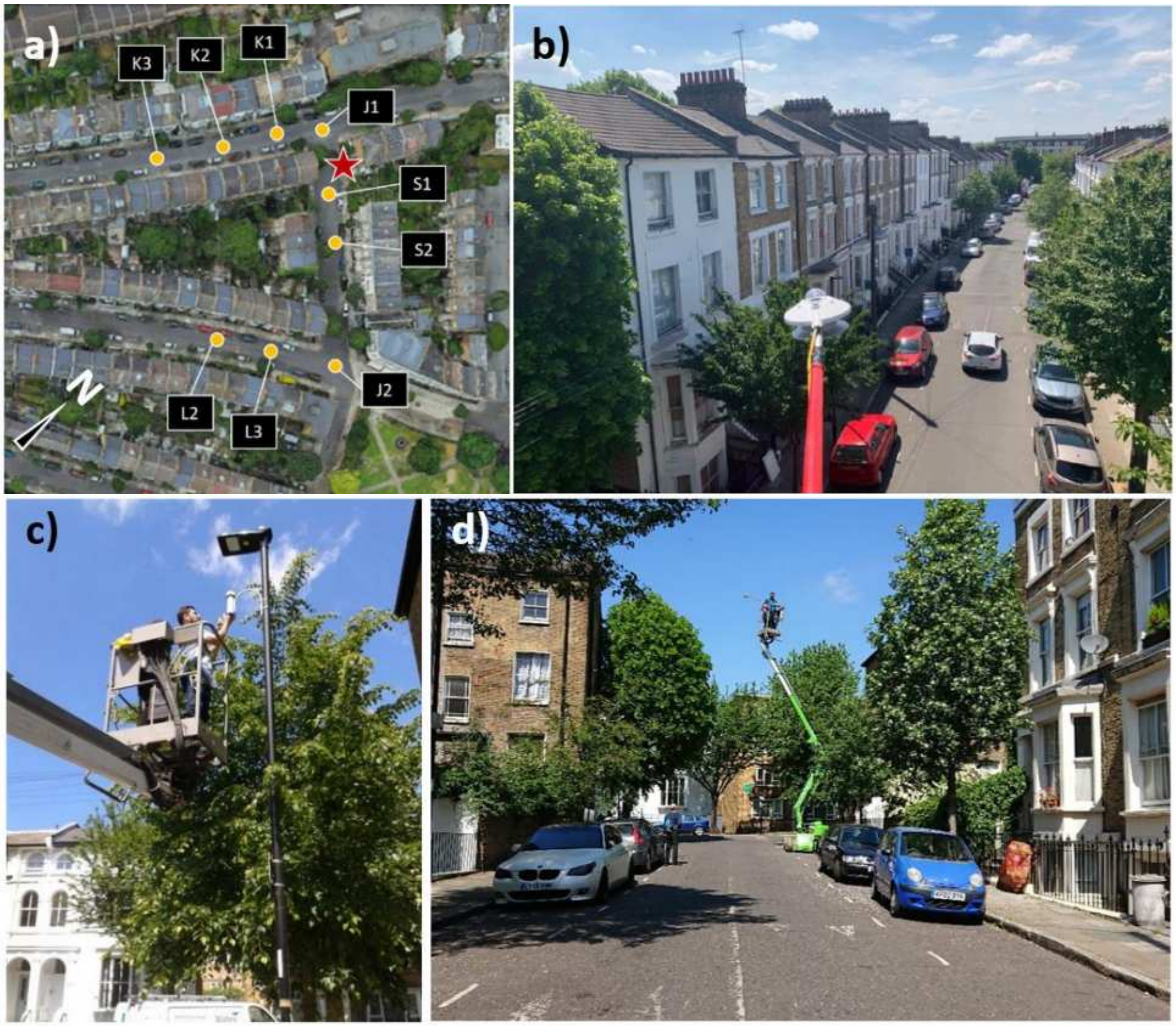


Figure 1 : a) Radiation measurement points in three roads (K_Rd, S_Rd and L_Rd); b) albedometer and radiation measuring at eaves level; c) installation of the temperature sensor on the lamppost; d) cherry picker used for the radiation measurements

## 2.2. ENVImet model calibration and PET estimations for changing materials

An ENVImet model of the area was built to simulate the microclimate and thermal comfort implications of changing the reflectance of roads and facades in the case study area. A base model corresponding to the current situation was built based on field surveys, GIS data (Ordnance Survey, 2018) and satellite data (Google Earth) for urban geometry and vegetation.

A survey of materials was conducted to estimate the reflectivity and emissivity properties of facades, paving and road materials to be used in the ENVImet model. The reflection coefficients and material distribution of the base model are reported in table 1. The reflection coefficients of the materials have been estimated using digital photography techniques and the London Urban Micromet data Archive 'LUMA' (Kotthaus *et al.*, 2014). The distribution of materials on the different facades was calculated based on site surveys and google earth visualizations and reproduced with the same ratio in the ENVImet model.

Table 1. ENVImet base model material reflectivity and distribution

| **Material & reflectivity coefficients** | | **K_rd** | | **S_Rd** | | **L_Rd** | |
|---|---|---|---|---|---|---|---|
| **Façade (divided by orientation)** | | **ESE** | **WNW** | **SSW** | **NNE** | **SSE** | **NNW** |
| Red Bricks | r= 0.32 | 9% | 40% | | 69% | 8% | 4% |
| Yellow bricks | r= 0.43 | 25% | | 33% | | 31% | 33% |
| painted brick | r= 0.2 | 9% | | | | | |
| Dark paints | r= 0.08 | | | 3% | 1% | | |
| White painted bricks | r= 0.56 | 38% | 35% | 40% | 17% | 33% | 42% |
| Clear glass | r= 0.05 | 19% | 25% | 24% | 13% | 28% | 22% |
| **Roads** | | | | | | | |
| Tarmac | r= 0.19 | 100% | | 100% | | 100% | |

Table 2. ENVImet scenarios tested

| **Scenarios** | **A1 - High reflectivity facades** | **A2 - Low reflectivity facades** | **A3 - High reflectivity Roads** | **A4 – Combined scenario** |
|---|---|---|---|---|
| **Facades** | r = 0.6 | r = 0.1 | as base case | r = 0.1 |
| **Roads** | as base case | as base case | r = 0.5 | r = 0.5 |

The ENVImet mesh size, area size and simulation parameters were defined according to the criteria developed in a previous work for the same urban area which led to the best air temperature accuracy estimation (Salvati and Kolokotroni, 2019). The ENVImet model correspond to an area of 200m by 200m (mesh size of 2m), so as to include the upwind urban area that affect the temperatures in the point of measurement and avoid border effects on the results (Salvati and Kolokotroni, 2019).(Salvati and Kolokotroni, 2019).

The simulations have been performed in "full forcing mode", using the 30min frequency air temperature and relative humidity data measured by the bluetooth sensor on the 29$^{th}$ of June 2019 as forcing conditions. The use of local air temperature observations as forcing conditions was found to provide the best accuracy in ENVImet estimations (Salvati and Kolokotroni, 2019). A buffer time of 12hrs was considered for model pre-conditioning.

ENVImet air temperature accuracy was assessed by comparing the simulation results at the point corresponding to the sensor location measuring air temperature. All the simulations have been performed using the advanced IVS radiation algorithm for reflection calculation.

The accuracy of ENVImet in the calculation of reflections within the urban canyons was also assessed. To this aim, an ENVImet simulation was forced using the incoming solar radiation data measured on the 23$^{rd}$ of May 2019 on site and the IVS method for radiation transfer. The ENVImet radiation output "Reflected shortwave radiation lower hemisphere" (Figure 4) was compared with the reflected radiation measured on site in three urban canyons at different heights (figure 1).

The validated model has been used to test the potential microclimate impact of high albedo and low albedo materials for paving and building facades. Four scenarios have been simulated, changing the surface albedo of facades and roads as reported in table 2. The surface albedo values for the scenarios “high reflective facades” and “high reflective roads” were set to 0.6 and 0.5 respectively; these are common values found in the scientific literature on high albedo materials for microclimate mitigation.

The impact of the different scenarios on the thermal environment has been assessed in terms of air temperature and mean radiant temperature at 1.5m height at different points within the three main streets of the studied area. The physiological equivalent temperature (Hoppe, 1999) – PET – has been used for assessing the impact of the canyon materials’ surface albedo on the outdoor thermal comfort. The correlations between PET, mean radiant temperature, surface temperatures and solar radiation received by the urban surfaces in each scenario is also discussed. This highlights whether high albedo materials are effective in mitigating heat risks in typical urban settings in London.

## 3. Results

### 3.1. Measured reflections in urban canyons

The measured incoming and reflected radiation within the three case-study urban canyons are reported in figure 2. The three canyons have the same geometry ratio (i.e. ratio of the building heights to the street width) of approximately 0.75 and different orientation and material distribution as reported in table 1.

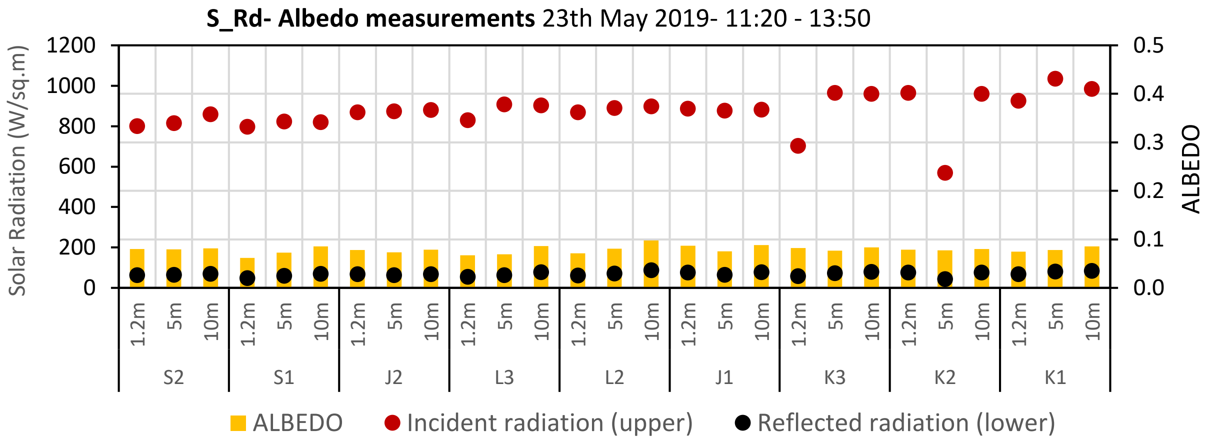


Figure 2 Measured incoming (incident) and outgoing (reflected) radiation and urban albedo values within urban canyons in the case study area

The radiation measurements showed that, for a datum geometry, the reflections are not influenced by street orientation and materials distribution. Also, the measured reflections did not vary with measurement height, being approximately the same value at the street level (1.2m height), 2$^{nd}$ floor height (5m agl) and eaves level (10m agl) as reported in figure 2. Therefore, the measured urban albedo, namely the ratio of the measured outgoing to the incoming radiation, showed very small variation. At the street level, the UA varied between 0.06 and 0.09, with an average value of 0.08. At the 2$^{nd}$ floor, the UA was even less variable, with a maximum and minimum value of 0.08 and 0.07 and an average value of 0.08. At the eaves level, the UA varied between 0.1 and 0.08, with an average value of 0.09. The highest values of UA (0.1) was recorded at point L2, namely in the street with the façade that received more radiation at the time of measurements (South-South East oriented façade).

### 3.2. Accuracy of ENVImet estimations: air temperature and reflected radiation

The accuracy of ENVImet in estimating air temperature is strongly related to the meteorological forcing conditions used in the simulation (Salvati and Kolokotroni, 2019). Therefore, to obtain the best accuracy, the local air temperature measured at 5m height in the studied area was used to force the simulation. The simulated day was the 29th of June 2019, when London experienced a heat wave with temperatures up to 35.6 ºC in the case study area (figure 3).

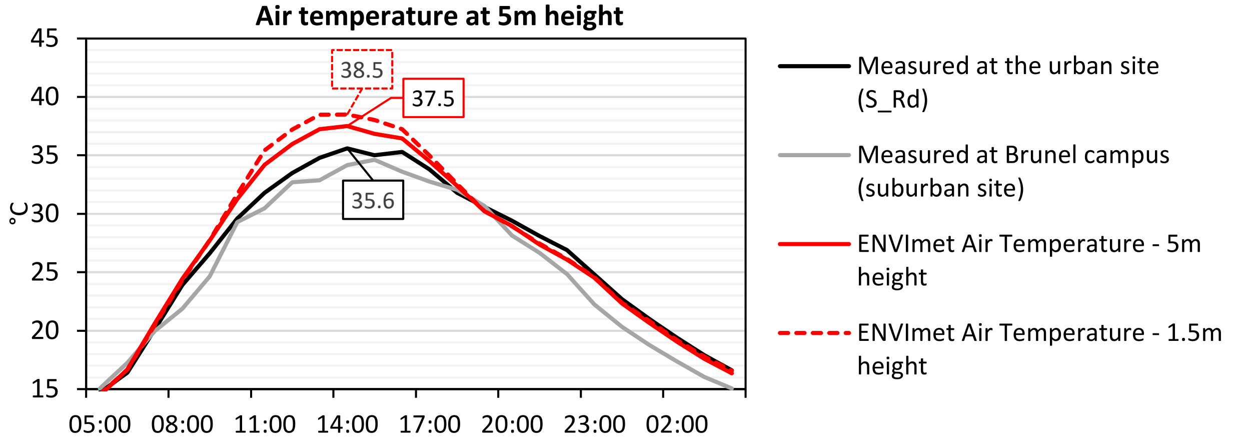


Figure 3 Comparison of measured and estimated air temperature over the 29th June 2019 heat wave event in London

Figure 3 compares ENVImet air temperature estimations to the measured data. The comparison shows that air temperature is overestimated by ENVImet between 12:00 and 16:00. The maximum overestimation reaches about 2 °C at 14:00, when the temperature recorded by the sensor was about 35.6 ºC while ENVImet estimates 37.5 ºC. At the street level (1.5m height) ENVimet estimates a further increase up to 38.5 ºC, which probably is similarly overestimated of about 2°C. The RMSE over the 24hr of heatwave day is about 1.18 °C, which is in line with previous ENVImet works (Salata et al., 2016; Salvati and Kolokotroni, 2019).

The accuracy of ENVImet calculation of reflections and UA within urban canyons is reported in Figure 4.

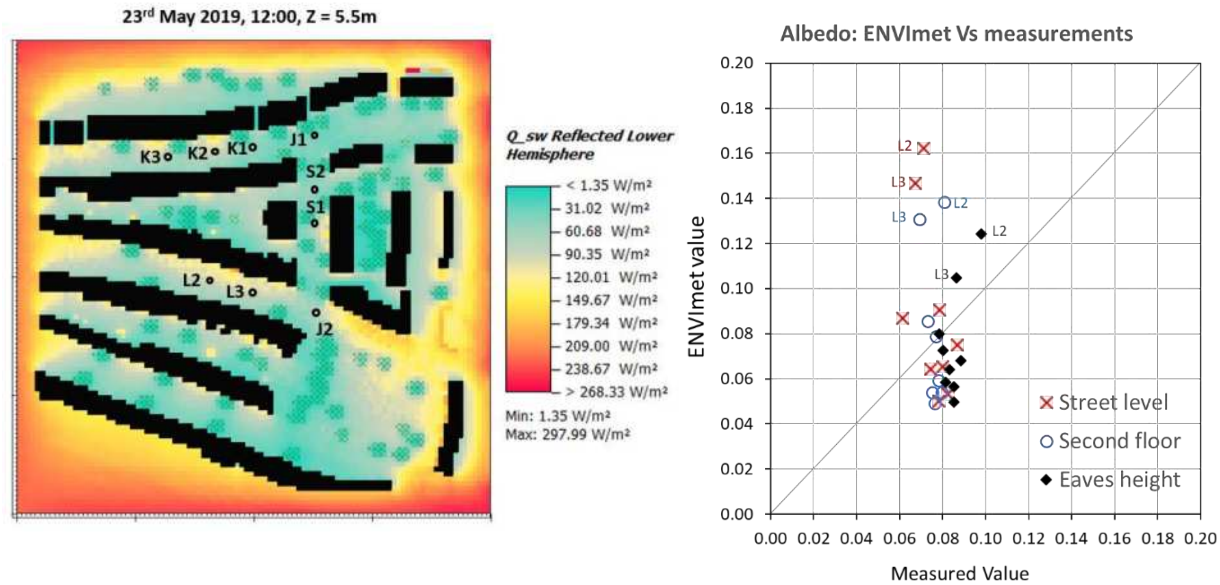


Figure 4 on the left: ENVImet Reflection estimations in the simulated domain. On the right: comparison between the ENVImet urban albedo estimated values and the measured urban albedo values.

The simulation results indicate a good estimation of the reflections within urban canyons for most of the points except for points L2 and L3, where urban albedo is overestimated by ENVImet. This is due to an overestimation of the canyon reflections in these points, in particular at the street level and at the second-floor level. This means that ENVImet probably overestimates the canyon reflections in canyon with facades that receive high solar radiation. For all the other points, the UA estimation is very accurate and always below 0.1. It should be noted that this accuracy was reached only using the advanced IVS algorithm for radiation transfer. When the simplified method for reflection calculation is used, the reflections within urban canyons are all the same and overestimated compared to the measurements.

### 3.3. Impact of materials reflectivity on outdoor thermal comfort

The impact of the four scenarios tested (table 2) on the PET value at street level is reported in figure 5. The PET is defined as the air temperature at which, in a typical indoor setting (without wind and solar radiation), the heat budget of the human body is balanced with the same core and skin temperature as under the complex outdoor conditions to be assessed (Hoppe, 1999). In other terms, the PET value corresponds to the temperature of an indoor environment with no direct solar irradiation, wind velocity equal to 0.1 m/s, mean radiant temperature equal to air temperature and relative humidity of about 50% at Ta=20°C which would determine the same thermal sensation than the outdoor environment.

The PET has been calculated with the Biomet (4.4.3) module of ENVImet, based on the microclimate outputs of the microclimate simulations for each scenarios. The heat stress scale reported in figure 5 refers to Matzarakis and Mayer classification (1996).

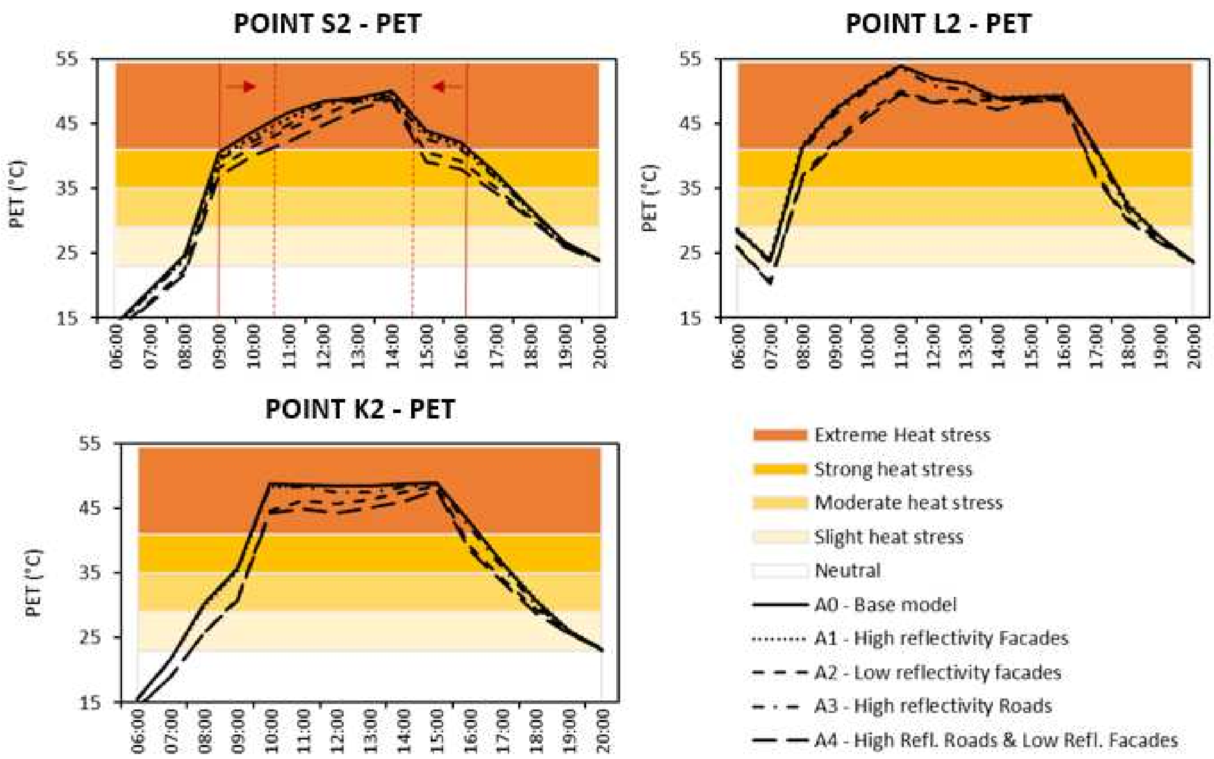


Figure 5 Impact of roads' and facades' materials albedo on the physiological equivalent temperature over the studied heatwave day in London. The location of the three points is reported in Figure 1,a.

The graphs in figure 5 clearly show that none of the scenarios is able to avoid extreme heat stress over the hottest hours of the heatwave day. However, in some cases, the duration of the heat stress time can be reduced. This happens for example at point S2 for the scenario A4, namely a combined scenario with low reflectivity facades and high reflectivity roads. The combined scenario A4 allows reducing the hours of extreme heat stress from about 7 hours in the base case (from 9:00 to 16:00) to about 4 hours (from 10:30 to 14:30).

The combined scenario indicates the ability to reduce heat stress in all the canyons. The highest PET value is reached at point L2, at 12:00. This probably happens because point L2 is located in the canyon with a SSE façade, which receives the maximum radiation in the early hours of the morning, leading to very high heat stress levels. In this canyon, both the scenarios A4 and A2 allow a sensible decrease of the maximum PET. These scenarios have in common a reduced reflectivity of facades. It has to be noted that point L2 is located in the canyon with the highest overestimation of reflections by ENVImet compared to the measurements. Therefore, the impact of surface albedo of materials on the PET value could also be overestimated in this point.

## 4. Discussion

The results of this study outline the complex relationship between urban variables and outdoor thermal comfort, due to the multiple factors that affect the urban microclimate in real-world urban areas. Increasing the surface albedo of urban materials may have countering effects on urban microclimate and outdoor thermal comfort. On the one hand, increasing the albedo of surfaces determines a decrease of surface temperatures. On the other hand, the consequent increase of reflections within complex urban geometry leads to an increase of solar radiation received by urban surfaces, which may have a negative impact on the outdoor and indoor thermal comfort. The overall balance of these opposite effects depends on the regional climate (i.e. solar elevation and radiation intensity) and the urban canyon aspect ratio (ratio of the height to the width of the street).

The canyon aspect ratio in the case study area is approximately 0.75 (building height equal to 12m and street width equal to 16m). In this kind of geometry, at London's latitude, the simulation results show that increasing the wall albedo does not improve the outdoor thermal comfort while increasing the road albedo has a significant positive impact on the PET index. This result is explained by the impact of the roads' and facades' albedo change on the air temperature and mean radiant temperature at street level, reported in Figure 6. The trends reported in the figure correspond to point S2, but they are similar in all the canyons. In terms of air temperature, changing the albedo of facades does not influence air temperature. A significant decrease of air temperature is instead obtained with the increase in road albedo (scenario A3). On the other hand, for the studied geometry, increasing the reflectivity of facades (scenario A1) has a negligible impact also on the mean radiant temperature. Conversely, a substantial decrease in facade albedo (scenario A2) allows a reduction of the mean radiant temperature at the street level.

Similar results were also reported in other latitudes (Alchapar and Correa, 2016) and can be explained by the impact of the walls' albedo on the multiple reflection of solar ration within urban canyons. In fact, the solar radiation received by the canyon' walls varies significantly for different values of surface albedo, as shown in figure 7. Similar results were found by Levinson (2019), who showed that the wall's solar availability in an urban context may increase up to 30% in deep urban canyons when the albedo of the neighbouring building is raised from 0.25 to 0.6.

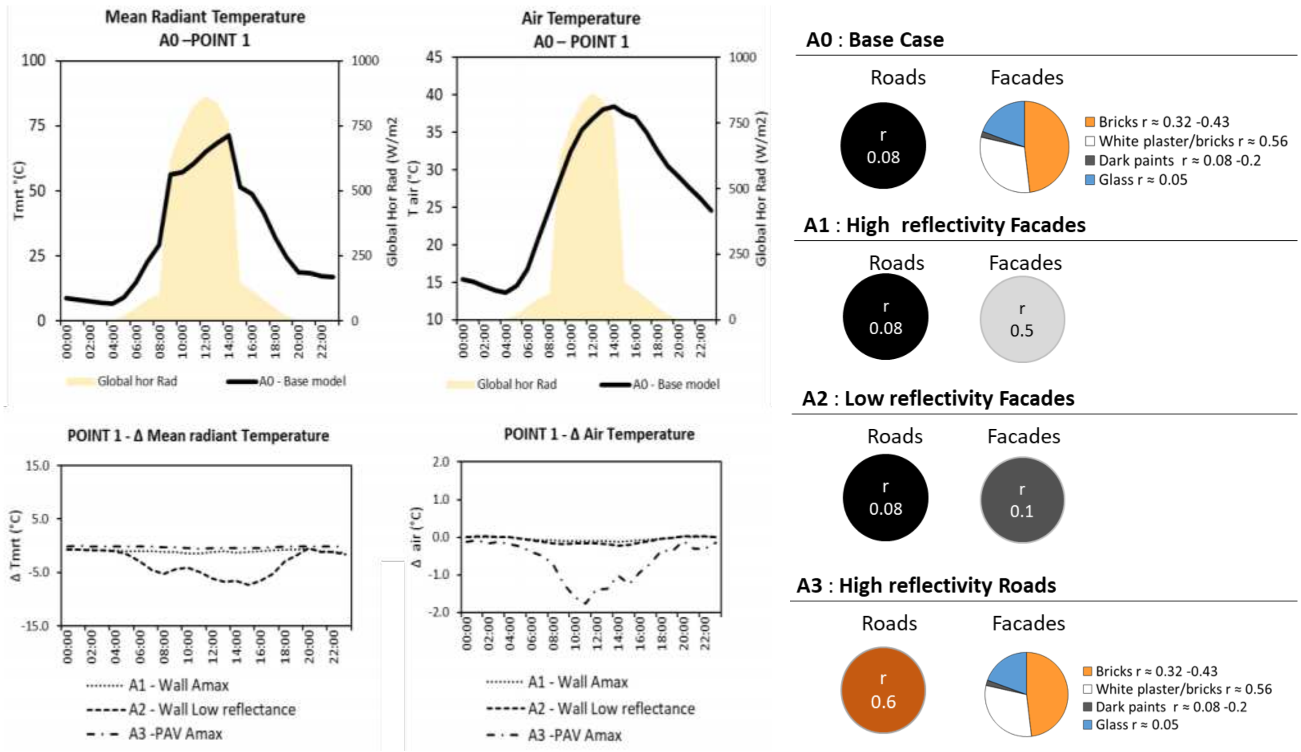


Figure 6 Impact of roads and facades' materials reflectivity on air temperature and mean radiant temperature at street level compared to the current scenario (base case).

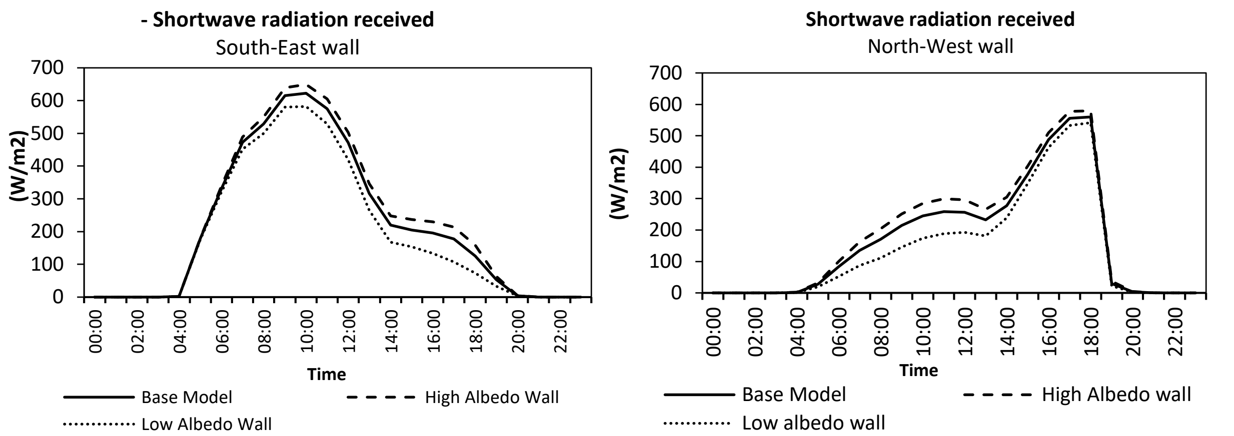


Figure 7 : Shortwave solar radiation received by the South-East (left) and (North-west) wall surrounding point L2 for different scenarios

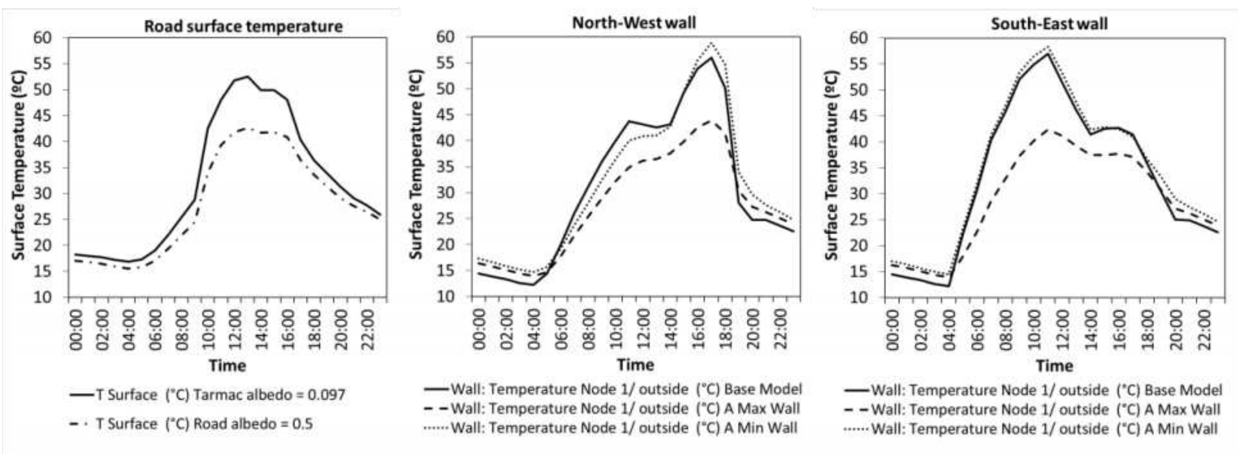


Figure 8 Left: Tarmac surface temperature over the heat wave. Right: surface temperature decrease using a high reflectivity material for paving

The combined scenario of low albedo facades and high albedo roads allowed the maximum improvement of outdoor thermal comfort in the case study area, being beneficial for both street level air temperature and mean radiant temperature. However, in terms of surface temperatures (figure 8), the high-albedo walls show a significant decrease in surface temperature compared to the base case and the low albedo walls. Surprisingly, this change in surface temperature does not entail a similar change in mean radiant temperatures or improved PET values. The same applies for the increase of surface albedo of the road, which entails a significant decrease of surface temperature, but it does not impact the mean radiant temperature at street level (Figure 6).

This could be explained by the fact that ENVImet takes into account all radiation fluxes in the calculation of the mean radiant temperature, including direct and diffuse irradiance, reflected radiation and long wave radiation (Naboni *et al.*, 2019). Therefore, changes in the direct and diffuse irradiance may have a bigger impact on the mean radiant temperature compared to the change in surface temperature of walls and roads. This is supported by other studies on the impact of reflective paving on outdoor thermal comfort, which show that the reduced surface temperature is not enough to offset the increased radiation loads from the surfaces (Erell, Pearlmutter and Boneh, 2012; Yang, Wang and Kaloush, 2015). However, to validate this result, more investigations into the mean radiant temperature calculation method of ENVImet are necessary. The lack of information to fully assess the accuracy of the outdoor thermal comfort estimations was reported also for other tools (Evola *et al.*, 2020). This highlights the need of more experimental data to completely validate these complex simulation tools.

Further developments of this research will include the assessment of the impact of the albedo of urban materials in different urban geometries and in the winter season.

## 5. Conclusion

This work analyses the potential of changing the albedo of facades' and roads' materials for reducing heat stress in London over heatwave events. The results provide new insights on the relationship between surface albedo and urban albedo and the effectiveness of high albedo materials in improving outdoor thermal comfort in complex urban geometries at London's latitude.

The analysis is based on microclimate simulations with the software ENVImet, validated with experimental data of air temperature and solar radiation measured in a case-study residential area of London. The incident and reflected solar radiation measurements within three urban canyons of the case-study area indicate that, for a datum geometry, the reflections are not influenced by street orientation and materials distribution. In the measured canyons (aspect ratio approximately 0.75), the average urban albedo varied between 0.08 and 0.09. The comparison of reflections measurement with ENVImet estimations showed a good agreement using the detailed IVS method for the computation of reflections.

The validated model was used to assess the impact of changing surface albedo of facades and roads on the outdoor thermal environment. The results showed that increasing the albedo of facades has a negligible impact on the thermal environment, while a substantial decrease of the facades' albedo may have a beneficial impact on the heat stress level during heatwaves, because it determines a decrease of the mean radiant temperature. The results also showed that increasing the albedo of roads allows a decrease of street-level air temperature, with positive impact on the PET value. These findings are relevant for the development of urban planning guidelines for improving thermal comfort and reducing outdoor heat stress under heat wave events in London.

## Acknowledgement

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# Adapting high-rise buildings to local climates: Studies for an optimum envelope scenario towards energy efficiency for a high-rise building in the Mediterranean climate

**T. Saroglou[a], T. Theodosiou[b], I. A. Meir[a]**

[a] Department of Structural Engineering, Faculty of Engineering Sciences, Ben-Gurion University of the Negev, Israel

[b] Department of Civil Engineering, Aristotle University of Thessaloniki, Greece

**Abstract:** High-rise buildings around the world increase rapidly. Nevertheless, this fast pace is not corresponding with a know-how on the design of this building typology according to climate. In addition, the increased transparency of the building envelope from the mid-twentieth century onwards, resulted in high-energy loads, especially prominent in high-rise construction. With planning policies moving towards targets for low-carbon built environments, this challenging typology needs further research and experimentation. This study focuses on an office high-rise in the Mediterranean climate of Tel Aviv and the reduction of high cooling loads relevant to this climate. In this process, the envelope becomes the most important constituent between indoors and outdoors, by dictating the required use of energy for achieving thermal comfort. Simulations revealed that a ventilated double-skin façade (DSF) with the Low-E glazing as the exterior layer reduced cooling loads by 15% on average, from a typical DSF in temperate climates where the Low-E glazing is on the interior layer. However, cooling loads were also present during winter, when the DSF openings were closed, prompting for a more dynamic DSF design throughout the year. A further study is conducted, where the DSF openings alternate between open/closed DSF in relation to: building height, exterior environmental conditions, and interior thermal comfort, for optimum energy efficiency in high-rise buildings.

**Keywords*:* Energy efficiency; ventilated DSF; high-rise; thermal comfort**

## 1. Introduction

World population is growing at a very fast pace, affecting the growth and density of the urban environments. In addition, considering the fact that since 2007 more than half of the world's population is living in urban areas (a figure expected to rise to 60% by 2030 (United Nations, 2014)) the implications of higher density city living take on a humanitarian perspective. The increase in world population and urbanization also dictates an increase in building demand. Thus, it is possible to predict that high-density urban environments will soon be the norm. According to annual research reports by the Council of Tall buildings and Urban Habitat (CTBUH) the numbers of tall buildings around the world increase rapidly (CTBUH_ResearchReport, 2019; Safarik *et al.*, 2020).The typology of high-rise buildings has been mainly introduced as an important solution to high-density city living, within the already dense urban centres.

However, current high-rise buildings do not present an all-around successful solution to an increasing population or examples of prosperity, as their large scale is also translated into high-energy demands. Nevertheless, tall buildings have to also comply with up-to-date strict regulations on building energy efficiency (EU, 2010). One of the main parameters in increasing energy efficiency towards low carbon goals is to focus on the initial design and construction stages of the building, and more precisely on the design of the building envelope, as the mediator between interior and exterior conditions (Givoni, 1969; Cheung, Fuller and Luther, 2005; Yik, 2005; Saroglou *et al.*, 2017). An important criterion in this relationship is the climate and microclimate of the building's location. A climatically responsive building envelope interacts with the ambient climatic conditions of the building's location in a way that takes advantage of passive design strategies, thus reducing operational energy for heating and cooling (Cheung, Fuller and Luther, 2005; Yik, 2005; Choi, Cho and Kim, 2012).

On the other hand, current architectural tendencies initiated from the mid-20th century onwards, especially obvious in high-rise buildings today, show an increased transparency of the building envelope, accompanied by a lightness of the structure resulting in high energy loads (Allard and Santamouris, 1998). In recent years, a step towards improving energy efficiency is the implementation of a double-skin façade (DSF). DSFs are considered a more energy efficient option from the single-skin curtain wall, by creating a buffer zone between the interior and the exterior of the building, without compromising visibility. But, despite the number of built DSF projects, and the studies conducted, there are no official guidelines on DSF energy performance, especially in relation to local climate, which is the aim of this study with a focus on the Mediterranean climate (Joe *et al.*, 2014; Ahmed *et al.*, 2015; Ghaffarianhoseini *et al.*, 2016).

This paper, which is part of a wider research on high-rise energy efficiency (Saroglou *et al.*, 2017; 2019; 2020), acknowledges the current architectural trend for transparency in the structure, and proposes through a set of DSF studies, design strategies towards reducing energy loads. The performance of a DSF for a high-rise reference model is studied in the hot and humid climate of Tel Aviv, at different heights, presenting, thus, information on the relationship between the building envelope and its microclimate, in relation to height above ground. The focus is on the DSF's natural ventilation properties, as a passive design strategy that will ultimately reduce high cooling energy loads. The methodology is based on thermal simulations using EnergyPlus. Studies on naturally ventilated DSFs are limited, with most cases so far focusing on mechanically ventilated ones (Choi *et al.*, 2012; Dama, Angeli and Larsen, 2017). Moreover, DSF studies in hot climates are especially important, due to the high levels of direct and diffuse solar radiation that penetrate a glass façade, increasing thermal and visual discomfort, cooling loads and carbon emissions. In addition, DSF research in hot climates is currently limited (Hamza, 2008; Shameri *et al.*, 2010; Halawa *et al.*, 2018), with most research located in cold and moderate climates (Pomponi *et al.*, 2016).

Heating and cooling loads are compared between different design scenarios of the DSF envelope for improving energy efficiency. However, the focus is on the high cooling scenario and needs relevant to the Mediterranean climate of Tel Aviv where the studies take place. This relationship had been emphasized even further by simulating an office building that has high internal heat gains (Saroglou *et al.*, 2017; Saroglou, Meir and Theodosiou, 2017, 2018). The aim of these studies on the optimum curtain wall envelope design for energy efficiency is in response to the current state of the art in architecture, and especially in high-rise design, where the desire of transparency in the structure is high. The results of these studies will also be relevant for other regions with similar climate, such as southern Europe, the Mediterranean coastal plane, and the Middle East, that show a comparable process of high-rise development (Meir *et al.*, 2012).

## 2. Design considerations for energy efficiency in high-rise buildings

The main feature of high-rise buildings is essentially their height. The tallness of the structure poses a number of design considerations within the urban fabric, i.e., urban solar access for the surrounding buildings, potentially negative implications on fresh air intake, alternating the wind patterns in close proximity of the tower's location (downdraught and channeling affect), and more, which make this building typology a challenging one that requires careful detailing during planning and design. On the other hand, increasing the building height creates potentials for energy savings, relative to the climatic conditions of the building's location. A building interacts with its environment through the thermal properties of the building envelope (walls, roof, and windows) through heat exchange with the ambient air by conduction, convection and radiation (Ellis and Torcellini, 2005; P. Lotfabadi, 2014). So, when estimating the energy loads (heating and cooling) of a high-rise building, it is important to consider the changing microclimate with height, and more specifically the effect of wind speed increase and of dry bulb temperature drop, in relation to height above ground (NOAA NASA and USAI, 1976; ASHRAE, 2009).

Building height also affects the natural ventilation (NV) potential of high-rise structures. Natural ventilation as a passive design strategy has the potential of considerably reducing cooling loads, which are especially prominent in hot climates. However, the effectiveness of natural ventilation is relevant to the building's climate and microclimate (Capeluto and Ochoa, 2013; Zhou *et al.*, 2014), and in the case of high-rise buildings, is also relevant to the changing microclimate with height. A study conducted on the NV potential of high-rise structures located in US cities with different climatic conditions, showed that the presence of humidity created minimal variations in NV hours from ground to top, while where the humidity levels were low the NV hours decreased. In cities with seasonal variations, like New York and Chicago, there is no NV potential during winter, while during summer the NV hours increased substantially suggesting considerable reductions on cooling energy (Tong, Chen and Malkawi, 2017). Nevertheless, implementing natural ventilation strategies in tall buildings can be challenging. An effective way to do so is through a double skin envelope. The exterior layer of the double skin acts as a buffer zone to the higher wind speed intensities that are created at higher altitudes, making possible the introduction of natural ventilation through the opening of windows towards the DSF cavity, in accordance to the climatic conditions and seasonal variations of the building's location.

## 3. The DSF envelope

Over the last few decades, as a step forward from the single-skin curtain walls, the application of DSFs in buildings has gained popularity [10]. The double-skin envelope is comprised of three main layers: the interior-façade surface (No.1), the middle-cavity (No.2), and the exterior-skin surface (No.3). DSFs are considered an advanced choice to a building's energy performance in comparison to a single-skin curtain wall, by creating a thermal buffer zone between the interior and the exterior, while maintaining visibility. Studies on the DSF energy performance are increasing, as well as the numbers of DSF built projects. However, there are still no official DSF specifications, or a clear understanding, of the complex nature of airflow and heat transfer in a DSF (Joe *et al.*, 2014; Ahmed *et al.*, 2015; Ghaffarianhoseini *et al.*, 2016). The studies are based on experimental results that validate the simulation results, and vice versa, showing a good agreement between the two, and that the DSF envelope can significantly improve the thermal performance of a building. A vital consideration in this relationship is the adjustment of the DSF to the climatic conditions of its location, i.e., opening / closing of DSF openings (Quesada *et al.*, 2012; Cabeza *et al.*, 2013). DSF research is still ongoing, but with a higher level of confidence on thermal simulations as a research tool.

DSF typologies are classified according to their ventilation strategies: natural, mechanical, or hybrid, and according to the type of air-exchange strategies with the ambient air: “exhaust air”, “supply air”, “static air buffer”, “external air curtain” and “internal air curtain” (Haase, Marques Da Silva and Amato, 2009). A third classification refers to the design of the DSF: “box window”, “shaft-box façade”, “corridor façade”, and “multi-story façade” (Pomponi *et al.*, 2016). However, these classifications are relevant to the design and construction of the DSF, while there are no guidelines on optimum design configuration according to climate, with most DSF built examples relying on a concept design rather than a drive towards energy efficiency (Wood and Salib, 2013). In this research, the adaptability of the DSF is tested for the Mediterranean climate of Tel Aviv. The aim is the reduction of the high cooling loads that are relevant to an office building in a hot climate. The studies focus on different design compositions of a ventilated DSF envelope, as a passive design strategy, for optimum energy efficiency in relation to interior thermal comfort.

When considering a naturally ventilated DSF for high-rise buildings, design strategies like the segmentation of the DSF, i.e., per floor height, become important in order to minimize wind intensities that may be created through buoyancy forces and to generate, thus, a higher level of wind control within the cavity (Etheridge and Ford, 2008). In addition, a corridor DSF avoids large temperature gradients within the cavity, that may be created in a multi storey DSF, and behaves better in relation to acoustical and fire security issues that are relevant in high-rise construction (Hensen, Bartak and Kal, 2002; Poirazis, 2004). The proposed DSF under study for a high-rise reference model is a corridor DSF, where the DSF is segmented per floor level. Two windows are located on the exterior layer No.3, top and bottom, for best performance of the DSF throughout the year. During the hot season, natural ventilation cools passively the structure, reducing the high cooling loads that are prominent in the Mediterranean climate of Tel Aviv.

## 4. Methodology

High-rise buildings are a global phenomenon, whose construction does not relate to the presence of ideal climatic conditions. Thus, it becomes important to break down the design process, and study the behavior and energy saving potential of the elements that make up such a challenging building typology. The focus of this study is on the natural ventilation properties of a DSF for improving energy efficiency, and more specifically for reducing cooling loads relevant to the Mediterranean climate. Results from a previous publication on optimum DSF glazing configurations in the Mediterranean climate (Saroglou *et al.*, 2019) where in favour of a DSF composition with: **low-e double-glazing as exterior surface No.3**, **a 1-meter air cavity No.2**, and **single glazing as interior surface No.1**. This is a deviation from the typical DSF design seen in temperate climates where the low-e glazing is positioned as layer No.1, and the single-clear as layer No.3. An average of 15% reduction was recorded in the proposed DSF design for the Mediterranean climate (Figure 1). Locating the low-e coatings on the exterior façade surface (No.3), increases the insulating performance of the glass, by reflecting the infrared part of the spectrum before entering the DSF zone, while the single clear glazing on the façade surface (No.1) allows for exhausting heat gains, ideal for a hot climate. In addition, the 1m-cavity gap of the DSF allows for sufficient space for cleaning, as dust levels are high in hot dryland environments. In terms of energy performance, a wide cavity has increased air volume, that allows for significant pre-cooling of the air during summer, leading to reductions in cooling demand, mostly appropriate for hot climates (Balocco, 2002; Hamza, 2008; Papadaki, Papantoniou and Kolokotsa, 2014; Saroglou *et al.*, 2020).

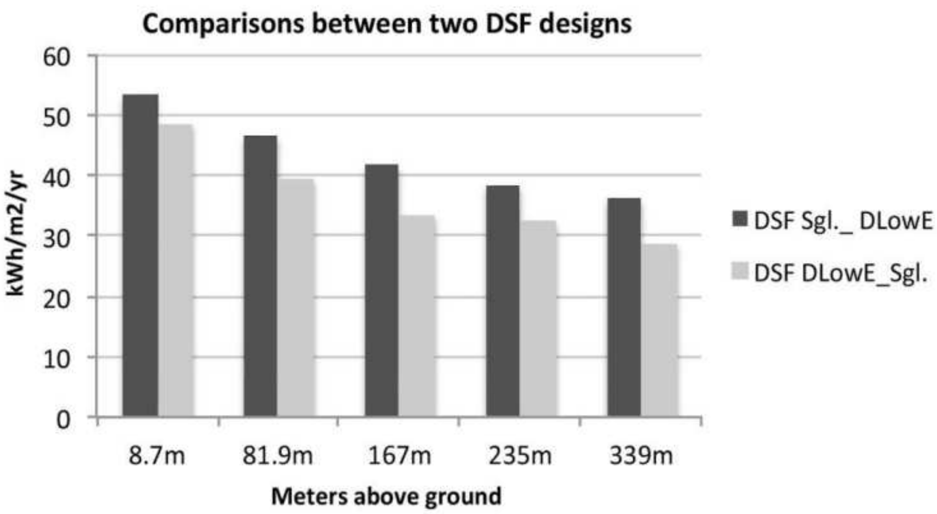


Figure 1. Annual energy load comparisons between 2 DSF designs. Sgl_DLowE: single clear glazing exterior surface No.3 and double low-e interior surface No.1. DLowE_Sgl.: double low-e exterior surface No.3 and single clear interior surface No.1.

The methodology used is thermal simulations using EnergyPlus that includes a variable in its calculations for estimating wind acceleration with height according to ASHRAE ('Airflow around buildings, in: ASHRAE, 2009), and air temperature drop by elevation, appropriate for the simulation of a high-rise building. Natural airflow within the cavity is calculated with the Airflow Network (AFN) method in EnergyPlus, which is a validated process in the depiction of double skin façade behavior (Joe *et al.*, 2013; Chan and Chow, 2014; Mateus, Pinto and Da Graca, 2014; Ancrossed, Signelkovic, Mujan and Dakic, 2016). AFN allows for the annual study of the DSF, while most studies are restricted to short simulation periods representing summer and/or winter conditions (Deuk-Woo and Cheol-Soo, 2011; Ancrossed, Signelkovic, Mujan and Dakic, 2016). Conclusions are drawn in regards to heating and cooling loads, in relation to indoor thermal comfort standards: 20°C for winter, and 26°C for the summer (Fanger, 1970; Givoni, 1981). Natural ventilation occurs through two windows on layer No.3, an air inlet at the bottom, and an air outlet at the top of each floor level of 3.9m (2.7m office space and 1.2m plenum).

Simulations are performed at three floor levels: 8m (ground level), 168m, and 340m above ground. The floor level height characteristics are taken from the database of CTBUH (CTBUH, 2015). The building envelope characteristics [U-values of walls and window-to-floor ratio (WFR)] meet the voluntary Israel Energy Rating of Buildings Standard (SI 5282), which is one of the basic requirements in the Sustainable Construction Standard (SI 5281) in Israel (SII, 2011). These values refer to climatic zone A of Israel's coastal plane with hot and humid climate. The climate is mild with an annual average temperature of approximately 20°C, and a lowest daily average in January of around 13°C. The annual relative humidity average is high, ranging from 60-67%. Annual wind speed values fluctuate between 3-5m/s and have a predominant W and NW orientation. The summer season of Tel Aviv is long, stretching from about mid-March to the end of October. Global solar radiation can be as high as 3.43 $MJ/m^2$ in the summer, and 1.53 $MJ/m^2$ in winter (Figure 2). Tel Aviv's typical meteorological weather file (TMY2), taken from the Beit Dagan Meteorological Service center, located in the periphery of the city, is used in the simulations.

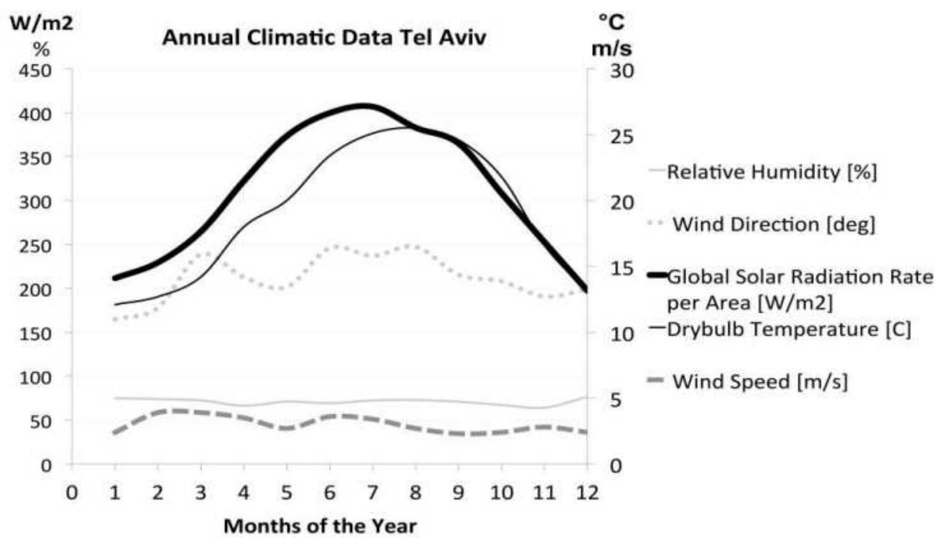


Figure 2. Tel Aviv's annual climatic data

### 4.1 Phase 1

Figure 3 shows the annual heating and cooling loads of the proposed DSF scenario for the Mediterranean climate. The windows located on layer No.3 are closed during the cold season (air buffer / airtight DSF), from November 1 – March 31, and open during the hot season (air buffer / airtight DSF), from April 1 – October 31 (Figure 4). AFN calculates the airflow within the cavity (stack effect and buoyancy), and the heat transfer to and from the thermal zone of the building. The AFN methodology is analyzed in depth in a previous publication (Saroglou *et al.*, 2019). Results of Phase 1 are first published in (Saroglou *et al.*, 2020). The efficiency of the DSF is essentially measured in kWh per month, per thermal zone of $460m^2$. From the comparison between heating vs. cooling loads (Figure 3) it is obvious that cooling loads are much more prominent, while cooling energy is also present during the winter months for an office building in the Mediterranean climate.

Based on the above results, an hourly analysis is conducted on the behavior of the DSF for a summer day, 21 June, and for a winter day, 21 December. Conclusions are drawn on the relationship between three parameters: **building height**, **time of the day**, **seasonal variations** (summer/winter), and **interior thermal comfort**. Results are presented in Figures 5 and 6.

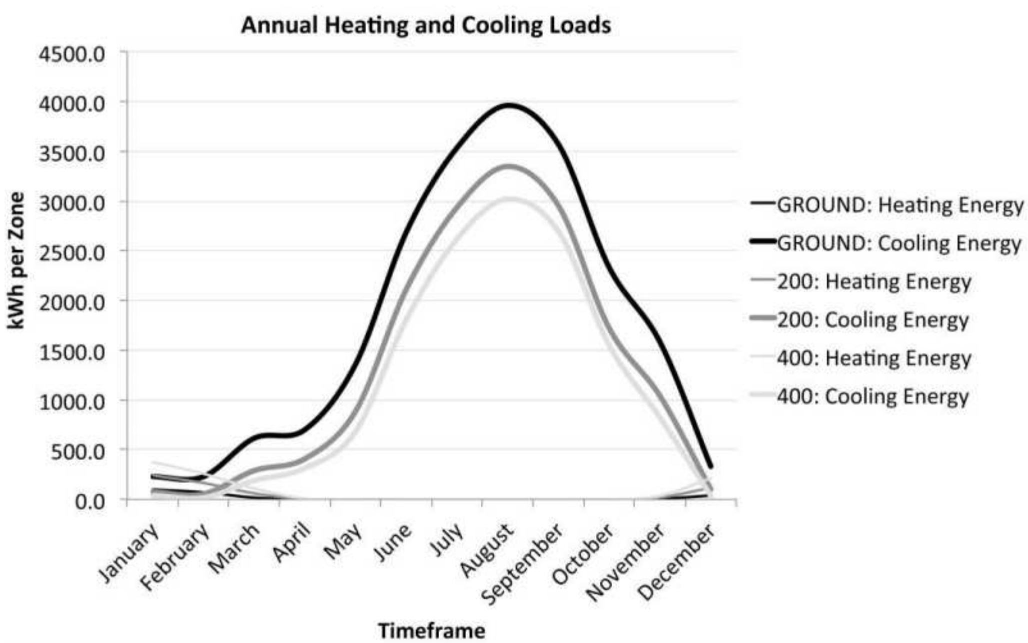


Figure 3. Annual heating and cooling loads of the proposed DSF for the Mediterranean climate, calculated in kWh per zone (460m$^2$).

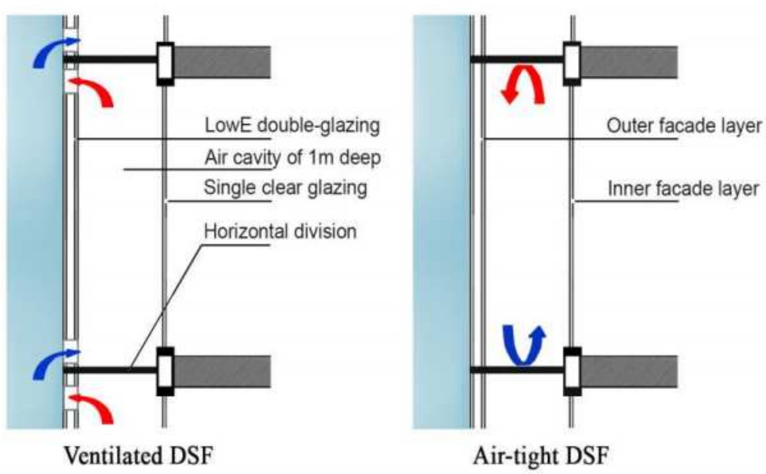


Figure 4. Ventilation strategies of proposed DSF design: **low-e double-glazing as layer No.3**, **1-meter air cavity for layer No.2**, and **single glazing as layer No.1**.

### 4.2 Phase 2

Further simulations are then conducted, with a focus on reducing the cooling loads that are present also during winter. In this case scenario the DSF alternates between an airtight (air-buffer DSF) and an open air (external air-curtain DSF) during the cold season (November 1 – March 31). Based on a study on the air temperatures that are created within the cavity during the 'cold season', the DSF remains closed until 9:30, then alternates between an open/closed DSF until 17:30, and then closes again. In the timeframe between 9:30-17:30, when temperatures rose above 26 °C within the cavity the DSF opens, otherwise it remains closed. During the hot season (April 1 – October 31) the DSF remains constantly open.

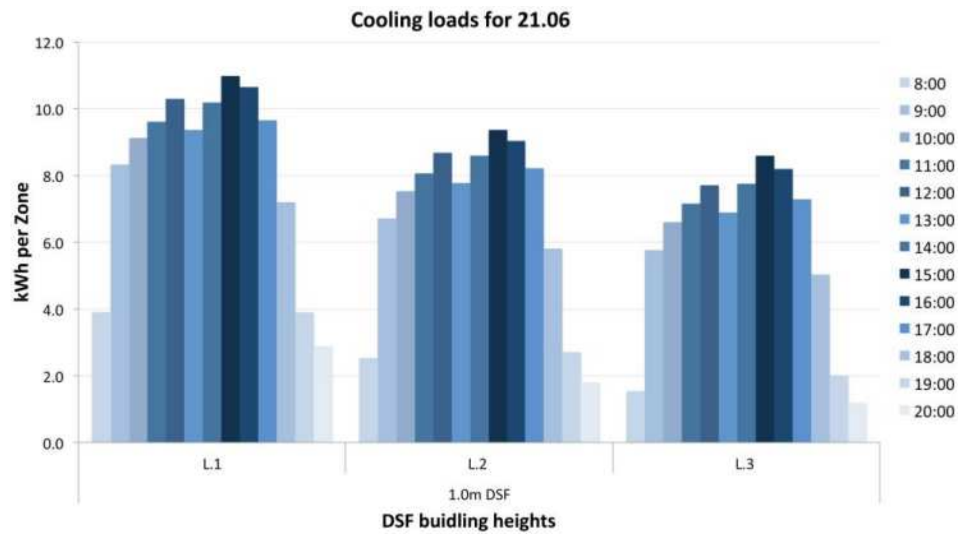


Figure 5. Cooling loads for the 21 June at three building heights: L1= 9m (ground floor), L2= 167m, L3= 339m.

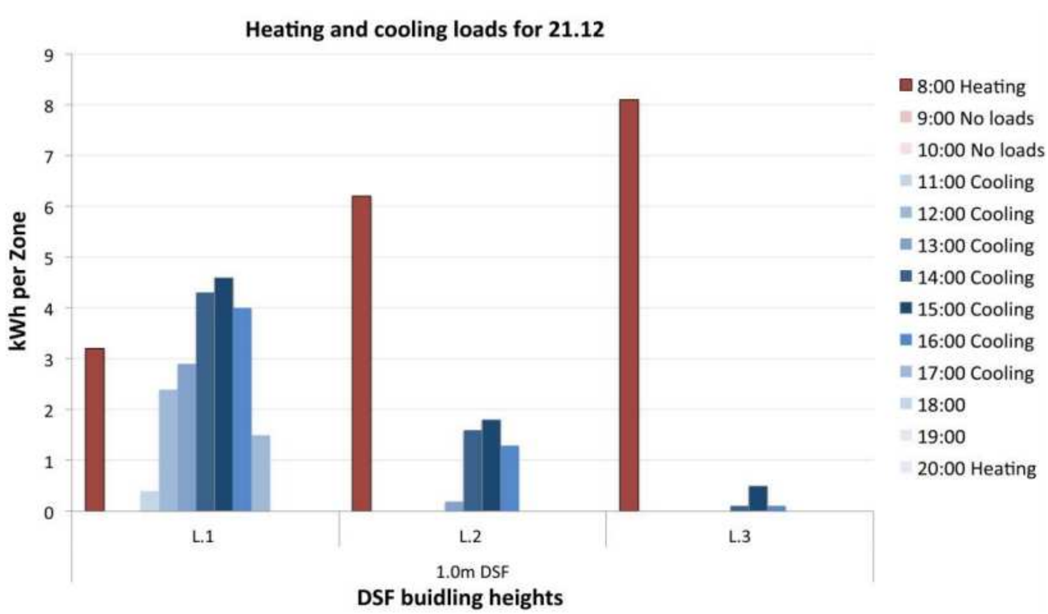


Figure 6. Heating and cooling loads for the 21 December at three building heights: L1= 9m (ground floor), L2= 167m, L3= 339m.

## 5. Results

Figures 5 and 6 show the results of Phase 1. An hourly analysis between 8:00 to 20:00 when the office is operating provided an in-depth understanding between heating versus cooling requirements, for both summer and winter days. Figure 5 depicts the summer day simulations (21 June) and refers to cooling loads, while Figure 6 depicts the winter day simulations (21 December) and is relevant to both heating and cooling loads. From both figures it is obvious that with height cooling energy drops, while in Figure 6 we see that with height heating energy increases. In addition, the relationship between cooling vs. heating loads works in a reverse manner. This means that ground level (9 meters high) has the highest cooling and the lowest heating loads, while when the height increases the opposite occurs. Another observation is that the highest cooling loads for both figures occur from about 10:00 to 17:00, while in Figure 6 heating loads are present only during the morning hours, i.e., mainly around 8:00.

Figure 7 shows the comparisons between heating and cooling loads during the cold season of the two DSF scenarios. Scenario 1 refers to the Phase 1 DSF where the cavity remains closed during the cold season, and scenario 2 refers to the Phase 2 DSF where the cavity alternates between an open/closed DSF from 9:30-17:30 during the cold season. From the graph we see that November has the highest cooling energy loads from all other months and that the reductions that occur between the two scenarios are approximately 50%, while the increases in cooling energy are low. Second in place in terms of cooling loads is March, however, cooling energy is almost 1/3 from November to begin with, and while it drops by 50% in scenario 2, heating energy increases, especially for the top level of approximately 400m high. For all other months, December–January, cooling loads are almost eliminated, however heating energy increases become substantial, with the highest values occurring in January. It is obvious that the increases in heating energy loads escalate with height, and that the highest values occur at the top floor level.

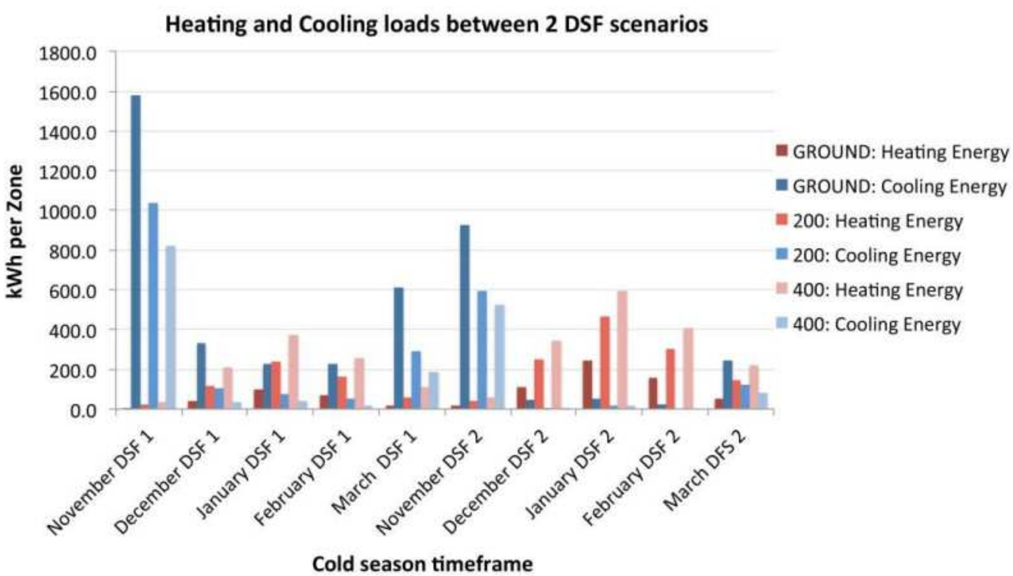


Figure 7. Heating and cooling comparisons between DSF scenarios 1 and 2 during the cold season, from November 1 – March 31.

The above results prompt for further studies on the building envelope towards improving even more the DSF energy efficiency of a high-rise structure. Given the higher increases in heating energy towards the top level thermal zones, further design strategies could include a different handling of the building envelope according to height above ground. This could be especially beneficial during the cold month of February where the heating vs. cooling load reductions are more prominent for scenario 2 at ground level, while higher up heating energy takes over. On the other hand, January does not present substantial reductions in the comparison between scenarios 1 and 2.

## 6. Conclusions

This paper focused on the design of a ventilated DSF envelope towards improving the energy efficiency of a high-rise building in the Mediterranean climate. The ventilation potential of the cavity is seen as an important passive design strategy towards reducing cooling loads, especially prominent in a hot climate. Results from previous research and publications in relation to the optimum design of the DSF for the hot and humid climate of Tel Aviv were used, and studies were conducted on further detailing the building envelope for reducing energy loads even more. The main design consideration was the adjustment of the DSF design to fit the specific climatic conditions of the building's location. An hourly analysis during a winter day, revealed the presence of both heating and cooling loads. The elimination of cooling loads during winter became the focus of these studies, while the results prompt for a dynamic DSF envelope design that alternates between open/closed DSF cavities during the cold season, in relation to: **building height**, **ambient air temperatures**, and **interior thermal comfort**.

The conclusions made in this study point out the importance of detailing of the building envelope in relation to specific climate and microclimate of the building's location during the initial design stages. The focus was on high-rise construction that is becoming a prominent typology around the world, and has to also follow the strict energy efficiency standards like all other new construction and building refurbishments. The conclusions formed in this study, provide information for further studies to be conducted on optimum DSF design for energy efficiency in a high-rise structure in the Mediterranean climate.

It is obvious from these conclusions that achieving thermal comfort in tandem with lowering energy demand in hot humid climates such as the one discussed here is possible, by appropriate detailing and operation of the façades of high-rise buildings. This was shown to be possible even for the inherently energy dependent curtain wall high-rise office buildings. However, it is vital that such studies be carried out for different climatic regions, so that energy conservation will not compromise thermal comfort needs.

## 7. Acknowledgements

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# The Impact of the Tree in the Patio on the building microclimate and the indoor thermal environment, Case of Study south of ALGERIA

**Mohamed Yacine Telli [1] Giridharan Renganathan [2] Richard Watkins [3]**

[1] University of Kent, UK, mt547@kent.ac.uk
[2] University of Kent, UK, g.renganathan@kent.ac.uk
[3] University of Kent, UK, r.watkins@kent.ac.uk

**Abstract:**
The purpose of this study was to investigate the effects of building microclimate on the indoor thermal environment of traditional houses in the south of Algeria, focusing especially on the shading effect of the Palm tree in the patios. The indoor thermal environment was found to follow the outdoor conditions due to the open-plan and, eco-friendly material which has a high thermal mass. Moreover, air temperatures of the living rooms in the two case study houses were lower than the corresponding outdoor ones by approximately 3°C and 10°C, respectively. It was found that the semi-outdoor spaces acted as thermal buffers for promoting cross-ventilation as well as pre-cooling to provide “warm but breezy” conditions to the surrounding indoor spaces. The results showed that the surface temperature of semi-outdoor spaces can be reduced by shading, among which shading has prolonged effects and can reduce the surface temperature during peak hours and the following night.

**Keywords:** Ghardaia, Patios, Trees, indoor cooling, thermal comfort

## 1 Introduction:

Ghardaia is located in the centre of the northern part of the Algerian desert. It is situated 600 km south of the capital Algiers at latitude 32° North and longitude 2°30’ East. The climate of the Ghardaia city is a hot desert climate characterised by summers with torrid heat reaching 50°C and soft winters with the average minimum just above freezing point. Relative humidity is very low except for the winter months where 60% is common (Tidourt, Mayer,2005). Precipitation is low and less than 25 mm/month throughout the year. The thermal comfort zone (TCZ) for the hot and arid climate of Algeria is according to ASHRAE 55-2015 standards 18°C < T < 30°C . Figure 1 presents the average yearly sum of global horizontal irradiation covering a period of 16 years.

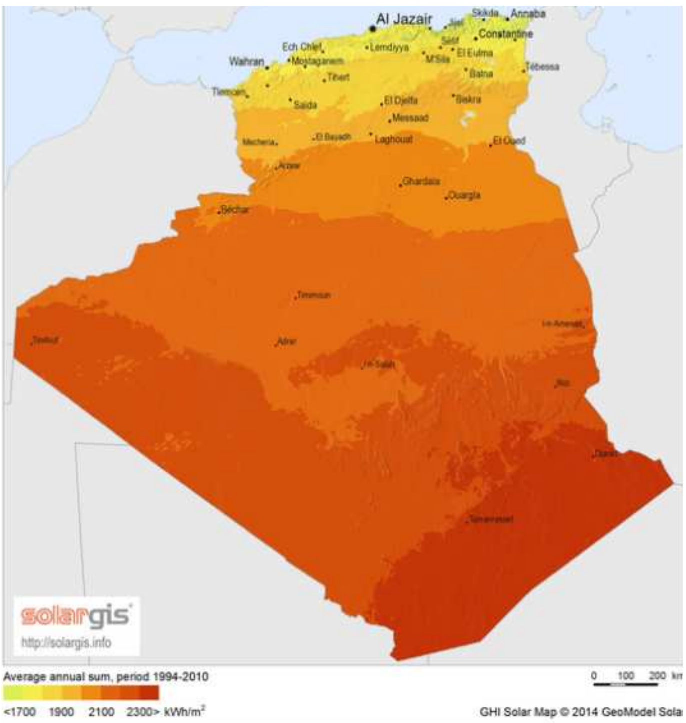


Figure 1. Total annual Irradiance, (1994-2010), kWh/m$^2$
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In the hot dry climate of Ghardaia, a vernacular building design can be used as a starting point to realise how the environmental stresses and climatic hazards influence the architectural elements of the home and how the buildings can be more responsive. However, in Algeria building regulations did not consider the climatic design issue that conditions should follow. There is also a lack of knowledge between the authority, architects, contractors, and residents to improve indoor thermal performance (Djenane, 1998). Accordingly, the key objective of this study is to consider the influence of climate on the architectural elements and to determine passive strategies that can produce comfortable indoor spaces to enhance people's living standards and future well-being. In brief, the field studies identified these facts which then led to the use of building thermal simulation that focused on how the internal performance of buildings can be enhanced for comfortable living and for providing good satisfaction by passive cooling techniques. Ghardaia was selected because it has traditional, eco-friendly and new concrete-based houses (Nikolopoulou et al, 2001).

This research aimed to investigate the thermal performances of two traditional houses considering the effect of the palm tree in the patio, with contemporary designs, on the indoor temperature of the surrounding rooms in the context of the summer season. Another objective was to assess if these houses required any improvements to be made as a good model for future construction in Algerian desert cities.

## 2 Research methodology:

To understand the impact of the tree in the patio and the thermal performances of the various houses of the Ksour (settlements built on rocky mountain peaks; see Figure 2), which overhang the valley, the methods undertaken in this study were the buildings' measurement survey and the climatic data monitoring. The building survey was pertinent to this study to get similar physical and climatic parameters for consistency of the collected data and results, at the same time and the same location. Two houses were selected due to their differing house types (designated H1 and H2) as required for this study and from the same location. The first is H1 without a palm tree inside the patio; the second a typical H2 (same location) with a palm tree inside the patio. The two houses were selected, and physical measurements were taken and drawn on ArchiCAD and VI-SUITE. The environmental parameters used for the analysis were indoor air temperature, relative humidity and the outdoor air temperature. The readings were taken during the summer from 6-14$^{th}$ August 2018. Measuring instruments and devices included Onset Hobo data loggers to measure

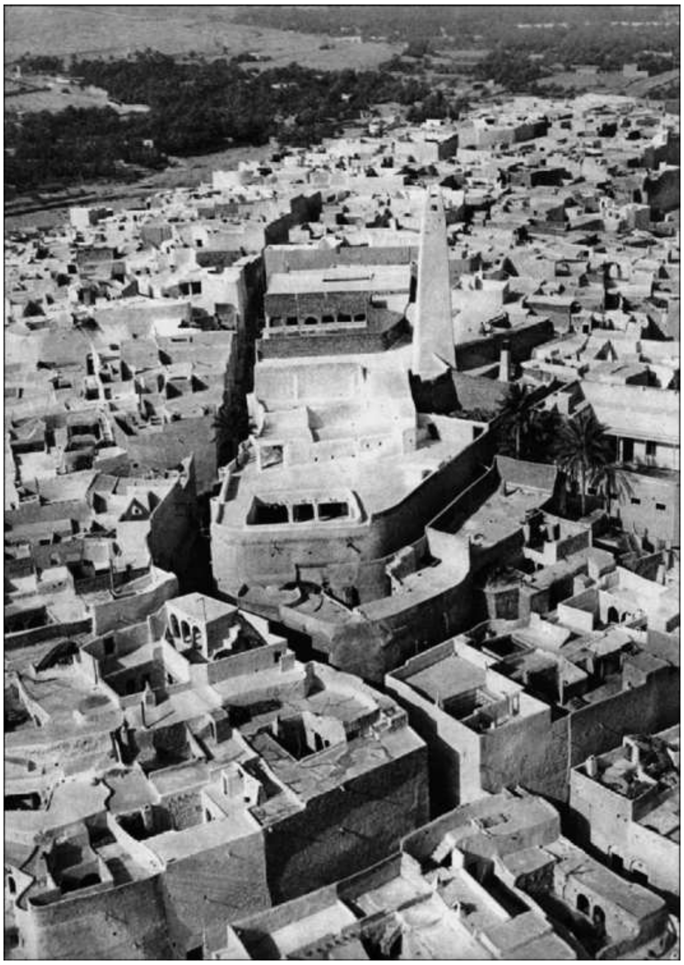


Figure 2. A view of the compact urban fabric of the upper part of the old city of Beni-Izguen (Roche 1973)

relative humidity and air temperature every 15 minutes. The external logger was housed in a radiation shield.

## 3 Building descriptions:

The urban structure reveals the distinctive influence of the climatic conditions, which are just as important as the cultural dimension. The medium height houses are inward-facing buildings allowing extreme compactness of the urban fabric (Figure 3).


Figure 3. The old city of Beni-Isguen, Mzab valley, Algeria


Figure 4. Timchent


Figure 5. Stone vault with Timchent and trunks of Palm

Only the rooftops and a few façades are exposed to the intense solar radiation. The streets are very narrow and shaded by the neighbouring walls, in some places also covered or further protected from the sun with trellis, cloth and awnings. The placement of the house design further controls radiant heat and glare using the superimposed patios. The patio is the main source of light as the outside façades generally are windowless. At ground level, there is a skylight that can be covered with a lattice screen. This level and underground spaces are refuges during the hottest time of the day. Moreover, the walls made of stone and gypsum together with their whitewashed coloured surfaces further prevent daytime summer overheating. Even if these houses were built to cope primarily with very hot and long summers, the winter conditions are improved with the southern orientation of the semi-outdoor living spaces on the terraces (galleries) and by taking advantage of the heat storage capacity of the buildings (Ravérau, 1981). Air movement occurs through small openings in the walls, and doors are left open most of the time. Thermal differences between the cool street, the house and the warm terrace may promote indoor ventilation. Even though the urban fabric and the building envelope are the main climatic filters, the people of these cities also show adaptation to the severe thermal regime by employing a 'nomadic' way of living in their houses.

### 3.1 Traditional house (H1): (Patio without tree)

The H1 was constructed in 1870 and located in Ksar Beni Isguen approximately 15 m from the H2. The layout of the building is similar to the closely packed H2. This house has a 120 m$^2$ plot area and 11 m$^2$ Patio and was constructed using 500 mm thick stone external walls in the basement level (Figure 6). A hard quick-drying plaster (timchent), local limestone/gypsum which is heated to produce plaster, was used for making the building blocks. The external rendering of buildings is still applied in the traditional way with palm branches, giving an energetic surface texture to the wall. The woodwork was limited to the ingenious use of palm; large planks were sawn from the trunks for doors and shutters, branches cut in two as initial support for vaulted roofs, and the nervure bent and tied to form permanent centring for arches. (Figures 4,5).

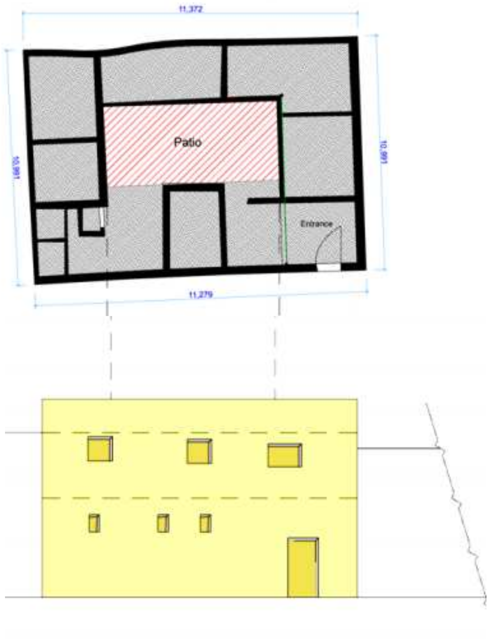



Figure 6. H1 patio without Palm tree

### 3.2. Traditional house (H2): (Patio with tree)

The H2 was also constructed around 1830 and located in Ksar Beni Isguen with a plot area of 112 m$^2$ and patio of 12 m$^2$. The construction materials used were the same as H1: (Figure 7), with stone exterior walls 400 mm thick and constructional details the same for both buildings. In order to protect the walls from direct sunlight, they used a palm tree in this example The tree has a diameter of 3 metres and a height of 7 metres and it covers an area of 30 m$^2$ and it occupies 20 % of the house surface, and thus all the patio is covered by the palm tree leaf around the day.

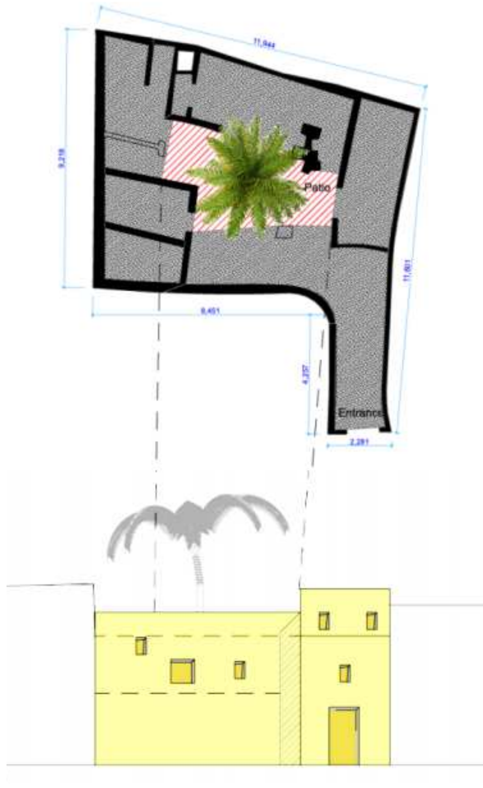



Figure 7. H2 patio with Palm tree

### 4 Results and Discussion:

Data loggers were located at five different locations in the houses. This paper discusses those situated in the living, kitchen and patio areas only. In both houses, only the kitchen walls were next to the outdoors. The other walls of the houses were attached to neighbouring buildings.

**4.1 Physical measurements for H1:**Over the one-week monitoring campaign, the recorded measurements from the outdoor data logger show that the mean daily temperatures ranged from 32.2°C to 38.4°C. The Patio's temperature variation was found to be notable; the temperature varied very little (2-3K) through the week (35°C on average). Meanwhile, the data reveal that the relative humidity (RH) ranged from 15% (or even lower as the limit of the sensor had been reached) to 35%.

(see Figure 8).

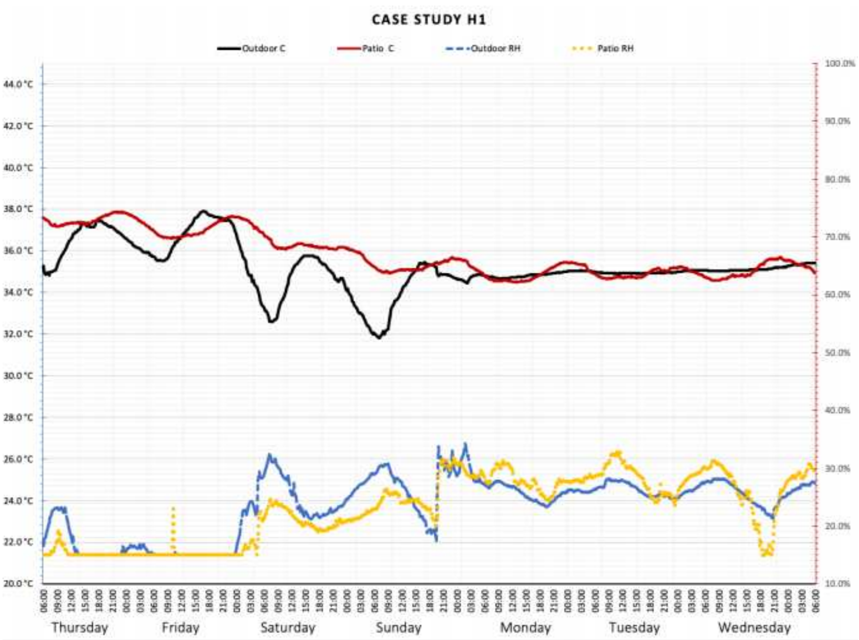



Figure 8. Measured external and Patio dry-bulb temperature and RH for H1.

Looking more closely at Figure 8, the patio air temperature fluctuates much less than the external air temperature in the first three days. After this the external temperature varied little but was generally 1-2°C higher than the patio air temperature. For house H1, the excessive heat gains through the non-insulated exposed roof, together with the unavailability of an air conditioner and/or an evaporative cooler, and the lack of openings facing the street for social reasons and also to avoid dust getting inside the space, all openings are into the patio and result in a hotter and relatively drier, indoor environment there. In particular, the impact of the poor building envelope and its failure in

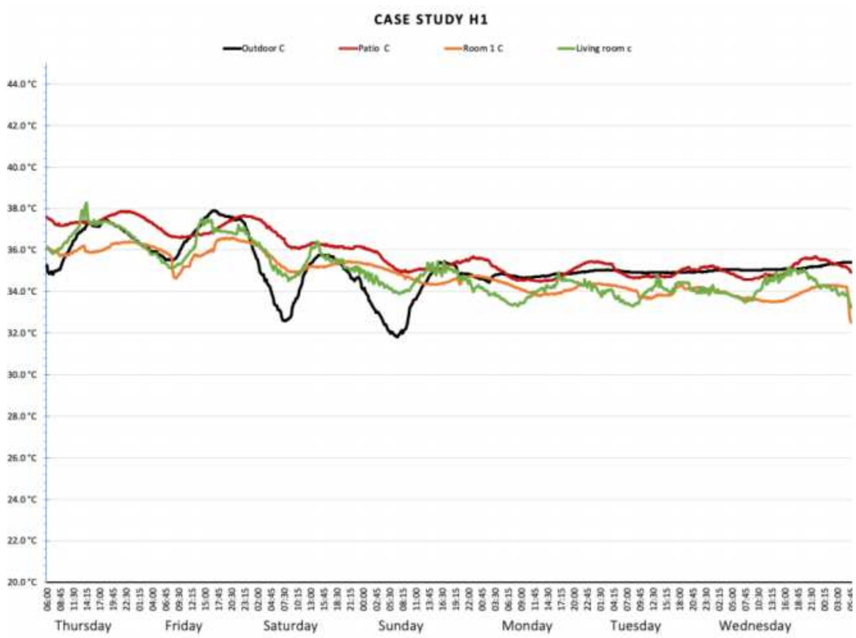



Figure 9. Measured indoor and outdoor dry-bulb temperatures for the period (August 6th to August 14th) for H1

delaying the heat transfer is evident in numerical data analysis showing a notable correlation between internal and external temperatures, particularly in the bedrooms, patio, and the outdoors Interestingly (see Figure 9).

The relative humidity (RH) in the two spaces (Patio and External) was generally between 35% and 15%, i.e. both are very dry environments and uncomfortable because of their effect on the mucous membranes of the residents.

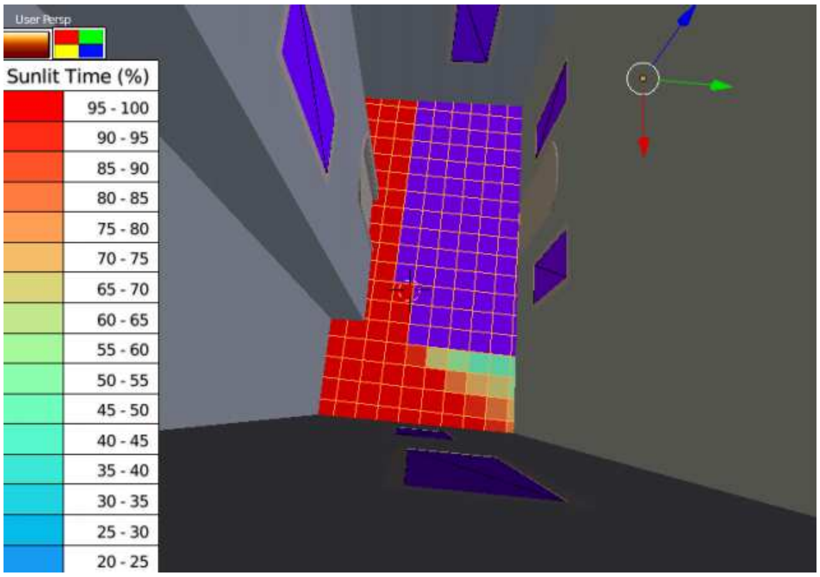



Fig. 10. Shadow Mapping analysis for the patio H1 for one day

Figure 10 shows shadow mapping analysis for the patio of H1. The sun strikes surfaces on the ground and heats them up; 80% of the patio is exposed to the sun during the day. These surfaces start interacting with the air layer above them and exchange heat and energy. The extent of this exchange is dependent on the physical properties of the surface being irradiated. Patio and building roofs become 27-39°C hotter than the ambient temperature. (Asaeda 1996). The fabric heats up during the day but it releases the heat during the night. Desert climates worldwide are known to have a significantly large diurnal temperature range resulting in cold nights even in the summer, as the stored heat in the roofs and floors is all radiated back to the clear desert sky (Olgyay 1963).

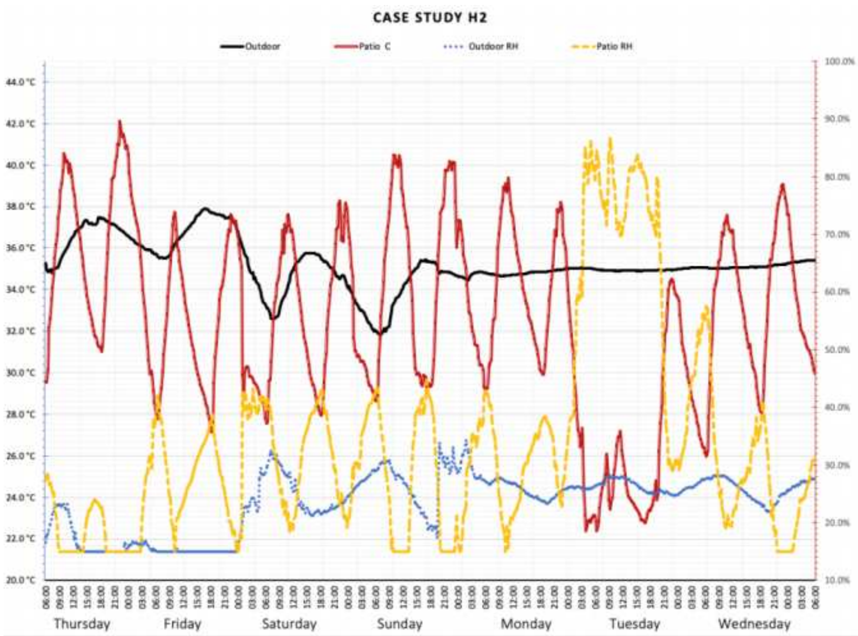
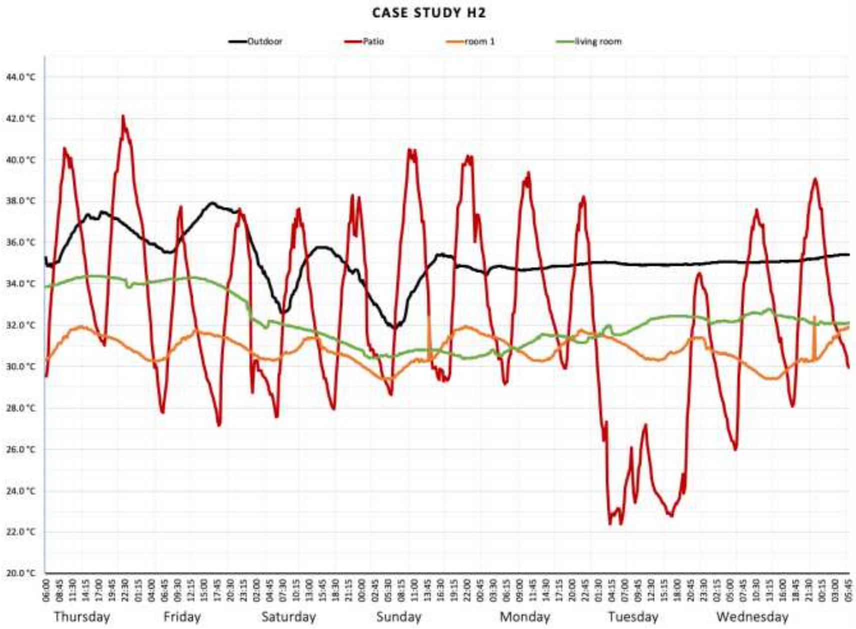



Figure 9. Measured indoor and outdoor dry-bulb temperatures for the period (August 6th to August 14th) for H2

## 4.2 Physical measurements for H2




Over the one week of monitoring, whilst the outdoor data logger shows that the mean daily temperatures ranged from 32.2°C to 38°C, the diurnal temperature variation in the patio was found to be 15K on average), starting from 25°C early in the day until late at night reaching 42°C. Meanwhile, the data reveal that RH ranged from 15% to 27% outdoors (see Figure 11), compared to the patio which has the RH range from 15% to over 80%

Figure 12. Measured indoor and outdoor dry-bulb temperatures for the period (August 6th to August 14th) for H2

Trees affect our climate, and therefore our weather, in three major ways: they lower temperatures, reduce energy usage and reduce or remove air pollutants. Figure 12 describes the temperature difference in the same house showing the impact of the patio in the house and how it can induce airflow due to a pressure difference from the cool to the hot courtyard. In the hot-dry regions, there is a large diurnal temperature swing and the air temperature drops greatly during the night-time especially in the patio. Consequently, the semi-outdoor spaces act as a cooling source to the adjacent spaces. As spatial strategies of climate integration, the traditional house develops concepts worthy of a referential repertoire for the sustainable architecture which associates comfort and respect of the environment. Figure 13 shows that the patio is 100% shaded during the whole day.

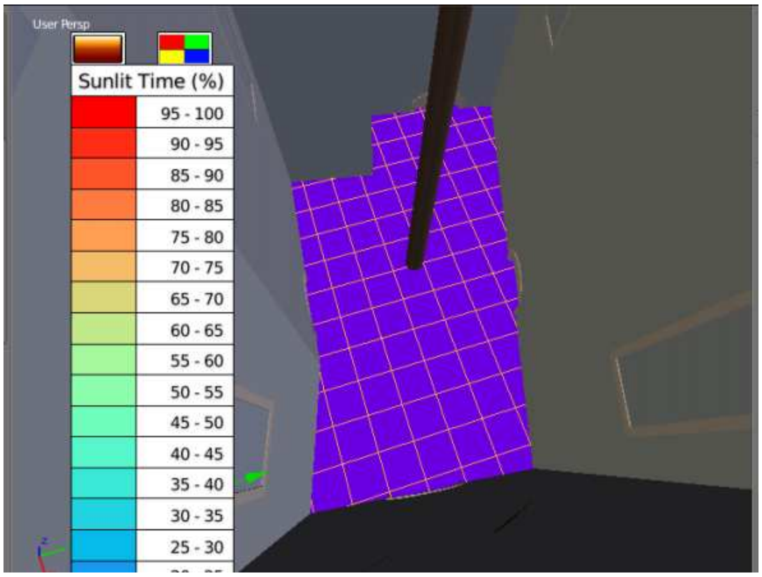



Figure. 13. Shadow Mapping analysis for the patio H2 for one day

The palm tree inside the patio promotes the air temperature reduction because it blocks sunlight, and hence it increases the coolness and reduces the energy consumption. The evaporation of water from the surface of the leaves of the tree helps reduce the air temperature, and so the tree acts as a natural air conditioner. Trees thus help to conserve energy and are to be encouraged as the residents in the south of Algeria usually have issues with the high cost of air conditioners and the intermittency of electricity during the day peak (12:00-16:00) in the summer season.

## 5.Conclusion:

The effect of the palm tree in the patio was investigated during this study and it was concluded that the urban tree plays a major role in shading the surfaces and decreasing their surface temperature and heat gain compared with the exposed surfaces. As indicated house 2 has a cooling effect compared with house 1. In addition, it has positive effects on the microclimate: it can lower the outdoor temperature and surrounding air which is usually saturated with humidity, and reduce an energy consumption. In these conditions, the tree inside the courtyard owes its survival to its suitability to the climate which in turn reduces fuel use and makes pollution control easier because it reduces energy consumption. Future research might investigate the old building with reference to new buildings which can help the architects and urban designers to learn from the past to develop our future building design.

## 6.References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# Indirect Evaporative Cooling Strategies Applied in Experimental Modules for Promoting Resilient Cooling in Hot Humid Climates

**José Roberto García Chávez[1], Anaís Carrillo[2], Karina García[3]**

[1] Universidad Autónoma Metropolitana-Azcapotzalco, CyAD, Medio Ambiente, Posgrado en Diseño Bioclimático. Ciudad de México, México. e-mail: joserobertogsol@gmail.com;
[2] Posgrado en Diseño Bioclimático. UAM Azcapotzalco. CyAD. Av. San Pablo 180. Ciudad de México. México. e-mail: doc.anasalas@gmail.com;
[3] Escuela Técnica Superior de Arquitectura de Sevilla Universidad de Sevilla, Avda. de la Reina Mercedes, 2 Sevilla, Andalucía, España. e-mail: gkarinap9@gmail.com

**Abstract**
The increase of ambient temperatures due to effects of the Global Warming (GW) and the Climate Change (CC) have provoked an accelerated use of air conditioning (AC) in buildings. A promising alternative to mitigate this problem is the application of passive cooling, which can contribute to reducing energy consumption whilst providing hygrothermal comfort for the building´s occupants. In the case of buildings located in hot humid regions, the commonly applied approach is to use indirect evaporative cooling, integrated with other passive cooling techniques, to enhance and provide a better performance. This research presents the results of an investigation carried out in experimental modules in the city of Mérida, Yucatán, Mexico, a representative hot humid climate. The thermal performance of five indirect evaporative passive cooling systems complemented by other passive cooling technique was evaluated, relative to a control module. These modules integrated the experimental systems on their rooftop covers. The results showed that the most promising cooling system investigated was the one that integrated indirect evaporative cooling, with thermal mass, solar protection and night radiative cooling techniques, demonstrating a mean temperature reduction of 5.7 K relative to the mean exterior temperature and a reduction of 8.1 K of the maximum temperature inside the module relative to the maximum exterior temperature.

**Keywords:** Indirect evaporative cooling, experimental modules, resilient cooling, hot humid climate.

## 1. Introduction. Global energy consumption and temperature increase

At present, global energy consumption, which mostly come from fossil fuels, has increased considerably, causing an increase of temperature in the earth's surface during the Period 1880 to 2019 (Figure 1), (NASA, 2019). Historical statistics, of energy consumption worldwide since 1830, shortly after the rise of the Industrial Revolution, to 2018 (NASA, 2019), indicate that, to supply the required goods and services, anthropogenic activities resulted in the burning of ten times more energy than in the previous century. Of the total energy consumed in 2018, 80% came from fossil fuels, 11.3% from bioenergy, mainly from wood and firewood combustion, 5.5% from nuclear energy, 2.2% from hydraulic energy and only 0.4% of other renewable energy sources. Recent energy consumption statistics (REN21, 2019) showed a reduction of that from fossil fuels of 79.7% and an increase of the renewable share relative to 2018 (Figure 2). Renewable energies accounted for an estimated 18.1% of Total Final Energy Consumption (TFEC).

Certainly, the intensive use and burning of the fossil fuels due to anthropogenic activities, have affected intensively and extensively various ecosystems of the planet.

Updated data in real time indicate that the temperature increases from 1880 to 2019 have been evident and constant (NASA, 2019) (Figure 3).

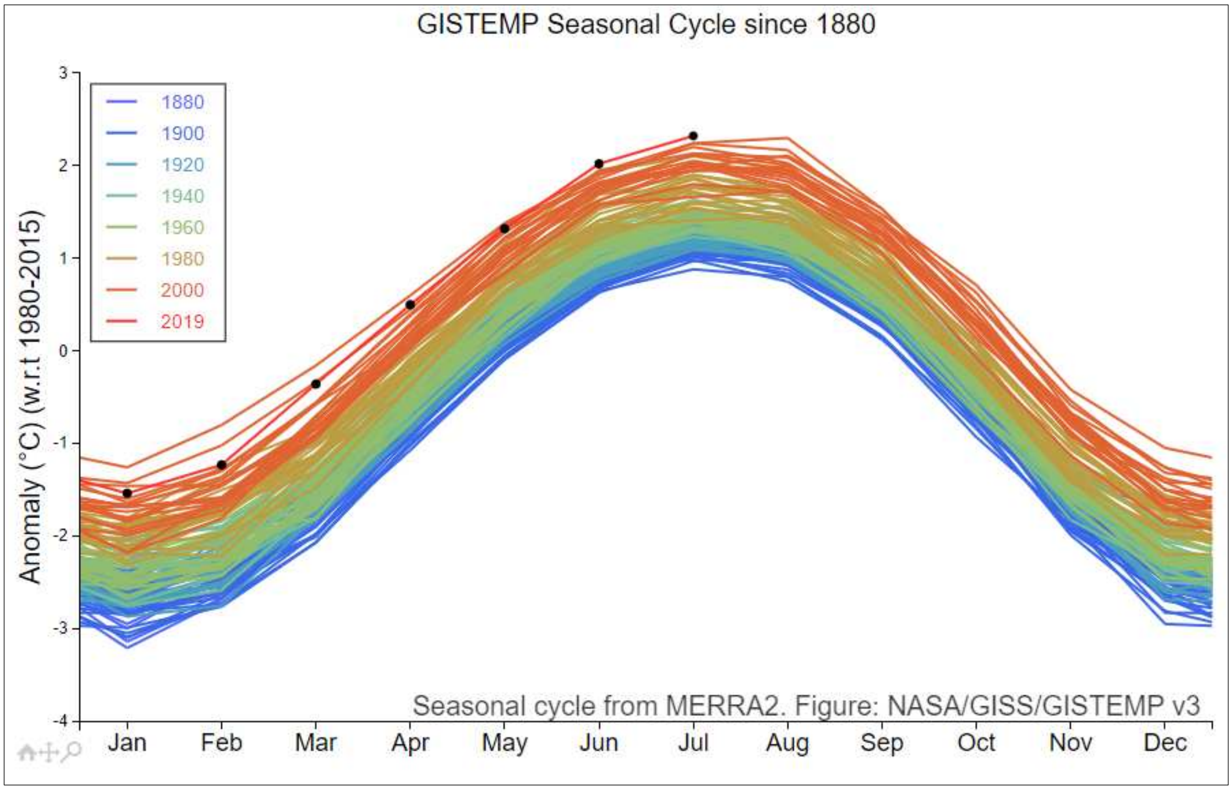



**Figure 1.** Seasonal cycle of temperature variation in the earth's surface during the Period 1880 to 2019. Source: NASA 2019. Merra2. NASA / GISSTEMP Oct, 2019

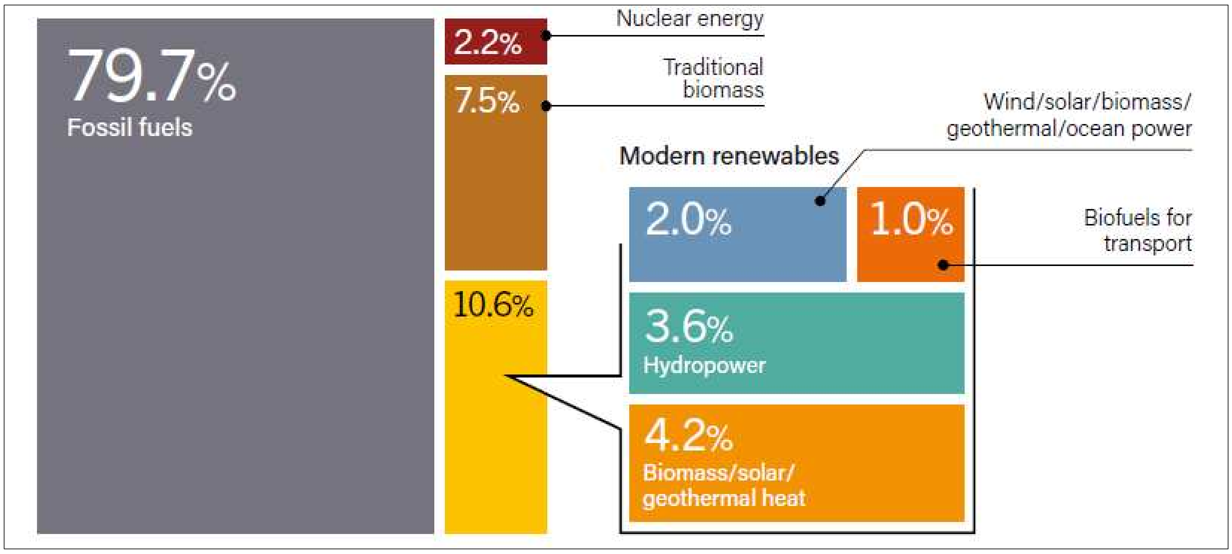



**Figure 2.** Global Total Final Energy Consumption, 2018.
Source: OECD/IEA and IEA SHC

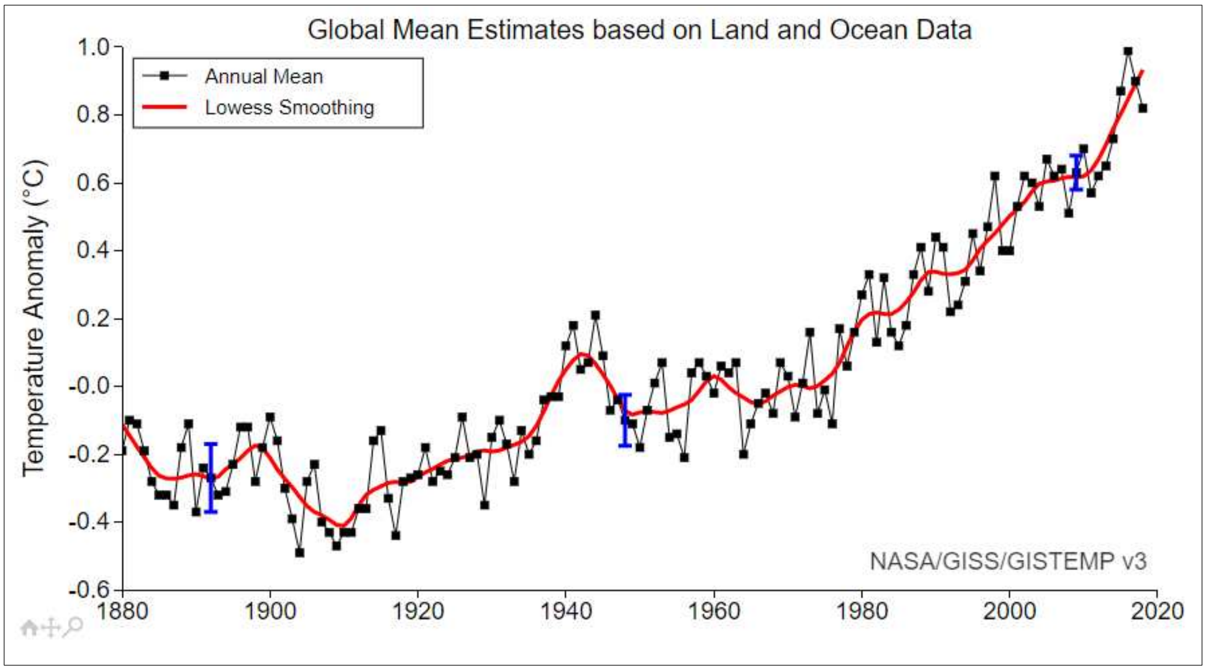



**Figure 3**. Global Mean Estimates of Land and Ocean Data. Period 1880 to 2019.
Source: NASA 2019. Merra2. NASA / GISSTEMP Oct, 2019

## 2. The State of Energy Consumption for Space Cooling in Buildings

The increase in Global Warming (GW) and the exacerbation of Climate Change (CC) at global level is directly mirrored by the exponential progression in the use of air conditioning systems in buildings and shows a fast increase, particularly in urban locations. Another important aspect in the amount of energy used, is that close to 80% comes from the highly polluting fossil fuels (Figure 4).

The utilization of energy for space cooling is increasing faster that any other end use in buildings (IEA, 2018). Currently, the use of air conditioning systems represents almost 20% of the total electricity used in buildings worldwide and 10% of all world electricity consumption (IEA2, 2018). This trend will increase due to factors such as increases in the standards of living in the growing global populations, and there is evidence to show that this rate of increase is noticeably higher in hot regions, as well as in mild climates during the overheating season. Therefore, the use of heating, ventilation and air-conditioning equipment (HVAC) will increase enormously, becoming one of the main factors of global electricity demand and the consequent high emission of pollutants in the form of greenhouse gasses (GHG) to the atmosphere and the eventual climate deterioration.

In countries such as the United States and Japan, more than 90% of households have HVAC systems, compared to only 8% of the 2.8 billion people living in the poor countries with the hottest regions of the world (IEA2, 2018).

The total use of electricity for HVAC worldwide increased to 2,000 TWh in 2016, which corresponds to almost 10% of the 21,000 TWh of electricity consumed worldwide in all sectors.

Therefore, it is especially necessary to develop solutions to the problems provoked by the intense and growing use of air conditioning. A key first step is to improve system energy efficiency, to reducing the need to build new power plants as well as to reduce GHG emissions and mitigate the effects of Climate Change globally.

This approach may contribute in a sustainable way to achieve economic benefits and indoor comfort conditions for building´s occupants and most importantly, can lead to improve their quality of living and health. However, this is not enough. The use of air conditioning systems is, the fastest-growing user of energy in buildings is for space cooling, mainly in building located in both hot humid and hot dry regions where incomes and temperatures are escalating, as well as in the advanced industrialised economies, where there are high consumer expectations of thermal comfort.

Total energy use for space cooling in residential and commercial buildings worldwide more than triplicated between 1990 and 2016 to reach 2,020 TeraWatt hours (TWh) (IEA2, 2018) (Figure 4). The share of cooling in total energy use in buildings rose from about 2.5% to 6% over the same period. For commercial buildings, the share reached 11.5% in 2016, up from 6% in 1990. Cooling accounted for 18.5% of total electricity use in buildings, up from 13% in 1990 (Figure 4).

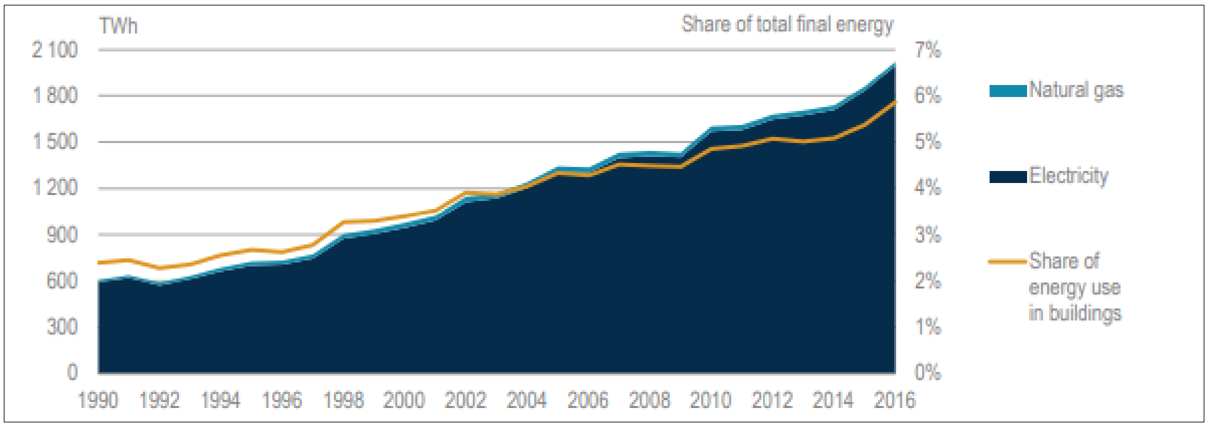



**Figure 4**. World Energy Consumption for the Cooling of Spaces in Buildings
Source: IEA2, 2018.https: //www.iea.org/publications/freepublications/publication/The Future of Cooling

Considering the current worldwide energy consumption and the consequences of the severe environmental deterioration, it is urgent to implement alternative solutions to solve this problematic. A promising alternative to mitigate this situation, particularly in hot climates and under overheating conditions, is to improve the efficiency of the HVAC systems, as well as with the application of passive cooling techniques, and mainly in hot humid conditions the implementation of Indirect Evaporative Passive Cooling Systems (IEPCS). This is an encouraging approach, which can contribute to reduce the high consumption of electricity, and at the same time provide hygrothermal comfort conditions for the building occupant´s and reduce the emission of GHG whilst mitigating the CC, and thus contribute to the preservation and improvement of the environment in the planet.

## 3. Evaluation and Characterization of Indirect Evaporative Cooling Techniques Applied in Experimental Modules

The experimental arrangement of this work was located north of the City of Merida, which is located 50 km from the Gulf of Mexico in the north-western part of the State of Yucatán and at a distance of 1557 km from Mexico City (Figures 5, 6 and 7).


**Figure 5.** Geographical site location
Source: Google Earth, 2019

**Figure 6**. City Location


**Figure 7**. Location of the experimental site within the urban area of the City of Merida.
Source: Google Earth, 2019

It has an average annual temperature of 26.7 °C, registering an average minimum of 21°C, and an average maximum of 33.5 °C.

The hottest period is from March to August and the average annual rainfall is 1,036.9 mm, where the rainy season takes place from June to October with an average annual relative humidity of 71.48%, therefore its climate conditions corresponds to the classification of warm-humid. The main objective of this research was to evaluate and characterize different IEPCS, complemented with other passive cooling techniques in experimental modules, in their rooftop cover, aimed at achieving both thermal comfort conditions in buildings in hot-humid climates of Mexico and energy savings.

The methodology consisted of the characterization of IEPCS through the monitoring of the hygrothermal conditions inside five experimental modules compared with a control module (Figures 8a, 8b and 8c). These modules integrated different systems on its rooftop cover: Indirect evaporative cooling and solar protection (IEC + SP); thermal mass and thermal insulation (TM + TI); night radiative cooling and thermal mass (NRC + TM); indirect evaporative cooling, thermal mass and solar protection (IEC + TM + SP), and indirect evaporative cooling, thermal mass, solar protection and night radiative cooling (IEC + TM + SP + NRC). The monitoring was carried out concurrently for 30 consecutive days during the prevailing overheating period.

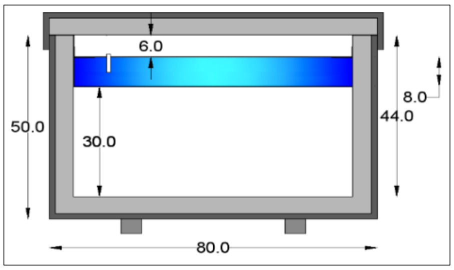



**Figure 8a**. Geometry and characteristics of control module (section)

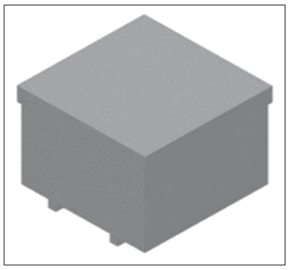


**Figure 8b**. Control module (isometric)

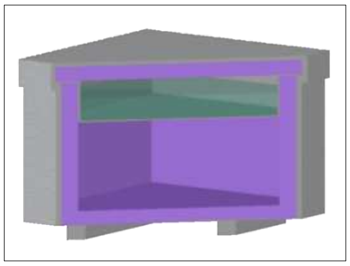


**Figure 8c**. Control module (section, component view)

The modules were built with an hexahedral geometry of 0.8 meters long x 0.8 meters wide and 0.47 meters high, with 0.015 cm thick plywood structure, covered inside by a foamular ® plate of 0.045 meters as thermal insulation, to allow adiabatic conditions.

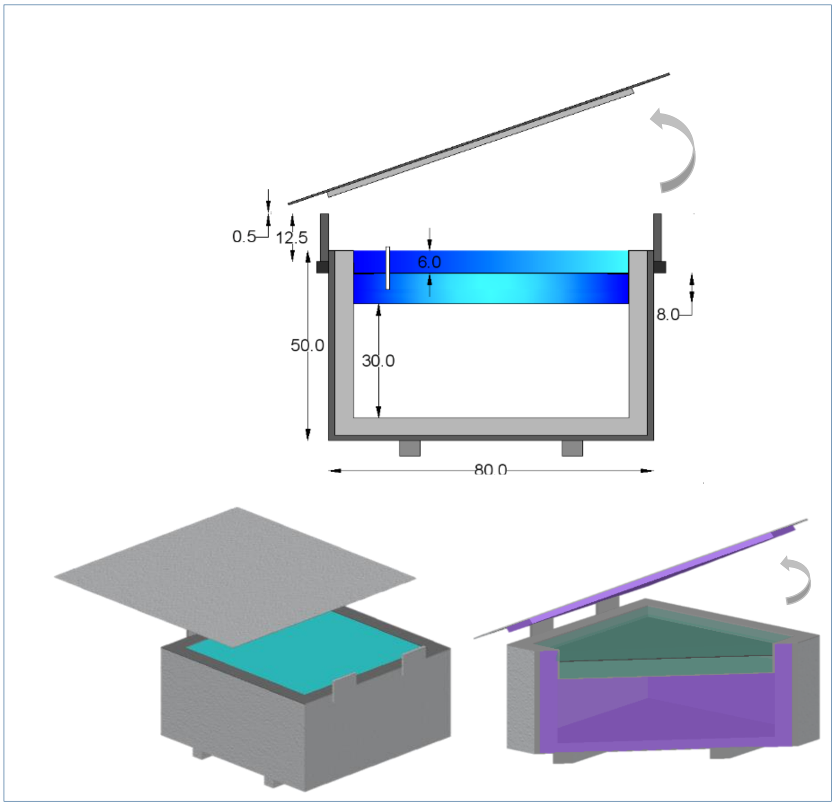
This material is a thermal insulation made of rigid polystyrene foam with a thermal conductivity value (K) for an average external temperature of 24 °C, its value is: 0.0288 W/mK; for an average outdoor temperature of 4.4 °C, its value is: 0.0259 W/mK. It was selected for its high resistance to humidity and steam, it is hydrophobic, that is, water repellent and due to its exclusive structure of closed cells, it does not allow spaces through which water leaks, therefore, it does not produce condensation. The exterior was provided with a layer of sealer for wood, to prevent weathering of the material exposed to the sun and rain; and lastly, coated with white epoxy paint.

The base of the modules consists of two wooden bars of dimensions 3 "X 1.5" X 8.¼ ', to separate the six modules from the floor and to prevent heat gains (Figures 9 and 10).

In the procedure of modules where the NRC system was implemented, a variant was included, with respect to the other modules, which consisted of removing the rooftop cover at 18:00 hrs and place it again at 6:00 am period (Figures 11 a, b and c).

**Figure 9**. Module and data loggers locations

**Figure 10.** Experimental arrangement with during data monitoring of IEPCS complemented passive cooling techniques




**Figures 11 a, b and c**. Experimental module with the implementation of passive cooling systems: NRC + IEC + TM + SC. Night mode: Rooftop cover removed from 6:00 p.m. to 6:00 p.m. the next day. Day mode: Place rooftop cover from 6:00 a.m. to 6:00 p.m. on the same day

Subsequently, the calibration process and the climate analysis of the location, a simultaneous monitoring of indoor dry bulb temperatures (DBT) was carried out in the modules concurrently for 30 consecutive days during a typical overheating period. During the monitoring, the climatic values of the exterior were obtained concurrently, through the nearest EMA (Automated Meteorological Station).

## 4. Analysis and Interpretation of Results

Throughout the monitoring period, values of DBT and relative humidity were recorded at ten minutes interval during a typical overheating period in May, when the average exterior temperatures varies from 27 °C and 38 °C. The values obtained were ordered and averaged over a 24-hour cycle. Results indicated that the average temperatures inside the modules decreased with respect to the mean and maximum external temperatures of the Automated Meteorological Station on the location (EMA). The results showed that the most promising cooling system investigated was the one that integrated indirect evaporative cooling, thermal mass, solar protection and night radiative cooling techniques, that showed a mean temperature reduction of 5.7 K relative to the mean exterior temperature and a reduction of 8.1 K of the maximum temperature inside the module relative to the maximum exterior temperature (Figure 12).

An additional passive cooling technique was implemented in the most promising system, using a Phase Change Material (PCM) on the rooftop cover by substituting the thermal mass of the water with a polycarbonate shell that encapsulated an organic element called *cocus nucifera*, an organic PCM, embedded in a polycarbonate plate placed at the cover of the experimental module, aimed at minimizing the energy use for space cooling (Module M5). This material utilizes the temperature difference between day and night for the storage and release of thermal energy. The results with this passive cooling strategy presented an additional temperature reduction of 8.1K of the maximum temperature in the module, relative to the maximum external temperature (Figure 12).

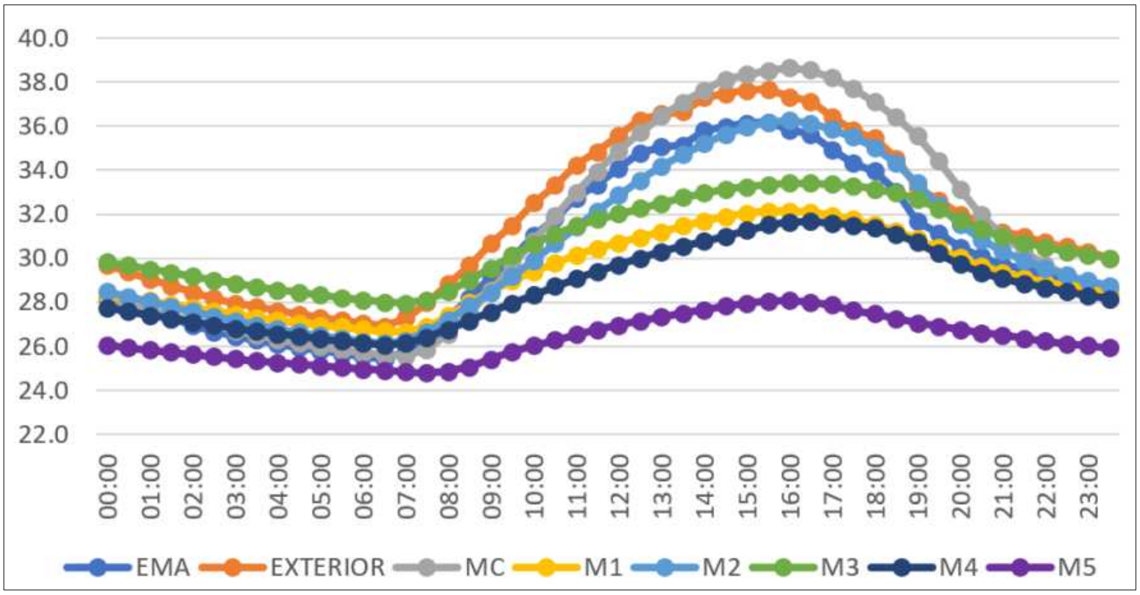



**Figure 12.** Summary of results for average hourly temperatures in the modules investigated

## 5. Conclusions

In the hot, and particularly hot humid regions of the world, building occupant comfort is being increasingly challenged by rising temperatures. The values obtained in this work showed that low energy cooling is possible in such regions using a combination of enhanced passive cooling systems. This research demonstrated that it is feasible to achieve temperature reductions with the cooling systems investigated and, consequently, resulting in higher levels of comfort without the use of mechanical, fossil fuels-driven systems. The results also revealed a good potential for energy savings in the systems investigated, from which lessons can be extrapolated that can then be applied to the integration of other stand alone or combined cooling systems in real buildings in hot humid climates, whilst improving occupants thermal comfort conditions.

Certainly, the envelope of the buildings plays a very important role in the thermal behaviour of such systems, and has a huge impact on the AC requirements of the contained spaces. The choice of building materials is of great importance. In particular, the thermal mass is essential for the reduction of thermal swings. Therefore, the use of thermal mass, with integrated water systems, as applied in this work, pointed towards an important approach for the cooling of spaces that needs further development. In addition, the implementation of these passive cooling systems in buildings and homes, where people cannot afford the purchase of AC equipment and the payment of electricity, may well provide a viable and effective alternative route to providing low energy thermal comfort to many people in a heating world. The implementation of these bioclimatic strategies has also a significant social-economic value as is associated with a reduction of energy consumption, directly related to energy savings and the improvement of the economy and the environment, providing multiple benefits to populations through more climate-appropriate architecture.

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# Outdoor Thermal Assessment in Urban Design Perspective for Ipoh City Center, Malaysia

**MeiYee Teoh[1] Michihiko Shinozaki[2], Kei Saito[3] and Ismail Said[4]**

[1] School of Architecture, Shibaura Institute of Technology, 135-8548 Tokyo, Japan, email: na18504@shibaura-it.ac.jp
[2] School of Architecture, Shibaura Institute of Technology, 135-8548 Tokyo, Japan, email: sinozaki@shibaura-it.ac.jp
[3] Faculty of Urban Life Studies, Tokyo City University, 158-8586 Tokyo, Japan, e-mail: saitok@tcu.ac.jp
[4] Faculty of Built Environment & Surveying, Universiti Teknologi Malaysia, 81310 Johor, Malaysia, e-mail: ismailbinsaid@gmail.com

**Abstract:** Incorporating microclimate and thermal comfort considerations into urban design and planning is not a novel idea, but it remains challenging in practice. The problem is primarily because of the existing weak performance among urban designers and planners in interfacing a given urban model with local climate characteristics, and vice versa. In order to reduce the technical constraint, this article focused on a case study that integrates computational modelling method to illustrate and examine the relationship of urban morphological characteristics and thermal performance of Ipoh downtown in Malaysia. The paper firstly explained the method and procedure connecting the climatic and geospatial modelling data. Then it discussed the simulated microclimate variations including temperature performance and wind distribution, and their consequences on outdoor thermal comfort at pedestrian-level from an urban design perspective. The results of surface temperature distribution were further illustrated by thermal images captured by using an infrared camera. In the discussion, it reinforced the importance of urban design elements, such as trees, the building mass and the space between buildings, in the formation of microclimate pattern of the city. In conclusion, this study also suggested a future potential of microclimate study for urban attractiveness and pedestrian network design.

**Keywords:** outdoor thermal comfort, urban design, spatial modelling, climate modelling, Ipoh

## 1. Introduction

Urban resilience in a heating world is rooted in the city itself. Cities and their climate and thermal comfort are mutually interdependent, implying that good urban design can improve the urban thermal environment and thereby mitigating the city-induced heat and climate change. On the other hand, outdoor thermal comfort itself is a far-reaching factor in urban vibrancy and sustainability. It is a crucial determinant, ranging from human climate perception (Bruse, 2007) to their subsequent willingness to participate in outdoor activities, and ultimately to the effectiveness of urban spaces (Reiter and Herde, 2003). The interaction between the urban environmental design and the climate condition has increasingly aroused people's interest in achieving a climate-responsive environment, giving more impetus to apply thermal comfort in the urban planning agenda.

Considering that the thermal comfort level of a city highly relies on urban pattern (Yahia et al., 2018), evaluating the thermal performance of a given urban morphology become the most common subject of the field. Diverse subjects are being evaluated under this topic, including the form, geometry and density of the city, the urban greenery, as well as the material properties used for the city's surface (Ragheb et al., 2016; Jamei and Rajagopalan, 2017). Urban form, geometry and density play a significant role in manipulating the climatic variation in terms of temperature, wind velocity, and humidity (Golany,1996; Emmanuel and Fernando, 2007; Taleb and Abu-HIjleh, 2013; Yang et al., 2013). At the same time, the material properties of urban surface are crucial for the absorption, storage, and dissipation of radiant energy inside a city (Johansson, 2006; Morini et al., 2016). Urban greenery, which have a high portion of natural elements like trees and water, do provide cooling effects to urban canopy through shade and evapotranspiration (Gunawardena et al., 2017). The compilation of these urban elements is, therefore, a design, which is decisive for the effectiveness of an urban climate action planning for the targeted city.

However, despite there have been numerous relevant studies on the urban thermal environment, the implementation of thermal comfort consideration in urban practice is not as expected. This is mainly because most of current urban thermal knowledge are still more on a climate geoengineering basis, and require specific computational modelling tools and skills in interfacing a given urban model with local climate characteristics. Mastering these scientific thermo-spatial relations and the sophisticated study tools and skills, undoubtedly, become a challenge for most urban planners and designers who has no prior knowledge of climate science and engineering (Eliasson, 2000; Ebrahimabadi et al., 2017).

Therefore, in order to bridge the gap, we need a modified urban climate assessment framework that is less complicated for planners and designer use. The interfacing of the local climate characteristics and the given urban context through computer simulation is relatively new in urban planning practice. Even though the modelling tools has been much improved respectively for climate analysis and spatial analysis, making an integrated analysis of climate and urban design interaction is still a technical challenge, especially in terms of compatibility. In other words, it is necessary to enable the climate data to be compatible with other spatial factors used in urban design consideration. Therefore, this paper aimed to develop an integrated methodological framework that incorporates climatic factors into urban geospatial model in order to assess thermal effect from an urban design perspective. By using computational simulation approach, this is a step towards connecting the thermal information with the spatial attribute of the simulated model.

## 2. Study area context

This paper focused on a case study by examining the relationship of a traditional tropical downtown area with the local climate. This is because many past studies showed that most traditional cities and buildings correspond to local climate and tend to passive thermal strategies in their design concepts (Mohammadi et al., 2018; Biqaraz et al.,2019). There are many historic cores of Southeast Asian cities, including Malaysia, remains to be explored in the subject of thermal comfort. Most of the traditional townships in Malaysia are characterised by the colonial infrastructures, buildings and shophouses, but these old urban fabrics are gradually disappearing due to the new development of infrastructure and buildings in urban process (Wagner, 2017). Their significance to climate, therefore, should be examined for future reference in tropical urban planning.

The studied model focused at Ipoh downtown, a typical old township in Malaysia with a distinctly traditional urban structure. Ipoh, as one of the oldest cities in Malaysia, features with British colonial-style architecture, vernacular shophouses and greenery. The traditional shophouses is a "long-standing architectural tradition" developed in Malaysia and Singapore during the colonial period from the late 18th century to the early 19th century (Wagner, 2017).

They combined residential and business uses of residents, allowing them to live at the upper stories with the family business on the ground floor. Vast greenery is mostly found along the Kinta River, coupled with majestic mountain range, limestone hills and caves around the city.

### 2.1. Climatic background

Ipoh, the capital of Perak state today, located on the western coast of Peninsular Malaysia at latitude 4.5975° N and longitude 101.0901° E. It is located in the equatorial region, having a distinctive tropical climate featured with high temperature, abundant rainfall and heavy precipitation throughout the year. The climate variation is small, subject to a range of 26 - 28 °C in temperature (Malaysian Meteorology Department, 2019). The near-surface air temperature usually ranges from 23 ◦C to 33 ◦C. For the model simulation purpose, microclimate data was collected from the nearest meteorological station in Ipoh. The mean annual trend of climate is summarised in Table 1.

Table 1. The mean annual trends of air temperature, relative humidity and wind speed of Ipoh in 2018.

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Average Temperature (◦C)** | 25.7 | 27.3 | 27.4 | 27.6 | 27.3 | 27.9 | 27.7 | 28.2 | 26.8 | 26.6 | 27.1 | 26.6 |
| **Average Relative Humidity (%)** | 86.2 | 75.4 | 78.8 | 82.3 | 84.7 | 76.9 | 76.3 | 71.2 | 80.8 | 84.5 | 82.7 | 84.1 |
| **Average Surface Wind Speed (km/h)** | 1.6 | 1.8 | 1.8 | 1.7 | 1.5 | 1.6 | 1.8 | 1.8 | 1.8 | 1.7 | 1.6 | 1.5 |

Source: Malaysian Meteorology Department, 2018

### 2.2. City's characteristics

Ipoh has evolved from a Malay village and developed as one of the main hubs for Kinta mining industry under British rule in 1870s. The occurrence of The Great Fire of Ipoh in 1892 destroyed most of the original wooden and *attap* houses that scattered disorderly in the town, giving Ipoh an opportunity to be reconstructed in a properly planned manner. Similar to other British colonial cities in Southeast Asia, British ruler rearranged the town into a more orderly grid pattern by "straightened the road network, redrew the land boundaries and issued new title deeds" (Tate and Chai, 1962, p. 13,18). The downtown is basically divided into two parts by Kinta river (Figure 1), named as Old Town and New Town.


Figure 1. The layout of Ipoh downtown, where core area is indicated in yellow line and buffer zone in green (adapted from: Google Earth, accessed 9th July 2019).

Transportation hubs like bus terminal and railway station, governmental institutions like town hall and courthouse, schools and the *padang* (a typical open space used for public events and sports in Malaysia), were once most centralised in Old Town. In Old Town, there are several blocks of vernacular shophouses that clustered in various forms and sizes. The streets intertwining between the clustered blocks also differ in sizes and width. Due to the multi-orientation of building layout within a block, there are some narrow alleys running in the middle of the block, in the form of either straight line, 'T' or 'H' pattern (see the example in Figure 2).


Figure 2. The characteristics of Old Town in term of layout and pattern of building massing (adapted from: Google Earth, accessed 9th July 2019).

The booming of mining town had driven the New Town development from 1905 to 1914, and the development continued throughout 1920s and 1930s following the expansion of the city (Myheritage Technovation Sdn Bhd, 2009). It consisted mainly of blocks of shophouses other than a food market and theatre. New Town's configuration is relatively simple compared to Old Town. Majority of the blocks only encompassed two rows of shophouses that are uniformly lying in a linear direction, in either an East-West or North-South orientation (see the example in Figure 3). The layout and size of shophouses were uniform, and a wider straight service backlane was provided in the middle of the block for vehicle access. Streets between the blocks are uniform in terms of size and width. This kind of model has been continued into the recent urban planning structure of Malaysia.


Figure 3. The characteristics of New Town in term of layout and pattern of building massing (adapted from: Google Earth, accessed 9th July 2019).

## 3. Methodology

### 3.1. Model building in ArcGIS

In order to manage and visualise all spatial attributes of the study area, we used ArcGIS to create the geospatial database in this study (Figure 4). This approach is also designed to enable the following simulated microclimate data to be incorporated into the same model environment and connected back with the spatial elements. This process enabled us to assess the thermal performance of the study area as a whole.

For climate simulation, the building process in ArcGIS consisted of three phases. First, the creation of a model that covered all necessary input data for climate simulation, including buildings and trees with their height and materials used for land surface. Second, the format transformation from Vector file to Raster files. Third, the transformation from spatial format to a *.acsii* format (an interchange file format) before the model to be adaptable for ENVI-met software in later simulation stage. In this study, the map and building footprint were mainly imported from GIS and AutoCAD database given by the local authority. Whereas the height of building, the location and height of trees, as well as the surface material attributes, most referred to Google Earth resources and field survey.

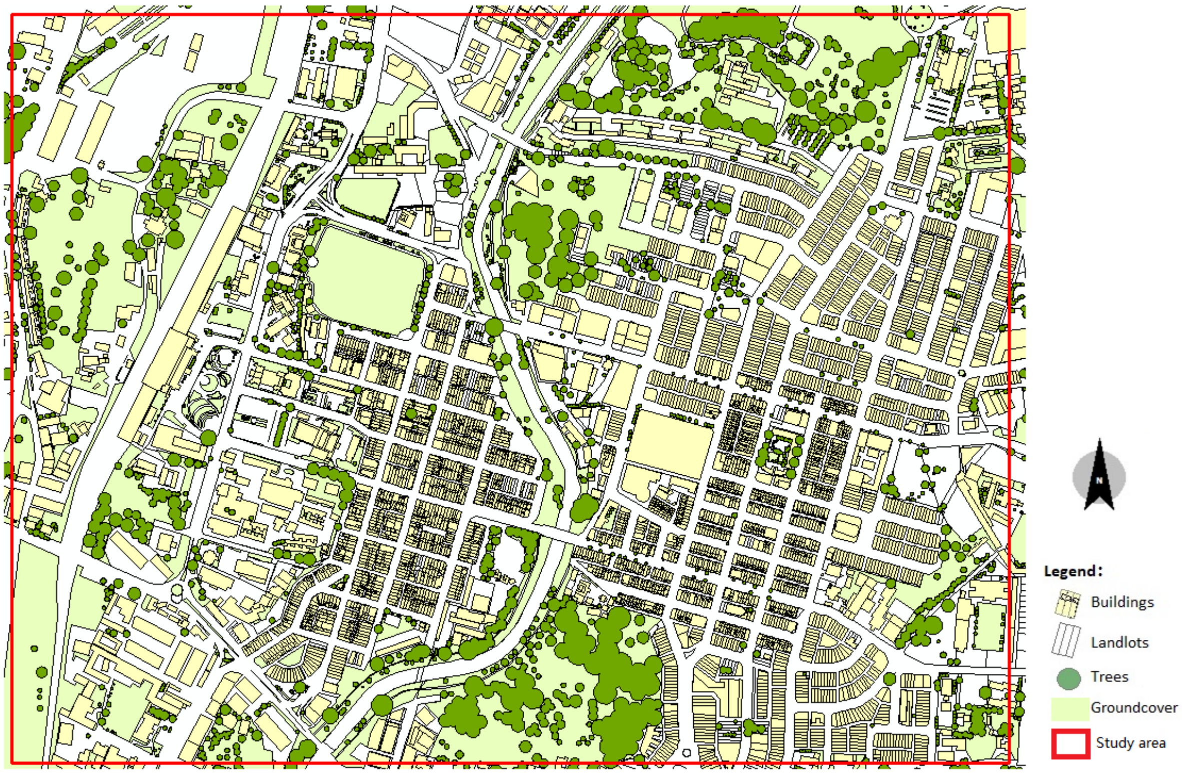


Figure 4. The layout of the study model created in ArcGIS for climate simulation.

### 3.2. Microclimate simulation in ENVI-met

To assess the thermal performance of the study model, ENVI-met 4.4.3 was used. Based on the principles of thermodynamics and fluid mechanics in atmosphere physics, ENVI-met simulates the surface-plant-air interactions of urban environments in a three-dimensional manner (Bruce, 2019). The validation of ENVI-met model in simulating thermal performance of different climates has been extensively reported in previous similar studies (Song et al., 2014; Kei et al., 2017; Bande et al., 2019).

The microclimate simulation was carried out for 21 June 2018, lasted from 06:00 until 18:00. The date was a solstice day in which typically represented the longest day of the year.

The selected areas were fitted into a model area of approximately 400m x 300m x 70m, with the model grid resolution of 5m x 5m x2.5m in dx, dy and dz directions respectively. The model considered both above-ground layer and ground-surface layer. Each cell represented the physical properties of studied subjects, in which the upper layer encompassed the height of buildings, grass cover and trees while the ground surface layer referred to the land cover materials like concrete, asphalt, and uncovered soil. The input data was summarised and shown in Table 2. Air temperature, surface temperature, wind speed and relative humidity were selected as the main variables to determine the studied thermal environment.

Table 2. The configuration data used in the ENVI-met simulation.

| Setting | Input data | |
|---|---|---|
| **Time** | Date | 21.6.2018 |
| | Duration (hours) | 12(06:00-18:00) |
| **Meteorology** | Wind Speed in 10 m ab. Ground [m/s] | 1.7 |
| | Wind direction (degree) | 45 |
| | Initial Temperature Atmosphere (Celsius) | 28.1 |
| | Relative humidity in 2m (%) | 80.4 |
| **Simulation** | Model size (m) | 2000 x 1500 x 140 |
| | Model area (no. of grid) | 400 x 300 x 70 |
| | Size of grid cell (m) | 5 x 5 x 2.5 |
| | Nesting grids | 3 |
| | Latitude & Longitude | 4.59, 101.08 |
| | Reference time zone | GMT+8 |

In this study, the area input layout was imported from ArcGIS. To be readable in ENVI-met, the file format was edited and converted from *.ascii* to *.in* (area input file format used in ENVI-met) through code modifications in Cygwin and Notepad++. The workflow is presented in Figure 5. After the simulation, the output data will be saved in *.csv* file for converting back to GIS readable format (*.ascii*) through code modification software again (Figure 6).

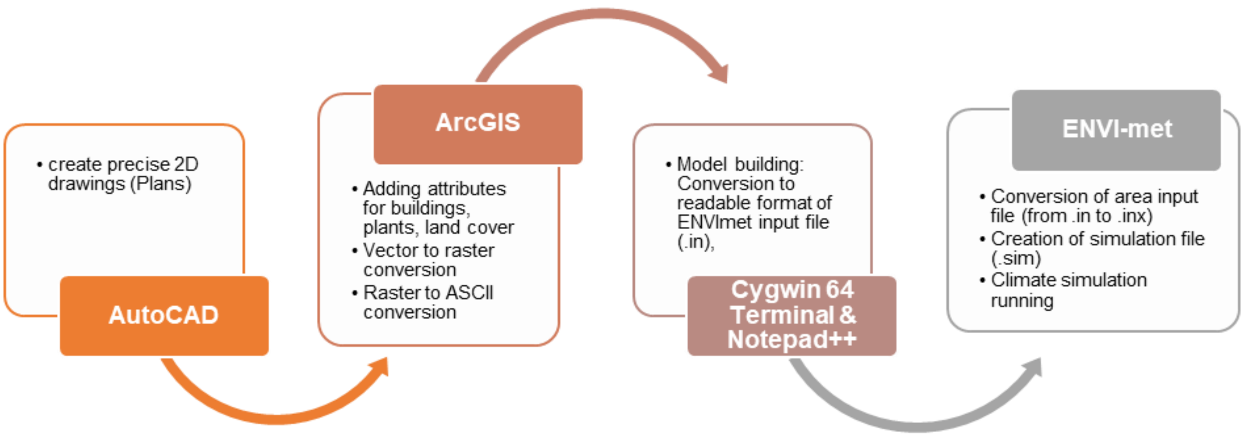


Figure 5. The workflow from creating climate model from a geospatial database.

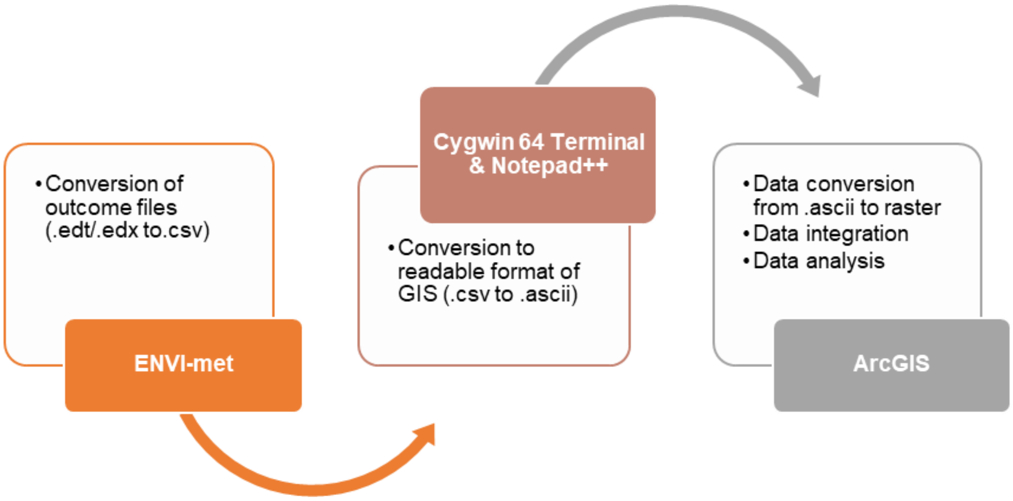


Figure 6. The workflow of transferring climate data back into a geospatial database.

### 3.3. Calculation of PET

The use of Physiological Equivalent Temperature (PET) in outdoor thermal comfort studies is unquestionable. PET has been widely adopted in many relevant studies as summarised in Deb and Ramachandraiah (2010). The PET is most calculated by using Rayman introduced by Matzarakis et al. (2007 & 2010), in which all necessary climate input variables – air temperature(°C), mean radiant temperature(°C), air velocity (m/s) and relative humidity (%) – can be obtained from the ENVI-met simulation. To evaluate thermal comfort in the tropical context, in this study, authors had set the human metabolic rate at 93W and the clothing insulation at 0.3clo, by referring to the index used in previous study in Malaysia (Kei et al., 2017). This study also used the thermal comfort classification of tropical region modified by Lin and Matzarakis (2008), as showed in Table 3. Similar to the ENVI-met outcomes, the result was also converted and integrated back into ArcGIS in the same way for further analysis and discussion.

Table 3. Thermal comfort classification used for tropical region

| Thermal perception | Temperature range [ºC] |
|---|---|
| Very cold | <14 |
| Cold | 14-18 |
| Cool | 18-22 |
| Slightly cool | 22-26 |
| Neutral | 26-30 |
| Slightly warm | 30-34 |
| Warm | 34-38 |
| Hot | 38-42 |
| Very hot | >42 |

## 4. Results

All simulated and calculated results from ENVI-met and Rayman were converted back to be analysed in ArcGIS, in line with the urban outdoor configuration pattern. The imported parameters included air temperature (Figure7), surface temperature (Figure 8), mean radiant temperature (Figure 9), air velocity (Figure 10), relative humidity (Figure 11), and PET (Figure

12). This paper mainly presented the thermal results with the following specifications: first, at 14:00, which is the hottest hour of the day; second, at a 1.7-meter height above the ground, where is closest to a typical pedestrian's height from the surface.

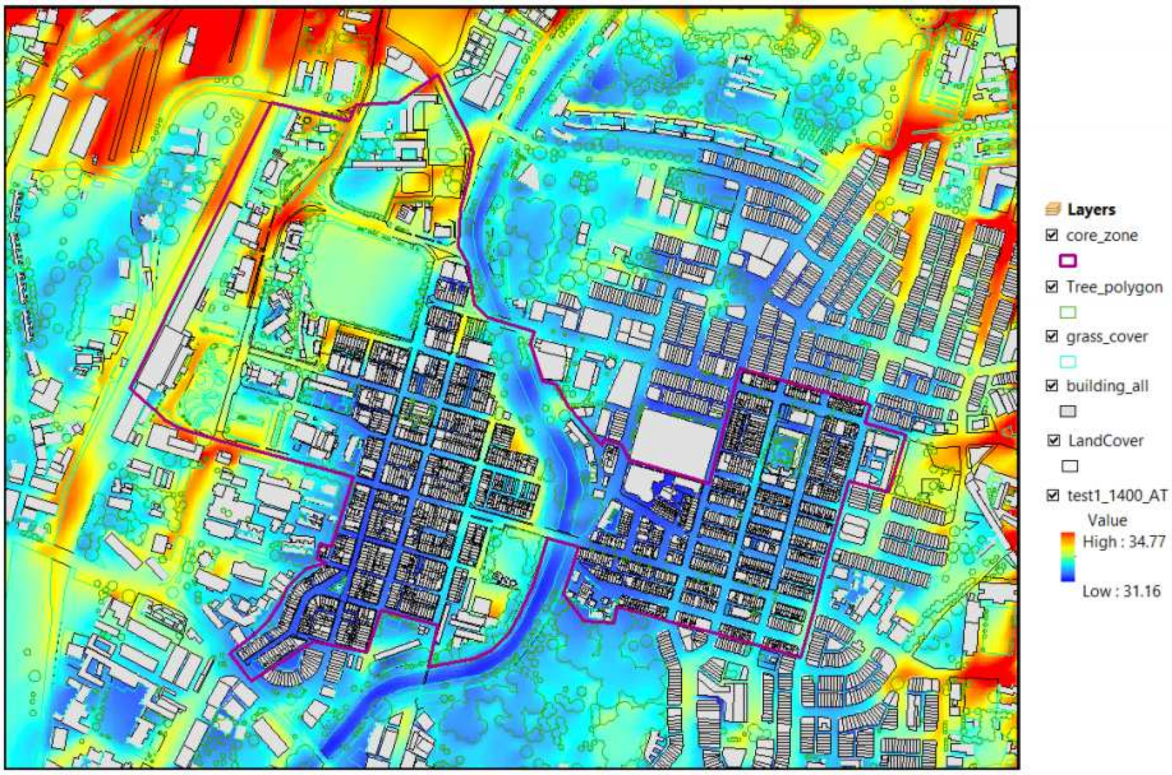


Figure 7. Air temperature distribution of 1400 LT at the height of 1.7m above the ground.

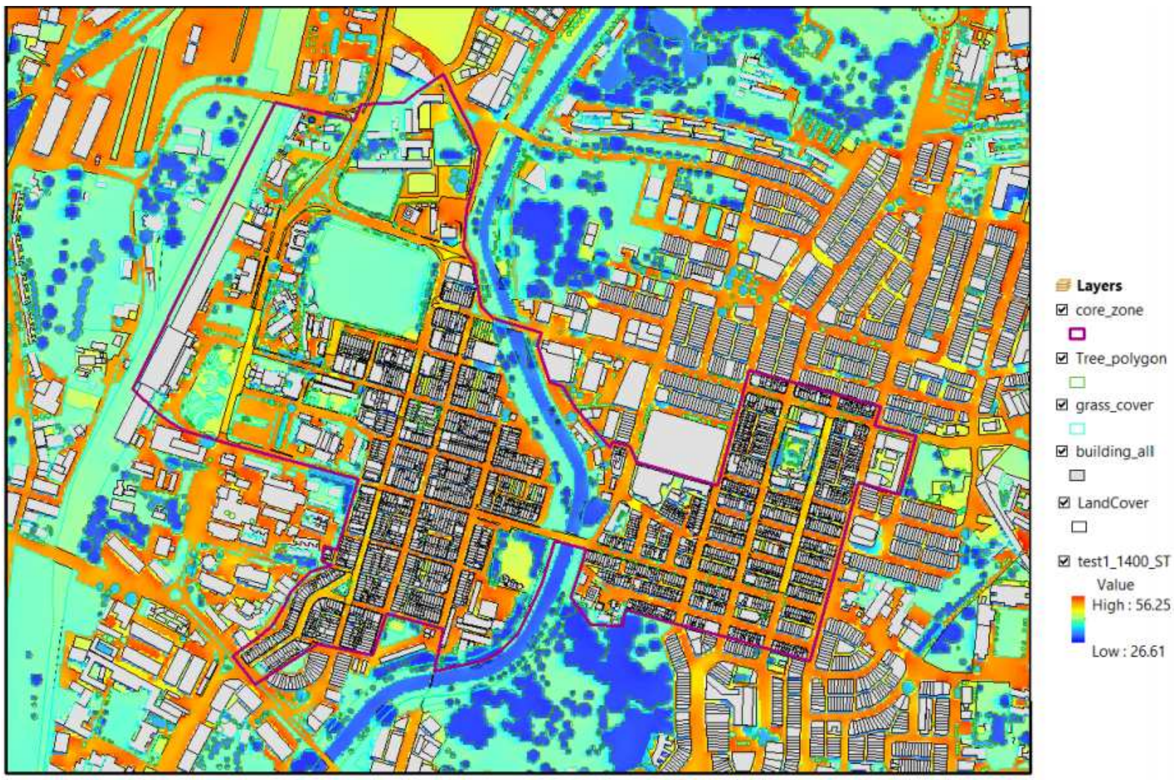


Figure 8. Surface temperature distribution of 1400 LT.


Figure 9. Mean radiant temperature distribution of 1400 LT at the height of 1.7m above the ground.

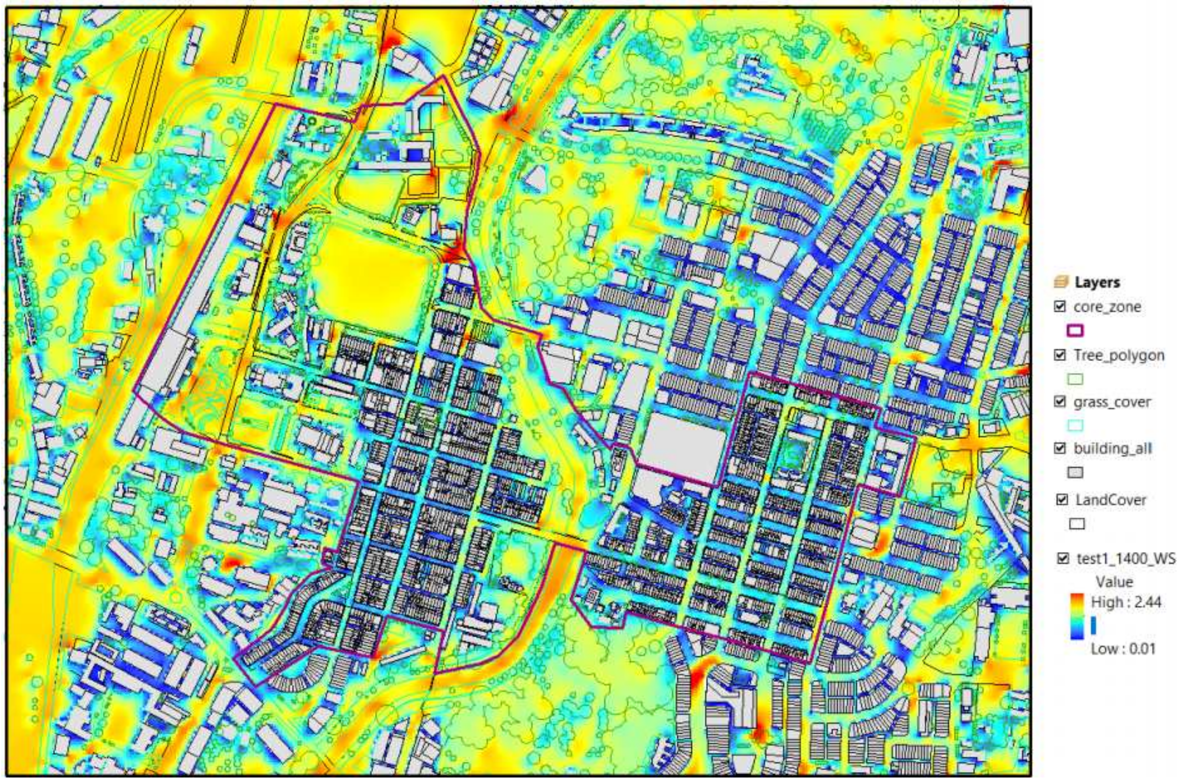


Figure 10. Air velocity distribution of 1400 LT at the height of 1.7m above the ground.

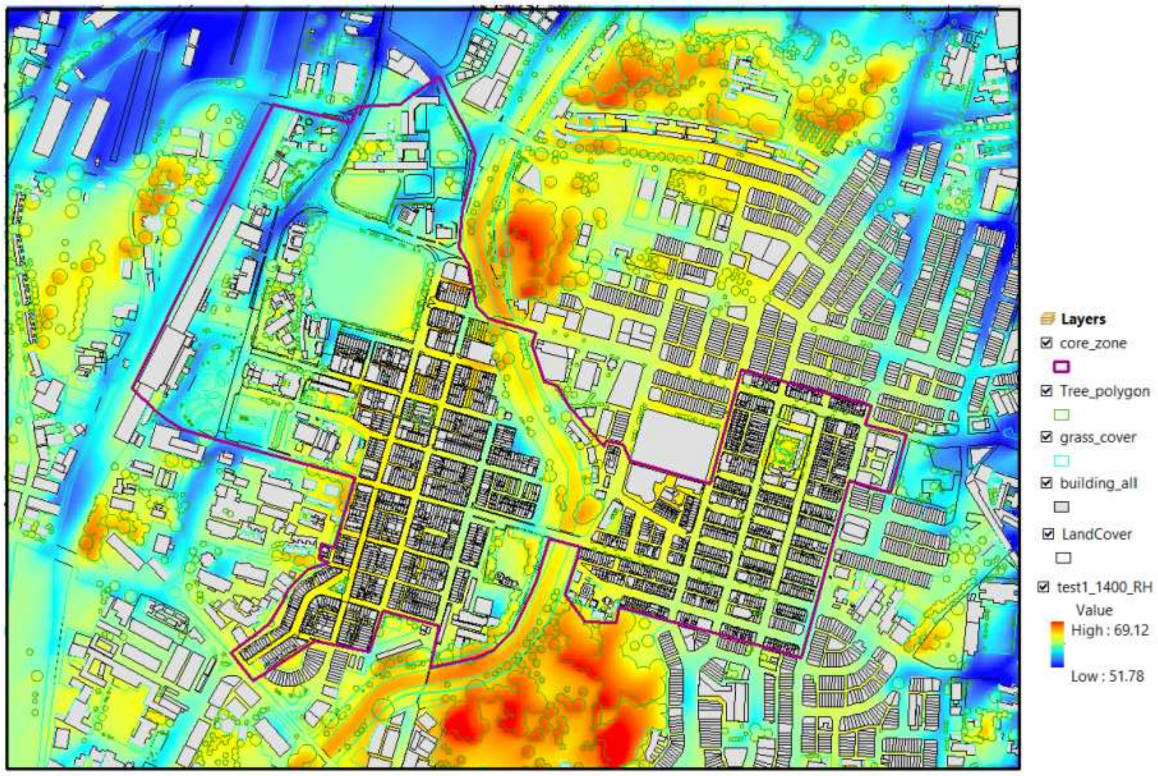

Figure 11. Relative humidity distribution of 1400 LT at the height of 1.7m above the ground.

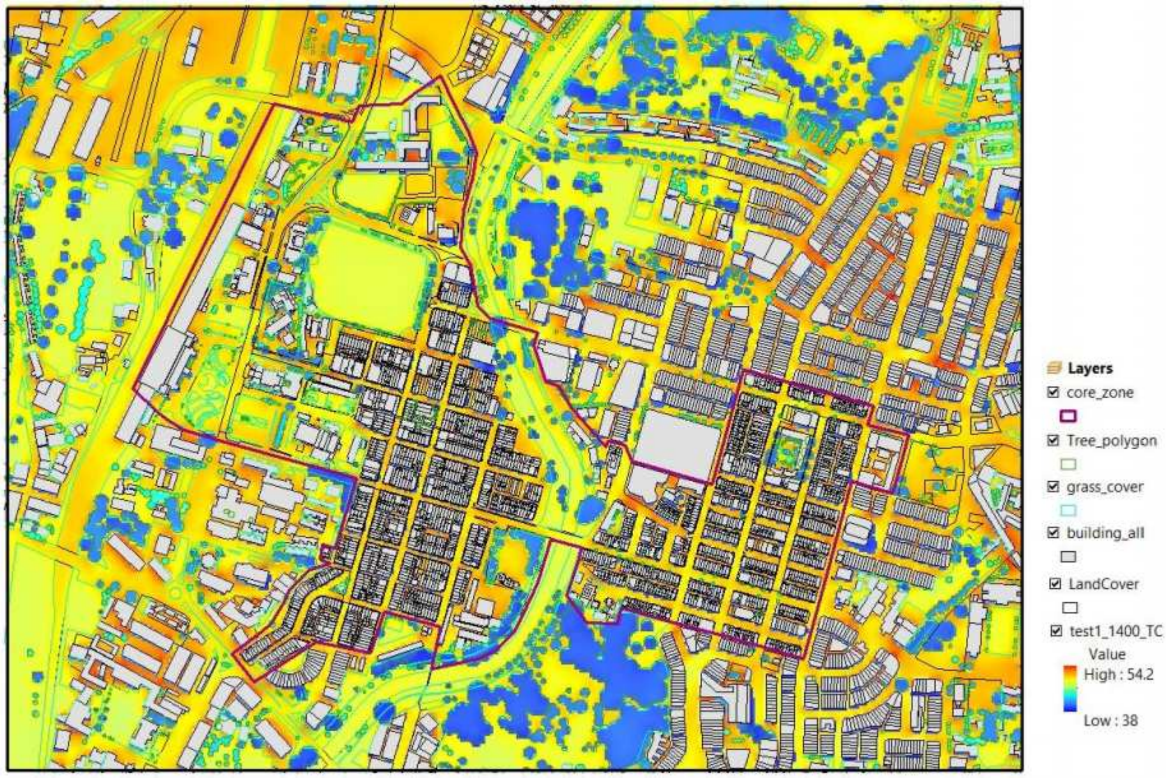

Figure 12. PET distribution of 1400 LT at the height of 1.7m above the ground.

### 4.1. Air temperature

Figure 7 shows the air temperature distribution of downtown Ipoh. We found that the air temperature index values were varied around 3-4$^{o}$C with a highest degree at 34.77$^{o}$C. However, the air temperature in the center of downtown was relatively lower than the surrounding, where some were at the point as low as 31.16$^{o}$C. Such index value was lower than 32.8 $^{o}$C - the temperature recorded at the nearest meteorological station for June 21, 2018, 14:00. When we further scaled down to the cooler area, it showed that the lower temperatures index values were mainly found at those areas with water, higher green coverage, irregular pattern of block setting (including size, height and arrangement), and in more compact layout. This indicated that air temperature had been lowered mainly by various effective shading. The shade has reduced direct short-wave radiation received at pedestrian level and avoid the air to be warmed up adequately in the hot hours.

### 4.2. Mean radiant temperature (MRT) and Surface temperature

The variation of distribution for mean radiant temperature and surface temperature were relatively large when compared to air temperature distribution. They most demonstrated the effects of urban design on microclimate, varied according to the availability of vegetation, the use of materials, as well as the width of roads.

Figure 13. Lower surface temperature was found along the narrow lanes compared to the vehicle roads.

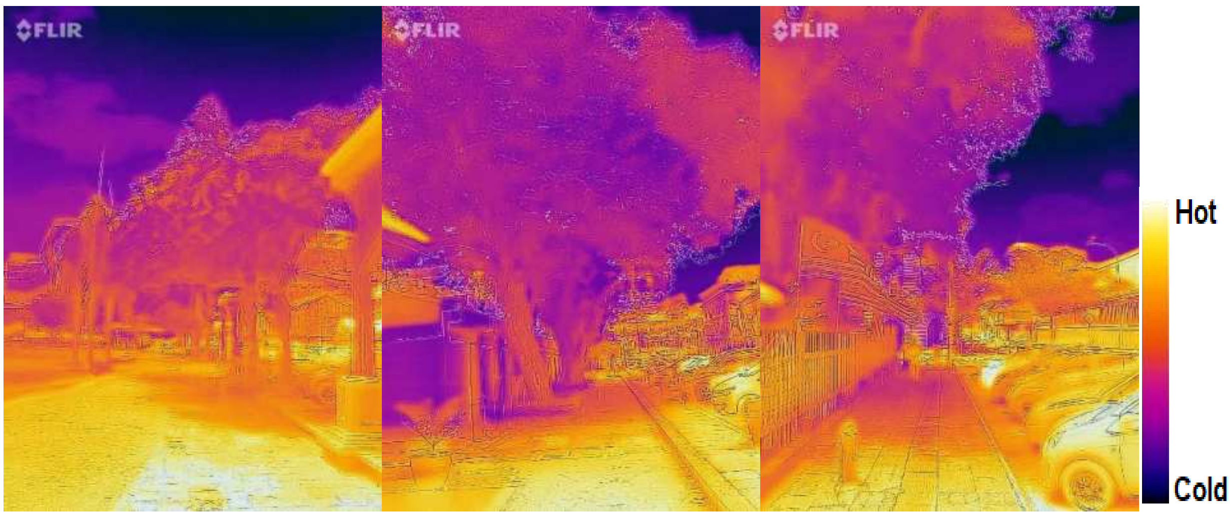

Figure 14. Lower surface temperature was found under trees shade compared to the unshaded areas

Figure 15. The land surface was cooler at the North side (right side in the pictures) of several East-West oriented street

Figure 16. The surface temperature is highest at the typical asphalt roads with full concrete buildings and no greenery

From Figure 8, it showed that lowest surface temperature index values were mostly found along the narrow lanes (also refer to thermal image Figure 13), river, lakes, and under the trees (also refer to thermal image Figure 14). Whereas the grass cover for all *padang*s and unsealed soil areas also had a prominent effect on cooling the land surface during the hot times.

Moreover, we found that the land surface was cooler at the North side of an East-West oriented street (also refer to thermal image Figure 15). At the same time, typical asphalt roads with full concrete buildings and no greenery created the highest index values of surface temperature in this study (also refer to thermal image Figure 16). The result proved that the road orientation and the material used could manipulate the micro-distribution of surface temperature within the street as well.

The MRT distribution was prone to a higher index (Figure 9). However, the MRT difference was relatively large, from a 43.41°C to 67.32°C. The lowest MRT index values were also recorded under the shade of trees. The result also showed that the width of road affected MRT values. The MRT value of those narrow lanes was lower if compared to those typical roads. Again, we found that MRT index values were lower at the North side of an East-West oriented street due to the shading created by the building blocks. In summary, the existence of vegetation, the buildings, and the road orientation and sizes all played a regulating role for microclimate.

### 4.3. Air velocity

Air velocity ranged from 0.01m/s to 2.44m/s in overall (Figure 10). Lower index values were most found at the east-west roads along the shophouses zone. The narrow lanes intertwining between the blocks also rarely experienced high speed of wind. This prevented the hot air to be directed into these areas by winds during the hot hours like at 14:00, resulting in lower temperature showed in section 4.1. On the other hand, the river and railways acted rather as air tunnels which obtained highest index values, and influenced the air velocity of their adjacent area as well, particularly at those more opened spaces.

### 4.4. Relative humidity

The relative humidity (RH) index ranged from 51.78% to 69.12% at outdoors context (Figure 11). It is obvious to see that green areas, especially with the big trees compound, have the highest RH index values. This proved the capability of urban green in maintaining the high air moisture that cool the environment. Besides, the result also showed that positive RH distributed mostly at the downtown centre that consisted of numerous blocks of shophouse, indicating air moisture could be locked in the compact urban layout. The urban layout as well as the vegetation available on site, therefore, have their impact on humidity regulation.

### 4.5. PET

Figure 6 demonstrated the overall PET index values distributed in the study model, ranging from 38$^{o}$C (hot) to 54.2$^{o}$C (very hot) at 14:00 (Figure 12). Overall, it is difficult for pedestrians to stay long at outdoors during 14:00 unless the pedestrians keep themselves under the tree shade. The low thermal comfort perception at shophouses zone was mainly due to the absence of natural elements on site. In other words, being closer to natural open spaces like river, lake, and grassland would relatively improve the thermal comfort perception.

## 5. Discussion

The paper has evaluated the urban configuration through the lens of microclimate. The existence of trees played a determinant role for urban climate planning in tropical region. This finding corresponds to the findings of most previous studies, in which the vegetation, particularly the dense trees, was highly positive to shading potential, evaporative cooling and thermal reflectivity (He et al., 2015; Lee et al., 2016; Louafi et al., 2017; Kong et al., 2017; Lin et al., 2017).

This study also found the role of street pattern and building massing in microclimate regulation of Ipoh. The compact grid pattern and the irregular building mass have a particular impact on the distributions of all studied variables of the study. The pattern created by air blocks (buildings and trees) and air lanes (including streets, open spaces, river and railway) in the studied areas affected the micro-scale wind speed and direction. The compactness of building massing affected the relative humidity distribution by their capacity in trapping the moisture in the air. The distance between buildings, as well as the orientation of streets, manipulated the micro-scale temperature. The shade created by the building significantly lowered the surrounding temperature and cooled the land and building’s surface, that regulated the temporal thermal comfort for pedestrians. Hereby, it is necessary to acknowledge that although the closer spaced building contributed to the shade formation, but it also decreased the ventilation efficiency within the lanes. This effect was two-sided: it prevented the inflow of hot air into the narrow lanes, but at the same time, this blocked the cool air flowing into the area as well. The promotion of air velocity design in warm-humid climate is, therefore, to be further explored.

In urban design perspective, for shophouses zone, narrow lanes and alleys in Ipoh are more thermally comfortable than the primary and secondary streets for pedestrian movement. Although these areas are currently less considered for pedestrian purpose due to safety issues in Malaysia, but from another viewpoint, these areas have less conflict with massive mobile-vehicle flows. This study thereby suggested that making good use of narrow lanes and alleys for pedestrian purpose is an advisable strategy in designing comfortable pedestrian route for Ipoh centre. For those two-facade shophouses that most found in Old Town, this finding reinforced the potential of their back facade to be revitalised for welcoming the walking crowds.

To improve the thermal comfort of majority roads in Ipoh, we suggested to replace the current slow-growing small trees with those fast-growing wide canopy trees species. More trees should be planted along the roadside pedestrian ways to cool down the environment for pedestrian comfort. The combination of urban man-made elements and vegetation is also highly recommended to maximise the shading effect for pedestrian's comfort. The pattern and ratio of these urban design elements would determine the efficiency in providing thermal comfort at outdoors.

To improve the weak air ventilation within shophouses zone, we suggested to partially do some modification at the compact building massing, especially at Old Town. More opening within a block would allow more air to be directed from open spaces into the block and create a higher airflow inside. Besides, we recommended to strengthen the redevelopment regulation in controlling the size and height of downtown buildings. The policy is initially used to maintain the historic skyline of the downtown from a heritage preservation perspective. However, in this study, this policy is advantageous to minimise the air-blocking effects in the downtown.

## 6. Conclusion

In summary, this study has proved that urban design can manipulate urban microclimate. This implies that there is possible to alter urban microclimatic condition through urban design parameters in tropical hot-humid region like Malaysia. Throughout the paper, it mainly explained and discussed the method and procedure of connecting the climatic and spatial data through the computational modelling tools, showing the exchange, transition or combination of information between ENVI-met and ArcGIS. This study showed that data switching between spatial and climate modelling tools enable a more comprehensive outcome for characterising climate and landscape of a city. Integrating geospatial factors into climatic design application, and vice versa, not only compensates for each other's technical and functional deficiencies but also provides an easier initial start-up for urban planners who get started with urban climate research. Furthermore, compared to some numeric method used in previous climate studies, mapping approach is more ideal for urban climate action and planning when the designers and planners can directly find out the effects of studied model to climate design.

As conclusion, the role of computational aid in urban climate action planning is unquestionable, but every single modelling software has its technical limitations in current.

Hence, in order to technically fill the gap for a synchronous climate and urban analysis, modelling software integration approach is recommended. This study also supports the use of climate simulation during the design stage in practice. Through simulation approach, a particular design idea can be virtually simulated and assessed according to the given climate and spatial input. Through the visualised outputs in geospatial software like ArcGIS, the result can be used to assist the selection of designs in the planning process. This approach allows thermal comfort design to be predicted in a more precise and accurate way before they are applied to real-world, thereby effectively saving the cost and time, as well as reducing the possibility of thermal discomfort for future urban design.

On the basis of bioclimatic concept of urban planning, the next focus will be placed on the integration of climate data into urban spaces and network analysis, especially in terms of place attractiveness and walkability. This approach method will be more constructive in achieving a more comprehensive pedestrian design and planning that contribute to the active use of urban spaces in tropical region, making our cities sustainable and resilient to the heating world.

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# Influence of Building Design on Occupant Comfort in Adaptive Climate Zones

**Renjith Jayapalan Nair[1], Eleonora Brembilla[1], Christina Hopfe[1], John Mardaljevic[1]**

[1]Loughborough University, Loughborough, United Kingdom

**Abstract:** The responsiveness of buildings to prevailing local climate plays an important role if the dual aspects of occupant comfort and low energy demand are to be met. This study takes as example the State of Kerala in India where the Government – as part of the project titled "Livelihood Inclusion and Financial Empowerment (LIFE) mission" – plans to build more than 750,000 houses across the State, using a uniform design, irrespective of the location or climate. A previous study has identified regions with different climatic characteristics within Kerala using a method based on adaptive thermal comfort model. This study aims to understand how the building design influences occupant comfort in the different adaptive climate zones by performing an uncertainty analysis on the output metrics. The thermal comfort was assessed based on the hours requiring heating/cooling while visual comfort was assessed based on the Useful Daylight Illuminance metric. A sensitivity analysis was also carried out to identify design parameters that influence occupant comfort. The results of this study will serve as a reference for practitioners during the early stages of design to achieve thermal and visual comfort for high performance residential buildings.

**Keywords:** Thermal comfort, visual comfort, climate zone classification, thermal simulation, daylight simulation

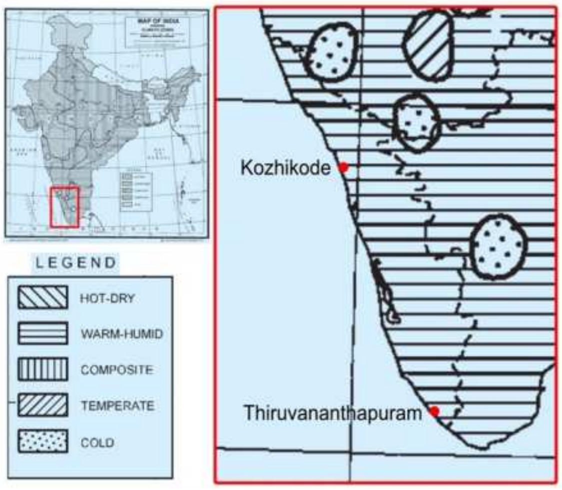
## 1. Introduction

India is one of the fastest growing economies in the world with an average growth rate of 6.5% a year since 1990 (IEA, 2015). The International Energy Agency (IEA) estimates that, of the total housing stock that would exist in India by 2030, only one-fourth has been built as of 2015 with the rest yet to be constructed (IEA, 2015). This is in marked contrast to developed regions such as Europe and the US.

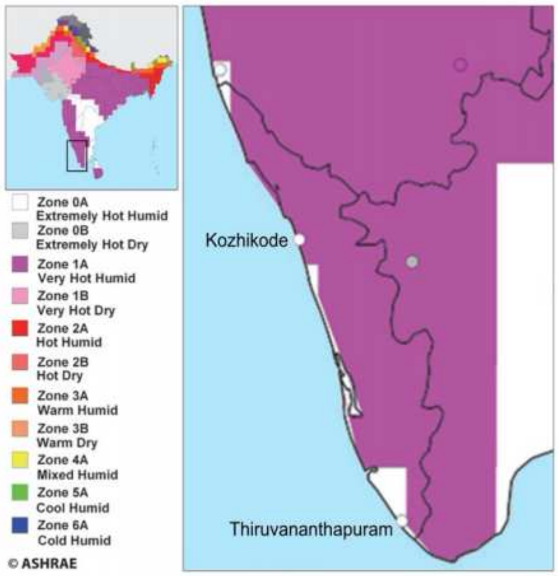
In Kerala, one of the 29 states in India, as part of the Government's vision to provide houses for all its citizens, a project titled "Livelihood Inclusion and Financial Empowerment "(LIFE) mission" (Issac, 2018) is being implemented. Under this project, the Government of Kerala plans to build more than 750,000 houses. The beneficiaries (i.e. the people of the State) are free to choose among 12 proposed building forms which will be used for the construction of the building irrespective of the location or climate. The lack of climatic considerations is partly caused by the existing classification systems identifying Kerala as belonging predominantly under a single climatic zone.

The climate and environment in which buildings are located will influence their thermal behaviour and thus the final energy consumption (Reijenga and Brassier, 2017). The National Building Code (NBC) of India classifies the country into five major climatic zones (BIS, 2016) and Kerala under a single climate zone – Warm Humid (Figure 1a). This classification is based on the work done by Ali et al. (1993), in which mean monthly maximum temperature and humidity data were used to group the locations into zones depending on the prevalence of a defined climatic condition for six or more months in a year. The American Society of Heating Refrigerating and Air-conditioning Engineers (ASHRAE) climate zone classification method identifies the regions in Kerala as belonging predominantly under a Very Hot Humid Climate

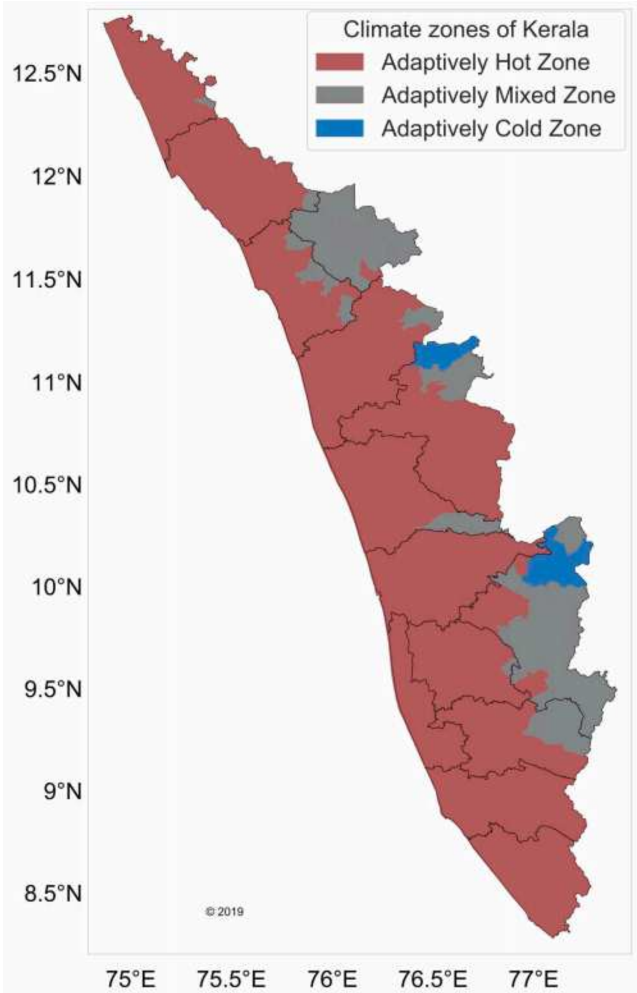
(Figure 1b). The ASHRAE climate zone classification method defines the climate into different zones based on heating and cooling degree days and into sub- zones based on precipitation (Standard 169, 2013). But related previous studies (Jayapalan Nair et al., 2018, 2019) identified the existence of regions with different climate characteristics within Kerala. This is in contrast to the observations of the NBC of India and the ASHRAE climate zone classification system.




(a) Climate zone classification as specified in the NBC of India. (Adapted from BIS (2016))




(b) Climatic zones of Kerala as specified in the ASHRAE standard 169-2013. (Adapted from Standard 169-2013(2013))




(c) Adaptive Climate zones of Kerala (Adapted from Jayapalan Nair et al. (2019))

Figure 1: Climate zones of Kerala based on different classification methods: (a) NBC of India (b) ASHRAE climate classification and (c) Adaptive climate classification

The study by Jayapalan Nair et al. (2019) had used a new method based on adaptive thermal comfort model. In this method, the climate data were analysed based on the "Indian Model for Adaptive Comfort" (IMAC) model related to mixed-mode ventilated buildings. All the hours in a year were classified into Hours Requiring Heating (HRH) and Hours Requiring

Cooling (HRC). HRH is defined as the hours at which the value of hourly outdoor dry bulb temperature goes below the IMAC lower acceptability limit ($T_c$ −3.5°C) and HRC is defined as the hours at which the value of hourly outdoor dry bulb temperature goes above the IMAC upper acceptability limit ($T_c$ + 3.5°C). This is an idealised case where no thermal envelope is considered. The actual HRH and HRC values for a building will depend on the thermal envelope characteristics. The comfort acceptability limits were calculated using the equation developed by Manu et al. (2016):

$$T_c = 0.28T_o + 17.9 \tag{1}$$

where $T_c$ is the neutral or comfort temperature in degree Celsius, $T_o$ is the 30-day outdoor running mean air temperature ranging from 13°C to 38.5°C. The limits of 90% acceptability are ±3.5°C.

Percentages of HRH and HRC were calculated for locations spaced on a 25 km grid across Kerala based on IMAC, and the zones were identified using altitude-dependent delimiting factors. Under the adaptive classification method, the regions in Kerala were classified into three climate zones:

1. Adaptively Hot Zone (AHZ),
2. Adaptively Mixed Zone (AMZ) and
3. Adaptively Cold Zone (ACZ).

Figure 1c shows the adaptive climates zones of Kerala.

Indoor comfort is greatly influenced by the outdoor weather conditions, and the responsiveness of buildings to the prevailing local climate plays an important role if the dual aspects of occupant comfort and low energy demand are to be met. The present study aims to understand how the building design influences the occupant comfort (thermal and visual) within the building in the different adaptive climate zones of Kerala. To understand this, an uncertainty analysis was carried out. The thermal comfort in buildings was assessed based on the hours requiring heating/cooling while visual comfort was assessed based on the Useful Daylight Illuminance (UDI) metric. A sensitivity analysis was also carried out to identify the major/principal design parameters that influence occupant comfort within the buildings.

## 2. Methodology

To understand the influence of design and physical model parameters on the indoor occupant comfort, two types of analysis were conducted:

1. Uncertainty analysis (UA) was carried out to understand the influence of variation of design parameters on the occupant comfort. UA helps to understand the uncertainty in the output (thermal and visual comfort) due to uncertainties in the input (design parameters).
2. Sensitivity analysis (SA) was carried out to identify the different design input parameters that influence the output (thermal and visual comfort) the most.

The thermal comfort inside the building was assessed by calculating the percentage of hours in a year in which the zone temperature remains within the adaptive thermal comfort ranges. This percentage of hours were termed as thermal comfort hours (TCH). The adaptive thermal comfort ranges, i.e. the thermostat set point temperatures for heating and cooling, were defined based on adaptive thermal comfort model. This was because the latest version of the NBC of India (BIS, 2016) adopted the IMAC. The upper and lower limits of 90%

acceptability comfort/neutral temperature were calculated using IMAC model (Equation 1) and were used as set point temperatures for cooling and heating respectively.

The percentage of hours in which the zone air temperature goes above the cooling set point temperature were termed as thermal discomfort hours - cooling (TDH-c). These represent the hours at which cooling is required to maintain comfortable indoor thermal conditions. The percentage of hours in which the zone air temperature goes below the heating set point temperature were termed as thermal discomfort hours - heating (TDH-h). These represent the hours at which heating is required to maintain comfortable indoor thermal conditions.

The visual comfort in buildings was assessed based on the climate-based metric Useful Daylight Illuminance (UDI). UDI was calculated in terms of UDI-not achieved (UDI-n), UDI-combined (UDI-c) and UDI-exceeded (UDI-e) (Mardaljevic, 2015).

- UDI-n was calculated as the percentage of annual occupied hours for which the illuminance values are lower than 100 lux.
- UDI-c was calculated as the percentage of annual occupied hours for which the illuminance values fall between 100 lux and 3000 lux.
- UDI-e was calculated as the percentage of annual occupied hours for which the illuminance values are greater than 3000 lux.

UDI-c gives an indication of the percentage of hours in a year in which the use of artificial lighting and shading can be avoided, thus representing the visual comfort range within the buildings.

The whole process of UA and SA could be divided into three stages – pre-processing, building performance simulation and post-processing. Figure 2 describes the different stages involved to carry out UA and SA.

### 2.1. Uncertainty/Sensitivity Analysis stage 1 – pre-processing

The pre-processing stage involves sampling of all the input parameters using suitable methods. To carry out the UA, the Latin hypercube sampling method was used. Using this sampling method, all the input parameters are varied simultaneously for each sample. The sampling was done using SALib library in Python (Herman and Usher, 2017). SALib is an open source library for performing sensitivity analysis and the sample generation function was used to create the input parameter values. The input design parameters were sampled 250 times.

For SA, the sampling was done using Morris method with 8 trajectories. In Morris method only one parameter is changed at a time i.e. only one parameter value is changed for subsequent simulations. Thus, the Morris method is also called one-step-at-a-time method. The number of samples depends upon the trajectories and the number of parameters. The number of samples is calculated as:

$$N = k\,(P + 1) \tag{2}$$

where N is the number of samples, k is the number of trajectories and P is the number of parameters. A total of 224 samples were produced for the SA.

Table 1 presents the different design parameters and the corresponding lower and upper limits considered for the UA/SA. The upper and lower limits were set based on practical values and those identified from literature (Brembilla et al., 2018), design guides (BEE, 2014, 2017), building codes (LSGD, 1999, 2011) and related reports (Rawal et al., 2014).

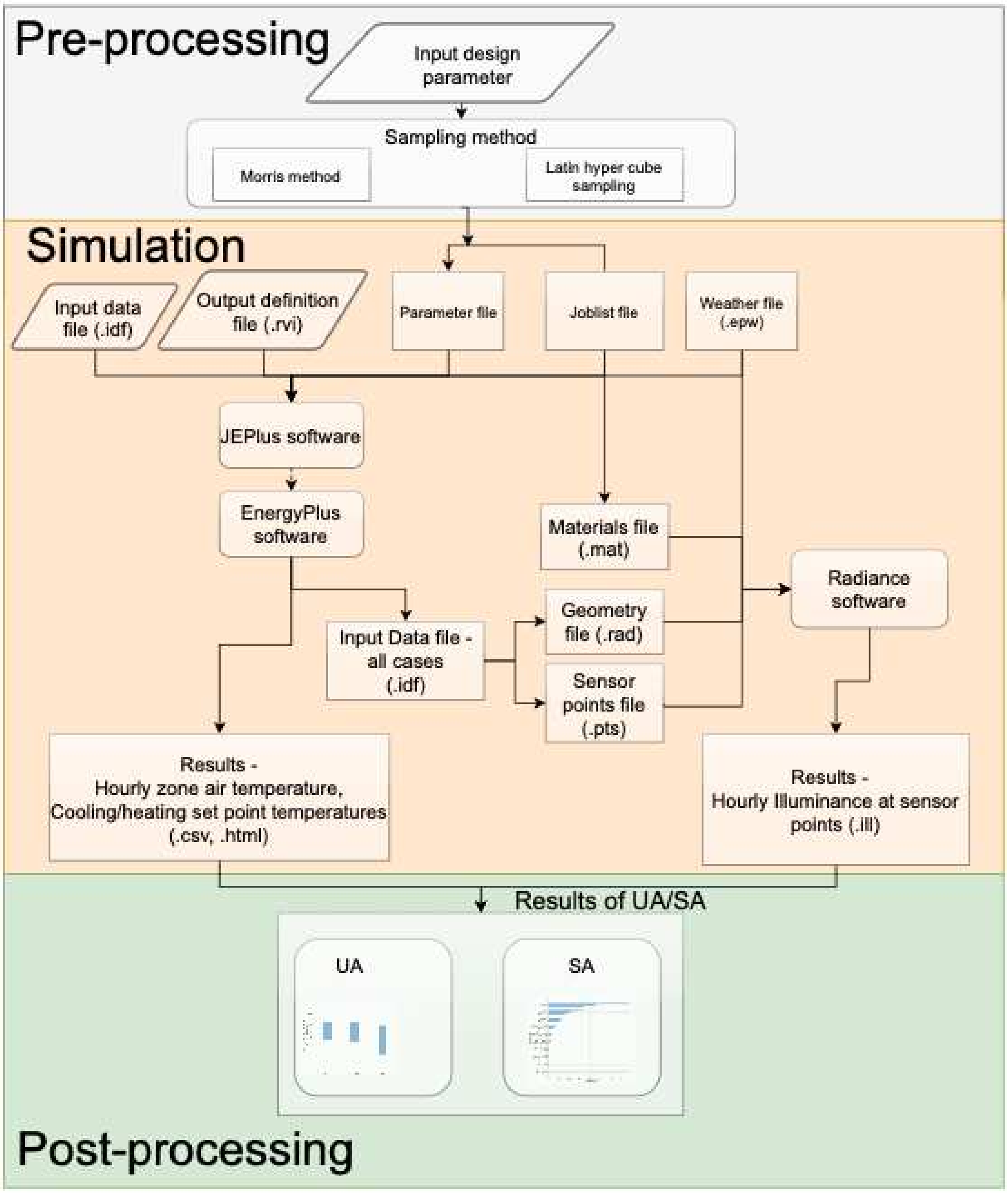



Figure 2: Workflow of UA/SA

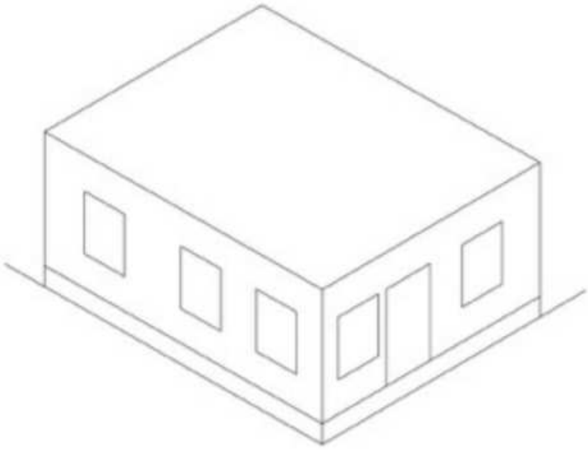
For sampling, the Window Wall Ratio (WWR), the U-values of walls and windows, the depth of overhang and the length of fins were varied separately for each wall. This was done to cover all possible design scenarios. In this paper only the results for South orientation are presented. Figure 3b shows the labelling used for the walls and other geometrical parameters.

**2.2. Uncertainty/Sensitivity Analysis stage 2 – Simulation**

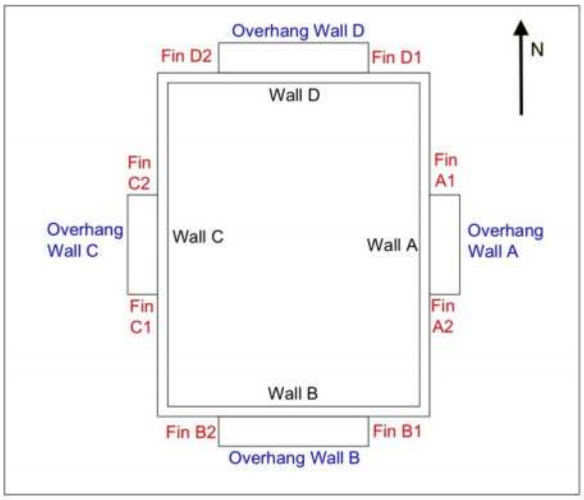
For carrying out the simulations, a building representative of Kerala's building typology was considered as the case study building. The design of the case study building (Figure 3a) forms one of the 12 building base form designs proposed by the Government as part of the LIFE mission project (Issac, 2018). The building has gross floor dimensions of 5.45m x 6.90m and a floor to ceiling height of 3m. The building design and physical model parameters were derived using the respective sampling method used for conducting the UA/SA.

Table 1: Lower and upper ranges of design parameters considered for UA/SA

| Parameters | Lower limit | Upper limit |
|---|---|---|
| Window Wall ratio | 10% | 70% |
| Roof U-value (W/m$^2$.K) | 0.10 | 3.60 |
| Floor U-value (W/m$^2$.K) | 0.10 | 2.94 |
| Wall U-value (W/m$^2$.K) | 0.10 | 3.50 |
| Window U-value (W/m$^2$.K) | 0.70 | 7.10 |
| Overhang depth (m) | 0.01 | 0.60 |
| Fins length (m) | 0.01 | 0.60 |
| Ground reflectance | 0.05 | 0.30 |
| Floor reflectance | 0.05 | 0.40 |
| Wall reflectance | 0.20 | 0.85 |
| Ceiling reflectance | 0.50 | 0.95 |
| Window transmittance | 0.40 | 0.90 |



(a) Isometric view




(b) Labelling of geometrical parameters of case study building for UA/SA.

Figure 3: Case study building

To calculate the thermal comfort hours, simulations were carried out in EnergyPlus v8.9 software (DOE, 2010) with JEPlus software. JEPlus is an EnergyPlus simulation manager for parametric simulations (Zhang and Korolija, 2010). For the simulation, the whole building was assumed to be a single thermal zone and free-running, i.e. without a HVAC system for heating or cooling. The thermostat set point temperatures for heating and cooling, i.e. the adaptive thermal comfort ranges, were defined based on IMAC model.

The ventilation was controlled by opening the windows (at an angle of 90$^o$) when both mean zone and outside air temperature were within the IMAC acceptability comfort limits (90%). The buildings were also modelled to have ceiling fans operating when the indoor zone temperature was above 25$^o$C and when the HVAC was not ON. The operation of the windows and ceiling fans is presented in Figure 4. The use of ceiling fans is considered as one of the main mechanisms in Warm-Humid climates to improve the indoor thermal comfort (Manu et al., 2014; Nicol, 1974; Cheng and Ng, 2006). When ceiling fans were in operation the cooling set points (i.e. IMAC 90% acceptability upper limit) were offset by 2.2$^o$C (Standard 55, 2013). Energy Management System (EMS) programs were written in EnergyPlus to define the ventilation and ceiling operation schedules.

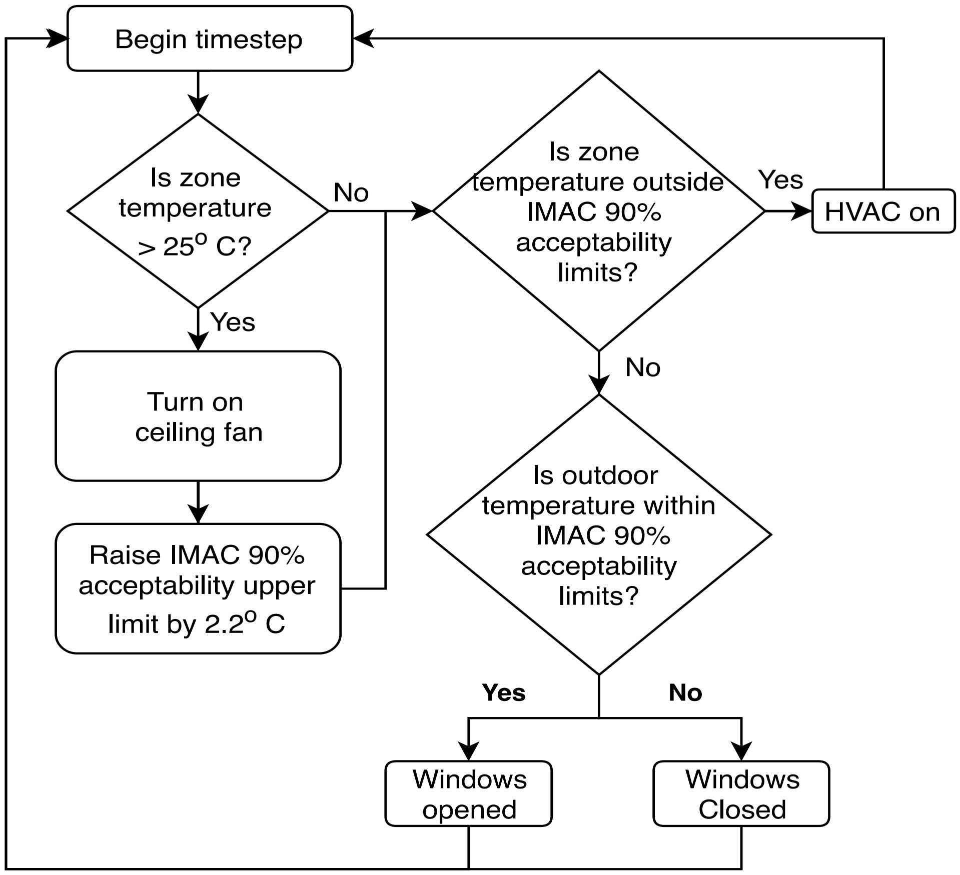



Figure 4: Window and ceiling fan operation flowchart.

The UDI metrics were calculated by carrying out climate-based daylight modelling (CBDM). The daylight simulations were carried out after the thermal simulations, so that the EnergyPlus Input Data Files (IDF) produced as a result of the thermal simulations could be used to create the RAD files required for daylight simulations. This was done so to maintain uniformity in the geometry used in both daylight and thermal simulations. Thus, for both thermal and daylight performance, the geometrical design parameters were the same.

A number of Radiance-based methods are available to perform CBDM. Since the study does not involve complex glazing systems, the 2-Phase method (with high sky resolution) was used to assess the daylight performance of buildings. The time schedule 08:00-17:00 (without considering daylight saving time) was used as occupancy period. The sensor grid points were placed on a horizontal working plane at a height of 0.8 m above the floor level and at a spacing of 0.25 m from the surrounding walls.

The UA and SA were carried out for the case study building when located at Thiruvananthapuram, Kalpetta and Munnar representing the three adaptive climate zones - AHZ, AMZ and ACZ respectively.

**2.3. Uncertainty/Sensitivity Analysis stage 3 – post-processing**

In the post-processing, the results from the simulations were collected and then compared to the sampled design inputs. From the thermal simulations, the hourly zone air temperature and heating and cooling set-point temperatures were used to calculate TCH. From the daylight simulations, CBDM produces a time series of illuminance values at each sensor point.

The hourly illuminance values recorded at the sensor points were used to calculate UDI-c. These were done using custom scripts in Python.

The results of UA are presented in the form of box and whisker plots showing the variation in the output in the form of interquartile ranges of the results. For SA, the Morris analysis was used to identify the elementary effect of the input parameter and are presented in the form of histograms. The input parameters are ranked according to their effect i.e. higher the effect higher is its influence on the results.

## 3. Results and discussion

### 3.1. Uncertainty analysis

The effect on indoor thermal comfort due to variation in the building design parameters was examined by conducting an uncertainty analysis. This was done for representative locations from each of the adaptive climate zones of Kerala. Figure 5 presents the box and whisker plots of TCH for the different adaptive climate zones of Kerala. The boxes show the 25th-75th percentile (i.e. the interquartile range) and the whiskers are placed at 1.5 times interquartile range. The median and the 25th and 75th percentile values are also presented in Table 2.

From Figure 5a, it could be observed that the TCH in AHZ shows higher variations than compared to the other zones with the 25th and 75th percentile values achieving 62% and 77% TCH respectively. The median TCH value in AHZ is 72%. ACZ shows comparatively lesser variation in TCH with the 25th and 75th percentile values being 83% and 93% and has the highest median TCH value (90%) among the different climate zones.

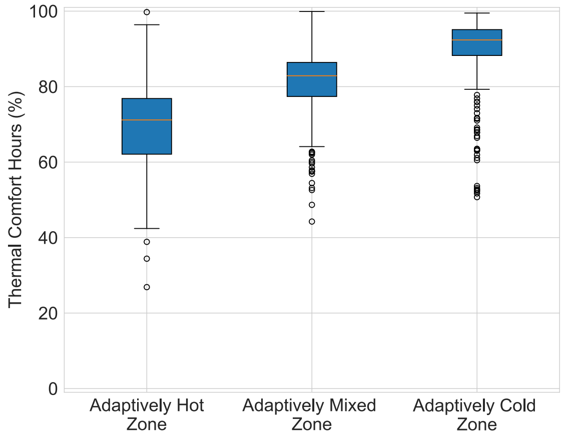
In case of Thermal Discomfort Hours - heating (TDH-h), variation was only observed in the climate zone - ACZ and the median values of TDH-h in AHZ and AMZ are nearly 0% (Figure 5b). This was also expected as ACZ includes regions that require heating to meet the indoor comfort demands. The 25th and 75th percentile values of TDH-h in ACZ are 2% and 6% respectively. The median TDH-c value in ACZ is 4%.

Figure 5c shows the variation of Thermal Discomfort Hours - cooling (TDH-c) for the three climate zones and it could be observed that AHZ shows higher variation of TDH-c with a median value of 38%. The higher TDH-c value in AHZ, compared to other climate zones, was expected as it includes regions that require cooling to meet the indoor comfort conditions. ACZ exhibits comparatively lower variation with the 25th and 75th percentile values being 1% and 11% respectively. The median TDH-c value in ACZ is 3%.

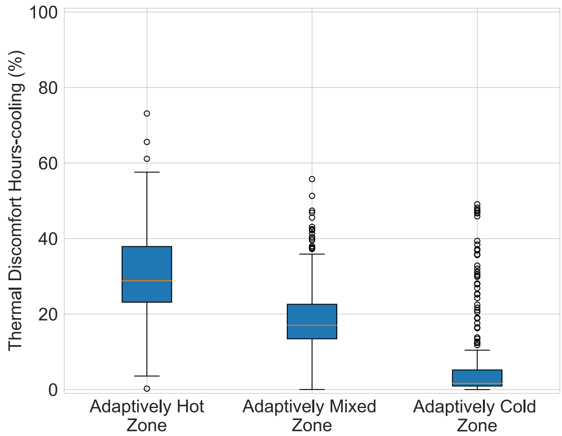
Compared to TCH, visual comfort shows higher variation within each climate zone. Figure 6 presents the box and whisker plots of UDI-c for the different adaptive climate zones of Kerala. The boxes show the 25th-75th percentile (i.e. the interquartile range) and the whiskers are placed at 1.5 times interquartile range. The median and the 25th and 75th percentile UDI values are also presented in Table 2.

The median values of UDI-c for AHZ, AMZ and ACZ are 58%, 67% and 65% respectively (Figure 6a). The results of UA show wider variation for UDI-c and UDI-e. UDI-n shows low variation irrespective of climate zone and has a median value of almost 0%.

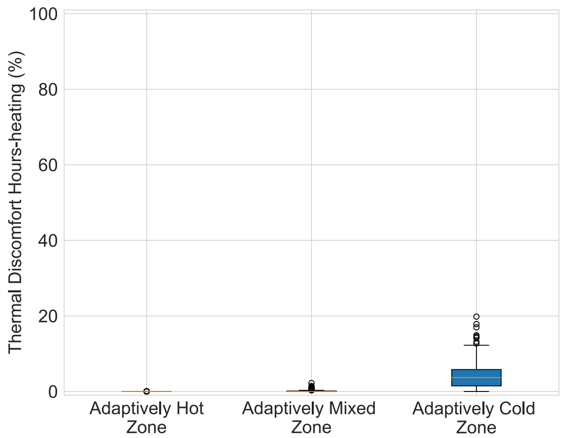
The median values of UDI-c are similar for AMZ (67%) and ACZ (65%) and are higher than that for AHZ (58%). Similarly, the median values of UDI-e are also similar for AMZ (52%) and ACZ (52%) and lower than that of AHZ (58%). This was expected as the AMZ and ACZ regions lie at higher altitudes than the regions in AHZ.




(a) Thermal Comfort Hours



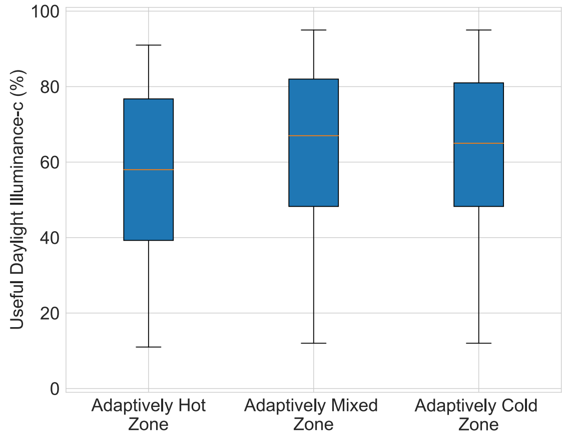

(b) Thermal Discomfort Hours - cooling



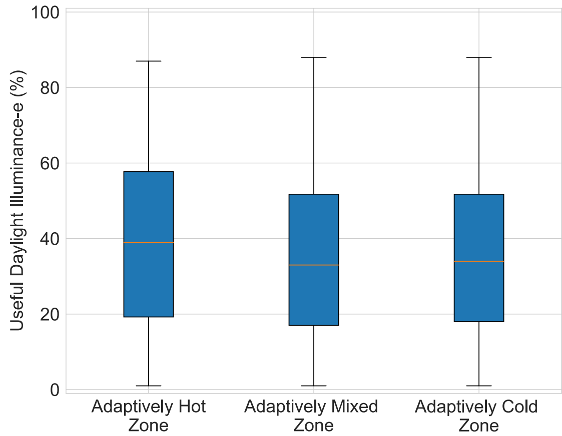

(c)

Thermal Discomfort Hours - heating

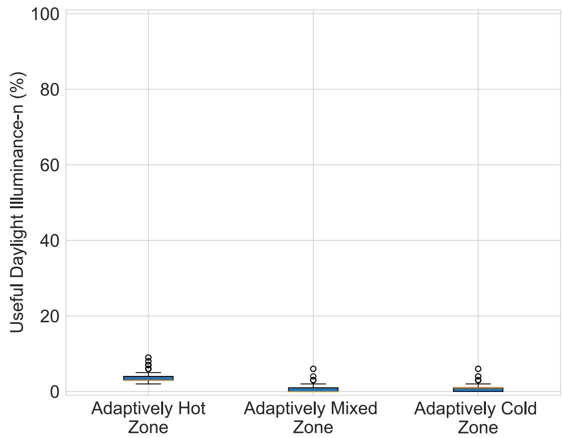
Figure 5: Box and whisker plots of (a) Thermal Comfort Hours (TCH), (b) Thermal Discomfort Hours - cooling (TDH-c) and (c) Thermal Discomfort Hours - heating (TDH-h) for the different adaptive climate zones of Kerala. The bars show the 25th-75th percentile of TCH, TDH-c and TDH-h for the different zones and the whiskers are at 1.5 times interquartile range.




(a) Useful Daylight Illuminance - combined




(b) Useful Daylight Illuminance - exceeded




(c)

Useful Daylight Illuminance - not achieved

Figure 6: Box and whisker plots of (a) Useful Daylight Illuminance-combined (UDI-c), (b) Useful Daylight Illuminance-exceeded (UDI-e) and (c) Useful Daylight Illuminance-not achieved (UDI-n) for the different adaptive climate zones of Kerala. The bars show the 25th-75th percentile of UDI-c, UDI-e and UDI-n for the different zones and the whiskers are at 1.5 times interquartile range.

## 3.2 Sensitivity analysis

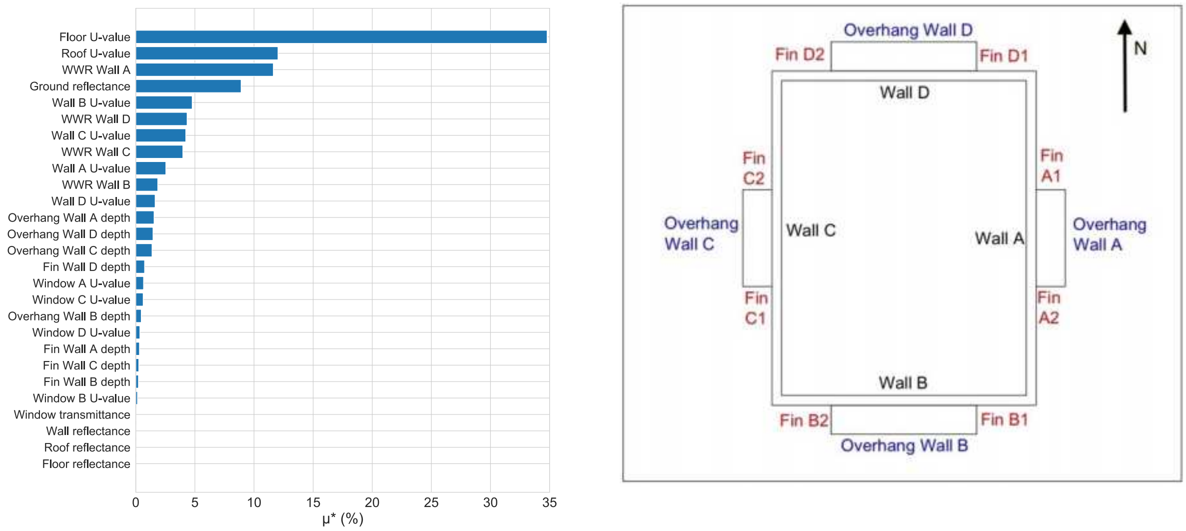
The SA was carried out to identify the design parameters that influence the outcome, i.e. the indoor comfort the most. The Morris analysis method was used to identify the influential design parameters. Figures 7 and 8 present the results of the SA for TCH and UDI-c, respectively, for the different climate zones. The results of SA for UDI-c for AMZ and ACZ were similar and so the figures are not presented in this paper. The design parameters are ranked according to the absolute mean (μ*) of their respective output distribution. The higher the μ* the more sensitive the parameter. The sensitive design parameters for TCH and UDI (μ*> 5) are presented in Table 3. From Table 3, it could be observed that the order of sensitivity varies with climate zone for the different parameters for the TCH whereas for UDI-c, the order of sensitivity of parameters is the same.

Table 2: Results of UA showing the 25th and 75th percentile and median values for TCH and UDI in the three adaptive climate zones.

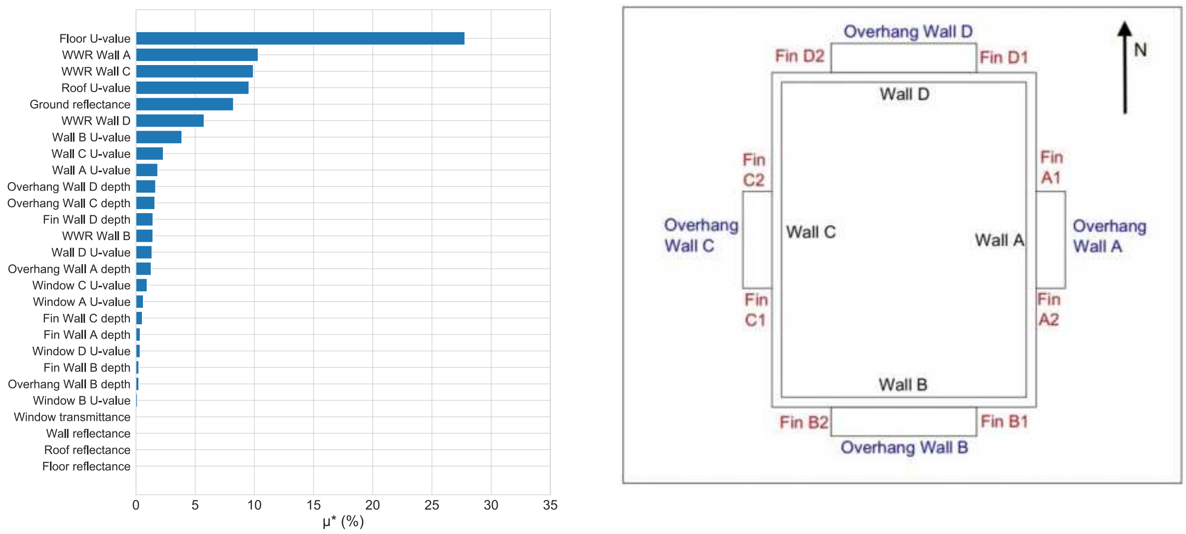
| Climate Zone | Thermal Comfort Hours (%) | | | Useful Daylight Illuminance-combined (%) | | |
|---|---|---|---|---|---|---|
| | 25 percentile | Median | 75 percentile | 25 percentile | Median | 75 percentile |
| Adaptively Hot | 62 | 72 | 77 | 39 | 58 | 77 |
| Adaptively Mixed | 73 | 84 | 86 | 48 | 67 | 82 |
| Adaptively Cold | 83 | 90 | 93 | 48 | 65 | 81 |
| | Thermal Discomfort Hours -cooling (%) | | | Useful Daylight Illuminance-exceeded (%) | | |
| | 25 percentile | Median | 75 percentile | 25 percentile | Median | 75 percentile |
| Adaptively Hot | 23 | 28 | 37 | 19 | 39 | 58 |
| Adaptively Mixed | 13 | 16 | 27 | 17 | 33 | 52 |
| Adaptively Cold | 1 | 2 | 11 | 18 | 34 | 52 |
| | Thermal Discomfort Hours -heating (%) | | | Useful Daylight Illuminance-not achieved (%) | | |
| | 25 percentile | Median | 75 percentile | 25 percentile | Median | 75 percentile |
| Adaptively Hot | 0 | 0 | 0 | 3 | 3 | 4 |
| Adaptively Mixed | 0 | 0 | 0 | 0 | 0 | 1 |
| Adaptively Cold | 2 | 4 | 6 | 0 | 1 | 1 |

Table 3: Results of Sensitivity Analysis. Table shows the design parameters that are most influential ($\mu^*$ > 5) to indoor occupant comfort in the different climate zones.

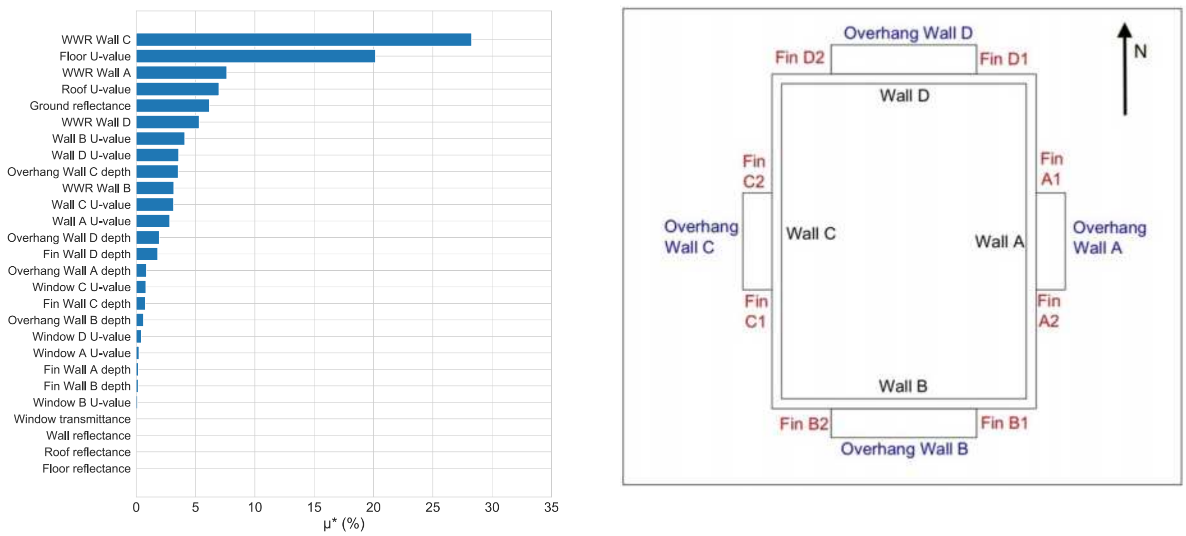
| Indoor Comfort criteria | Adaptively Hot Zone | | Adaptively Mixed Zone | | Adaptively Cold Zone | |
|---|---|---|---|---|---|---|
| | Design parameter | μ* (%) | Design parameter | μ* (%) | Design parameter | μ* (%) |
| Thermal Comfort Hours | Floor U-Value | 34.8 | Floor U-Value | 28 | WWR Wall C | 28.3 |
| | Roof U-Value | 12.0 | WWR Wall A | 10.3 | Floor U-Value | 20.2 |
| | WWR Wall A | 11.6 | WWR Wall C | 9.9 | WWR Wall A | 7.6 |
| | Ground Reflectance | 8.9 | Roof U-Value | 9.5 | Roof U-Value | 7.0 |
| | | | Ground Reflectance | 8.2 | Ground Reflectance | 6.2 |
| | | | WWR Wall D | 5.7 | WWR Wall D | 5.3 |
| Useful Daylight Illuminance -combined | WWR Wall A | 41.2 | WWR Wall A | 40.3 | WWR Wall A | 41.1 |
| | WWR Wall C | 38.3 | WWR Wall C | 38.1 | WWR Wall C | 38.5 |
| | WWR Wall D | 33.5 | WWR Wall D | 34.6 | WWR Wall D | 33.3 |
| | WWR Wall B | 22.1 | WWR Wall B | 21.0 | WWR Wall B | 22.1 |




(a) Thermal Comfort Hours - AHZ




(b) Thermal Comfort Hours - AMZ




(c) Thermal Comfort Hours - ACZ

Figure 7: Results of sensitivity analysis for Thermal Comfort Hours in the three adaptive climate zones.

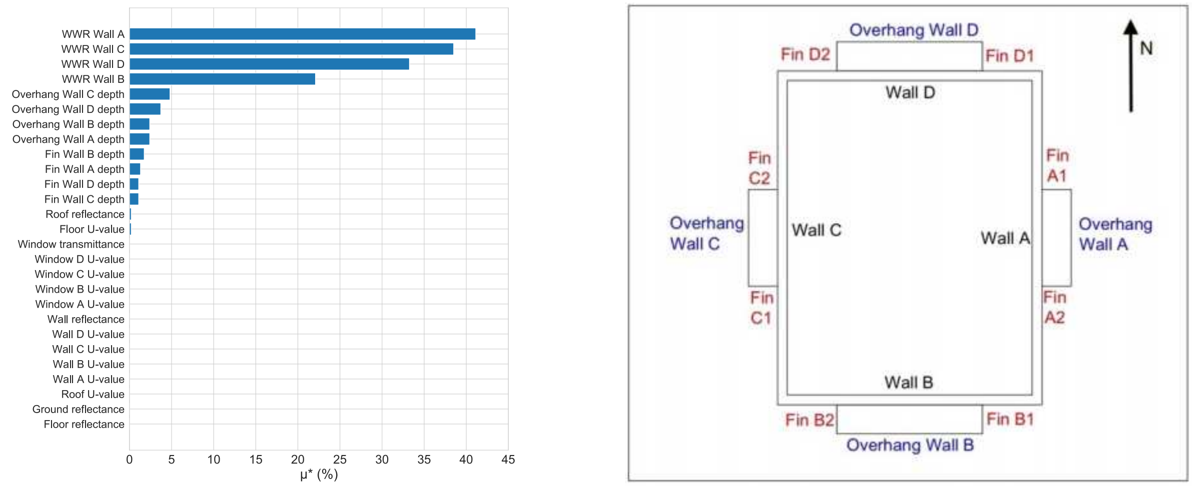


Figure 8: Results of sensitivity analysis for Useful Daylight Illuminance- combined in the adaptively hot climate zones.

## 4. Conclusions

A related previous study (Jayapalan Nair et al., 2019) had introduced a new method of climate zone classification for building performance simulation purposes. This classification system was based on adaptive thermal comfort model and was used to classify the regions in Kerala (India) into three adaptive climate zones namely Adaptively Hot Zone, Adaptively Mixed Zone and Adaptively Cold Zone. Considering that a huge number of buildings are planned to be constructed in Kerala in the very near future, and that the selection of various design parameters depends upon the designer and their preferences and priorities, it is important to understand the variation in the indoor comfort conditions for different design parameters and their realistic ranges.

An uncertainty analysis was conducted to understand this variation. To carry out the analysis, a building representative of the Kerala's building typology was modelled and simulated 250 times for the different design parameters sampled using the Latin-hyper cube sampling method. The simulations were carried out separately for representative locations from each of the adaptive climate zones in Kerala. The indoor occupant comfort was assessed in terms of Thermal Comfort Hours (%) (thermal comfort) and Useful Daylight Illuminance-combined (%) (visual comfort).

From the results of UA, it was observed that the choice of design parameter can account for up to 15% variation in the thermal comfort hours and up to 38% in the useful daylight illuminance- combined. In terms of indoor thermal comfort, the case study building in the climate zone - AHZ showed higher variation (15%) of thermal comfort hours when compared to AMZ (13%) and ACZ (10%). The least variation was observed for buildings in ACZ. Thus, it can be concluded that the choice of design parameter has high influence on the occupant's thermal comfort conditions inside the building and more importance needs to be given while designing buildings in locations that comes under AHZ to provide acceptable thermal comfort inside the buildings and thereby reduce the energy demand for cooling/heating. In terms of visual comfort, the case study building showed high variation of UDI-c irrespective of the climate zones. Thus, the choice of design parameters will highly influence the visual comfort inside the buildings irrespective of the climate zones.

Considering the high variation observed on thermal and visual comfort inside the buildings due to the choice of design parameters, it is important to identify the ones that influence them the most. A sensitivity analysis was conducted to identify those principal parameters that have the most influence on the indoor occupant comfort. The case study building was modelled and simulated 224 times for the different design parameters sampled using the Morris sampling method. The floor U-value, roof U-value, window wall ratio on the East and West facades and ground reflectance were the main sensitive parameters identified as a result of SA on TCH. In case of visual comfort, window wall ratio on the four facades were identified as the most sensitive parameter that needs to be considered. The results of this study will inform designers during the early stages of design process to identify the parameters that needs to be considered to design building that would provide better indoor comfort conditions in the adaptive climate zones of Kerala. It will also allow local authorities to rule out options that are more likely to exceed certain comfort criteria, therefore enabling them to provide recommendations to designers that will consequently build more robust building solutions in the future.

This study forms part of a bigger project aimed to develop a design methodology that will assist designers during the early design stages for the construction of buildings that would exhibit high thermal and daylight performance. The results of this study will be used to develop a web-based design guide where the results from UA will be used to classify the building performance into high, medium and low. Additionally, the results from SA will be used to present the major/principal building parameters that needs to be considered for designing high performance buildings.

## 5. Acknowledgment

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# Geospatial thermal stress assessment and a new bioclimatic classification for Ethiopia

**Belay Zeleke[1] and E. Rajasekar[2]**

[1] Indian Institute of Technology Roorkee, Department of Architecture and Planning, Roorkee, Uttarakhand, India, abeshselom.me@gmail.com;
[2] Indian Institute of Technology Roorkee, Department of Architecture and Planning, Roorkee, Uttarakhand, India, erajas@gmail.com;

**Abstract:** This paper deals with spatial thermal severity variations in Ethiopia and a plausible bioclimatic design zoning using Mahoney's method. The objectives of the study are (a) to geospatially analyse the thermal severity of Ethiopia and evaluate the relevance of existing climate classifications, (b) to present a comparison of thermal stress estimated using different comfort models and (c) to develop a bioclimatic zoning of Ethiopia based on Mahoney's method and present a critical assessment of its merits and demerits. The study focuses on analysing regional thermal stress conditions. By using a high-resolution climate dataset, monthly and annual thermal severity conditions are identified and mapped. The relevance of existing climate classifications in the context of thermal performance is evaluated. The study highlights that the existing agro-ecological zones of Ethiopia are not relevant in predicting thermal stress and deducing thermal performance regulations of buildings. Based on Mahoney's method, geospatial delineation of effective bioclimatic strategies is carried out resulting in 50 bioclimatic zones. A comparison of thermal stresses predicted using Mahoney's method, Adaptive comfort model (ASHRAE 55) and Physiological Thermal Stress (PET) is presented. A significant evidence of association between the three estimates is found. The paper presents a critical assessment of the bio-climatic classification, its merits and demerits for adoption in thermal performance studies.

**Keywords:** thermal stress, climatic classification, bioclimatic zoning, Ethiopia

## 1. Introduction

Reduction of energy demand and improved indoor thermal comfort in residential buildings are achieved through a location-specific decision making considering the climate characteristics (Markus, 1982). Climate zones help different stakeholders such as designers, regulators and policymakers make these decisions (Xiong et al., 2019). Assessment of thermal severity and climate zoning is the precursor to any thermal comfort and energy efficiency measures. This is demonstrated in recent studies conducted in the field (Walsh et al., 2017a), (Naveen Kishore and Rekha, 2018), (Wan et al., 2010), (Xiong et al., 2019), (Rajasekar et al., 2019), (Verichev et al., 2019), and (Walsh et al., 2017b) to name a few. Assessment of thermal stress at a regional and country level is essential in dealing with wide scale climate severity mitigation, adaptation and response programs (WMO and WHO, 2015). Currently available tools and climate datasets can be used to highlight severities and required intervention measures. These tools can be used to make informed decisions in designing policies regarding urban and regional planning, create public awareness about long-term thermal severity conditions, target rapid responses to authorities to extreme weather events and waves, drive the adaptation of designs / community development, and prescribe adaptive measures in the built environment. Landscape planners, environmental managers, public policymakers, architects, planners, and the public can benefit from the outcomes of these analysis.

Thermal severity analysis involves the use of different climate variables. By far, the most frequently used climate variables are outdoor dry bulb temperature and relative humidity. Other derived variables of temperature, such as the diurnal temperature range, is also an essential factor in determining thermal severity. Thorough thermal severity assessments involve several indexes (de Freitas and Grigorieva, 2015) that combine two or more climate variables. For instance, the Physiological Equivalent Temperature (PET) combines temperature, humidity, solar radiation, and wind velocity.

Once the thermal severity conditions are established, ideal indoor environments are identified, and building thermal performance requirements are identified then bioclimatic strategies can be recommended. Bioclimatic design gives preference to the utilization of environmental resources in heating and cooling buildings (Daemei et al., 2019). These design strategies are useful tools in the predesign stage. Bioclimatic analysis can be done on a case-by-case basis for individual locations through bioclimatic charts (Givoni, 1992), Mahoney tables (MAHONEY et al., 1971), or can be used on a broader scale as bioclimatic zones (Pawar et al., 2015), (Mahmoud, 2011), (Roriz et al., 1999).

Many countries have incorporated some form of climate responsive design guidelines, including bioclimatic zoning to optimize indoor comfort while curbing the ever-increasing energy demand for heating and cooling. In a recent review, (Walsh et al., 2017a) reviewed 64 methods adopted by 54 countries. In the current study area, Ethiopia, no climate zones suited for building energy efficiency programs are made.

The objectives of the study are (a) to geospatially analyse the thermal severity of Ethiopia and evaluate the relevance of existing climate classifications, (b) to present a comparison of thermal stress estimated using different comfort models and (c) to develop a bioclimatic zoning of Ethiopia based on Mahoney's method and present a critical assessment of its merits and demerits.

## 2. Methods and Materials

The study focuses on Ethiopia, located in East Africa between 3° - 15° North latitude and 33° - 48° East longitude. Altitude of the country spans from 4533 meters a.s.l. at the highest point in Ras Dejen to 125 meters b.s.l. at the lowest point in the Danakil depression. These variations are the major driving factors in determining the country's significant temperature distinctions. $T_{out\_Amax}$ in Ethiopia ranges from 12°C to 41°C, while the $T_{out\_Amin}$ changes from -6°C to 22.5°C. $RH_{A\mu}$ ranges between 45% and 76%. Additionally, annual mean solar radiation $I_{A\mu}$ fluctuates between 4.73 kWh/m$^2$ to 6.41 kWh/m$^2$.

In this research, geospatial thermal severity assessment of Ethiopia using a high-resolution spatial data is presented. A comparison of thermal severity is performed through Tcomf, PET, and Mahoney's method. The method includes a spatial analysis of monthly climate variables. Based on the above framework, a thermal stress assessment is performed using (a) annual maximum temperature, (b) annual minimum temperature, (c) annual mean temperature, (d) annual mean relative humidity, and (e) annual mean solar radiation. In addition, a climate severity map based on combinations of $T_{out\_A\mu}$, $RH_{A\mu}$, and $I_{A\mu}$ is created. Finally, a bioclimatic design classification through Mahoney's method is performed.

### 2.1. Data types and sources

Analysis of thermal severity involves spatial and temporal aspects. In this research, focus is given to high-resolution spatial data. However, in terms of the temporal aspect only monthly and annual values are considered. The reason for choosing a lower time resolution data is (1) lack of hourly and daily data for a high-resolution spatial extent, and (2) to minimize the amount of redundant information that in later stages will be aggregated into simplified monthly and annual values. Outdoor climate data is acquired from online repositories such as WorldClim (Fick and Hijmans, 2017), CRU (New et al., 2002), Meteonorm, and Energyplus. Plan layouts and construction details for selected housing typology are collected from Addis Ababa Housing Agency. A reference shapefile of Ethiopia is collected from 'GADM.org.'

Table 1. Climate data sources.

| No. | Source | Dataset | Spatial resolution | Time interval | Duration | Format |
|---|---|---|---|---|---|---|
| **1** | **Worldclim2** | **$T_{out\_max}$** | **30"** | **Monthly** | **1970-2000 (average)** | **Raster** |
| | | **$T_{out\_min}$** | " | " | " | " |
| | | **$I_{\mu}$** | " | " | " | " |
| **2** | **CRU CL v. 2.0** | **$RH_{\mu}$** | **10'** | " | **1961-1990** | **ASCII** |
| **3** | **Meteonorm** | **TMY data** | | **Sub-hourly** | | **epw** |

## 2.2. Thermal severity

The thermal environment is one of the factors that influence the comfort, health, and wellbeing of human beings (de Freitas and Grigorieva, 2015). Quantifying the levels of comfort/discomfort under a given set of environmental and human conditions is essential. Thermal severity or climate severity represents both hot discomfort and cold discomfort conditions that occur due to excessive heat, low temperatures, and other climatic factors. Climate severity analysis is vital to identify climate-specific thermal comfort conditions that are experienced in different locations. Assessment of individual climate elements such as temperature sets the stage for further climate classification techniques that require analysing combined interactions between different climate variables. In this context, earlier climate classifications such as the traditional climate zoning of Ethiopia are done using a single parameter in this case topography. According to the traditional climate zoning, the country is divided into six groups. This method is essential in highlighting temperature variations occurring due to topographical differences. In the current study, thermal stress is analysed through the direct use of climate data instead of secondary measurements such as altitude.

## 2.3. The Mahoney's Method

Mahoney's method recommends passive design strategies based on a thermal stress analysis using monthly temperature, relative humidity and precipitation. This method offers systematic procedures presented as a series of tables. In step one, monthly climate data ($T_{out\_max}$, $T_{out\_min}$, $RH_{\mu}$, and Rainfall) is tabulated. In the next step, annual and monthly temperature ranges, as well as annual mean temperature ($T_{out\_A\mu}$), are calculated. In the third stage, monthly mean relative humidity values are categorized into four groups. RH values <30% are considered as group 1, RH < 50% and > 30% are classified as group 2, group 3 includes RH between 50% and 70%, and finally group 4 represents RH > 70%. In a similar fashion, AMT values are classified into three groups ($T_{out\_A\mu}$ > 20°C = G1, $T_{out\_A\mu}$ < 20°C and > 15°C = G2, and $T_{out\_A\mu}$ < 15°C = G3). In step four, comfort temperature limits are set through crosschecking $T_{out\_A\mu}$ groups and $RH_{\mu}$ groups. Mahoney created the comfort bands through a survey conducted in Nigeria considering the most comfortable months during day and night (Evans, 2007). In step five, thermal stress is determined by comparing the comfort band with monthly maximum and minimum temperatures for daytime and nighttime conditions and three thermal conditions (hot, comfortable, and cold) are identified (Rabah and Mito, 2003). In step six, a list of indicators or remedial actions is prescribed.

The final step of this method is counting the frequency of occurrence of an indicator and bioclimatic design recommendations. For instance, if the indicator A1 occurs for 0-10 months, north to south orientation is prescribed. Accordingly, depending on each locations disposition suitable design recommendations are selected from 23 strategies. One aspect of Mahoney's method that is considered as a limitation is it neglects the effects of solar radiation on thermal stress as well as resulting design strategies. In this paper, solar radiation groups are created from monthly mean solar radiation values and results are overlaid on the resulting bioclimatic strategy groups. This is essential in identifying sources of heating in cold climates that receive better solar radiation.

## 3. Results and Discussion

### 3.1. Spatial assessment of climate severity

Outdoor temperature is one of the critical environmental factors studied to determine the climate severity of a place. Figure 1 presents yearly maximum and minimum temperature representing the peak daytime and peak nighttime severity conditions, respectively. As shown in figure 1a, $T_{out\_Amax}$ is higher in lowland areas indicating hot discomfort, while $T_{out\_Amin}$ is severe on the plateaus (Figure 1b).

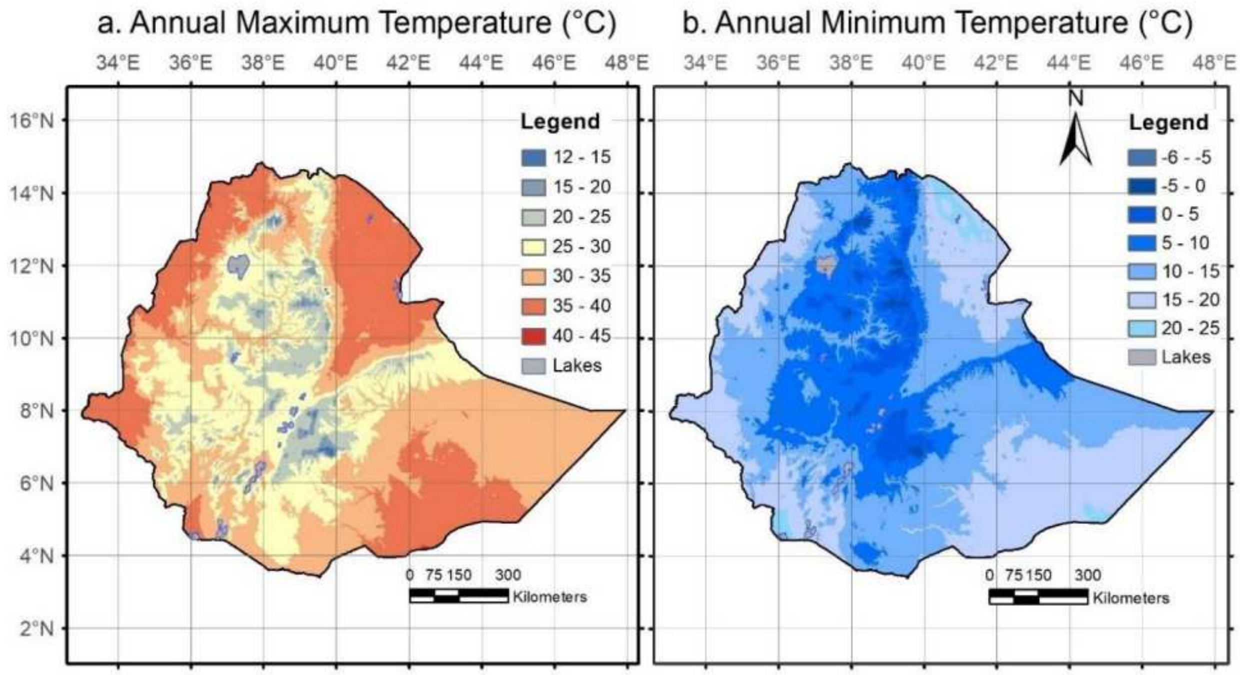


Figure 1. Annual maximum and minimum temperature profile

Another climate variable essential in climate severity analysis is relative humidity. This variable is ignored in the derivation of current climate classifications in Ethiopia. There is an east to west divide of annual mean relative humidity (Figure 2a). High solar radiation is also prevalent in the northern and eastern parts of the country (Figure 2b).

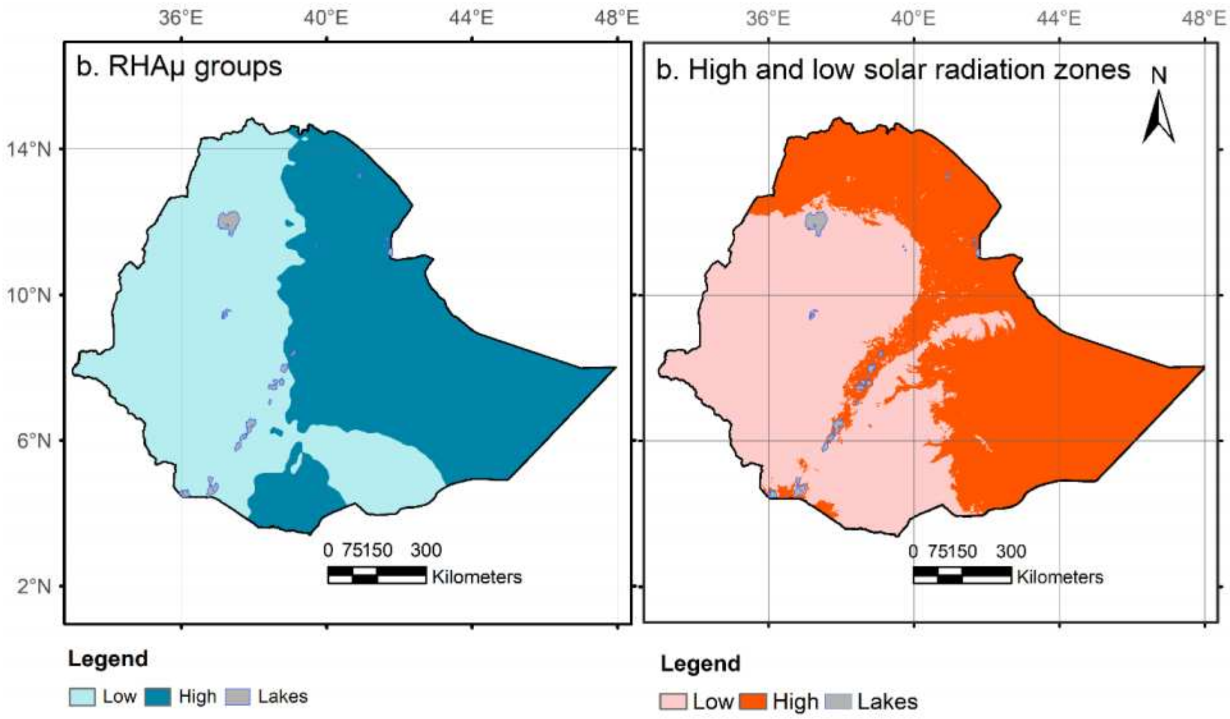

Figure 2. Climate severity based on $RH_{A\mu}$ and $I_{A\mu}$

### 3.1.1. Integrated assessment of thermal severity

To highlight the effect of combined climate variables and their distribution, a statistically based climate partitioning is used. The authors previously used this method on the sub-classification of Indian cold climate (Rajasekar et al., 2019). In the current analysis, the annual mean temperature of Ethiopia is segmented into five groups. The cut-off points are taken from the minimum, first quartile, median, third quartile, and maximum values. $RH_{A\mu}$ and $I_{A\mu}$ each are split into two groups at their median values. Finally, these groups are combined to create an integrated climate severity map of the country (Figure 3).

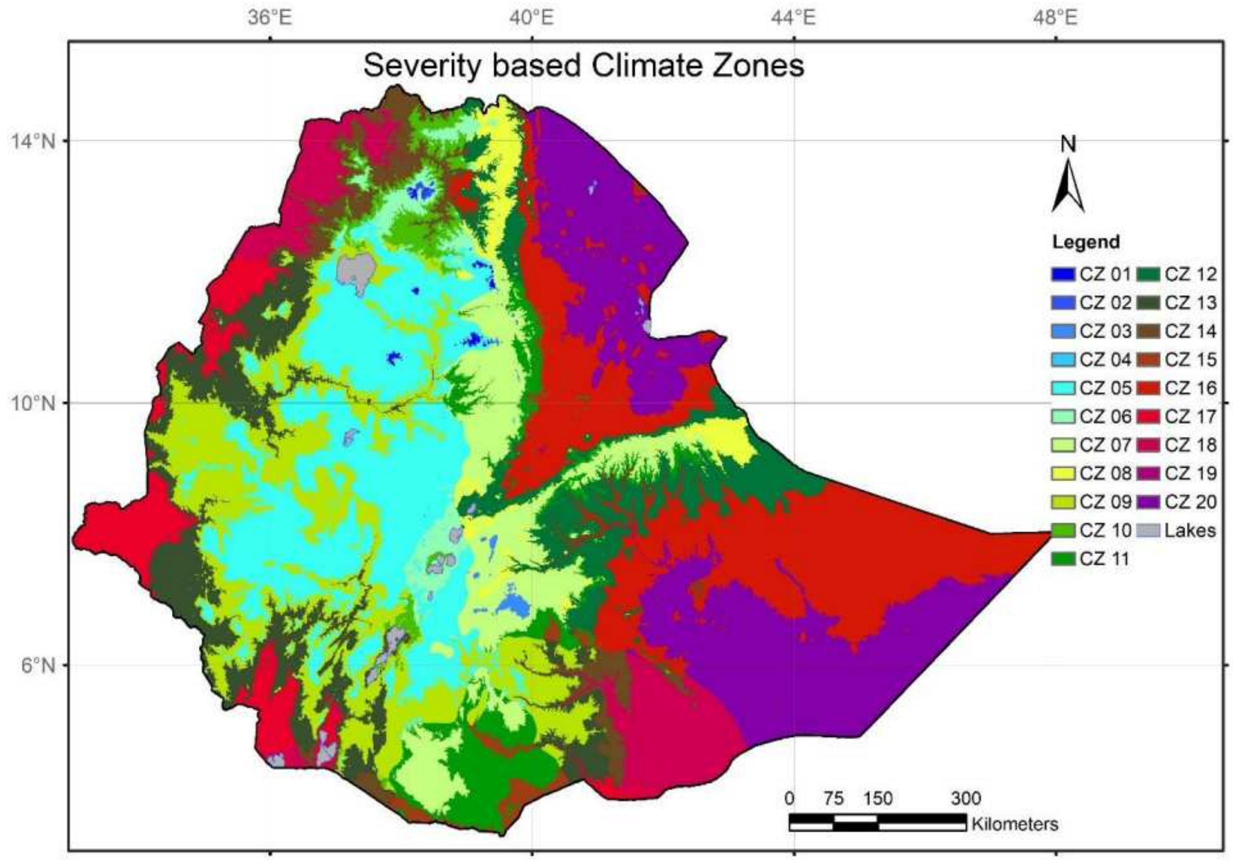


Figure 3. Severity based climate classification.

Table 2. presents the climate summary of the integrated climate severity map. In this regard, CZ 01 is characterized by very cold annual mean temperature (<10°C), low relative humidity (<60%), and low solar radiation. On the other end, CZ 20 represents places that are hot, humid and high solar radiation at $T_{out\_A\mu}$ > 26°C, RH > 60%, and $I_{A\mu}$ > 5.62 kWh/m$^2$. An areawise comparison indicates the coverage of severely cold dry areas is minimum as compared to hot humid and sunny places, the latter has 129 times more area (Figure 3).

Table 2. Summary of severity based climate zones

| Climate Zone | $T_{out\_A\mu}$ (°C) | $RH_{A\mu}$ (%) | $I_{A\mu}$ (kWh/m$^2$) | Remark |
|---|---|---|---|---|
| CZ 01 | < 10 | < 60 | < 5.62 | Very Cold, Dry, low solar radiation |
| CZ 02 | " | " | > 5.62 | Very Cold, Dry, high solar radiation |
| CZ 03 | " | > 60 | < 5.62 | Very Cold, Humid, low solar radiation |
| CZ 04 | " | " | > 5.62 | Very Cold, Humid, high solar radiation |
| CZ 05 | 10 - 19 | < 60 | < 5.62 | Cold, Dry, low solar radiation |
| CZ 06 | " | " | > 5.62 | Cold, Dry, high solar radiation |
| CZ 07 | " | > 60 | < 5.62 | Cold, Humid, low solar radiation |
| CZ 08 | " | " | > 5.62 | Cold, Humid, high solar radiation |
| CZ 09 | 19 - 23 | < 60 | < 5.62 | Moderate, Dry, low solar radiation |
| CZ 10 | " | " | > 5.62 | Moderate, Dry, high solar radiation |
| CZ 11 | " | > 60 | < 5.62 | Moderate, Humid, low solar radiation |
| CZ 12 | " | " | > 5.62 | Moderate, Humid, high solar radiation |
| CZ 13 | 23 - 26 | < 60 | < 5.62 | Warm, Dry, low solar radiation |
| CZ 14 | " | " | > 5.62 | Warm, Dry, high solar radiation |
| CZ 15 | " | > 60 | < 5.62 | Warm, Humid, low solar radiation |
| CZ 16 | " | " | > 5.62 | Warm, Humid, high solar radiation |
| CZ 17 | > 26 | < 60 | < 5.62 | Hot, Dry, low solar radiation |
| CZ 18 | " | " | > 5.62 | Hot, Dry, high solar radiation |
| CZ 19 | " | > 60 | < 5.62 | Hot, Humid, low solar radiation |

| | | | | |
|---|---|---|---|---|
| **CZ 20** | “ | “ | **> 5.62** | **Hot, Humid, high solar radiation** |

## 3.2. Spatial assessment of thermal comfort

### 3.2.1. Evaluation of adaptive comfort temperature

According to ASHRAE 55 standard, Comfort temperature or neutral temperature is defined as “the indoor thermal index value corresponding with a mean vote of neutral on the thermal sensation scale” (ANSI/ASHRAE, 2004). The thermal index value refers to the operative temperature that is considered as “thermally neutral by the largest proportion of a group of people” (Nicol and Humphreys, 2010).

Daytime thermal stress is computed from $T_{out\_max}$ using de Dear and Brager’s equation (De Dear and Brager, 2002). Additionally, nighttime thermal stress is calculated from $T_{out\_min}$, and later results are compared with Mahoney’s thermal stress. As indicated in figure 4, the central highland areas have a lower comfort temperature as compared to North Eastern low lands. It is also apparent that in most of the country, seasonal changes bring about a change in comfort temperature. However, in Gambella as well as parts of the Somali regional state, comfort temperature maintains the same levels during summer and winter months.

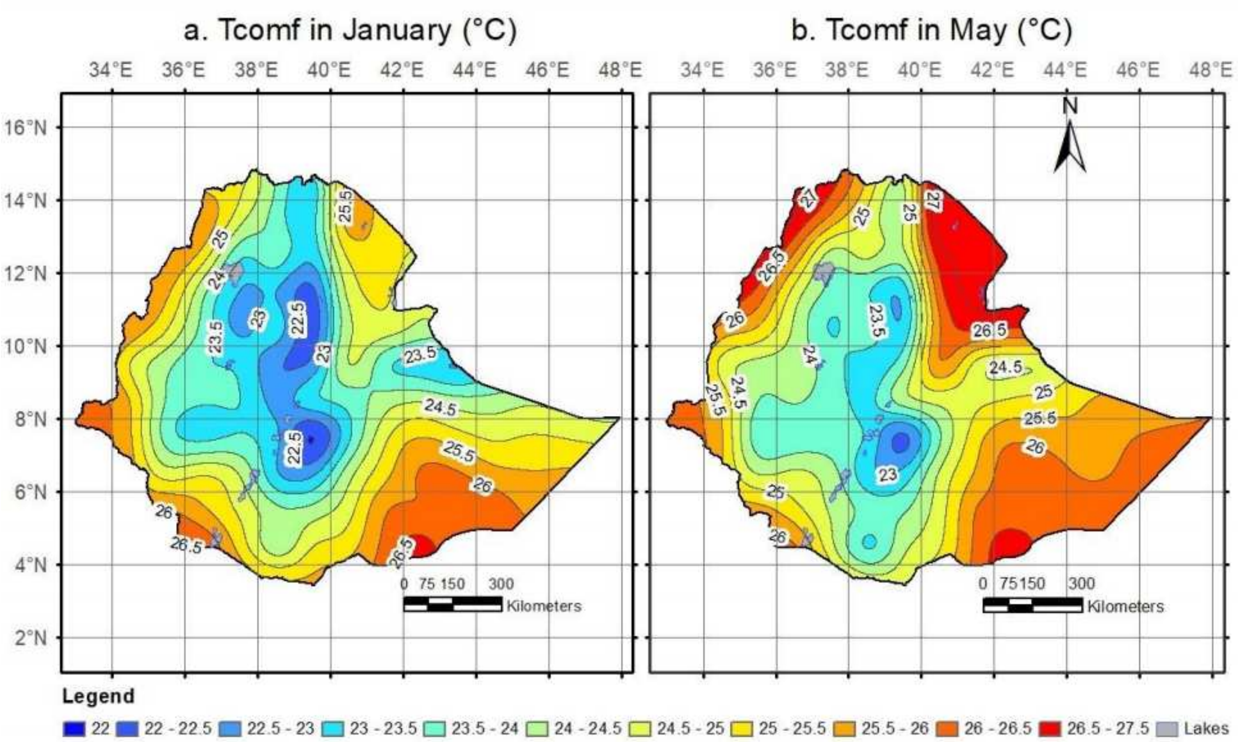


Figure 4. Adaptive comfort temperature during (a) January and (b) May

### 3.2.2. Evaluation of Physiological equivalent temperature

PET is the estimate of equivalent temperature for an isothermal reference environment at which the heat balance of a reference person is maintained (Höppe, 1999). For indoor settings, PET assumes the reference person to have a metabolism rate of 80W, and clothing insulation of 0.9 clo. Monthly PET values can be useful in understanding a location’s extreme thermal severity conditions. However, annual PET is also essential to have a simplified climate characterization of a place. For example, (Daneshvar et al., 2013) calculated the annual mean PET for Iran.

The computation of PET involved the following steps: (1) physiologically equivalent temperature is calculated for a typical day of each month using the RayMan tool. (2) The categories of stress for each month are reclassified using spatial analysis software. The levels of thermal stress were condensed from a 9-class scale (very cold, cold, cool, slightly cool, comfortable, slightly warm, warm, hot, and very hot) to a 3-class scale before statistical comparison. The middle three classes were considered as comfortable in the new 3-class categorization.

PET in Ethiopia is higher during winter such as in November exceeding 41°C (Figure 5, left). In a typical summer month (Figure 5, right) majority of the highland areas which are 1500 meters a.s.l. are either comfortable or have a cold discomfort. However, the lowland desert around the Dallol depression experiences hot and very hot stress during both seasons.

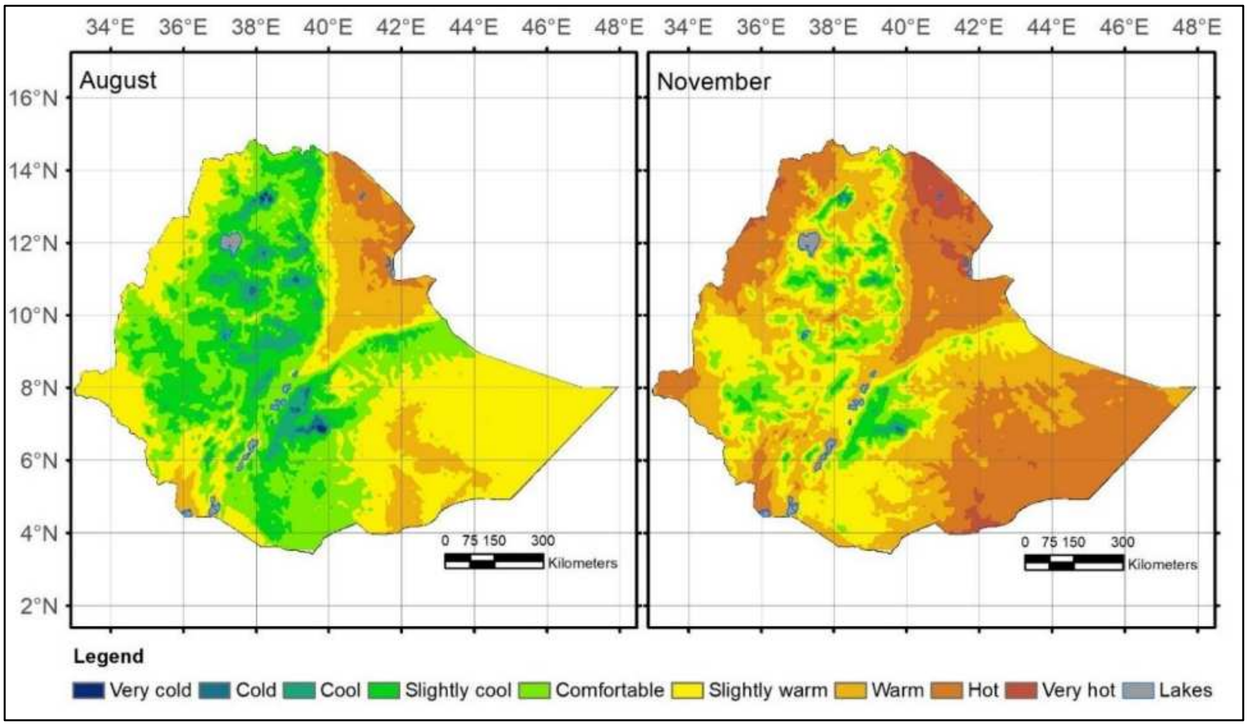


Figure 5. Typical winter month and summer month PET.

### 3.2.3. Evaluation of Mahoney's thermal comfort

Daytime thermal severity for each month is determined by comparing $T_{out\_max}$ with daytime comfort upper and lower limits. The same analysis for nighttime stress is done by taking $T_{out\_min}$ and nighttime comfort limits set according to table 1. In the current study, the analysis is done on multiple locations through the use of spatial data and the results are presented as distribution maps indicating different levels of thermal stress at once.

Figure 2a presents daytime thermal stress in January. While 53% of Ethiopia shows no daytime stress in January, hot stress is more prevalent with 45% than cold stress, which covers below 2%. On the other hand, cold stress is more predominant during nighttime covering 74% of the country (Figure 2b).

In summer conditions, the daytime thermal severity conditions stay relatively similar to that of January; however, during nighttime, only 46% of areas are under cold stress. Areas covered under nighttime hot stress increases from less than 1% in January to 6.2% in June.

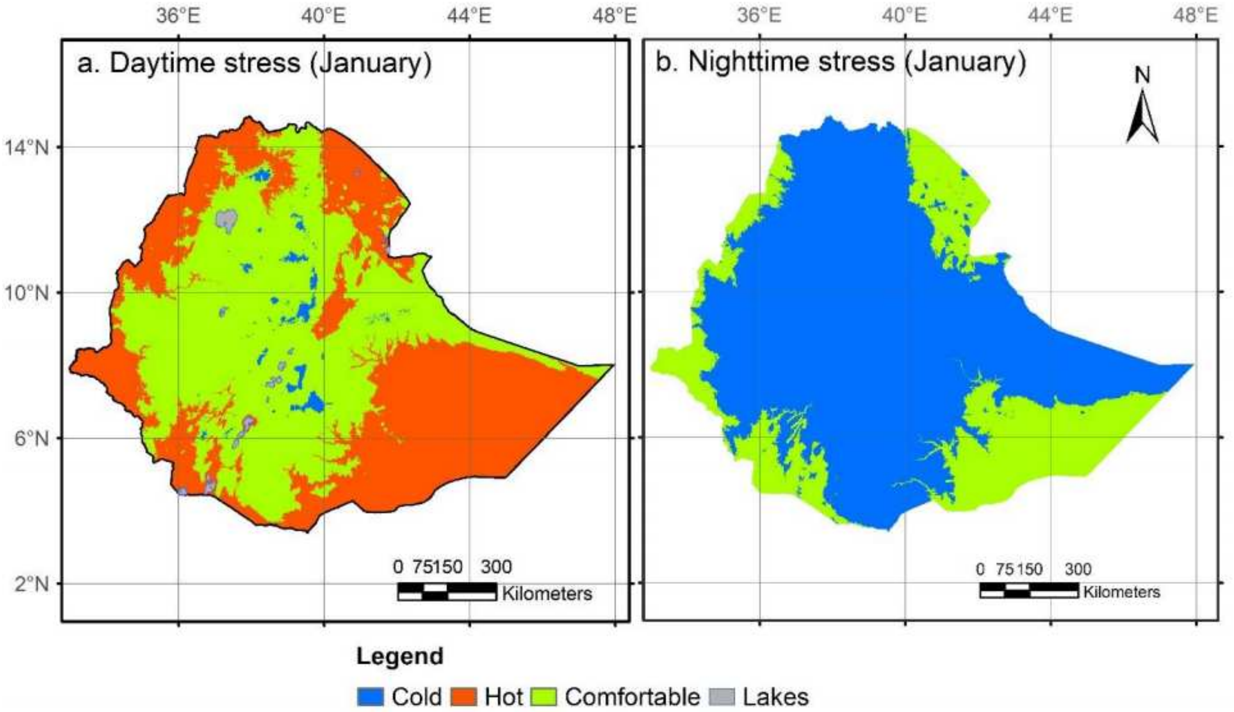


Figure 6. Mahoney's thermal stress in January during (a) daytime and (b) nighttime

Monthly comfort conditions combined with temperature range and humidity group are essential in determining remedial actions that are listed as arid and humid as indicated in table 2. However, by combining monthly thermal stress conditions, we can create a thermal severity classification that shows the type of stress coupled with duration throughout the year. Such a climate severity classification is presented in figure 3. The number of months under hot stress (figure 3a) and cold stress (figure 3b) are presented separately.

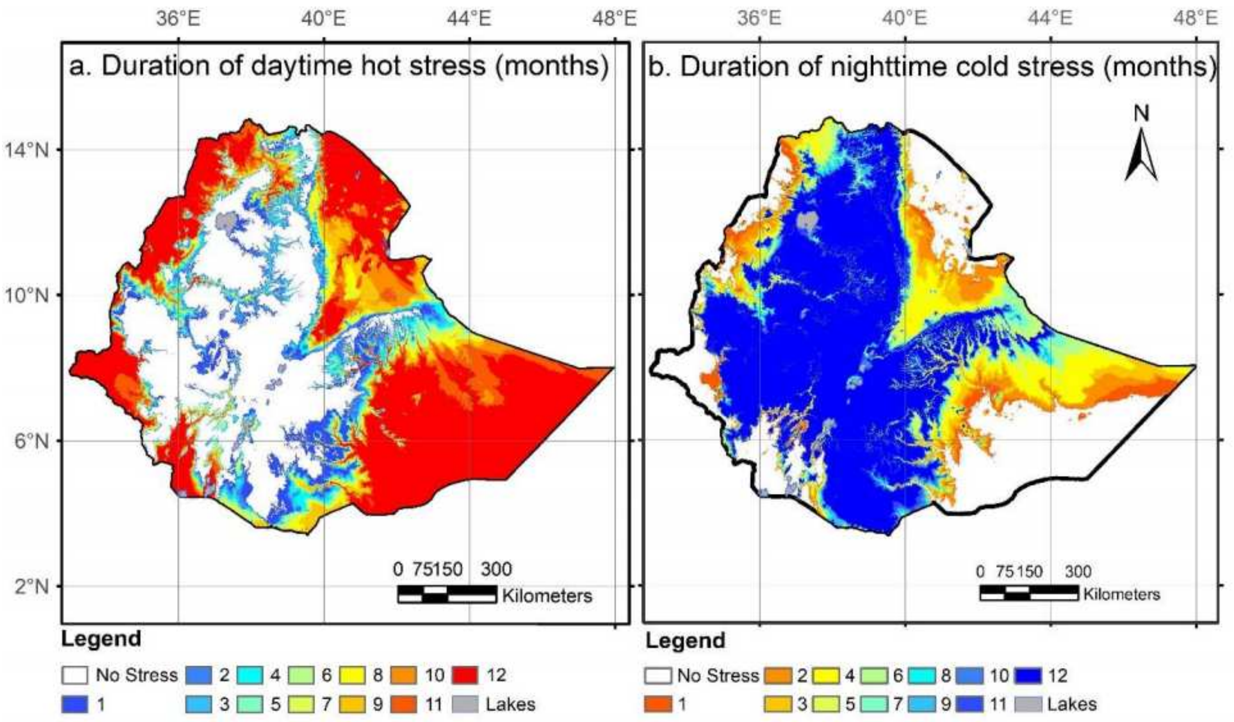


Figure 7. Annual thermal stress (a) daytime hot stress and (b) nighttime cold stress

### 3.2.4. Comparative analysis of thermal severity

A direct comparison is made between thermal severities predicted through the above methods. As a starter, results are converted to a uniform 3-scale measurement. The level of similarity among these outputs is then tested through the Pearson Chi-square test. The result indicates, at the 0.5 level, there is significant evidence of association between thermal severity conditions predicted using adaptive comfort temperature and thermal stress based on the Mahoney's method. Similar results are observed between PET-based thermal severity and that of Mahoney's method.

The comfort class predicted by the three methods indicate a good agreement. A state-level comparison of thermal stress for a typical summer and winter month is presented in table 3. In all three indicators, cold discomfort covers less than 5% of the country during winter.

Table 3. Percentage of areas under hot, cold, and comfortable conditions by regional state predicted through three methods

| % within Regional state | | Mahoney's daytime stress | | | Adaptive comfort | | | PET | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | **Cold** | **Hot** | **Comfo-rtable** | **Cold** | **Hot** | **Comfo-rtable** | **Cold** | **Hot** | **Comfo-rtable** |
| **Addis Ababa** | **Winter** | **1.4%** | | **98.6%** | **29.8%** | | **70.2%** | | | **100.0%** |
| | **Summer** | | | **100.0%** | **29.3%** | | **70.7%** | **13.6%** | | **86.4%** |
| **Afar** | **Winter** | | **67.9%** | **32.1%** | **0.0%** | **54.9%** | **45.1%** | | **81.1%** | **18.9%** |
| | **Summer** | | **99.8%** | **0.2%** | | **99.7%** | **0.3%** | | **96.6%** | **3.4%** |
| **Amhara** | **Winter** | **4.7%** | **19.3%** | **76.0%** | **15.4%** | **24.7%** | **59.9%** | **1.6%** | **19.9%** | **78.4%** |
| | **Summer** | **1.6%** | **36.5%** | **62.0%** | **14.8%** | **34.0%** | **51.2%** | **12.1%** | **3.6%** | **84.3%** |
| **Benishangul Gumuz** | **Winter** | | **57.8%** | **42.2%** | **0.0%** | **82.7%** | **17.3%** | | **57.8%** | **42.2%** |
| | **Summer** | **0.4%** | **46.0%** | **53.6%** | **1.2%** | **46.0%** | **52.8%** | **0.3%** | | **99.7%** |
| **Dire Dawa** | **Winter** | **0.2%** | | **99.8%** | **2.9%** | | **97.1%** | | **10.2%** | **89.8%** |
| | **Summer** | | **66.9%** | **33.1%** | **0.1%** | **66.9%** | **33.0%** | | **13.1%** | **86.9%** |
| **Gambella** | **Winter** | | **89.9%** | **10.1%** | | **95.2%** | **4.8%** | | **70.6%** | **29.4%** |
| | **Summer** | | **90.5%** | **9.5%** | **0.9%** | **90.5%** | **8.6%** | **0.0%** | | **100.0%** |
| **Harari** | **Winter** | | | **100.0%** | **5.7%** | | **94.3%** | | | **100.0%** |
| | **Summer** | | | **100.0%** | | | **100.0%** | | | **100.0%** |
| **Oromia** | **Winter** | **2.3%** | **13.7%** | **84.0%** | **9.5%** | **26.5%** | **64.0%** | **1.0%** | **20.6%** | **78.4%** |
| | **Summer** | **2.5%** | **13.3%** | **84.2%** | **13.6%** | **12.7%** | **73.7%** | **7.3%** | **1.3%** | **91.4%** |
| **Somali** | **Winter** | | **80.2%** | **19.8%** | **0.0%** | **81.4%** | **18.6%** | | **92.6%** | **7.4%** |
| | **Summer** | | **87.0%** | **13.0%** | | **86.5%** | **13.5%** | | **13.3%** | **86.7%** |
| **SNNP** | **Winter** | **0.9%** | **30.3%** | **68.7%** | **4.6%** | **51.4%** | **44.0%** | **0.1%** | **28.3%** | **71.6%** |
| | **Summer** | **5.2%** | **21.1%** | **73.7%** | **14.6%** | **21.1%** | **64.3%** | **6.1%** | **4.6%** | **89.3%** |
| **Tigray** | **Winter** | **0.1%** | **51.8%** | **48.1%** | **5.0%** | **53.2%** | **41.7%** | **0.0%** | **40.4%** | **59.5%** |
| | **Summer** | **0.0%** | **74.2%** | **25.7%** | **0.4%** | **70.2%** | **29.4%** | **0.6%** | **22.5%** | **76.9%** |
| **Country total** | **Winter** | **1.4%** | **44.7%** | **53.9%** | **5.5%** | **51.7%** | **42.8%** | **0.5%** | **50.0%** | **49.4%** |
| **Country total** | **Summer** | **1.5%** | **51.3%** | **47.3%** | **7.5%** | **50.4%** | **42.1%** | **4.4%** | **14.2%** | **81.4%** |

It needs to be noted that, adaptive comfort and PET are based on worldwide studies. The Mahoney's comfort class is derived from field studies in Nigeria that with comparable climatic and cultural conditions to that of the study area. Hence, in this study Mahoney's comfort class is adopted for further analysis.

### 3.3. Bioclimatic classification through Mahoney's method

#### 3.3.1. Remedial actions (Indicators)

Six general remedial actions are identified for every month and are aggregated. Figure 8 presents the annual aggregates of each indicator showing the number of months a particular remedial action is required in each geographic location. The sixth remedial action (H3) is omitted here because it solely depends on precipitation values and is only used to determine the requirements of rain protection in buildings. As indicated in figure 4A1, thermal capacity is required across the country at least for a month. Additionally, a significant portion of the country demands a high thermal capacity building. On the other hand, only a few patches of highland areas require protection from cold in addition to high thermal capacity.

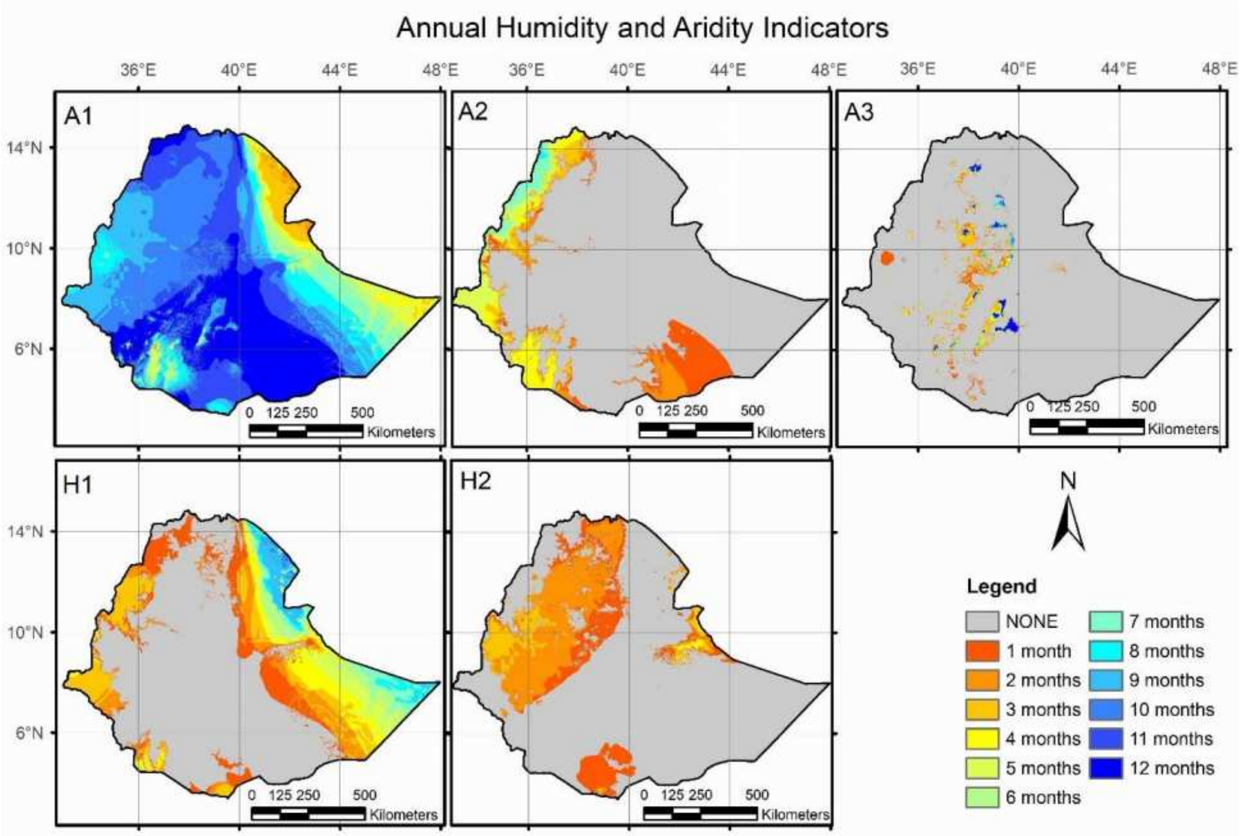


Figure 8. Humidity (H1, H2) and aridity (A1, A2, A3) indicators

#### 3.3.2. Bioclimatic Zoning

Depending on the duration of particular remedial actions required in every location, bioclimatic strategies are recommended. Maps showing the required strategies are prepared for individual categories. For example, the first category (layout) includes two design strategies (1) long axis facing East-West, and (2) compact courtyard planning (Figure not included). Similarly, seven other categories are mapped separately. Finally, these layers are added using a value notation system to prepare the Mahoney's bioclimatic zoning map. However, the final classification involves a further climate analysis of solar radiation. This classification is done under the assumption that a bioclimatic zone exhibiting different levels of solar radiation will also result in varying thermal performance of buildings. This assumption is tested through sol-air temperature analysis as well as simulation conducted on sample locations from the same bioclimatic zone. The results show a variation in building thermal performance due to difference in solar radiation levels. Based on these results, a new bioclimatic classification that combines building design strategy zones, as well as solar radiation groups, is proposed (Figure 9).

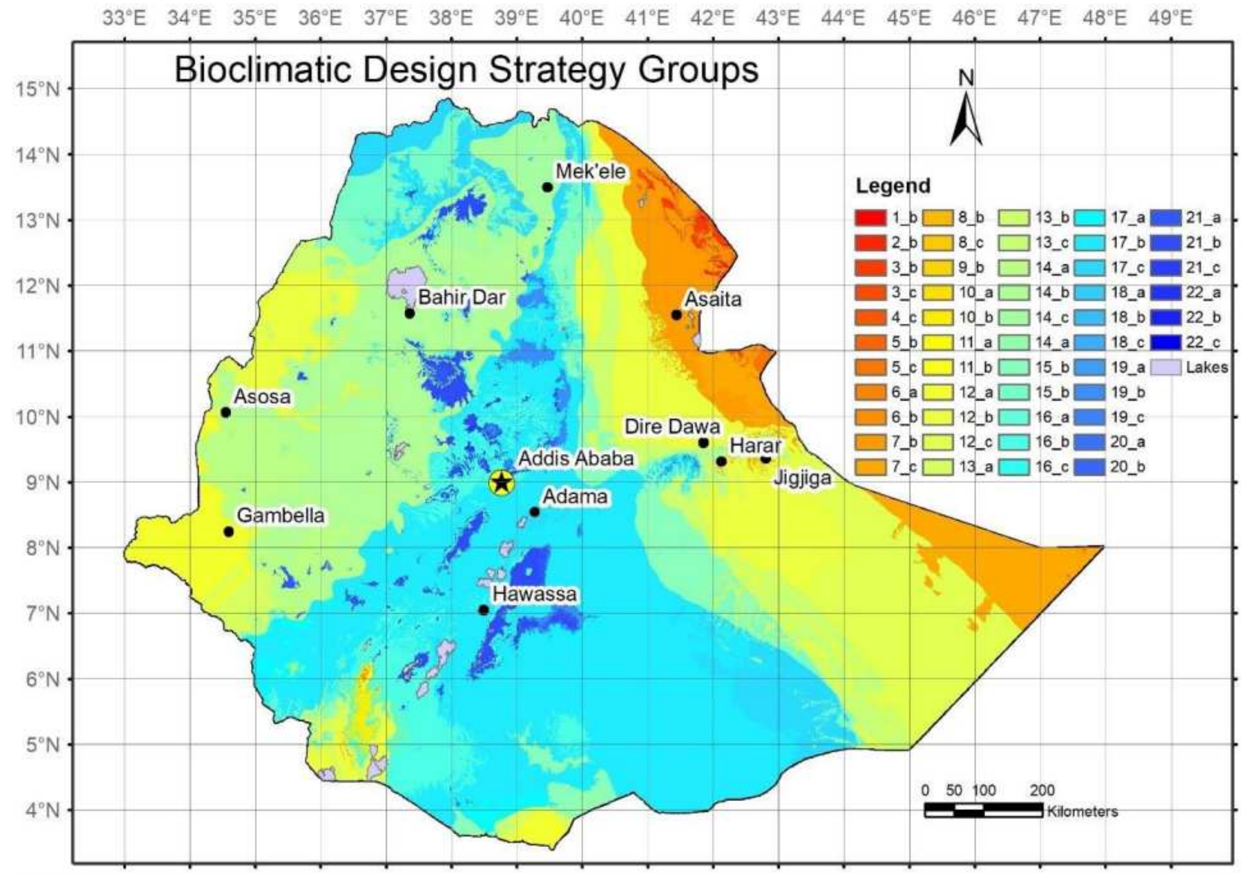


Figure 9. Bioclimatic zones based on a combination of Mahoney's classification and solar radiation groups

Suitability of existing climate classifications for building energy efficiency programs is assessed through a cross-tabulation between bioclimatic strategy groups and Köppen climate zoning. The result affirms there is little to no association between Köppen zones and Mahoney's bioclimatic zones. For instance, climate zones covering a large area (Aw climate zone 357,734 km$^2$) included as many as 16 bioclimatic strategy groups, while smaller climate zone areas (Cfa 107 km$^2$) contained only 2 of the bioclimatic strategy groups.

## 4. Conclusions

This paper presented an integrated assessment of thermal severity that incorporates three climate variables. During the daytime, geospatial thermal severity in Ethiopia is dominated by a hot discomfort (Figure 1a). Cold spots are limited to mountain ranges of Semien mountains and Bale mountain. It also offered a comparative investigation of thermal severity in Ethiopia based on $T_{comf}$, PET and Mahoney's method. Thermal stress predicted by $T_{comf}$ overestimates cold discomfort while maintaining an overall similarity with Mahoney's method (Table 3). At a country level, PET-based stress estimates disparities between winter and summer hot discomfort. Current climate classifications in Ethiopia are based on agro-ecological climate delineations and are unsuitable for thermal comfort and energy efficiency programs. A high-resolution bioclimatic design zoning of Ethiopia is presented, resulting in 50 strategy group zones (Figure 9). In pursuit of a robust bioclimatic map, a trade-off is made to keep all zones that reduced readability. For increased readability and lesser zone count, a generalization of bioclimatic zones to the smallest administrative boundaries is recommended. The results from this research can be used to facilitate both indoor and outdoor thermal stress mitigation, take necessary adaptiation measures at a pre-design stage, and identify hotspots for timely response. Community housing schimes in Ethiopia such as the Integrated Housing Development Program (IHDP) and similar countrywide projects can be targeted as a pilot in the implementation.

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# Sensitivity Analysis of Windows and Shadings Control on Cooling Load Simulation for Australian House Energy Rating

**Siti Aisyah Damiati[1], Veronica Soebarto[1], Terence Williamson[1], Zhengdong Chen[2]**

[1] School of Architecture and Built Environment, The University of Adelaide, Adelaide, Australia;
[2] CSIRO Energy, Melbourne, Australia

**Abstract:** As global warming intensifies, appropriate policies are needed to encourage passive and energy efficient designs without sacrificing thermal comfort in buildings. Amongst building typologies, the residential sector has the highest energy demand growth, mostly caused by the introduction of new electrical appliances, with HVAC systems being the largest contributor. The Australian Nationwide House Energy Rating Scheme (NatHERS) aims to promote energy efficiency by rating houses based on annual heating and cooling load. However, houses with typical design components in warm climates are estimated by NatHERS to have higher cooling loads, thus lower house energy rating compared to identical houses in cooler climates. There are also gaps found between monitored energy consumption and simulation results, most markedly in individual projects, due to NatHERS assuming equivalent user behaviour across climates. This paper investigates the sensitivity of user behaviour related to their control on windows and blinds against cooling load calculation using AccuRate Sustainability, a NatHERS-certified computer simulation software. The quantified sensitivity of windows and blinds control are applied in cooling and free-running modes. The results for both modes showed that the lowest cooling loads and cooling degree hours can be achieved through the optimum usage of internal shading devices.

**Keywords:** occupant behaviour, cooling load, thermal performance simulation

## 1. Introduction

Thermal performance simulation tools have been developed across the globe and over many years to assist in assessing buildings' energy efficiency. In Australia, the Nationwide House Energy Rating Scheme (NatHERS) uses computational simulation tools to rate residential buildings on a 10-star scale, based on energy efficiency performance provisions in the National Construction Code (NCC) (ABCB, 2019). While energy rating is not the only method to comply with NCC, it is a recommended method considering the breadth of design improvement and innovation possible using the method, vis-a-vis other methods such as elemental provisions.

A star rating is awarded to a house based on its predicted total heating and cooling load, which has specific benchmarks depending on the climate zone where the house is built. The load is calculated from design and construction elements such as building envelope materials and dimensions, insulation, house orientation, and local climate. In this calculation, as with other building performance simulations, the user characteristics are assumed to be typical or standardised.

The standardised user characteristics, including their occupancy profiles and adaptive behaviours, are implemented in NatHERS to provide a fair assessment and simplify the process, as user characteristics are too variable to be accurately modelled. However, this assumption could be the cause of large gaps between monitored and simulated energy use in Australian homes. Using Chenath engine, the residential energy use simulations can accurately predict energy use in homes on an average basis, but it performs poorly on individual projects (Ren, Chen and James, 2018).

It is undeniable that building occupants play a key role in determining energy consumption. Therefore, to properly assess a building's energy usage, studies about user characteristics will be a valuable factor to weigh in a building performance simulation. Due to the complexity of user characteristics, it is a logical step to start a study of energy usage-related occupant behaviours. Studies developing models for these behaviours are categorised based on the object, which can be a feature that is a part of house design and does not require electricity to operate, such as windows and operable shading devices.

This study investigates the sensitivity of different user behaviours related to windows and shadings operation on cooling load calculation using AccuRate Sustainability (Energy Inspection, 2019).

## 2. Methodology

This study is conducted using AccuRate Sustainability software version 2.3.3.13 SP4. User behaviour settings are mostly unchangeable in the software, so most the changes are made in a scratch file that is generated by the AccuRate simulation engine. All changes are made in non-rating mode. Output data of AccuRate Sustainability that are used in this study are hourly temperature in each room, hourly sensible cooling load in each room, hourly latent cooling load in each room, and a total cooling load for the whole house. All output data are presented for one-year duration. In the free running mode, only hourly temperature data are available.

### 2.1. House design

The design of a house used in the study was selected from the eight sample houses that were used by Australian Building Codes Board (ABCB) for NatHERS software accreditation. It is a two-storey house; the main living and bedroom spaces are on the upper level while on the ground level are a carport and rooms that can be used as additional living spaces. Such design is quite typical in Darwin or the Northern Territory, which is the focus of this study. The construction details of the house and house plans are shown in Table 1 and Figure 1.

Table 1 Model house design and construction details

| Components | Description |
|---|---|
| External walls | Aluminium sheet, timber stud, 10 mm plasterboard internal wall linings |
| Internal walls | 10 mm plasterboard on 90 mm studs |
| Floor | Concrete slab on ground in Store, Family, Bathroom/laundry<br>Framed 19 mm hardwood |
| Roof | Metal deck |
| Ceiling | 13 mm plasterboard,<br>R1.0 insulation to first floor ceilings |
| Windows & sliding doors | Aluminium frame with clear glazed louvres, 90% open ability with internal Holland blinds, no external shading device |
| External doors | 42 mm hollow core timber door, no weather strips and seals |
| Wall heights | Ground floor 2800 mm<br>First floor 2700 mm |

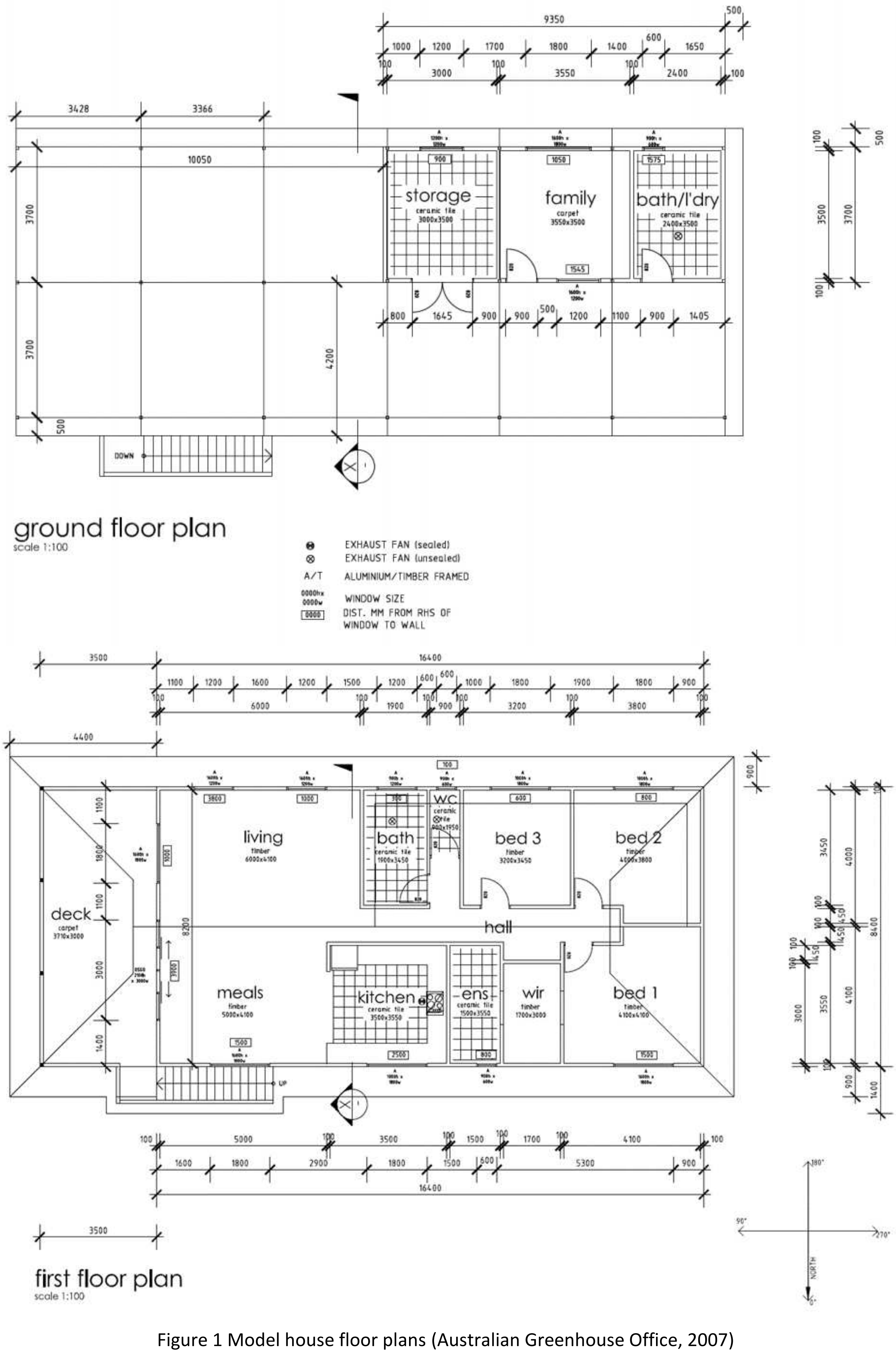



Figure 1 Model house floor plans (Australian Greenhouse Office, 2007)

## 2.2. Weather data

Focusing on cooling load calculation, this study located the model house in climate zone 1 based on NatHERS classification, which covers Darwin city and surrounding area in the Northern Territory. Climate data used in AccuRate Sustainability is sourced from Australian Bureau of Meteorology within the period of 1976 to 2004 (ABCB, 2006). The Typical Meteorological Year climate data for climate zone 1 is originated from 2003 records.

To acknowledge the changing weather throughout the year, some of the results are compared between seasons, such as the wet season (December to April), the dry season (May to September), and the build-up season (October to November), see Table 2. Figure 1 shows the 24-hour profile of average temperatures in each season to show the differences. It is to be noted that the build-up season is often identified as the most uncomfortable condition because of high temperature, high humidity, and lack of rainfall (Williamson, Coldicutt and Penny, 1991; Daniel, 2018).

Table 2 Descriptive statistics of outdoor air temperature

| Season | n | Outdoor air temperature (°C) | | | | Relative humidity (%) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Min | Max | Mean | Std. Deviation | Min | Max | Mean | Std. Deviation |
| Wet season | 3624 | 22.3 | 35.2 | 28.2 | 2.5 | 53.8 | 94.7 | 78.5 | 8.9 |
| Dry season | 3672 | 15.5 | 35.6 | 25.8 | 3.7 | 27.5 | 81.1 | 60.5 | 6.6 |
| Build-up season | 1464 | 20.9 | 35.4 | 29.1 | 2.6 | 55.1 | 84.2 | 68.5 | 11.6 |
| Overall in a year | 8760 | 15.5 | 35.6 | 27.3 | 3.4 | 27.5 | 94.7 | 69.3 | 12.8 |

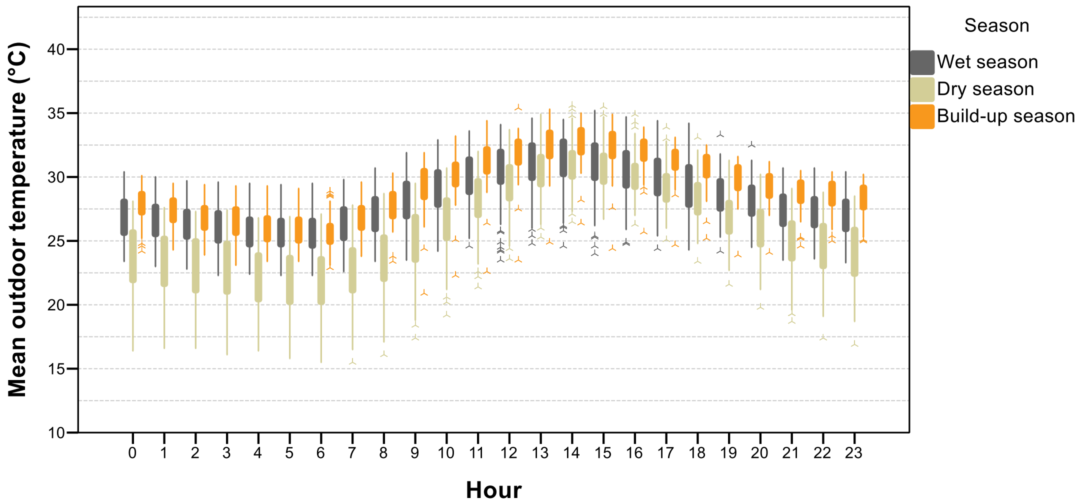



Figure 2 Hourly mean outdoor temperature in each season

## 2.3. Operation rules

User behaviour related variables in the simulation tested in this study are the operation of windows, indoor shading device, and outdoor shading device. The windows operation is firstly determined by the availability schedule set in the program (see Table 3), and secondly by environmental variable triggers which are the zone temperature and outdoor temperature. Outside the available hours, all windows are always closed regardless of other variables; unless the windows are set to be permanently open. Regardless of triggering temperatures, the state of windows will remain the same for a minimum duration of stickiness period, which is set to 3 hours for climate zone 1, to avoid unrealistic closing or opening windows every hour.

Inside available hours, windows that are opened in the last hour will be closed if the zone temperature is less than or equal the closing temperature ($T_{zone\text{-}close}$), or if the zone temperature is less than or equal the outdoor temperature. Windows that are closed in the last hour will be opened only if the zone temperature fits into both conditions: 1) zone temperature is greater than or equal the opening temperature ($T_{zone\text{-}open}$), and 2) zone temperature is greater than 4 °C below the outdoor temperature.

When the windows are open, the simulation will then determine whether the zone temperature is within thermal comfort criteria in the climate zone, which is predetermined to be slightly above 26.5 °C in Darwin, depending on the cooling effect of air flow. When the zone temperature exceeds the upper limit of thermal comfort zone, ceiling fans will be switched on if available, otherwise the windows will be closed, and air-conditioning will operate in cooling mode. However, the windows will not close if they are set to be permanently open.

Similarly, the internal shading device operation is determined firstly by the closing schedule, and secondly by thermal environment variables, such as outdoor air temperature ($T_{out}$) and solar radiation ($G$). Internal shading devices will be closed between the closing and opening times regardless of other conditions. Outside those hours, internal shading device only close if both $T_{out}$ and $G$ exceed the predetermined values in the program and if external shading devices are not available in that hour. Unlike the other two, the external shading device's operation rule is not controlled by a schedule. It will only be closed if both $T_{out}$ and $G$ exceed the predetermined values for external shading devices.

Comparisons of the default settings and six scenarios for this study are shown in Table 3, which are applied for both cooling (CL) mode and free running (FR) mode. It is to be noted that heating is disabled in all rooms because Darwin and Northern Territory in general does not experience winter thus heating is not required and therefore allowing calculation of the cooling load only. The air-conditioning for cooling still operates according to the default AccuRate settings for all CL mode scenarios, that includes scenario CL-W1 when all windows are set to be permanently open all the time. As for the FR mode, heating and cooling are disabled in all zones so that those zones become non-conditioned.

Table 3 Simulation settings

| Object | Code | Scenario | Settings |
|---|---|---|---|
| **Windows** | **D** | Default | Available hours: 0-24<br>$T_{zone\text{-}open}$: 26 °C<br>$T_{zone\text{-}close}$: 22 °C |
| | **W0** | Windows closed all the time | Available hours: 0-0 |
| | **W1** | Windows opened all the time | All windows are set to be permanently open |
| **Internal shading device** | **D** | Default | Closing time: 18, Opening time: 7<br>$T_{out}$: 29 °C<br>$G$: 200 w/m$^2$ |
| | **I0** | Internal shading closed during the day | Closing time: 5, Opening time: 20<br>$T_{out}$: 29 °C<br>$G$: 200 w/m$^2$ |
| | **I1** | Internal shading opened during the day | Closing time: 18, Opening time: 7<br>$T_{out}$: 35.6 °C<br>$G$: 200 w/m$^2$ |
| **External shading device** | **D** | Default | External shading is not available, conditions are the same as external shadings open all the time |
| | **E0** | External shading closed during the day | $T_{out}$: 15 °C<br>$G$: 1 w/m$^2$ |

| | | | |
|---|---|---|---|
| | **Ed** | External shading default settings | $T_{out}$: 26 °C<br>$G$: 75 w/m$^2$ |

Note: $T_{zone\text{-}open}$: Zone temperature above which windows may open, $T_{zone\text{-}close}$: Zone temperature below which windows always closed, $T_{out}$: Outdoor temperature above which shading devices may be closed, $G$: Solar radiation above which shading devices may be closed.

Within the total six scenarios listed in Table 3, there are two scenarios for each object. Scenarios of “open all the time” and “close all the time” are applied to windows and internal shading devices. Throughout 2003, the earliest sunrise was at 06:11 and the latest sunset was at 19:17 (Geoscience Australia, 2003). Based on this figure, scenario I0 sets indoor shading devices to close at 05:00 and open at 20:00 to ensure they are always open during the day. While there is no external shading device installed in default settings, such settings showed identical results with “open all the time”. Therefore, scenario settings for external shading device operation in this study are “closed all the time” (E0) and default thermal variable settings for external shading devices (Ed). The type of external shading used in scenario E0 and Ed is 60% shade cloth.

While AccuRate Sustainability simulates thermal performance for the whole house as well as for each zone separately, this study focuses on the performance of living and sleeping areas only, because such rooms are assumed to be equipped with air-conditioning in the NatHERS protocol.

## 3. Results

Thermal performance simulations are carried out separately for CL and FR mode. The results of scenarios in CL mode are compared using total and hourly energy usage (MJ), while those in FR mode are presented in zone temperature (°C) and cooling degree-hours.

### 3.1. Cooling mode

Cooling load calculation results for the model house in CL mode are specified into sensible cooling and latent cooling for one year. The summary on Table 4 showed that the latent cooling demand for CL window opened (CL-W1) is the highest of all scenarios and far stretched away from the rest of the data, with total cooling load increased by 172% from default settings. In CL-W1 the windows are open at all times, including when cooling is available. This much higher cooling load is heavily affected by outdoor temperature and humidity. The second highest total cooling load is also related to windows operations. In CL-W0, or when windows are closed all the time, the cooling load increases by 114% compared to the default scenario. The lowest cooling load is achieved in scenario CL-I0, in which internal shading devices are closed during the day, while the windows are open according to the default setting, causing total cooling energy decrease to 88%.

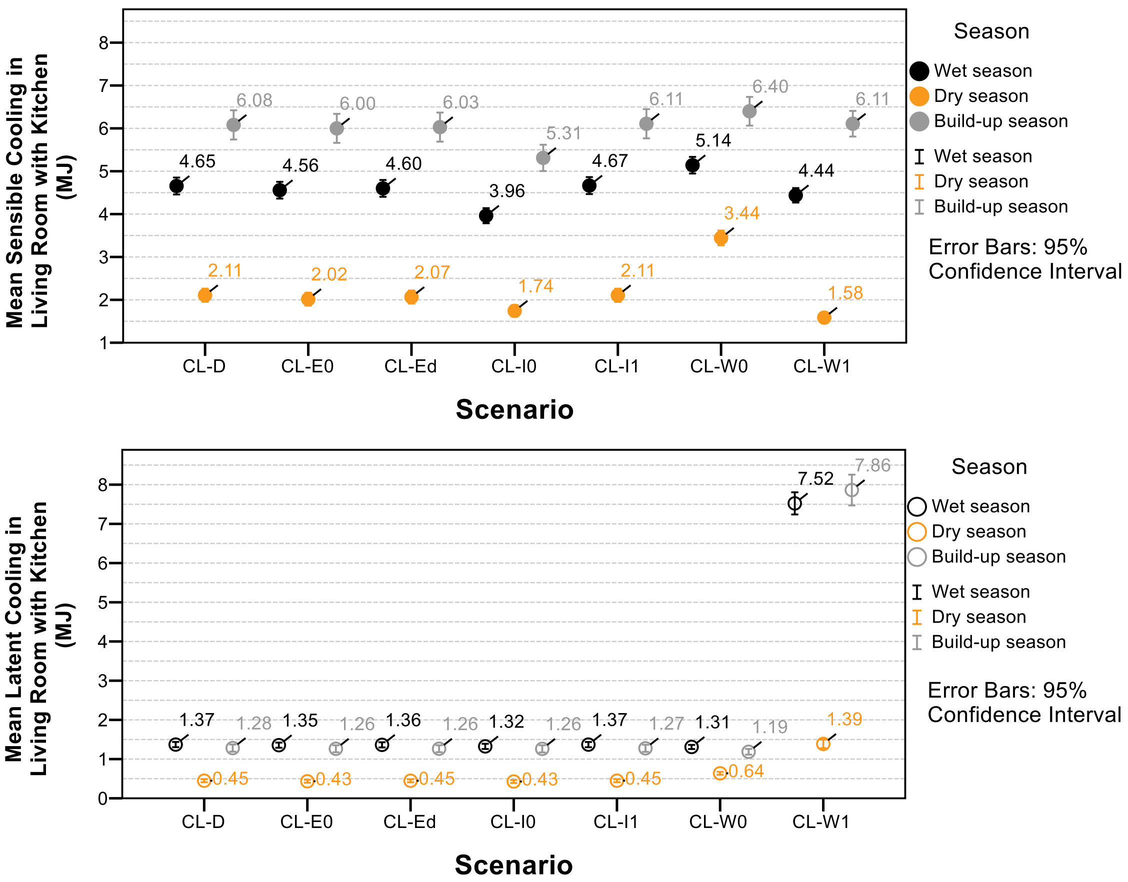
Table 4 Annual energy summary for each scenario

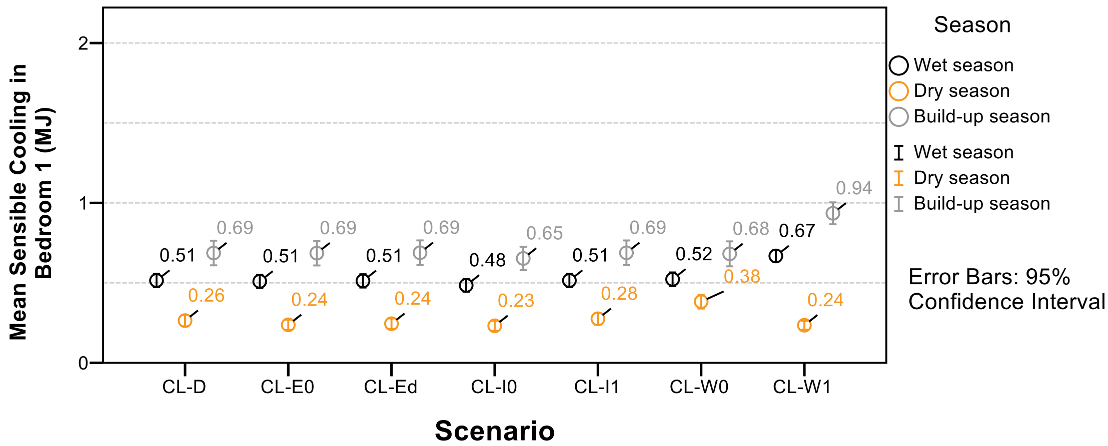
| Scenario | Total annual cooling energy | | Peak cooling energy demand | | Cooling energy per conditioned floor area | | |
|---|---|---|---|---|---|---|---|
| | Sensible (MJ) | Latent (MJ) | Sensible (kW) | Latent (kW) | Sensible (MJ/m$^2$) | Latent (MJ/m$^2$) | Total (MJ/m$^2$) |
| CL-D | 57294.9 | 16231.3 | 16.5 | 5.4 | 443.1 | 125.5 | 568.7 |
| CL-W0 | 67644.6 | 15926.7 | 15.8 | 5.0 | 523.2 | 123.2 | 646.3 |
| CL-W1 | 55532.8 | 71206.8 | 15.4 | 21.4 | 429.5 | 550.7 | 980.2 |
| CL-I0 | 49171.2 | 15709.0 | 15.6 | 5.4 | 380.3 | 121.5 | 501.8 |
| CL-I1 | 57440.4 | 16221.2 | 16.4 | 5.4 | 444.2 | 125.5 | 569.7 |
| CL-E0 | 55827.1 | 16032.9 | 16.3 | 5.4 | 431.8 | 124.0 | 555.8 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| CL-Ed | 56474.7 | 16141.7 | 16.4 | 5.4 | 436.8 | 124.8 | 561.6 |

Note: CL-D: Cooling mode with default settings, CL-W0: Cooling mode with windows closed, CL-W1: Cooling mode with windows opened, CL-I0: Cooling mode internal shading closed, CL-I1: Cooling mode internal shading opened, CL-E0: Cooling mode external shading closed, CL-Ed: Cooling mode external shading default

It is expected for the sensible cooling load to be higher than the latent cooling load, which is true for all scenario except for CL-W1. The differences between each scenario are presented by hourly sensible and latent cooling load. To count for seasonal variations, the mean and error bars of sensible and latent cooling load are shown in Figure 3. In line with the cooling load summary, scenario CL-W1 has the highest latent cooling load in both living area and sleeping area. It is also to be noted that living area with kitchen has much higher cooling load in general, compared to bedroom 1. This may be affected by assumed cooking activities that are generating heat two times daily according to the Protocol for House Energy Rating software.





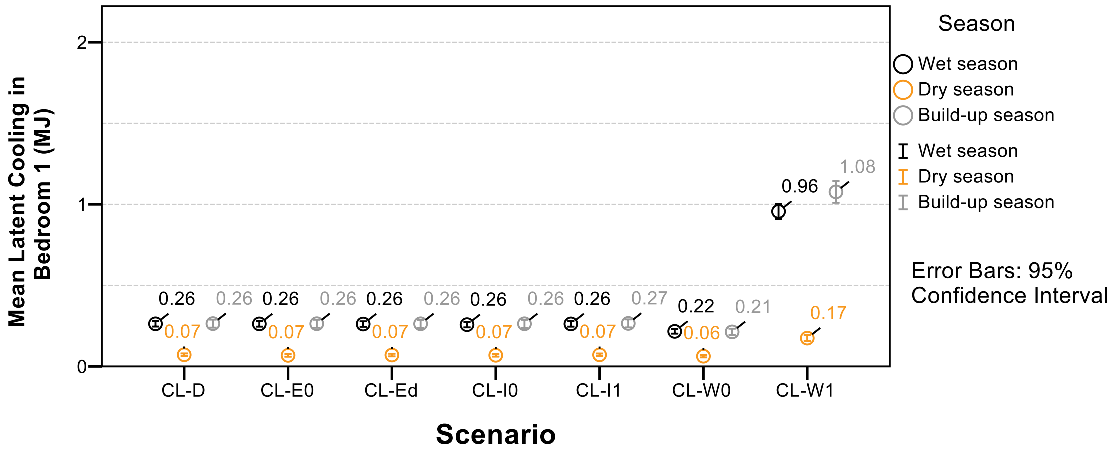




Figure 3 Mean and error bars of hourly sensible and latent cooling load in living and sleeping area

Seasonal differences are as expected as temperature is lower in dry season and it is the highest during build-up season. While closing the windows all the time (CL-W0) resulting in the highest sensible cooling load in the living room with kitchen; the opposite action, which is opening windows all the time (CL-W1) turned out as the highest sensible cooling load in Bedroom 1.

Referring to the summary, scenario CL-I0 has the lowest total cooling load for the whole house. This finding is consistent in Figure 3, where the mean sensible cooling load decreased as low as 82% during dry season in living room with kitchen. There is sometimes a fragment of information unrepresented when a mean value is calculated. To further examine this, hourly cooling load differences throughout the day is investigated for scenario CL-I0 and CL-W0 against default settings (CL-D) in the Living Room with Kitchen, as presented in Figure 4Figure 4

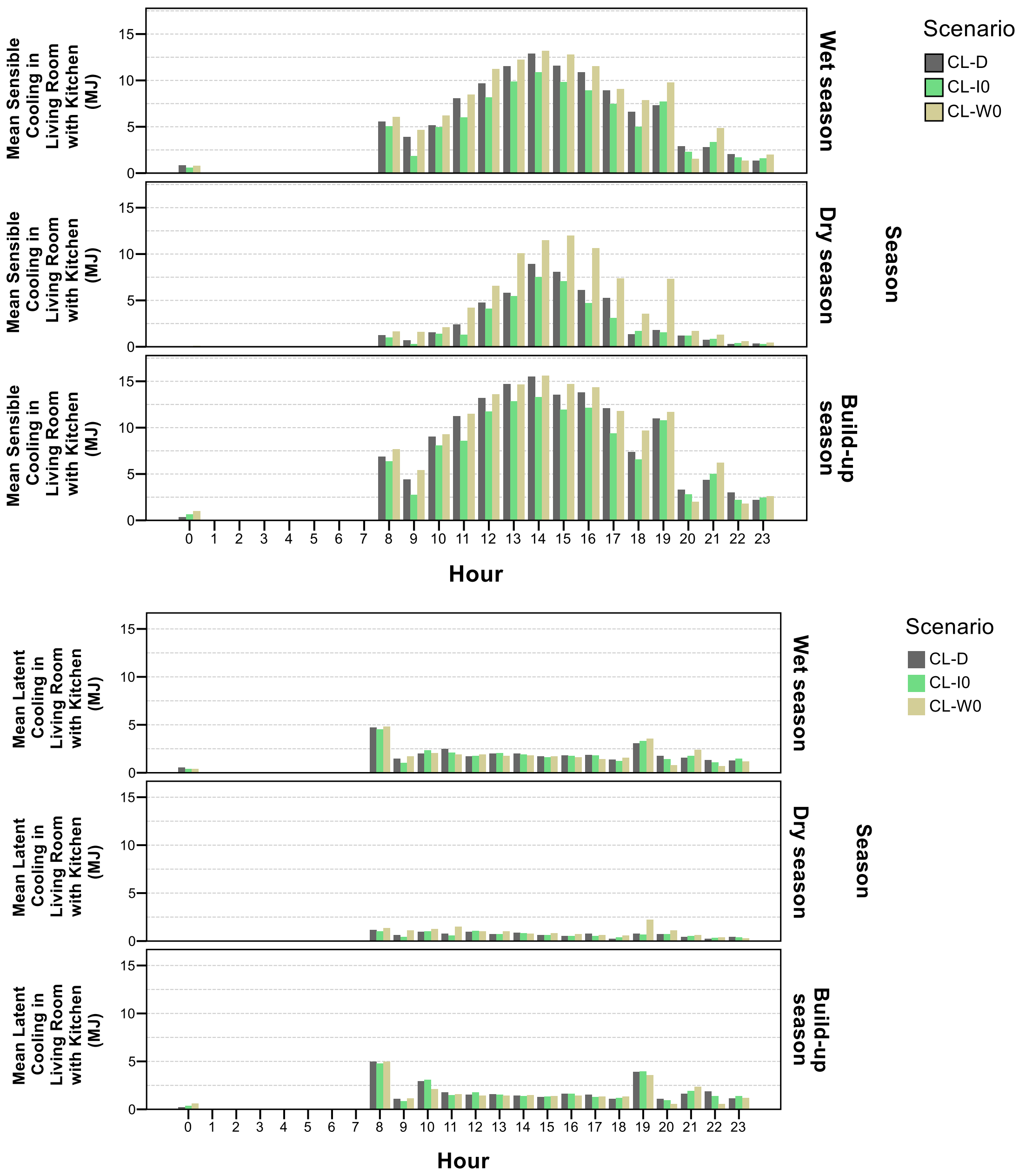



Figure 4 Hourly sensible and latent cooling load in 24 hours

Scenario CL-W0 has increased sensible cooling load especially during the dry season when outdoor temperatures are low and considered comfortable, thus opening windows at the appropriate times and conditions will help cool down the house by transferring the heat to outside air. The latent cooling load is generally low and unaffected by the three sample scenarios; however, it is apparent that predetermined schedule for cooking activities caused the two spikes for latent cooling load at 08:00 and at 19:00.

### 3.2. Free-running mode

The overall thermal performance of the house in free-running mode is measured by calculating the cooling degree hours, which is the sum of differences between hourly zone temperature and base temperature, to examine the weighted frequency of hourly temperatures that are greater than base temperature. In this study, base temperature is set to be the same as the AccuRate default cooling thermostat setting for Darwin climate zone, i.e. 26.5 °C. It means, while there is no cooling load calculation in FR mode, if any temperature above 26.5 is translated as a condition in which cooling is required, cooling degree hours can be used to quantify the occurrence of cooling demand and the degree differences. Cooling degree hours are estimated for each living and sleeping area in the model house, separately for each scenario as seen in Table 5.

Table 5 Cooling degree hours of living and sleeping area in all scenarios

| Scenario | Cooling degree hour | | | | |
|---|---|---|---|---|---|
| | Bedroom 1 | Bedroom 2 | Bedroom 3 | Living room | Living room with kitchen |
| FR-D | 19962.1 | 20648.5 | 19508.1 | 17842.1 | 18168.4 |
| FR-W0 | 27722.3 | 28136.6 | 27986.9 | 28094 | 26569.8 |
| FR-W1 | 19168.9 | 19553.8 | 18523.3 | 17187 | 17464.4 |
| FR-I0 | 18991.2 | 19655.6 | 18261.3 | 17005 | 17428.8 |
| FR-I1 | 20031.2 | 20663.1 | 19521.4 | 17846.8 | 18173.8 |
| FR-E0 | 19780.8 | 20982.5 | 19872.9 | 18065.3 | 19108.8 |
| FR-Ed | 19981.9 | 21069.9 | 19957.2 | 18134.7 | 19235.7 |

Note: FR-D: Free-running mode with default settings, FR-W0: Free-running mode with windows closed, FR-W1: Free-running mode with windows opened, FR-I0: Free-running mode internal shading closed, FR-I1: Free-running mode internal shading opened, FR-E0: Free-running mode external shading closed, FR-Ed: Free-running mode external shading default

Scenario FR-I0 & FR-W1 both has cooling degree hours lower than default scenario in all living and sleeping areas. The lowest value was achieved using FR-I0, with degree hour decreased into 94% of default settings in bedroom 3. On the other hand, scenario FR-W0 has the highest cooling degree hour that is 158% of the cooling degree hours using the default settings for the living room. To closely examine how the model house performs in FR mode, the mean of hourly temperature in the living room is plotted in Figure 5. By comparing the mean temperature of each scenario in living room, it is also apparent that scenario FR-W1 generated the lowest temperature in each season, followed closely by scenario FR-I0 which is consistent with the finding based on cooling degree hour. Figure 5 also further confirms that scenario FR-W0 has the highest zone temperature amongst all other scenarios.

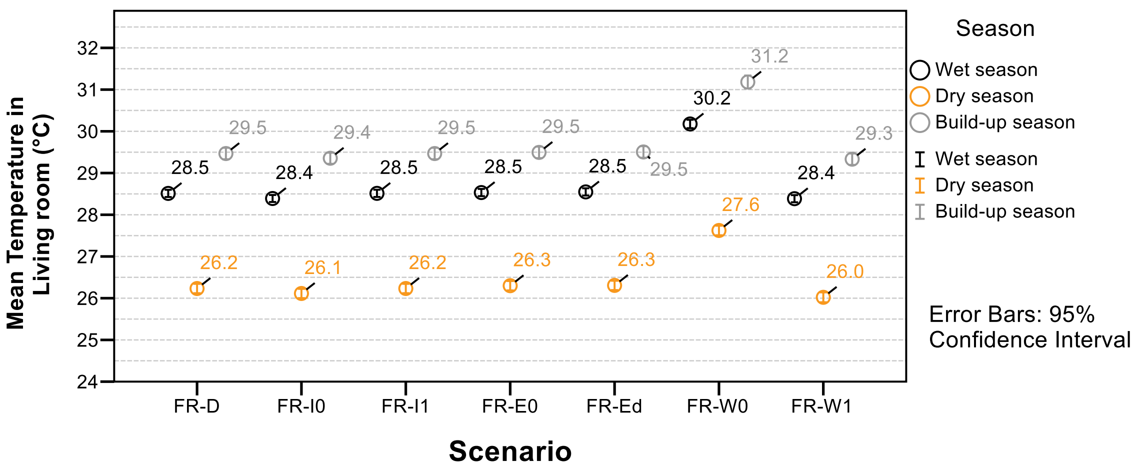



Figure 5 Mean temperature in living room for each scenario in each season

Unlike in the CL mode, the effect of selected scenarios on default settings are relatively constant despite seasonal changes, as seen on Figure 6. Hourly temperature differences between the scenarios with lowest temperature (FR-I0 and FR-W1) and default settings are subtle. However, it is still apparent that scenario FR-W0 increased the zone temperature especially between 12:00 to 21:00 in each season. The default zone temperature itself is closely related to outdoor temperature; with the highest mean temperature in build-up season and the lowest during dry season.

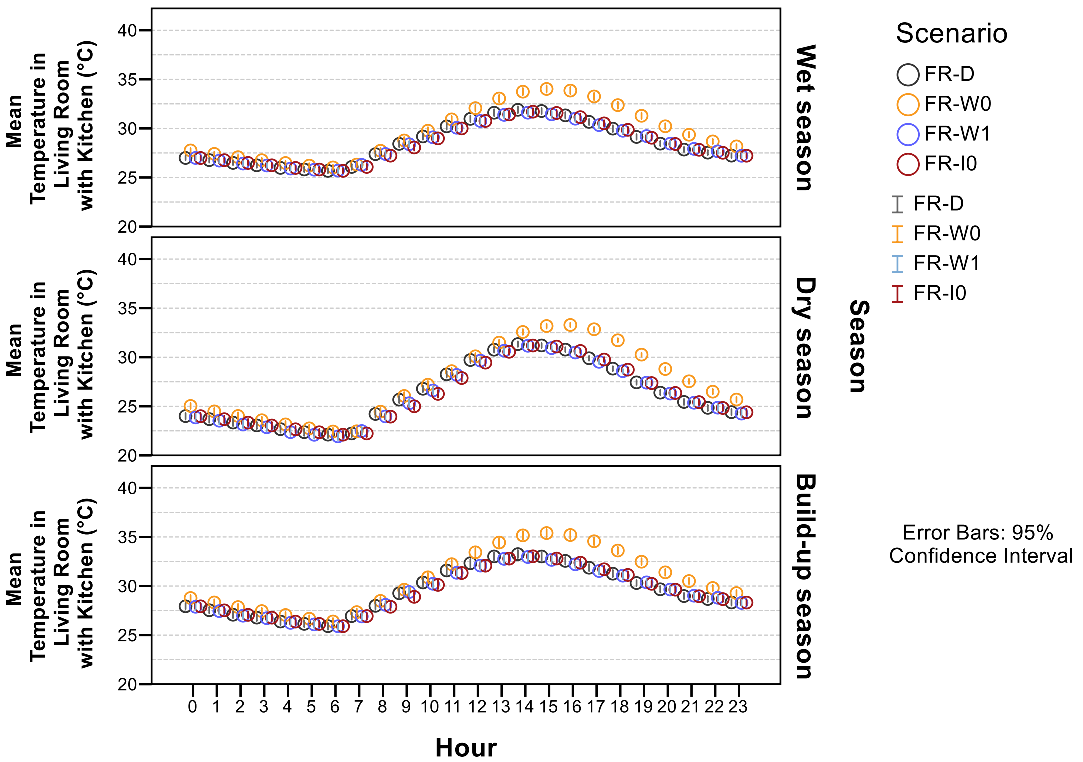



Figure 6 Mean hourly temperature in living room for 24 hours using default, FR-I0, and FR-W0 scenario

## 4. Discussion

Model house in CL mode has the least total cooling load in CL-I0, when the internal blinds are closed during the day. Overall results showed that this scenario can drop cooling load as low as 88.2% from the default settings. This finding is also consistent with the separated results of sensible and latent cooling load. In scenario CL-I0, it is important to note that while the internal shadings are closed all the time, the windows are operating as usual according to the AccuRate default settings. The load calculation in AccuRate also runs under assumption that internal shading devices do not affect the windows operation or natural ventilation. In actual house, this assumption might not be true, especially when the type of internal shading device is heavy or not aero-dynamic so it could block some air flow around the windows opening area.

It is expected that the highest total cooling load applies when all windows are permanently open while the cooling is operating at the same time to remove the latent heat coming from the outside, resulting in a cooling load that is abnormally high in comparison to other scenarios. The cooling load increase for scenario CL-W1 from the default settings is up to 172%. Interestingly the highest sensible cooling load occurs when all windows are closed all the time (CL-W0), because the house does not benefit from the cooling effect of air movement, especially when outdoor temperature is lower than zone temperature. Afterall, the highest cooling load are related to both extreme behaviours of windows operation.

During the FR mode, the model house also has the highest cooling degree hour when the windows are closed all the time (FR-W0), supposedly because of similar reasons to CL-W0. Conversely, the lowest total cooling degree hour is achieved when the internal shading devices are closed during the day (FR-I0), which is consistent with CL mode results. However, looking into the mean temperature in each zone and each season, lowest temperature is sometimes achieved when the windows are open all the time (FR-W1).

Overall FR mode results resonate with CL mode results, indicating occupant behaviour is not a trivial factor in house energy usage, even in simulation stage.

## 5. Conclusions

The results showed that regardless of ventilation mode, occupant behaviour related to windows operation has the highest effect on cooling load and cooling degree hour. Closing windows all the time was shown to increase cooling load in cooling mode and increase cooling degree hour. On the other hand, opening windows all the time was proven to decrease the cooling degree hour in free running mode. This study also found that closing internal shading device all the time is estimated to decrease both cooling load and zone temperature to the lowest value in comparison to other scenarios tested in this study, under assumption that the internal blinds are not affecting the ventilation air flow.

Findings from this study revealed how far the occupant behaviour may affect a calculation of a house thermal performance, while in most cases the user profiles are set to be typical. Further study will be needed to test more behavioural settings, using different scenarios or using other house feature that people use to overcome thermal discomfort.

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# Managing Thermal Comfort within the Residential Context of a Developing Region. A Field Investigation Based on Two Socioeconomically Distinct Households.

**Haval Abdulkareem[1,2], Henrik Schoenefeldt[1] and Marialena Nikolopoulou[1]**

[1] Kent School of Architecture and Planning, University of Kent, UK;
[2] College of Engineering, University of Duhok, Iraq

**Abstract:** Paying particular attention to the relationship between the inhabitants and the physical performance of the environment they occupy and the factors shaping that relationship is believed to be fundamental when conducting building performance researches. This paper follows that approach in examining the management and control of the indoor thermal environment within a sample of socioeconomically distinct households based in Iraqi Kurdistan (KRI). This is undertaken through a close coupling of qualitative and quantitative investigations employing a combination of in situ measurements, observations, and in-depth interviews capturing inhabitant's behavioural control actions with respect to the performance of their dwellings. The paper tends to develop a type of tentative hypothesis which can help structuring a framework to explore what the questions of thermal comfort and environmental control mean within the residential context of KRI. The investigations reveal how occupants' engagement in adjusting indoor conditions is shaped by non-thermal factors, mainly socio-economic ones, and so environmental design in such context requires a stronger focus on that.

**Keywords:** Socio-technical approach, Adaptive behaviour, Thermal comfort, Environmental control, Fuel poverty

## 1. Introduction

As key determinants in the functionality of buildings and the way inhabitants interact with the built environment, the questions of thermal comfort and environmental control within the residential context have gained increased attention across the building performance literature over years. The typical approach in undertaking such investigations has based on physiology and engineering-based methods and evaluations. This has been through monitoring the physical parameters, e.g. temperature and air quality, assessing how buildings actually perform in terms of providing and maintaining thermal comfort. This is besides the application of post-occupancy surveys that take occupant's viewpoint in such assessment, identify their expectations and needs, and rate their degree of satisfaction. With such an approach which has been relatively limited to the technical dimensions of environmental control and physical aspects of thermal comfort, however, one cannot rigorously understand the relationship between the inhabitants and the physical performance of the environment they occupy and the factors shaping that relationship (Leaman et al., 2010). One needs to go beyond that conventional approach and think in a wider sense with increased attention to the nature of that relationship (Cole et al., 2008).

There is a widespread belief that what people consider as a satisfactory thermal environment largely varies from one culture, place, climate or time to another (Chappells & Shove, 2005; Nicol & Roaf, 2017). And with no doubt, the human body's physiological and physical state is no longer seen as the only determinant driving the perception and management of comfort in buildings. It is according to (Chappells & Shove, 2005; Shove et al., 2008) only one element among others, such as socio-cultural context, ways of life, the building attributes, and the available measures by which comfort can be provided.

This belief can be supported by a number of field-based researches showing how influential those underlying components can be. For instance, Leaman & Bordass (2007) show that the expectations, tolerance thresholds, and thermal behavioural patterns of those living in a mechanically controlled environment undoubtedly differ from those of who live in a free-running building. Also, a study conducted by Wilhite et al. (1996) compares the way households manage and control the indoor environment of their buildings in Japan and Norway. It indicates the notable impact of cultural differences and available controls which resulted in clear differences in their comfort preferences and practices. Such impact is well analysed and described by Kempton & Lutzenhiser (1992). Another research conducted in a suburb of Copenhagen by Gram-Hanssen (2010) found that even families living in the same type of dwellings could have considerably different heat consumption and behavioural patterns for different reasons, such as thermal preferences and unfamiliarity with the environmental control systems. The study examined the issue from a socio-technical angle employing a combination of quantitative and in-depth qualitative investigations and pointed up the importance of incorporating occupants-centred approach in conducting building performance researches. Indeed, occupants' engagement in adjusting indoor conditions and its significant impact on performance outcomes is proven (Rijal et al., 2007; Hoes et al., 2009). Such engagement according to Cole et al. (2008) is shaped by a set of contextual, behavioural, cultural, psychological and physiological factors. These are alongside religious and economic ones (Humphreys, M., 1997). However, their degree of influence varies according to different conditions and circumstances.

In areas such as those of the developing world where the affordability of comfort is a common issue, human behaviour in controlling the environment becomes quite essential. And so considering the inhabitants as an integral part of the overall performance of the environment they occupy underlines the importance of valuing and engaging questions of human agency when studying thermal comfort and environmental control. And this is according to (Gupta & Chandiwala, 2010; Stevenson & Rijal, 2010) can be undertaken through social qualitative analysis offering intimate insights. Bringing this and methods concerning technical aspects together will form a socio-technical regime (Cole et al., 2008).

Drawing on such a regime, this paper tends to examine the management and control of the indoor thermal environment and factors leading to the behaviour and provide an empirical understanding of performance within the residential context of Iraqi Kurdistan (KRI). It employs the case study method (CSM), bottom-up approach, to develop a type of tentative hypothesis which can help structuring a framework to explore what the questions of thermal comfort and environmental control mean in KRI. The paper is based on data collected from two case studies where both selected from the opposite end of the socioeconomic spectrum. This was based on a framework set by a Joint Report by the Kurdistan Regional Statistics Office (KRSO) and the International Organization for Migration (IOM). The investigations reveal how thermal behavioural patterns of users are essentially shaped by non-thermal factors, mainly socio-economic ones. The paper underlines that human behaviour becomes quite essential in controlling the environment when the affordability of comfort is an issue. Accordingly, environmental design in such context requires a stronger focus on that.

## 2. The study area

The paper is based on field investigations conducted in the Kurdistan region, a region that is located in the northern part of Iraq (36.41° N, 44.38° E) bordering Turkey, Syria, and Iran and comprising the country's four northernmost governorates: Sulaymaniyah, Halabja, Erbil, and Duhok. The region has a semi-arid climate, with hot dry summers and cold, wet winters. The mean daily temperatures range from 32 °C to 36 °C and 4 °C to 11 °C during summertime and wintertime respectively.

The vast majority of residential units in the region rely on two sources of electricity supply: the national grid and a shared generator (or a small station) operating at a neighbourhood level. The first is considered as the main electricity source and is highly dependent on governmental support. However, owing to extreme strain on its capacities as a result of increased demand, mismanagement, and some other major barriers explained in (IEA, 2012), households often experience power failure throughout the day. In 2018, for instance, the average electricity supply through national grid in the city of Duhok was limited to nearly 13 hours per day (General Directorate of Duhok Electricity, 2018). This creates difficulties for the majority of households to keep their homes at right temperatures during both cooling and heating seasons. The second, which is privately owned by an Independent Power Producer (IPP), is used to fill some of the electricity supply gap that is experienced. However, it supplies electricity at considerably higher prices (1 USD per 4 kWh) creating a major barrier to many households across the region in operating heating and cooling technologies when necessary.

## 3. Methods

The approach followed in this study lies in a close coupling of qualitative and quantitative investigations employing a combination of in situ measurements, observations, and in-depth interviews capturing inhabitant's behavioural control actions with respect to the performance of their dwellings.

Starting with in situ measurements, data collection of the outdoor and indoor thermal environment, mainly in the occupied spaces in each dwelling, was carried out over the period of four weeks starting from July 25 to August 22, 2018. Similar to other monitoring researches [e.g. Oreszczyn et al., 2006; Hong et al., 2009; Cantin et al., 2010; Bozonnet et al. 2011; Kavgic et al., 2012; Soebarto and Bennetts, 2014], out of six thermal comfort variables that established in ISO 7730 (2006), relative humidity and dry-bulb temperature were measured continuously at 5-min intervals by employing data loggers, called Tinytag. The place in which each logger was hung was carefully chosen aiming for ideal locations taking into account ANSI/ASHRAE Standard 55 guidelines. Householders' guidance was also considered especially in terms of their identification of the main occupied spaces and also the places where they operate portable heaters and/or air coolers within each space. Sensors were positioned away from any source of coolth or heat, e.g. air conditioner, heater, sunlight, cooker, and etc. Alongside that, a smart meter was installed to measure energy consumption.

The monitoring process was accompanied by qualitative data collection through semi-structured interviews with the families and tours inside their houses. This stage aimed to provide a thorough understanding of the occupants' personal knowledge about the contribution of the building itself and the available measures in maintaining thermal comfort. This is in addition to establishing a clear picture about their behavioural control actions and strategies in coping with extreme thermal conditions throughout the cooling season in the light of the constant electricity blackouts that they experience with the

National Grid. The interviews were carried out during August 2018 at their residences. Not only personal thermal comfort preferences, reactions and experiences that are common in post-occupancy evaluations were addressed but also the historical, technical, cultural and social influences in achieving thermal comfort were discussed.

## 4. Case studies

Taking into account the socio-economic context which cannot be excluded from any in-depth analysis, the two case studies (see Fig. 1) were selected from the opposite end of the socioeconomic spectrum where one has a monthly income of 250,000 – 500,000 Iraqi Dinars (IQD) whilst the other earns over 5,000,000 IQD. This allowed higher degrees of comparability owing to differences in their lifestyles, their strategies of adjusting the indoor thermal conditions, their consumption patterns, and the quality of their buildings. The selection was based on a framework set by a Joint Report by the Kurdistan Regional Statistics Office (KRSO) and the International Organization for Migration (IOM).

**Case study 1** **Case study 2**

Figure 1 The front views of the examined houses (author)

The first case study is occupied by a family of two (a 62 year old housewife with her adult son) in which their average monthly income is around 300-350 USD, and thus adapting to conditions below the level of what might people consider as a normal lifestyle. The building incorporates two bedrooms in which one is used as a storage space, besides a kitchen, living room, bathroom, toilet, and staircase leading to rooftop. At the very outset, the house was naturally ventilated, but afterward, both living room and primary bedroom were fitted with three mechanical controls which are a split-type air conditioner, provided by a charity in recent years, an air-cooler and a ceiling fan.

The other case study is a double-storey unit occupied by an upper-class family of three, a man who is in his 50s with his two wives. The ground floor incorporates an open plan living area with dining, staircase, semi-open kitchen, en suite bedroom and toilet alongside an entrance which is connected to the garage, while the top floor consists of four bedrooms, two balconies, a storage, and a bathroom. The ground floor is used primarily and since the house is oversized for such a small family, only one bedroom is used on the first floor, and the rest are unoccupied. To modify the indoor environment, furthermore, the house is fitted with a combination of cooling and ventilation technologies, such as A/C units, air coolers, portable fans. Further characteristics of both case studies are shown in Table 1.

Table 1 The characteristics of both case studies

| | Case study 1 | Case study 2 |
|---|---|---|
| **Completion** | 1974 | 2008 |
| **Location** | Duhok | Erbil |
| **House Type** | One-storey, detached | Double-storey, detached |
| **Floor area** | 98 $m^2$ | 253 $m^2$ |
| **Utilised floor area** | 76 $m^2$ | 169 $m^2$ |
| **ceiling height** | 2.8 m | 2.9 m |
| **Roof type** | Concrete flat roof | double-roof system: flat reinforced concrete roof coupled with a pitched lightweight metal tile roof |
| **External wall materials** | Cement plaster, solid concrete blocks, cement plaster | Limestone, hollow bricks, gypsum plaster |
| **Roof's U-value** | 3.8 W/m2K | 1.3 W/m2 K |
| **External walls' U-value** | 2.8 W/m2K | 1.43 W/m2K |
| **Window type** | All window openings are old, steel framed and single glazed | Sliding windows, aluminium framed and double glazed |

## 5. Findings

Both numerical and qualitative data are presented in the following subsections.

### 5.1. Physical measurements

Indoor environment data showed an apparent difference between the measurements taken in the first case study and those taken in the second one. Overall, indoor thermal discomfort is evident across the first case, i.e. low-income household, where temperatures being high reaching 35 °C and 39 °C in the living room and bedroom respectively, particularly when A/C was not running. In the living room, which was occupied 24/7, the mean daily temperature ranged from 25.9 °C to 31.2 °C, and for 61% of the monitoring period, temperatures exceeded 28 °C. The bedroom experienced even higher indoor temperatures; its mean daily temperature had been between 29.9 °C and 34.9 °C. It has approximately 99% of occupied hours with records in excess of 26 °C. Readings show that the upper-income household had also experienced relatively warm indoor thermal conditions despite having access to air-conditioning round-the-clock, together with the better building thermal characteristic, i.e. lower U-value, compared with the previous case study. The mean daily temperature ranged from 29.1 °C to 31.2 °C and 27.9 °C to 29.7 °C in the living area and en suite bedroom respectively. The former had the lowest record of 26.4 °C despite the fact that the A/C units there were set to 24 °C. One could argue that the units' inadequacy to accomplish the set temperature is attributed to the fact that air conditioners are normally prone to lose their efficiency and power over time especially if there is a lack of maintenance. However, one should not deny: the impact of the room's layout and size being spacious (around 54 $m^2$) accommodating both the living and dining area. This is in addition to being attached to a staircase and a non-conditioned semi-open kitchen, where cooking takes place, allowing heat transfer to occur among those spaces through convection.

### 5.2. Adaptive behaviour and attitude

The qualitative interviews revealed that a range of thermal adaptation habits were being practised by the inhabitants to cope with the summer heat. These practices varied from personal adjustments, i.e. those associated with human body, to building adjustments (see table 2). The level of human intervention in adjusting indoor thermal conditions was found to be high within the low-income household as the occupants exploited many possible adaptive measures, mainly passive ones, to stay thermally comfortable. Meanwhile, the extremely low level of human intervention in overcoming thermal discomfort within the upper-income household was beyond question.

Table 2 Thermal practices of the two households

| Thermal adjustments | Low-income household | Upper-income household |
|---|---|---|
| Personal adjustments | Staying away from any source of heat<br>Sitting or lying on the screed floor<br>Dampening and adjusting clothes<br>Taking cold showers<br>Drinking cold water<br>Using hand fans | Adjusting clothes |
| Building adjustments | Sprinkling the roof and vegetation around the house<br>Removing carpets before summer starts<br>Washing the screed floor<br>Opening/closing doors<br>Turning on ceiling fans<br>Switching on A/C | Turning on cooling technologies (i.e. fans, air conditioners, and evaporative air-coolers)<br>Opening/closing windows<br>Adjusting blinds |

Their choice of practising a certain adaptive behaviour was not only driven by thermal factors. The cost implications of using cooling technologies, for instance, were found to have a potent role in configuring the thermal behavioural patterns of the low-income household. The operation hours of air conditioners were correlated to the availability of power from the national grid owing to the low electricity prices that it has offered over many years. The household used to close the doors and leave the air conditioners on at the lowest possible temperature setting whenever power was supplied from the public network. In this regard, the housewife stated: "*Nobody is using the bedroom over the day, but the reason why I leave it* [the air conditioner] *on is that I store some food there, and energy from public network is cheap; it does not cost me a lot, so I leave it on."* Nevertheless, frequent power breakdowns that are experienced with the public network hinder the continuous running of air conditioners in spite of having an alternative energy source, i.e. private generator at the neighbourhood level. High electricity prices that this supplier offers, i.e. 1 USD per 4 kWh, prevent the household to mechanically keep their home at right temperatures. Data recorded by the installed smart meters show that the energy consumption over the monitoring period via the generator is about one tenth (i.e. 1.7 kWh/m$^2$) of the amount consumed with the public network. This is despite the fact that the neighbourhood generator was supplying electricity for nearly 11-12 hours per day. In this regard, she stated: "*We cannot switch on A/C to adjust the thermal environment while we have electricity from the neighbourhood generator because it costs a lot and we cannot spend most of our income on that even though we want it*." This could be a clear indication of how ease-of-use is prevented by economy. Accordingly, the occupants resort to other personal and environmental adjustments (see Table 1) to overcome thermal discomfort when that is a restriction. Particularly, the chance of operating ceiling fans to create a downdraft accompanied by some humidification techniques, e.g. taking cold showers, dampening cloths or washing the floor, is very high and their role is believed to be important in alleviating discomfort from the heat. Alongside that, a platter full of plastic cups of frozen water was observed in the living room indicating the continual drink of cold water.

As a consequence of being on the higher rungs of the economic ladder, on the other hand, the upper-income household was predominantly relying on active cooling technologies to adjust the thermal conditions. In this respect, the householder explained by saying: "*With the extreme prevailing summer temperatures, it is almost impossible to avoid thermal distress with no cooling technologies in hand.*" In fact, A/C units were noted to be the most practised environmental control in the house. Associated cost implications were not desperately limiting their operation, and the operation hours (especially during night-time hours when occupants fall asleep) were not exclusively correlated to the supply of electricity through the National Grid. This can be noted through data recorded by the installed smart meter showing that the household had nearly four times more consumed electricity via IPP supplier than the low-income family. Despite the notably higher socioeconomic status the household has, the inhabitants were generally very keen to reduce their consumption of energy no matter from which source the power was supplied. Whatever the electrical appliance was, it was only in use when needed. Before moving from one space to another, for example, they switch off all the appliances; the operation of bedrooms' air conditioners was exclusively limited to the sleeping hours. The householder was asked if such an attitude was encouraged by cost concerns, but he asserted that it is not so; rather it is based on their moral principles being central in their energy-related behaviours. In this regard, he commented by saying:

> *It is definitely a non-economic factor. We morally feel uncomfortable to overspend or consume something in an extravagant way, and even religiously, we are not allowed to be wasteful as the Almighty Allah 'likes not those who commit excess' as it is stated in the Holy Qur'an. So it is not just about energy but I mean in general. Even when we prepare food, we cook only as much as we need and avoid food waste.*

The behavioural adjustments and indoor thermal conditions of both case studies were also influenced by the physical attributes of their buildings. Owing to the poor quality of the building fabric, for instance, the low-income household was practising certain techniques to reduce its impact on the indoor thermal environment. By virtue of the severe indoor conditions that caused by heat flux through the fabric, the family decided to use the least uncomfortable spaces, thus converting the south-facing bedroom into a storage area. Furthermore, since indoor thermal conditions were further exacerbated by heat gains through the non-insulated exposed roof, the hose was being taken to the housetop in the late morning with leaving the faucet running for few hours to reduce that. This was, in fact, a longstanding cultural practice in the region (Abdulkareem, H., 2016). This behaviour also promoted evaporative cooling to occur around the house while water was flowing into the land. While the researcher was filming this behaviour, the housewife, who had been living in a stone house at the village before moving to this house, commented on this action by saying: "*My mom used to do the same at the time* [….] *when I don't do that, we feel excessive heat coming down through the roof*." In addition, a thick cloth was used as a door bottom seal for cool retention in the occupied rooms, especially when A/C was running. Despite the existence of openable windows in the examined rooms, adhesive tape was used around the frames to seal gaps and avoid leaks, and this impeded the occupants from opening them when they need to. The researcher also noticed a few cracked window panes which were covered by a packing tape without being replaced. Resorting to such least expensive means of dealing with the building envelope's conditions again highlights the role of cost in driving decision making.

Building attributes like the internal layout, floor area, and the quality of the building envelope, were found to be affecting the thermal interactions of the upper-income household with the environment too. The way they dealt with, however, was notably different compared with the low-income household. The extra square meters of the living zone alongside its layout, which is semi-open, resulted in increased demand for cooling. Accordingly, the area was fitted with four cooling gadgets as described earlier where two of them, i.e. both A/C units, an air conditioner with the window-mounted evaporative air cooler, or the pedestal fan with air cooler, were often in function throughout the day depending on how extreme the internal conditions were. Furthermore, heat gains associated with the extreme trapped heat in the attic as a result of the corrugated roof being non-insulated causes an unfortunate impact on indoor thermal conditions particularly in the first-floor rooms. All occupants, in fact, voiced that the upper floor is indisputably warmer than the ground floor. For this, the household installed an evaporative air cooler in the attic to constantly supply cool air to the space and the corridor during the daytime to mitigate such impact. In this regard, the householder commented by saying: *Without having the air cooler there, believe me, it is very difficult to tolerate the heat coming down, and all the raw food like uncooked rice, flour, and etc. that we have in the storage area* [on the first floor] *will be spoiled.* All that made the achievement of a pleasant level of thermal comfort within this case study an expensive task.

## Conclusion

Inspired by socio-technical theories, this paper sought to address thermal comfort and environmental control within a sample of households being socially in a completely different position. The paper employs the case study method (CSM) presenting an empirical analysis with increased attention to the behaviour of human agency in relation to the physical performance. It has demonstrated that the way people control the environment in their buildings might not necessarily be driven by the human body's physiological and physical state. The paper has also shown that bringing qualitative and quantitative investigations together is of great importance. It generates a rigorous evaluation of the performance and a comprehensive understanding of the inhabitants' thermal behavioural patterns, and the physical attributes of the building. Furthermore, the study has provided supportive evidence of how human behaviour becomes quite essential in controlling the environment when the affordability of comfort is an issue.

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# Air conditioning use in residential buildings: how does it impact on thermal perception?

**Greici Ramos[1*], Renata De Vecchi[1] and Roberto Lamberts[1]**

[1] Laboratory of Energy Efficiency in Buildings, Department of Civil Engineering, Federal University of Santa Catarina, Brazil
* Corresponding author: greici.ramos@posgrad.ufsc.br

**Abstract:** The energy consumption associated to indoor thermal comfort has increased in residential buildings in the last decades as one of the occupants' behaviour consequences and the use of air conditioning (AC) systems. Studies have shown that the progressive and prolonged use of AC is changing the users' expectations, which can result in a dependency relationship. Thus, this paper aims to analyse how the preference for air conditioned environments may influence the occupants' thermal comfort perception, focusing on residential buildings located in a Brazilian subtropical area. 50 residences were monitored through indoor temperature and relative humidity measurements simultaneously to online questionnaires application during the summer. The participants were divided into two groups, based on their tendency to use the AC: 1) higher tendency (HAC); and 2) lower tendency (LAC). The mean indoor air temperature for the thermal sensation interval "slightly cool to hot", was lower in the HAC group, which also happened when comparing the acceptable temperature and the different environmental conditions. The lowest values for acceptable temperatures were observed in HAC group, mainly when the AC was on, with a difference of 1.3 °C between groups. The occupants' behaviour differs between groups: LAC group opt more frequently to behaviours that increase the air movement, while HAC group opts more to the use of AC, preferring lower temperatures when using the device.

**Keywords:** thermal comfort, AC addiction, adaptive behaviour, acceptable temperature

## 1. Introduction

The building sector was responsible for 29% of the world total final energy consumption in 2017 (International Energy Agency, 2019b), which represents 62.5% of the buildings electricity consumption in the Organisation for Economic Co-operation and Development (OECD) countries, and 37.7% of the Non-OECD countries (International Energy Agency, 2019a). In the current scenario, to keep an indoor thermal environment aligned with the occupants' expectations demands a large amount of energy. The cooling mode by itself is responsible to 18.5% of the total electricity used in buildings in 2016 (International Energy Agency, 2018). The end-use energy related to indoor thermal comfort relies on HVAC solutions and is fastly growing around the world, especially in residential and commercial buildings (Wu, Li, Wargocki, et al., 2019; Yang et al., 2014; International Energy Agency, 2018). Solely in Brazil, the electric energy consumption coming from AC use in the residential sector has increased 237% in the last 12 years, while the number of houses with AC units has increased only 9% in the same period (Empresa de Pesquisa Energética, 2018). In Mexico, the number of dwellings with air conditioning has increased at an annual average growth rate of 7.5%, while the total number of houses has increased by 2.7% per year (Oropeza-Perez and Østergaard, 2014). In Indian residences, indoor ventilation systems alone consume 47% of total energy (Indraganti, 2010). These results indicate that not only the number of houses with AC is increasing, but also (and mainly) the use of this device. This trend could be associated with a higher standard of living, which allows for better comfort conditions, normally achieved with air conditioning systems. The unwelcome news is that such systems are commonly associated with increases in energy use and greenhouse gas emissions, having a direct relation to the effects of global warming and possible long-term climate changes.

Another issue that deserves attention is that temperature control in buildings is getting narrow and restrictive. In the US, office buildings have similar temperatures during all year and some are even cooler during the summer (Mendell and Mirer, 2009). Despite all the environmental conditions control, and also the energy expenditure to maintain such conditions, occupants found to be dissatisfied feeling excessively hot and/or cold, regardless of the season (Moezzi, 2009). The dissatisfaction emerges from the *over-provision* of space conditioning, thus occupants of conditioned buildings have different expectations than those of naturally ventilated buildings or mixed-mode ones (Deuble and de Dear, 2012; Kim et al., 2019; De Vecchi et al., 2017; Rupp et al., 2018). In general, occupants are more tolerant to higher temperatures when in naturally ventilated (NV) rooms than when the AC is on. Apart from the temperature control, is the occupant predisposition, which could affect their perception and expectations. De Vecchi *et al.* (2017) identified that occupants of mixed-mode buildings choose to use the AC regardless of the season or the daily mean temperature. Other researchers found that thermal history impacts on perception; Wu et al. (2019a) identified that occupants with a longer permanence in conditioned buildings have different thermal sensation than those from NV buildings. Yu *et al.* (2012) showed that people with long-term thermal history on naturally ventilated environments have a stronger ability on their thermal regulations systems, compared to those accustomed to AC conditions; also, this physiological acclimatization has an important role on how the occupants' respond to thermal conditions (Yu et al., 2012).

In other words, people with long exposure to cooling systems usually prefer the air conditioner instead of the natural ventilation, suggesting an addiction to the 'static' thermal condition (Buonocore et al., 2019; Cândido et al., 2010; De Vecchi et al., 2017). This preference, or addiction, may influence how these occupants perceive the environment and also adapt it to meet their optimal thermal comfort. Considering that in residential buildings occupants have greater freedom to choose between different kinds of adaptive behaviours, does this preference still influence their behaviour? This survey aims to clarify if the preference for air-conditioned environments influences the occupants' thermal comfort perception and behaviours, focusing on residential buildings located in Florianopolis, Brazil.

## 2. Method

This survey was carried out focusing on the occupants' adaptive behavioural at home and the air-conditioner use. This paper is part of a larger longitudinal research conducted in Florianopolis – Brazil, and covers the AC influence on the occupants' thermal perception during the summer. The survey is based on monitoring data simultaneously to online questionnaires application.

Florianopolis is an island located in southern Brazil (27° 35'S), with a hot humid climate (2A) according to ASHRAE 169-2013 (ANSI/ASHRAE, 2013). During the summer, the monthly temperature varies from 20.3 to 29.3 °C, and mean relative humidity from 77.7% to 80.4% (INMET, 2015). Table 1 shows the mean outdoor temperature during the field study provided by the National Institute of Meteorology (INMET, n.d.). For this analysis, the summers of 2017/2018 and 2018/2019 (between December and March) was considered, when temperatures varied from 14.10 °C to 39.30 °C.

Table 1. Outdoor Temperature during the days of the experiment.

| Month | Dec. | Jan. | Feb. | Mar. |
|---|---|---|---|---|
| **Mean** | 24.17 | 25.93 | 25.14 | 24.33 |
| **Min.** | 14.1 | 17.4 | 18.2 | 17.1 |
| **Max.** | 33.4 | 39.3 | 37.7 | 34.2 |
| **SD** | 2.83 | 3.02 | 2.94 | 2.77 |

A total of 50 houses were monitored during the period of the experiment, focusing on the house living room and the bedrooms. In the cases that only one person participate in the survey, only his/her bedroom was monitored. The HOBO data loggers were used to measure the indoor air temperature and humidity, on a 15-minute interval. More information about the instruments is shown in Table 2.

Table 2. Instrument details: measurement range and accuracy.

| HOBO Temperature / Relative Humidity Data Logger | | U12 series | UX100-003 |
|---|---|---|---|
| **Indoor air temperature** | *Measuring range* | -20° to 70°C | -20° to 70°C |
| | *Accuracy* | ± 0.35°C (0° to 50°C) | ± 0.21°C (0° to 50°C) |
| | *Resolution* | 0.03 °C | 0.024°C |
| **Indoor relative humidity** | *Measuring range* | 5% to 95% | 15% to 95% |
| | *Accuracy* | ± 2.5°C (10% to 90%) | ± 3.5°C (25% to 85%) |
| | *Resolution* | 0.03% | 0.07% |

Previous to the monitoring period, the subjects answered a questionnaire to characterize their habits and behaviour, including questions with demographic information, operation of windows and air conditioning system (AC), as well as the adaptive behaviours chosen by the subjects when they were in a thermal discomfort situation. In one of the questions, the subjects should choose the five actions they regularly do when they are feeling hot. Based on the answers to this specific question, the dwellers were divided into two groups: 1) those more likely to use AC in case of discomfort (Higher Tendency on AC use, HAC); and, 2) those who prefer other means of adaptive behaviour (Lower Tendency on AC use, LAC). Figure 1 shows the options along with the subjects' answers frequency. The group with a higher tendency to use AC was defined by those who included "turning on the AC" among one of the options; those who did not mention the AC as an option were classified as the group with a lower tendency. Table 3 shows the characteristic of each group.

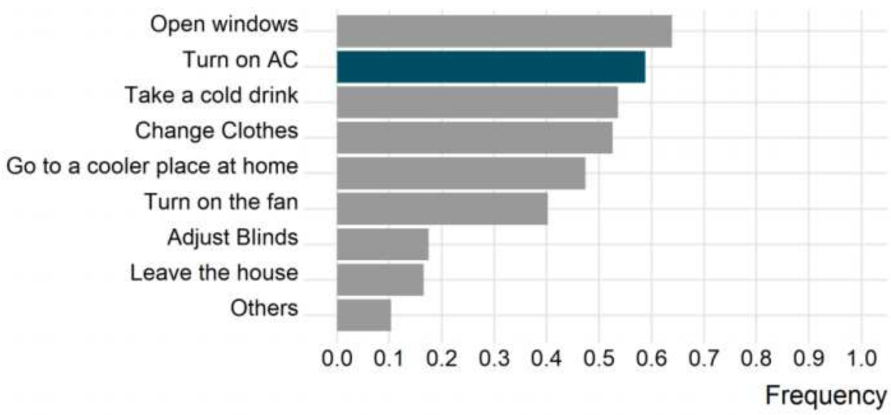


Figure 1. Frequency of the actions chosen by the subject.

Table 3. Groups Characteristics.

| | | Lower Tendency on AC Use | | | Higher Tendency on AC Use | | |
|---|---|---|---|---|---|---|---|
| | | *Total* | *Female* | *Male* | *Total* | *Female* | *Male* |
| **N** | | 42 (47%) | 29 | 13 | 55 (53%) | 24 | 23 |
| **Age** | *Mean* | 38.0 | 37.6 | 38.9 | 36.7 | 36.6 | 36.8 |
| | *Min/Max* | 21/61 | 21/61 | 22/60 | 15/60 | 15/59 | 16/60 |
| | *SD* | 11.2 | 11.2 | 11.5 | 12.2 | 12.4 | 12.2 |

During the monitoring period, the subjects received twice a month and on high temperature days, an online questionnaire. Questions were asked about their adaptive behaviours on that specific moment. It also included information about subjects' clothes, thermal sensation, and environmental conditions such as windows status, use of fans and AC. The questionnaire structure, showed in Figure 2, was adapted from Parkinson et al. (2013).

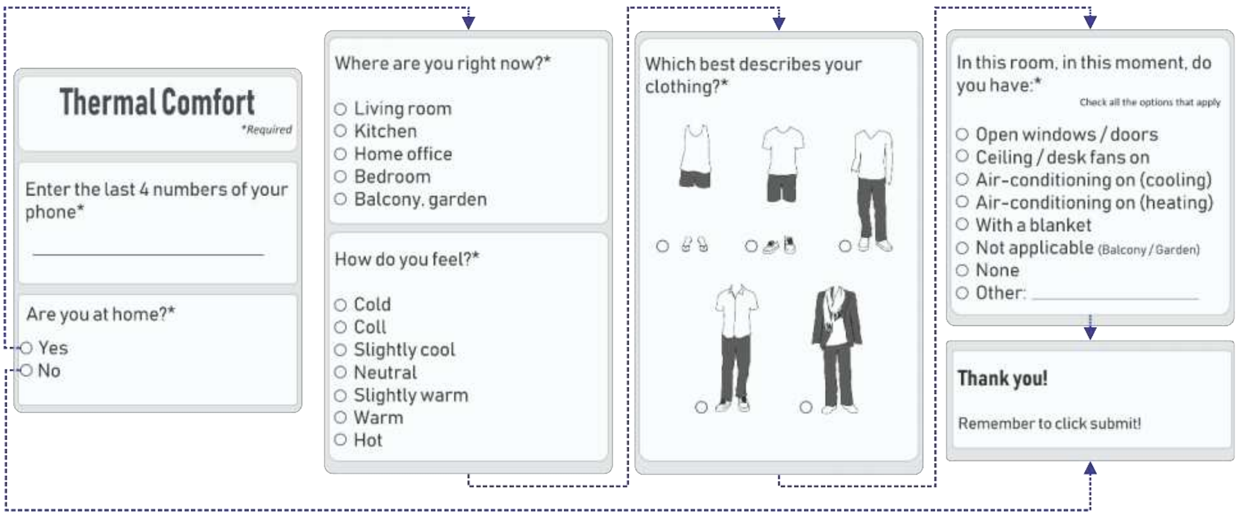


Figure 2. Online questionnaire layout.

A total of 768 questionnaires were received during the monitoring period. Occupants wore light clothes most of the time, varying from 0.20 to 0.6 *clo* (less than 8% of the answers have values above 0.3), which were estimated by the garment assembly chosen and the reference values from ISO 7730 (ISO, 2005) tables. For the analysis purposes, each questionnaire was combined with the real-time monitored data: air temperature and relative humidity.

## 3. Results and Discussion

Figure 3 shows the histogram of indoor air temperatures and subjects' thermal sensation votes in the monitored period. The mean air temperature is 27.14°C (sd=2.08), varying from 18 to 36°C. Based on Figure 3, it is possible to infer that the majority of subjects' votes are concentrated in neutral and slightly warm sensations (71,1%), indicating good thermal comfort conditions. A small percentage of the votes indicated hot discomfort (23,0%), and even a minimal cold discomfort (<1%).

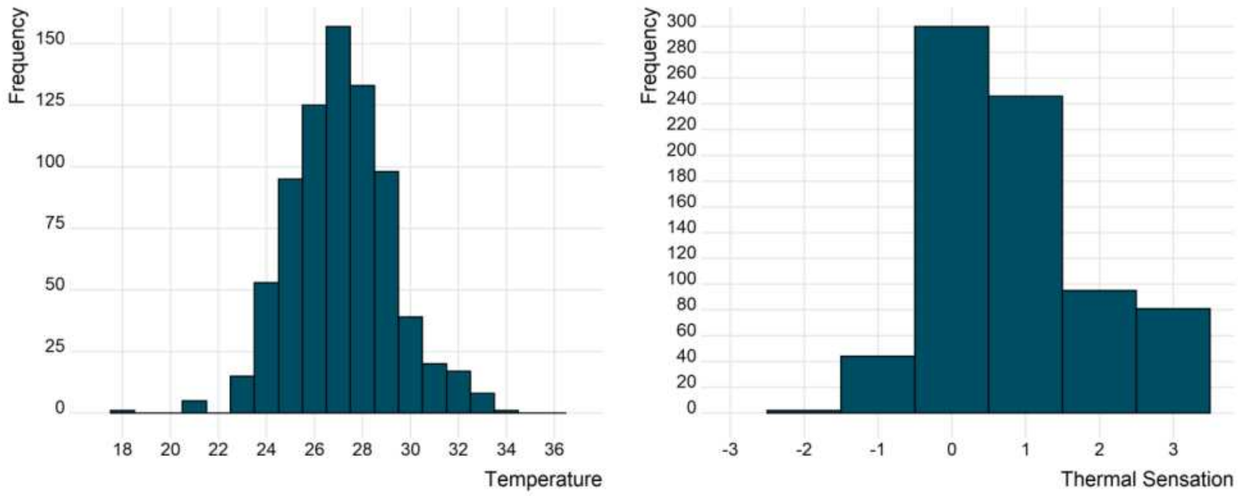


Figure 3. Indoor air temperature and Thermal sensation distribution

The following sections bring a summary of the behaviours taken by the occupants' groups and their environmental thermal perceptions.

### 3.1. Devices use

A common behaviour observed in Brazilian residences is the predominant use of natural ventilation strategy, which was confirmed in this study by 64.7% of the answers, while fans were used 20.1% of the time and the AC in 19.5%. Sometimes occupants use more than one device; Table 4 shows the frequency of answers from each combination, for both groups. The most frequent, regardless of the occupant tendency, is to open the windows - 49% for the Lower AC users and 52% for the Higher AC users. Even though the first group have a lower frequency of windows use, there is no statistically significant difference between them. The use of fans, combined or not with the windows opening is more frequent in the first group (Lower AC users); almost none of the users combined the use of fans and AC, resulting on only three answers of each group. As expected, the use of AC is more frequent in the group with a higher tendency to use the AC at home.

Table 4. Frequency of votes for each environmental condition

| | **Lower AC User** | **Higher AC user** | **Person's Chi-Square ($\chi^2$)** |
|---|---|---|---|
| **Open Window** | 49.3% | 52.2% | 0.54 ($\rho$=0.461) |
| **Open Window and Fans on** | 21.7% | 7.7% | 31.01 **($\rho$<0.001)** |
| **Fans on** | 8.6% | 3.0% | 10.37 **($\rho$=0.001)** |
| **AC on** | 11.3% | 24.6% | 21.15 **($\rho$<0.001)** |
| **AC and Fans on** | 0.9% | 0.7% | 0 ($\rho$=1) |

Figure 4 shows the behaviour of each group considering the outdoor air temperature. The LAC chooses to use ventilation with the windows open or combined with the use of fans and increases the use of AC as the temperature rises. The HAC group has a higher frequency of open windows in lower outdoor temperature conditions (20 to 24 °C) and use the AC more often when outdoor temperatures are higher than 25 °C. Comparing both groups, LAC choose to use more fans with the windows open as the outdoor temperature increases (before to turn on the AC), increasing the air movement. For example, at 28 °C, 69% of the LAC users have the windows open (window=19%, window and fans= 50%), while only 25% have the AC on. On the other hand, 50% of the HAC users have the windows opens (window=36%, window and fans= 14%), and 45% with the AC on.

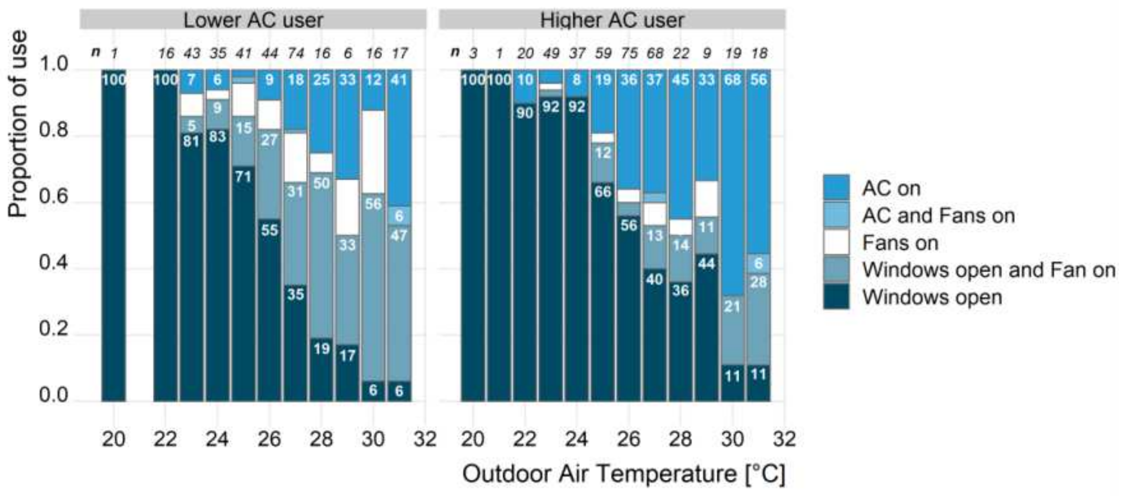


Figure 4. Frequency of occupant's action for the outdoor air temperature.

### 3.2. Environment perception

Analysing the thermal sensation votes of the groups separately, both groups have the major part of the votes between 'slightly cool' and 'slightly warm', 69% of the lower AC users and 83% of the higher AC users. However, the temperature ranges registered for each grade of the seven points-scale were different between the groups, as shown in Figure 5The one with a lower tendency to use the AC showed a higher mean value than the second group (neutral to warm: $\rho<0.05$). The higher difference (1.1 °C) can be seen in the neutral sensation, where HAC presents a mean temperature of 25.7 °C, while LAC presented 26.8 °C.

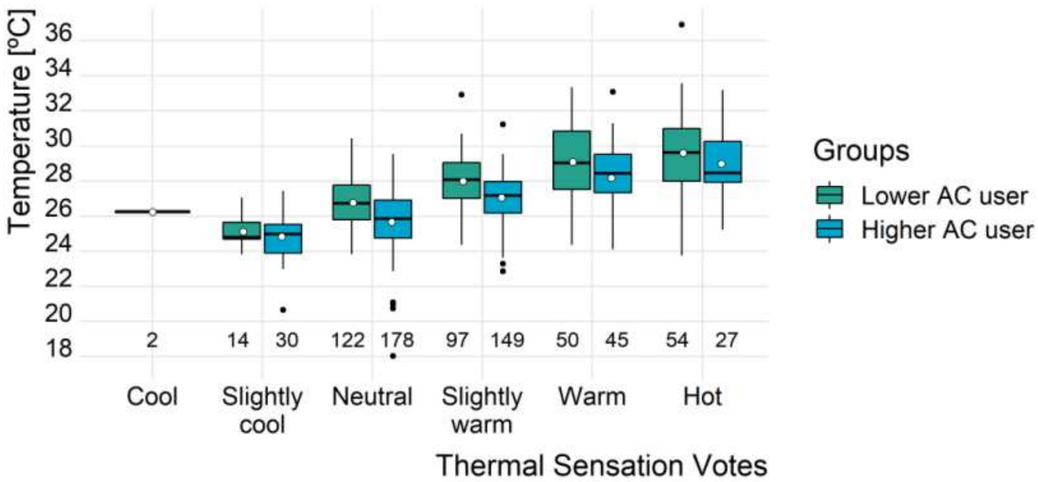


Figure 5. Indoor air temperature by thermal sensation and occupants' groups.

Considering both groups, for 'slightly cool' and the 'hot' votes, it was not possible to reject the null hypothesis (equal means), but the number of votes in these categories resulted in low power, 0.10 and 0.22 respectively, which increases the probability of a "type II error". For the votes with statistically significant results, the difference between LAC and HAC groups is approximately 1 °C. De Dear *et al.* (2018), compared the mean room air temperature for the groups considered as heavy and light AC users; between these groups, the authors found a difference about 2 °C.

These results suggest a preference to lower temperatures for those occupants with higher use or preference for conditioned environments. Comparing thermal sensation in schools, Buonocore *et al.* (2019) found this same tendency in the groups with and without long-term exposure to conditioned environments. To standard effective temperatures (SET) from 28 to 30 °C, the difference between both groups was close to 10 percentage points to warm and hot votes (Buonocore et al., 2019). De Vecchi *et al.* (2016) found a lower tolerance to the groups with prior exposure to AC. According to the authors, when SET values reached 25 °C, 30% of the subjects in this group voted as 'unacceptable', and for 26 °C it increases to 65%; while the groups without prior exposure remain with 20 and 25% of unacceptable votes (De Vecchi et al., 2016). These reactions can be explained by the occupants' long-term exposure to AC environments, which can make physiological adaptation to heat more difficult (Yu et al., 2012).

### 3.3. Acceptable Temperatures

The following analyses considered the acceptable temperatures in different environment conditions: windows open, windows open and fans on, fans on or AC use. The votes from 'slightly cool' to 'slightly warm' were considered as acceptable. In this condition, windows were open in 63.5% of the votes, electrical fans were on in 13.5% of the votes, and AC was on in 19% of them.

Figure 6 shows the acceptable indoors air temperature for different environments conditions: open windows, electrical fans and AC on, and electrical fan on with windows open. In all of the room conditions, the group with a lower tendency to use the AC accept a temperature higher than the second group. Environments with natural ventilation presented the highest temperatures (LAC= 32.92 °C and HAC= 31.24 °C). The lowest temperatures were found in two different environmental conditions for each group: 23.8 °C in the Lower AC users when windows were opened, and 18.04 °C in the Higher AC users when AC was on. The highest means were found when the users had the windows open and the fans on (LAC= 28.8 °C and HAC= 27.8 °C). Table 5 shows the difference in the mean acceptable temperature for each group. Environments with fans on have the lowest difference between the two groups (0.51 °C). The difference in the mean is higher when comparing the temperature of the environment with the air conditioner on; in this case, the difference between the groups was 1.29 °C.

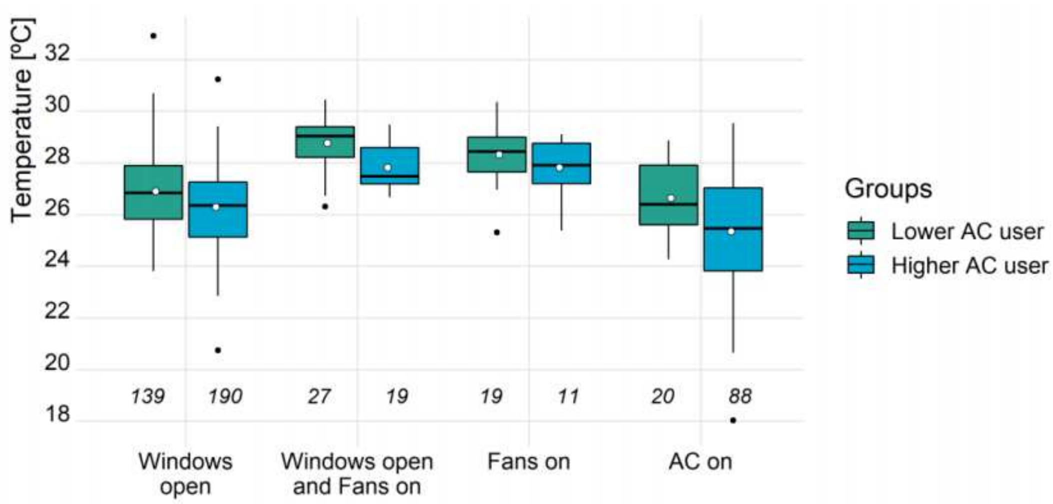


Figure 6. Indoor air temperature and environment conditions for acceptable thermal sensation votes.

Table 5. Difference in the acceptable temperatures for each group in different environmental conditions.

| Behave | Mean Temperature [°C] | | Difference Among Groups | |
|---|---|---|---|---|
| | *Lower Ac Users* | *Higher AC users* | *Difference [°C] (t.test)* | *Confidence interval [°C]* |
| Open Window | 26.91 | 26.3 | 0.61 **($\rho$<0.001)** | 0.27 – 0.96 |
| Open Window and Fans on | 28.78 | 27.85 | 0.93 **($\rho$=0.002)** | 0.36 – 1.53 |
| Fans on | 28.34 | 27.83 | 0.51 ($\rho$=0.442) | -0.39 – 1.42 |
| AC on | 26.65 | 25.36 | 1.29 **($\rho$=0.002)** | 0.48 – 2.10 |

Comparing the perception of different rooms conditions in each group, it is possible to see in Figure 7 that the acceptable temperature range in LAC group did not change statistically from a condition to another, but changed when the air movement increased; i.e., in this group, the statistically significant ($\rho$<0.01) difference was found comparing the rooms where electrical fans were on to those with no fans. On the other hand, for the Higher AC users group, the mean acceptable temperature to each type of room condition was different ($\rho$<0.001), except to rooms with fans on. As in the LAC group, the higher mean temperature corresponds to fans use, 27.8 °C with or without windows open, where the air movement improves the temperature acceptance; the lower mean temperature was verified in the "AC on" rooms (25.37 °C). The differences among the room conditions for the Higher AC users group is higher to 1 °C, going up to 2.4 °C when comparing the use of AC and electrical fans. This difference suggests that the Higher AC user group are more susceptible to the available devices, opting to lower temperatures when using the AC.

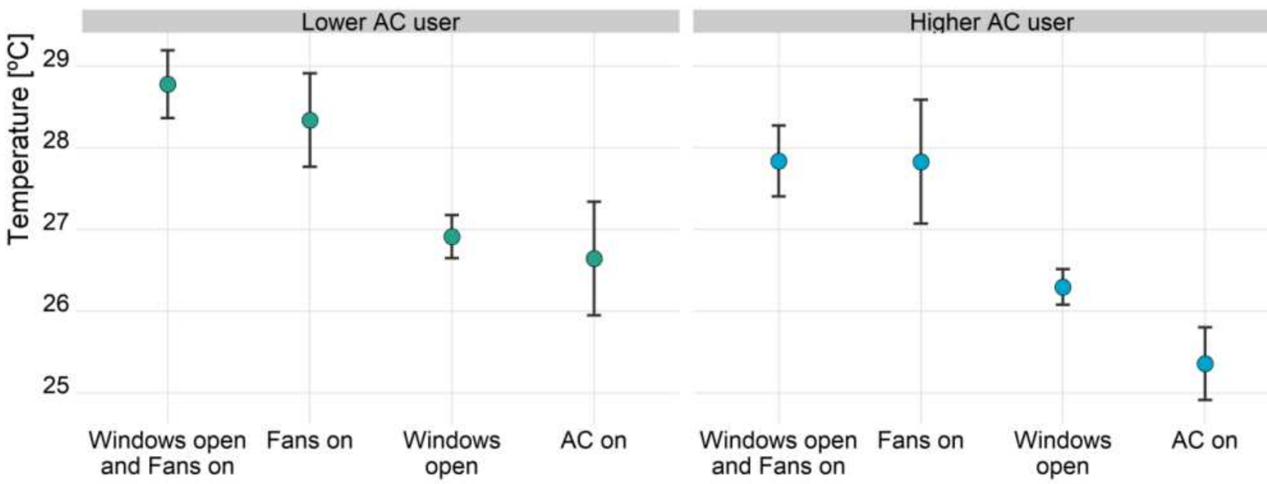


Figure 7. Mean acceptable temperature and confidence interval (95%) for different environmental conditions.

Analysing the occupants' behaviours compared to the outdoor air temperatures, and the results from the analysis of acceptable temperatures, it is important to highlight the differences between the behaviour from both the groups. HAC group opted for AC use more frequently than the LAC group and preferred lower temperatures when using this device. At the same time, the LAC group tended to behaviours that increase air movement, like natural ventilation and the use of fans, showing a more stable acceptable temperature range, regardless of the AC use.

## 4. Conclusion

This paper discusses the subjects' thermal environment perception according to the air-conditioner use in their homes. The subjects' with a greater tendency to use the AC have, in general, a lower mean acceptable temperature than those with a lower predisposition.

The group with a lower tendency to use the AC (LAC) presented mean acceptable temperature varying according to the air movement, 28.6 °C to rooms with higher air movement (fans on or windows open with fans on), and 26.9 °C with lower air movement (windows open or AC on). On the other hand, the group with a higher tendency to use the AC (HAC), showed different mean acceptable temperatures for each environment condition: 27.8 °C for when the fans were on, 26.3 °C for windows open with fans off, and 25.3 °C for AC on. Focusing on the use of the AC, while the LAC group uses it to achieve acceptable conditions similar to when the windows are open, the HAC group sets it to lower temperatures than they accepted when the windows were open, showing a preference for colder environments.

The frequency of adaptive behaviours also elucidates the preferences of each group. Opening the windows still is the most usual option, 71% of votes from LAC and 60% from HAC; followed by the use of fans for LAC (31.2%), and AC for HAC (25.3%). LAC group also combine adaptive behaviours more often than the HAC group (LAC=22.6%, HAC=8.4%). LAC uses other ways to achieve comfort before turning on the AC. We need more research to understand the reasons of this behaviour, as it can be a preference for naturally ventilated environments, financial or environmental concerns, among other factors. Considering all these aspects, design and regulations of residential buildings must take into account that occupants behave differently and that, in mild climates, natural ventilation is a recurring strategy for both groups.

Based on these results, it is possible to conclude that the preference for air-conditioned environments has an impact on how the dwellers behave, despite the greater freedom of choice that the occupants have in residential buildings. Even that natural ventilation is a usual strategy to both group, those that prefer the conditioned environments use the AC more frequently and with lower temperatures.

## 5. Acknowledgements

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# Optimising Comfort in Rural Villages of SW China

**Adrian Pitts[1], Yun Gao[2] and Vinh Tien Le[3]**

[1] Centre for Urban Design, Architecture and Sustainability, University of Huddersfield, UK. Email: a.pitts@hud.ac.uk
[2] Centre for Urban Design, Architecture and Sustainability, University of Huddersfield, UK. Email: y.gao@hud.ac.uk
[3] Centre for Urban Design, Architecture and Sustainability, University of Huddersfield, UK. Email: vinh.le@hud.ac.uk

**Abstract:** The rapid economic development of China has led to fast growth of its cities but also seen as increasingly important are its rural areas which were somewhat left behind in recent development; there are now many policies aiming to rebalance the variation. There are in addition particular circumstances impacting on redevelopment and design and construction which arises from the ethnic/nationality groupings to be found in SW China. One of the consequences of the rapid rural redevelopment is a focus more on acquisition of dwelling features found in urban apartments, rather than designing for the local climate and long-term sustainability. New dwellings are being constructed which whilst meeting the needs and requirements of the residents for more modern accommodation are not taking advantage of the potential to improve environmental design nor for occupant thermal comfort. Bioclimatic analysis and energy simulation software has been used to evaluate potential for improved dwelling design in the regions of interest. Results for five major city areas are presented and this demonstrates substantial opportunity to improve bioclimatic design and also to reduce discomfort. A research and practice network is helping draw stakeholders together to support and enhance future development and impact on choices being made so as to improve environmental outcomes.

**Keywords:** rural areas; dwellings; villages; comfort; China

## 1. Introduction

China has undergone a period of rapid urban and building development in the last 30 years; this development has been most obvious in the rapid expansion of its cities. Though China was originally a rural based economy with a largely rural based population, this situation has changed rapidly in recent times, and evidence to show the need to improve rural areas has influenced government policies. In addition, though it is less than previously, still approximately 570 million people live in what is classed as the countryside.

The urban development activities of recent decades have been undertaken with varying degrees of attention to sustainability issues. However, there have been many signs of a recognition of the need to address concerns of climate change and global warming, and of the need for efficient use of resources in construction and operation of the built environment [ref]. Whilst (as in the global west) economic sustainability takes precedence there is more attention now paid to issues of environmental, cultural and social sustainability.

In terms of overall development and prosperity, the lagging behind of rural areas began to give rise to concerns of inequality and the needs to consider promoting and supporting more specifically village redevelopment. The Chinese Government's 11th Five-Year plan of 2006 was the public start of this much needed redevelopment in rural areas (Government of the PRC, 2012). The subsequent speed of this revitalisation has meant that whilst many new dwellings have been constructed, the attention to sustainability has not been great and some opportunities for optimisation in the environmental design have not been taken.

Staff from the university of Huddersfield have been active in research into rural areas for a number of years: some of this has had a cultural theme; some other work has considered how dwellings could be designed with a greater emphasis on green and environmental issues (Pitts, 2016). In china as with almost all other countries a substantial amount of energy resource is needed to both construct buildings and also to maintain comfortable conditions inside buildings.

Many visits to rural areas of China have taken place allowing the research team to discover and evaluate different forms of construction with a specific emphasis in the Southwest quadrant of the country (Yunnan, Guizhou, Guangxi, Sichuan, and Chongqing) [Gao, 2016). This part of the country is somewhat removed from the more economically active East coast and also has a significant number of village areas that have been considered ripe for redevelopment.

This paper deals with a specific aspect of recent research, that is: evaluation of combinations of typical dwelling construction parameters in order to estimate the proportion of time that might be considered uncomfortable. This is being undertaken in order to provide both design professionals and also village leaders/residents with information to enable better choices about key building construction features that can be adjusted to improve comfort.

## 2. SW China

In SW China there are 4 provincial level areas (Yunnan, Guizhou, Guangxi and Sichuan) and one self –governing city (the only one not on the east Coast): Chongqing (Figure 1 illustrates the location). The total population is about 237 million (about 18% of the country's total). The region of SW China is culturally diverse with representation of many of China's 55 ethnic minorities (the population of China is largely of Han ethnic group – approximately 91.6% - with the remaining 55 minorities making up the other 8.4%). In the SW region populations from approximately 30 of those 55 other groups are to be found, and in some specific areas a particular nationality group will make up a significant fraction of the total. In some villages the situation can be even more important with almost all the local residents from a single group.

The impact of this is several-fold: there is a social and cultural closeness of the residents because of the family and clan-like structures; there are specific ethnic variations in traditional building design, clothing and language; there is tourist development potential to help support villages economically; and there is a drive from central government to help revitalise these areas.

The climate and topography of SW China are each rather variable: the are many changes in altitude which range overall from sea-level to over 4,000 metres and climate that ranges from hot and humid to cold. This means that solutions must be designed to meet the needs of specific locations and that a general regional or provincial approach is not satisfactory. In some areas where the altitude and other factors mean the temperatures are often below 0°C there is a need for heating whilst in others where temperatures regularly exceed 30°C with high humidity, there is a need for cooling. As a result it is important to understand how the building itself can be adjusted in each circumstance in order to improve comfort conditions and to reduce the needs for heating and cooling systems.

The region also has a number of areas of significant seismic activity which means new buildings have to be designed to meet appropriate building codes. Research involving the

Huddersfield team has also linked redesign/construction issues of traditional dwellings to seismic tests (Bai et al, 2019).


Figure 1: The Provinces of SW China (Pitts et al, 2019)

## 3. Rural Revitalisation

As mentioned previously, the issuing of the 11th Five Year plan in 2006 marked a clear start for rural revitalisation processes in China. Rural areas have both different citizenship statuses and also differences in land ownership. 'Villages' are also part of the government classification system in China and 'Administrative' villages are different to 'natural' villages. Natural villages can vary greatly in size though frequently in SW China they are relatively small affairs consisting of from a few tens to a few hundreds of inhabitants, and with a number of natural villages making up an Administrative village. The natural villages often consist mainly of inhabitants from one ethnic nationality and this can have impacts on the process of redevelopment (Gao, 2016), especially when there is also a tourist development aspect to the activity (Gao et al, 2014).

In specific areas guidance may also have been issued in support of redevelopment however this rarely considers climate-sensitive design and comfort (YHTCCD and YURP&DI, 2018a and 2018b). A further issue arises from the way in which redevelopment occurs, often involving construction companies taking the lead rather than designers, although village dwellers may also take the initiative themselves I certain projects. As a result, although there can be not insubstantial funding/subsidies available, there is more attention paid to maximising the size of the property and the inclusion of modern amenities rather than running costs such as for energy. This has the effect of bypassing consideration of more vernacular inspired designs or of a deeper consideration of those factors which can lead to use of bioclimatic techniques to achieve comfort/reduce discomfort. It also bypasses the craft skills and knowledge that might exist in a local area that could be used, and which would enhance economic and cultural sustainability.

Figure 2: Dwelling of traditional construction, Manzhang village, Yunnan

Figure 3: Dwelling of modern construction, Manzhang village, Yunnan

The outcome of this process can lead to the replacement of traditional, but old style dwellings, which lack modern features which local in habitants associated with a modern urban lifestyle, with a modern alternative constructed from concrete blocks walls and tiled roofs. Many bioclimatic design options that could address comfort requirements more 'naturally' are never considered. The contrasting 'before' and 'after' designs can be seen in examples from the same village shown in Figures 2 and 3.

## 4. Research Investigations

As part of a broader project, a range of investigations into aspects of sustainable development in rural villages in China has been undertaken. More than a dozen extended visits to villages in provinces of Southwest China occurred (sometimes more than once to the same village). Most of these visits included meetings with village leaders as well as examination of the planning of the village and of individual dwellings. Discussion indicated many opportunities to introduce climate sensitive design into the processes of rural development but that lack of awareness or confidence in using such options also existed. As a result some opportunities to improve thermal comfort are not taken thus increasing energy use and soring up problems for the future with warming climates.

Leading on from the village visits was the establishment of a research group: *The Sustainable and Creative Villages Research Network – SW China*; this was funded by the Arts and Humanities Research Council (AHRC). Additional funding arose from participants in the network who were willing to fund attendance by their staff at a number of symposia held over a two-year period and also in providing facilities and support for the hosting of these events.

Several online dissemination and discussion groups were also set-up to facilitate communication about the topic and this proved to be a good way to encourage collaboration between subgroups within the network, total membership of which stands at over 50 at the time of writing. A further value from this process was the support for stakeholders to increase their levels of confidence in applying climate sensitive and bioclimatic design strategies. Over a period of three years a substantial amount of research investigation and analysis took place with involvement of local partners and this resulted in a number of outputs.

The impacts arising from these activities have been felt in several areas: firstly impacts on the design approaches and factors considered by professionals in practice (planning and architecture); second encouragement for multiple university/research organisations to collaborate; and thirdly impacts on the teaching curriculum with inter-institutional projects undertaken in the field (i.e. attached to villages). The work has also been showcased at recent international exhibition/conferences: the 4$^{th}$ ASEAN Architecture Art Forum held in Nanning, China and the 4$^{th}$ CSCEC Cup Western '5+2' Biennale Exhibition of Environmental Art Design held in Kunming, both during November 2019.

These dissemination and impact features have proved to be very important and in order to provide valuable additional resources, further research was undertaken in SW China to examine potential to address comfort/discomfort issues. The evolution of these topics is discussed in the next section.

## 5. Energy and comfort

Arising from the investigations carried out within villages it seemed clear to the research team that whilst there was some understanding amongst stakeholders that alternative green and climate sensitive design options existed, that there was no clear mechanism for developing suitable solutions. Even professionals (planners and architects) lacked a clear understanding of what technologies and techniques existed and how to choose and design their integration into construction. The authors suggested that bioclimatic design techniques that are in common use elsewhere could be considered and that a simplified tool for assessing potential could be utilised. There was also a lack of understanding of different approaches to defining and assessing thermal comfort and whilst the PMV approach of Fanger (1970) was recognised, there was less understanding of adaptive approach such as shown in Nicol and Humphreys (2002) and Nicol (2011).

In order to address bioclimatic design issues, the authors identified the Climate Consultant software (UCLA, 2019) as providing the option with best combination of clarity and ease of use that was freely available. They also found a significant set of data records for climate existed for China in which 46 different locations in SW China could be identified.

The list of possible design techniques is provided in Table 1 below. The means to assess the potential for design benefit from these techniques was through the Climate Consultant software available from UCLA [ref]. The software produces outputs in a number of formats and for the purposes of this paper it was used to consider 5 major city areas in SW China for which climate data had been obtained through the EnergyPlus (EnergyPlus, 2019a) online link to weather files compiled by the China Meteorological Bureau (2015).

Of the list of techniques shown, about half can be considered to be 'passive' (that is requiring little or no external energy or sophisticated control system to function), and about half 'active' (those which do require additional energy and controls).

Table 1. Climate Sensitive Design Techniques in Climate Consultant Software

| | |
|---|---|
| 1 | Basic design for comfort |
| 2 | Sun shading of windows |
| 3 | High thermal mass |
| 4 | High thermal mass night flushed (ventilated) |
| 5 | Direct evaporative cooling |
| 6 | Two-stage evaporative cooling |
| 7 | Natural ventilation cooling |
| 8 | Fan-forced ventilation cooling |
| 9 | Internal heat gain |
| 10 | Passive solar direct gain low mass |
| 11 | Passive solar direct gain high mass |
| 12 | Wind protection of outdoor space |
| 13 | Humidification only |
| 14 | Dehumidification only |
| 15 | Cooling with dehumidification if needed |
| 16 | Heating with humidification if needed |

In addition to these differentiations it is also possible within the software to select calculation of comfort hours according to different comfort models. Two were chosen for this study: the 'ASHRAE Standard 55 and current Handbook of Fundamentals' model and the 'Adaptive Comfort Model in ASHRAE Standard 55 2010'. These produce different results because of the adaptive aspect of the second model. The data outputs are summarised in Table 2 for the five city regions: Chongqing; Nanning; Guiyang; Chengdu; and Kunming. In addition screen captures were collected of the resulting outputs using standard input conditions for the five locations showing the comfort potential zones on a psychrometric chart. These are shown in Figures 4- 8.

It was clear from these analyses that there was considerable opportunity to improve internal environmental conditions by making use of the design techniques; it was further noted that even if only 'passive' techniques were used, that there was a considerable benefit to be derived – up to 74% for one of the locations considered. Since it was the intention of the overall research programme to offer opportunities for design variation in a form that could be used by stakeholders, it was decide to pursue the investigation further. In order to do this a more sophisticated piece of software was selected EnergyPlus (2019b).

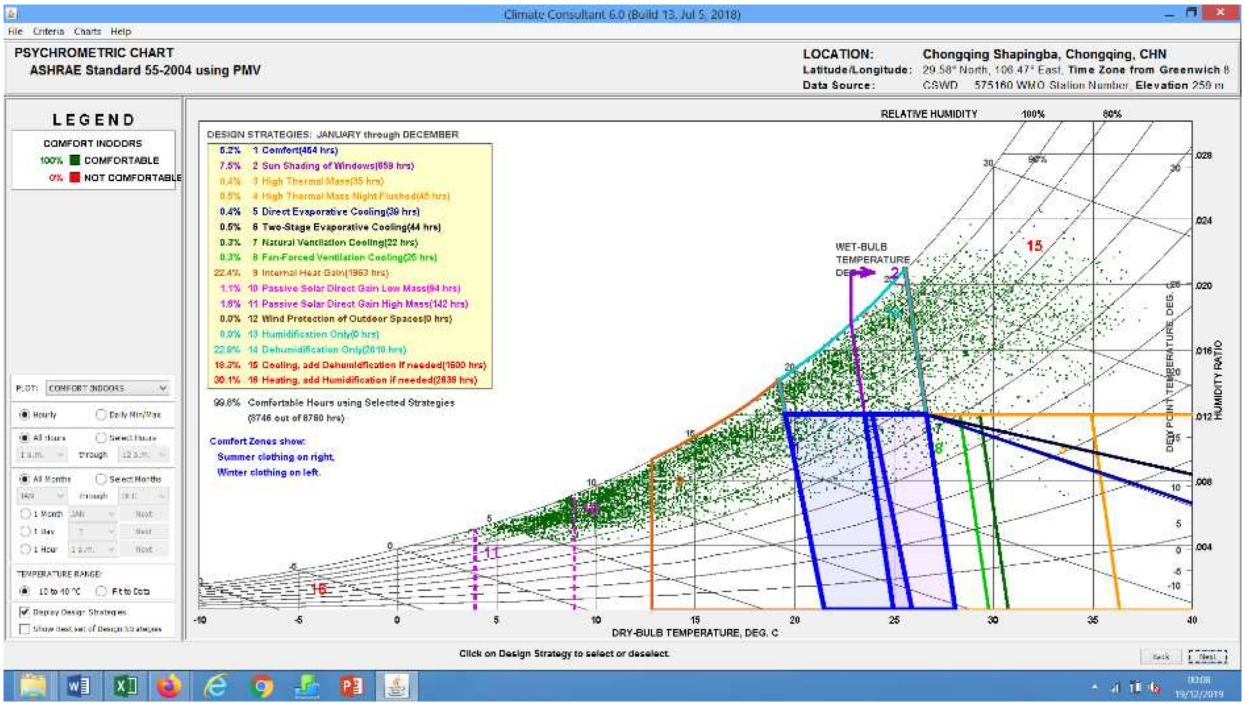


Figure 4: Design Strategies shown on Psychrometric Chart for Chongqing

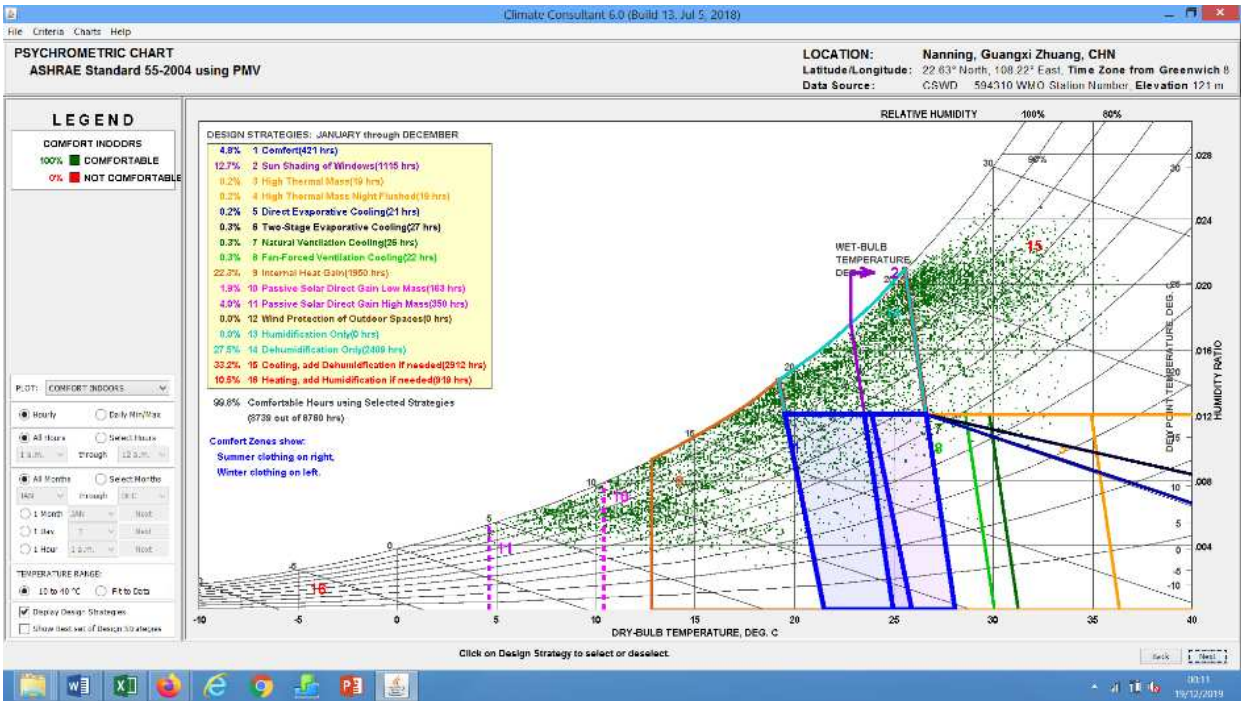


Figure 5: Design Strategies shown on Psychrometric Chart for Nanning, Guangxi

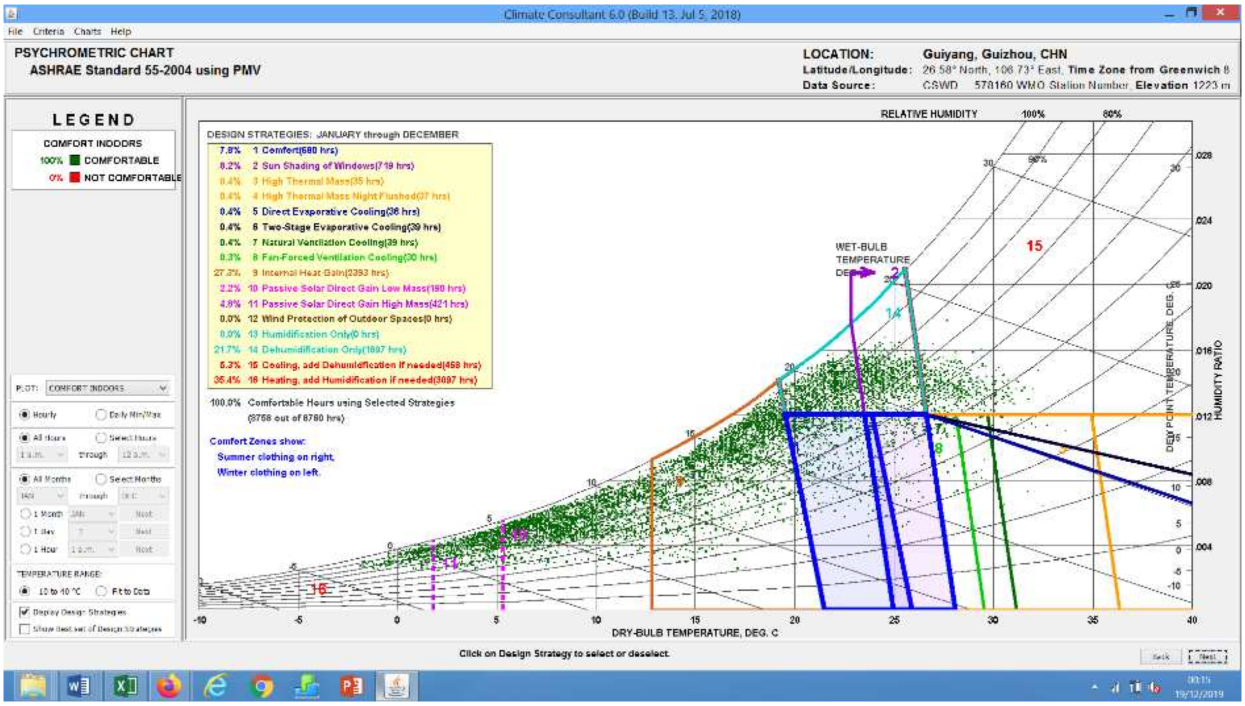


Figure 6: Design Strategies shown on Psychrometric Chart for Guiyang, Guizhou

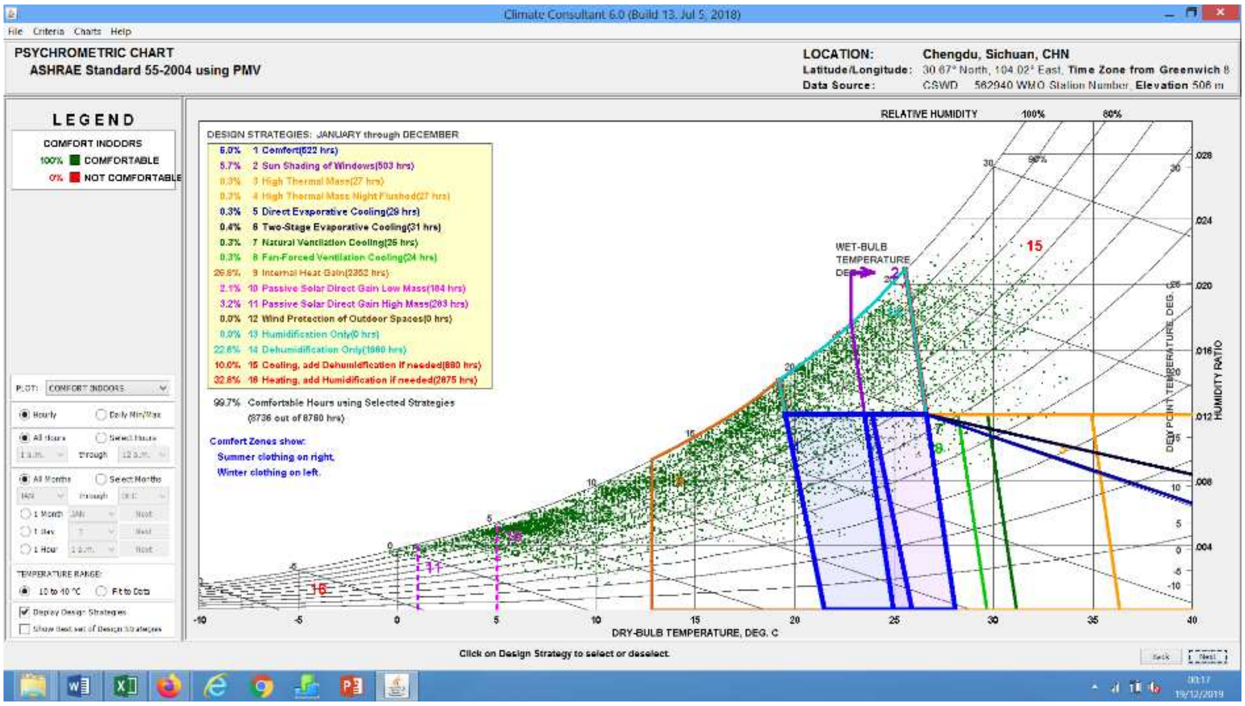


Figure 7: Design Strategies shown on Psychrometric Chart for Chengdu, Sichuan

EnergyPlus allows the modelling of internal conditions through use of a simulation technique. Required input data includes all thermal property and usage details for a building. A simple standard dwelling was chosen to be used together with parametric variations of the main features of design: wall construction; window area; air infiltration; orientation of the main façade; and also consideration of differences between upper and lower floor. The information box in the appendix indicates the range of variations considered; altogether these result in 216 simulations being carried out for each location.

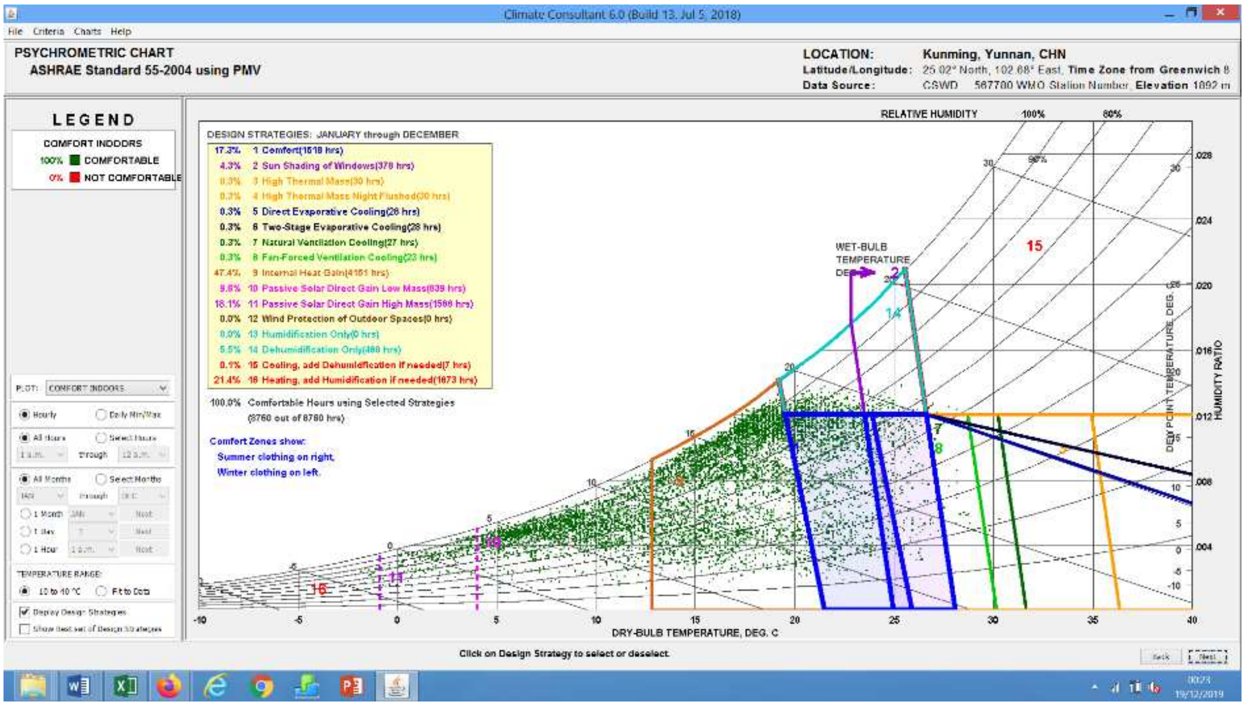


Figure 8: Design Strategies shown on Psychrometric Chart for Kunming, Yunnan

Following this process which generated very large datasets of values of internal conditions for every hour of the year for 216 simulation variations, analysis of outcomes was undertaken with reference to the predicted mean vote conditions. The variation from comfort was determined for every hour and then summed according to two different variabilities from neural. The acceptable variation from PMV of 0 is addressed in comfort standards with options to ±0.7, however in a previous study by one of the authors (Pitts and Bin Saleh, 2007) a case was made for extending the boundary for adaptable comfort to PMV ±1.0 and this was the criteria chosen. The reasoning for this came from the apparent acceptance of a wider range of conditions from local in habitants and particularly for inhabitants who had experience of very 'leaky' ethnic type dwellings. At this stage the comparison was undertaken for speculative reasons in order to examine the potential impact; further studies into this aspect are being undertaken but not reported here.

## 6. Results

As already stated Table 2 shows the variations in additional comfort hours (expressed as a percentage) that is generated by use of each technique using two comfort models. The total potential improvement is always less than the sum of the contributing techniques because in each case the adoption of one methods reduces the maximum benefits that can be accrued by use of another. Nevertheless, substantial improvements are demonstrated suggesting value in disseminating information to stakeholders and in particular to those in a position to influence design and construction decision making.

Tables 3 to 7 at the end of the paper provide comparative results from the EnergyPlus simulations for the five city region locations. The tables show the discomfort hours resulting if using an extended range of comfort prediction of PMV ±1.0.

### 6.1 Design evaluations:

*Wall construction and thermal insulation*

The results show that in many circumstances the use of thermal insulation in the lightweight wall constructions can produce some benefits. Since thermal insulation is not frequently used in building construction in Southwest China at the present time, this is something which designers might consider for the future. Benefits come not just from reducing heat loss in cooler periods but also from reducing heat gains in some warmer periods.

*Air flow and ventilation*

In many but not all situations there are benefits from controlling air flow in the building; more airtight constructions often performing better than leaky alternatives.

*Window/glazing area and orientation*

Variations in performance associated with changes to the glazing area are quite complicated to interpret in any general way and require the user to examine variations in conjunction with consideration of main orientation. This is not to say the variation is inconsequential, but rather it needs intelligent interpretation related to the actual site and climate.

*Ground or first floor*

There are differences in performance between ground floor areas and first floor areas. This can have significant implications for overall comfort – for instance in certain climates it may be better to have main living spaces on the ground floor and in other climates better to make more use of the upper first floor. It might also be useful to consider that at different times of the year the ground floor may be preferable whilst the first floor may be preferred at other times. The level of data analysis in the appendix does not allow that level of analysis at the moment though it can be considered at a later date.

**6.2 Site location opportunities**

The summary below indicates the general site location recommendations for each of the city regions.

Shapingba, Chongqing: average discomfort hours 75.8% (range 71.3%-78.9%). Lightweight construction with insulation gives a benefit of about 2%. Glazing ratio has little impact though low glazing ratio is the best by a small amount. North and South orientations slightly better than East and West. Ground floor location is better than first floor by about 2%. Medium air change rate is best by a small amount. The overall range of values for Chongqing is quite modest and the comfort level is low, however this might be expected for a city known as one of the 'three furnaces of China' because of the summer heat.

Nanning, Guangxi: average discomfort hours 73.6% (range 65.8%-78.9%). Lightweight construction with insulation gives a benefit of about 6%. Glazing ratio has little impact. Main orientation makes little difference. Ground floor location has similar outcomes to the first floor. Low and medium air change rate is best by about 2.5%. Again the range is modest because conditions are generally warm and humid.

Guiyang, Guizhou: average discomfort hours 69.3% (range 58.6%-75.4%). Lightweight construction with insulation gives a benefit of about 5%. Glazing ratio has little impact though low glazing ratio is the best by about 1%. North and South orientations slightly better than East and West by about 1.5%. Ground floor location is better than first floor by about 5%. Medium air change rate is best by about 1%. The range of values is a little higher in this city which does experience a wider range of climate.

Chengdu, Sichuan: average discomfort hours 71.8% (range 64.6%-76.9%). Lightweight construction with insulation gives a benefit of about 6%. Glazing ratio has little impact though. Main orientation has little impact. Ground floor location is better than first floor by about 2%. Medium air change rate is best by a small amount. Another city with only a rather modest range of climatic variation.

Kunming, Yunnan: average discomfort hours 57.3% (range 35.4%-71.6%). Lightweight construction with insulation gives a benefit of about 10%. Glazing ratio has little impact. South orientation is slightly better than others by about 1.5%. Ground floor location is better than first floor for two wall constructions, but not the best design of lightweight with insulation. Low air change rate is best by about 1.5%. Kunming offers the least uncomfortable conditions which is perhaps unsurprising for the city of 'eternal spring'; the worst overheating potential is ameliorated by the altitude of the location.

Though an initial reaction would be that the potential changes for a number of locations is modest, in every case, and bearing in mind the parametric variations were limited, there is potential to improve operation by reducing the percentage of discomfort hours by a significant amount.

## 7. Summary and conclusions

This paper has focused attention on the provision of comfort in dwellings of SW China. This region and its buildings are important because they represent a number of features of redevelopment in a sub-area of the country which is often neglected when thinking about environmental design and comfort. The fact that the population and number of dwellings affected is larger than most countries means the impacts can be very significant. Research is ongoing into this area and further outcomes will result.

The bullet point list below summarise the key findings:

- Rural China offers a large opportunity to improve energy efficient design both because of the type of settlements and because of the sheer number of inhabitants;
- there is an under-optimised opportunity to produce better climate sensitive housing;
- one of the key barriers to progress is lack of guidance and communication to stakeholders;
- design and construction professionals need better guidance and improved understanding of thermal comfort issues in dwelling design;
- local inhabitants have capacity to be involved and take more control to achieve comfort if they are better informed;
- rural buildings are neither built nor used like urban counterparts, yet occupants aspire to urban equivalents because of impressions of what modern design should be;
- there is need to understand the specific location for development and in particular the climate – this is because relatively short distances can produce significant swings in the optimum design techniques;
- the results from the analyses suggest alternative forms of construction should be considered, including greater use of insulation in the envelope;
- controlled natural ventilation can make a useful contribution to the achievement of comfort;
- the role of internal heat gains in offsetting impacts from cooler conditions should be better understood;
- the need for many of these actions is now, both because of the changing climate and also in SW China because of the speed that redevelopment takes place.

## 8. Acknowledgements

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**Appendix A:**

Appendix: Information box
Input data for EnergyPlus simulations

The main characteristics/features of the simple building were:

- Key external dimensions: width: 7.8 m; depth: 8.1 m; 2 floors—floor to floor height 3 m; intermediate floor 0.1 m concrete;
- Double wood door to front elevation 2.4 m high, 1.4 m wide;
- Walls: main component thickness (without insulation or cavity) = 0.24 m;
- Windows: 1.5 m in height; bottom of window 0.9 m above floor; glazing only to front (main) façade and rear façade; variations in window size accommodated by changing the width;
- 2 occupants per floor (1 met activity level); clothing insulation value: 0.7 clo; no other heat gains apart from occupants were incorporated due to the level of complexity.

A series of parametric alternatives were then chosen for other building features:

- Four principal orientations: north, east, south, west;
- Three glazing options (all single glazed):
  low glazing ratio: front window to wall area ratio (WWR) = 0.2, rear WWR = 0.15;
  medium glazing ratio: front WWR = 0.35, rear = 0.25;
  high glazing ratio: front WWR = 0.5, rear WWR = 0.35.
- Three variations in construction with different thermal impacts:
  Heavyweight: load bearing concrete frame with dense brick infill walls plus 0.015m internal plasterboard finish; concrete roof structure 0.1m thick, concrete floor 0.1m.thick;
  Lightweight: lightweight concrete block walls plus 0.015m internal plasterboard; concrete roof structure 0.1m thick, concrete floor 0.1m. thick;
  Lightweight with Insulation: lightweight concrete block walls with internal insulation of 0.1m; plus 0.015m internal plasterboard; concrete roof structure 0.1m with 0.1m internal insulation, concrete floor 0.1m (no insulation).
- Ventilation rates: 0.25/0.5/1.0 air changes per hour.

Table 2: Improvement in comfort hours experienced (expressed as a percentage of total hours in the year)

| | Comfort model | Comfort 1 | Sun shading 2 | High thermal mass 3 | High thermal mass + night Flush vent. 4 | Direct Evaporative Cooling 5 | Two-stage Evaporative Cooling 6 | Natural ventilation 7 | Fan-forced ventilation 8 | Internal heat gain 9 | Passive Solar Direct Gain Low Mass 10 | Passive Solar Direct Gain High Mass 11 | Wind Protection 12 | Humidification Only 13 | Dehumidification Only 14 | Cooling 15 | Heating 16 | **Selected design strategies (total for passive or all techniques)** Passive | All |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Shapingba** | PMV | 5.2 | 7.5 | 0.4 | 0.5 | 0.4 | 0.5 | 0.3 | 0.3 | 22.4 | 1.1 | 1.6 | 0 | 0 | 22.9 | 18.3 | 30.1 | **28.6** | **99.8** |
| **(Chongqing)** | Adaptive (+PMV) | 5.2 | 7.5 | 0.4 | 0.5 | 0.4 | 0.5 | **22.1** | 0.3 | 22.4 | 1.1 | 0.9 | 0 | 0 | 22.9 | 10.8 | 30.3 | **47.2** | **99.9** |
| **Nanning** | PMV | 4.8 | 12.7 | 0.2 | 0.2 | 0.2 | 0.3 | 0.3 | 0.3 | 22.3 | 1.9 | 4 | 0 | 0 | 27.5 | 33.2 | 10.5 | **28.8** | **99.8** |
| **(Guangxi)** | Adaptive(+PMV) | 4.8 | 12.7 | 0.2 | 0.2 | 0.2 | 0.3 | **37.3** | 0.3 | 22.3 | 1.9 | 2.3 | 0 | 0 | 27.5 | 15.9 | 11.3 | **62.1** | **99.9** |
| **Guiyang** | PMV | 7.8 | 8.2 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.3 | 27.3 | 2.2 | 4.8 | 0 | 0 | 21.7 | 5.3 | 35.4 | **37.9** | **100** |
| **(Guizhou)** | Adaptive(+PMV) | 7.8 | 8.2 | 0.4 | 0.4 | 0.4 | 0.4 | **18.3** | 0.3 | 27.3 | 2.2 | 3 | 0 | 0 | 21.7 | 3.5 | 36.5 | **50.0** | **100** |
| **Chengdu** | PMV | 5.3 | 10 | 0.7 | 0.7 | 0.7 | 0.7 | 0.6 | 0.5 | 21.5 | 2.4 | 3.3 | 0 | 0 | 26.9 | 8.9 | 34.9 | **29.6** | **100** |
| **(Sichuan)** | Adaptive(+PMV) | 5.3 | 10 | 0.7 | 0.7 | 0.7 | 0.7 | **20.1** | 0.5 | 21.5 | 2.4 | 1.1 | 0 | 0 | 26.9 | 5.3 | 35.8 | **45.1** | **100** |
| **Kunming** | PMV | 17.3 | 4.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 47.4 | 9.6 | 18.1 | 0 | 0 | 5.5 | 0.1 | 21.4 | **73.4** | **100** |
| **(Yunnan)** | Adaptive(+PMV) | 17.3 | 4.3 | 0.3 | 0.3 | 0.3 | 0.3 | **14.4** | 0.3 | 47.4 | 9.6 | 10.3 | 0 | 0 | 5.5 | 0.1 | 26.3 | **70.7** | **100** |

Table 3: Discomfort Hours for City of Chengdu, Sichuan with PMV>+1 or PMV<-1 (percentage of hours in the year)

| Discomfort hours summary | | Chengdu, Sichuan | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Heavy walls | | | | | | Lightweight walls | | | | | | Lightweight insulated walls | | | | | |
| | | 0.25 ACH | | 0.5 ACH | | 1 ACH | | 0.25 ACH | | 0.5 ACH | | 1 ACH | | 0.25 ACH | | 0.5 ACH | | 1 ACH | |
| | | Ground | 1st floor | Ground | 1st floor | Ground | 1st floor | Ground | 1st floor | Ground | 1st floor | Ground | 1st floor | Ground | 1st floor | Ground | 1st floor | Ground | 1st floor |
| Low glazing | South | 71.5% | 74.1% | 70.9% | 73.9% | 73.4% | 76.0% | 71.2% | 74.2% | 71.0% | 74.1% | 72.7% | 75.9% | 65.1% | 66.5% | 64.6% | 65.3% | 65.8% | 67.9% |
| | North | 71.4% | 74.2% | 71.1% | 74.0% | 73.4% | 76.0% | 71.3% | 74.3% | 71.1% | 74.2% | 72.8% | 76.0% | 65.3% | 66.7% | 64.7% | 65.7% | 65.9% | 68.1% |
| | East | 71.8% | 74.4% | 71.4% | 74.2% | 73.6% | 76.2% | 71.8% | 74.7% | 71.4% | 74.3% | 73.2% | 76.4% | 66.2% | 67.7% | 65.6% | 66.8% | 67.4% | 69.3% |
| | West | 71.9% | 74.3% | 71.2% | 74.2% | 73.6% | 76.2% | 71.7% | 74.7% | 71.4% | 74.5% | 73.2% | 76.4% | 66.3% | 67.9% | 65.6% | 66.9% | 67.3% | 69.4% |
| Medium glazing | South | 71.7% | 74.1% | 71.0% | 74.0% | 73.3% | 76.0% | 71.3% | 74.3% | 71.0% | 74.1% | 72.8% | 76.0% | 65.5% | 67.2% | 65.1% | 66.4% | 66.4% | 68.1% |
| | North | 71.8% | 74.3% | 71.1% | 74.1% | 73.4% | 76.1% | 71.4% | 74.4% | 71.1% | 74.2% | 72.9% | 76.0% | 65.8% | 67.5% | 65.5% | 66.7% | 66.8% | 68.6% |
| | East | 72.1% | 74.3% | 71.6% | 74.3% | 73.8% | 76.4% | 71.9% | 74.9% | 71.6% | 74.7% | 73.5% | 76.6% | 66.9% | 68.8% | 66.4% | 68.0% | 68.5% | 70.1% |
| | West | 72.2% | 74.5% | 71.6% | 74.4% | 73.7% | 76.4% | 71.9% | 75.1% | 71.6% | 74.7% | 73.4% | 76.6% | 67.2% | 69.3% | 66.5% | 68.4% | 68.5% | 70.3% |
| High glazing | South | 71.5% | 74.0% | 71.0% | 73.9% | 73.4% | 76.1% | 70.8% | 74.4% | 70.8% | 74.1% | 72.7% | 75.9% | 66.2% | 67.8% | 65.5% | 67.4% | 67.2% | 69.0% |
| | North | 71.7% | 74.1% | 70.9% | 74.0% | 73.5% | 76.2% | 71.0% | 74.4% | 71.0% | 74.2% | 72.8% | 76.1% | 66.4% | 68.2% | 65.8% | 67.7% | 67.6% | 69.4% |
| | East | 72.2% | 74.5% | 71.7% | 74.5% | 73.8% | 76.5% | 71.8% | 75.1% | 71.6% | 74.7% | 73.6% | 76.7% | 67.8% | 70.0% | 67.2% | 69.4% | 69.5% | 71.2% |
| | West | 72.2% | 74.5% | 71.7% | 74.5% | 73.8% | 76.5% | 71.9% | 75.2% | 71.6% | 74.9% | 73.6% | 76.9% | 68.1% | 70.3% | 67.4% | 69.8% | 69.6% | 71.7% |

Table 4: Discomfort Hours for City of Guiyang, Guizhou with PMV>+1 or PMV<-1 (percentage of hours in the year)

| Discomfort hours summary | | Guiyang, Guizhou | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Heavy walls | | | | | | Lightweight walls | | | | | | Lightweight insulated walls | | | | | |
| | | 0.25 ACH | | 0.5 ACH | | 1 ACH | | 0.25 ACH | | 0.5 ACH | | 1 ACH | | 0.25 ACH | | 0.5 ACH | | 1 ACH | |
| | | Ground | 1st floor | Ground | 1st floor | Ground | 1st floor | Ground | 1st floor | Ground | 1st floor | Ground | 1st floor | Ground | 1st floor | Ground | 1st floor | Ground | 1st floor |
| Low glazing | South | 67.8% | 72.8% | 66.4% | 71.9% | 68.0% | 73.5% | 67.5% | 72.6% | 66.7% | 72.0% | 69.4% | 73.9% | 59.5% | 64.5% | 58.6% | 63.3% | 62.6% | 64.4% |
| | North | 67.9% | 73.0% | 66.4% | 71.9% | 68.0% | 73.6% | 67.7% | 72.8% | 66.7% | 72.1% | 69.5% | 74.0% | 59.7% | 65.1% | 58.8% | 64.0% | 62.7% | 64.6% |
| | East | 68.4% | 73.5% | 67.1% | 72.4% | 68.4% | 73.9% | 68.4% | 73.2% | 67.5% | 72.6% | 69.9% | 74.4% | 62.9% | 67.5% | 61.5% | 66.6% | 64.1% | 67.7% |
| | West | 68.6% | 73.6% | 67.4% | 72.6% | 68.6% | 74.0% | 68.5% | 73.4% | 67.6% | 72.7% | 70.1% | 74.6% | 63.9% | 68.0% | 62.4% | 67.4% | 64.4% | 68.7% |
| Medium glazing | South | 67.9% | 73.0% | 66.8% | 72.1% | 68.2% | 73.5% | 68.0% | 72.8% | 67.0% | 72.2% | 69.6% | 74.0% | 61.8% | 66.3% | 60.6% | 65.0% | 63.3% | 66.2% |
| | North | 68.1% | 73.1% | 67.0% | 72.3% | 68.3% | 73.7% | 68.1% | 72.9% | 67.2% | 72.5% | 69.7% | 74.2% | 62.4% | 67.0% | 61.0% | 65.9% | 63.5% | 67.0% |
| | East | 69.0% | 73.9% | 67.7% | 72.8% | 68.9% | 74.1% | 68.8% | 73.6% | 67.9% | 72.9% | 70.3% | 74.8% | 65.8% | 69.7% | 64.1% | 68.8% | 65.4% | 70.4% |
| | West | 69.4% | 74.0% | 67.9% | 73.0% | 69.3% | 74.4% | 69.1% | 73.9% | 68.1% | 73.2% | 70.7% | 74.9% | 66.8% | 70.6% | 65.3% | 69.9% | 66.2% | 71.8% |
| High glazing | South | 68.3% | 73.1% | 66.9% | 72.3% | 68.5% | 73.7% | 68.1% | 72.9% | 67.2% | 72.3% | 69.7% | 74.2% | 63.8% | 68.2% | 62.1% | 67.1% | 64.4% | 67.7% |
| | North | 68.4% | 73.2% | 67.0% | 72.5% | 68.5% | 73.8% | 68.3% | 73.1% | 67.4% | 72.4% | 69.9% | 74.4% | 64.6% | 68.7% | 62.8% | 67.6% | 64.8% | 68.5% |
| | East | 69.8% | 74.3% | 68.3% | 73.3% | 69.5% | 74.6% | 69.6% | 73.9% | 68.6% | 73.3% | 70.8% | 75.1% | 68.0% | 71.7% | 66.6% | 70.9% | 67.3% | 72.6% |
| | West | 70.1% | 74.6% | 68.6% | 73.6% | 70.0% | 74.9% | 69.8% | 74.5% | 68.8% | 73.6% | 71.1% | 75.4% | 68.8% | 72.4% | 67.7% | 71.8% | 67.8% | 73.9% |

Table 5: Discomfort Hours for City of Kunming, Yunnan with PMV>+1 or PMV<-1 (percentage of hours in the year)

| Discomfort hours summary | | | | Kunming, Yunnan | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Heavy walls | | | | | | Lightweight walls | | | | | | Lightweight insulated walls | | | | | |
| | | 0.25 ACH | | 0.5 ACH | | 1 ACH | | 0.25 ACH | | 0.5 ACH | | 1 ACH | | 0.25 ACH | | 0.5 ACH | | 1 ACH | |
| | | Ground | 1st floor | Ground | 1st floor | Ground | 1st floor | Ground | 1st floor | Ground | 1st floor | Ground | 1st floor | Ground | 1st floor | Ground | 1st floor | Ground | 1st floor |
| Low glazing | South | 52.0% | 58.7% | 55.1% | 59.2% | 68.7% | 64.5% | 54.2% | 62.0% | 56.8% | 62.7% | 70.2% | 68.8% | 46.5% | 38.2% | 51.3% | 41.2% | 70.5% | 52.4% |
| | North | 52.4% | 58.9% | 55.4% | 59.5% | 69.0% | 64.8% | 54.6% | 62.5% | 57.3% | 63.2% | 70.6% | 69.0% | 47.9% | 41.0% | 52.6% | 43.4% | 71.6% | 53.9% |
| | East | 51.9% | 59.4% | 54.6% | 59.9% | 67.7% | 65.1% | 54.6% | 63.0% | 56.8% | 63.5% | 69.2% | 69.0% | 45.5% | 43.4% | 49.9% | 43.9% | 67.0% | 51.0% |
| | West | 52.0% | 59.6% | 54.5% | 60.0% | 67.2% | 65.1% | 54.8% | 63.3% | 56.8% | 63.6% | 68.9% | 69.2% | 44.5% | 44.4% | 49.0% | 44.7% | 65.3% | 51.0% |
| Medium glazing | South | 51.3% | 58.6% | 54.0% | 59.2% | 67.2% | 64.4% | 53.5% | 61.8% | 55.9% | 62.4% | 68.9% | 68.5% | 44.5% | 35.4% | 49.2% | 37.8% | 66.9% | 48.7% |
| | North | 52.0% | 59.1% | 54.6% | 59.6% | 67.8% | 64.9% | 54.2% | 62.7% | 56.7% | 63.0% | 69.5% | 69.1% | 47.0% | 41.5% | 51.2% | 43.1% | 68.7% | 52.2% |
| | East | 51.5% | 59.9% | 53.9% | 60.1% | 66.2% | 65.1% | 54.6% | 63.6% | 56.4% | 63.9% | 68.0% | 69.1% | 44.6% | 47.9% | 48.1% | 47.1% | 63.1% | 51.7% |
| | West | 51.8% | 60.3% | 53.9% | 60.2% | 65.5% | 65.4% | 55.0% | 63.7% | 56.6% | 63.9% | 67.8% | 69.2% | 44.1% | 48.9% | 47.2% | 48.5% | 61.1% | 52.3% |
| High glazing | South | 50.7% | 58.8% | 53.5% | 59.2% | 65.9% | 64.4% | 52.9% | 61.5% | 55.3% | 62.2% | 67.8% | 68.0% | 41.4% | 37.6% | 46.8% | 38.3% | 64.2% | 46.4% |
| | North | 51.4% | 59.4% | 54.1% | 59.8% | 66.6% | 64.9% | 54.0% | 62.7% | 56.2% | 63.2% | 68.5% | 68.9% | 45.9% | 42.7% | 49.9% | 43.4% | 65.9% | 51.3% |
| | East | 51.7% | 60.6% | 53.6% | 60.7% | 64.8% | 65.2% | 55.0% | 63.8% | 56.4% | 64.2% | 67.2% | 69.2% | 45.3% | 52.3% | 47.7% | 51.2% | 60.2% | 54.2% |
| | West | 52.0% | 61.1% | 53.9% | 61.3% | 64.4% | 65.6% | 55.2% | 63.8% | 56.7% | 64.3% | 67.0% | 69.3% | 45.8% | 53.7% | 47.5% | 52.5% | 59.2% | 55.2% |

Table 6: Discomfort Hours for City of Nanning, Guangxi with PMV>+1 or PMV<-1 (percentage of hours in the year)

| Discomfort hours summary | | | | Nanning, Guangxi | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Heavy walls | | | | | | Lightweight walls | | | | | | Lightweight insulated walls | | | | | |
| | | 0.25 ACH | | 0.5 ACH | | 1 ACH | | 0.25 ACH | | 0.5 ACH | | 1 ACH | | 0.25 ACH | | 0.5 ACH | | 1 ACH | |
| | | Ground | 1st floor | Ground | 1st floor | Ground | 1st floor | Ground | 1st floor | Ground | 1st floor | Ground | 1st floor | Ground | 1st floor | Ground | 1st floor | Ground | 1st floor |
| Low glazing | South | 73.5% | 76.1% | 73.5% | 75.9% | 77.3% | 78.4% | 73.4% | 76.0% | 73.4% | 75.8% | 76.4% | 77.0% | 65.8% | 66.8% | 66.6% | 66.4% | 71.1% | 69.5% |
| | North | 73.6% | 76.2% | 73.6% | 76.1% | 77.5% | 78.5% | 73.6% | 76.1% | 73.7% | 75.8% | 76.5% | 77.2% | 66.6% | 66.9% | 67.4% | 66.8% | 71.6% | 70.1% |
| | East | 74.0% | 76.5% | 74.0% | 76.5% | 77.8% | 78.8% | 74.1% | 76.3% | 74.1% | 76.0% | 77.0% | 77.7% | 67.7% | 68.0% | 68.4% | 68.0% | 72.7% | 71.7% |
| | West | 73.9% | 76.4% | 74.1% | 76.4% | 77.7% | 78.7% | 74.1% | 76.3% | 74.1% | 76.2% | 78.3% | 78.9% | 67.8% | 68.1% | 68.5% | 68.2% | 72.8% | 71.7% |
| Medium glazing | South | 73.1% | 75.9% | 73.1% | 75.7% | 77.1% | 78.2% | 73.0% | 76.0% | 73.1% | 75.8% | 76.0% | 77.0% | 66.0% | 68.4% | 66.5% | 67.5% | 70.2% | 69.5% |
| | North | 73.3% | 76.1% | 73.3% | 75.9% | 77.3% | 78.5% | 73.3% | 76.1% | 73.5% | 75.8% | 76.2% | 77.0% | 66.6% | 68.1% | 67.2% | 67.6% | 71.2% | 70.4% |
| | East | 73.9% | 76.4% | 73.8% | 76.2% | 77.7% | 78.8% | 73.8% | 76.5% | 73.9% | 76.3% | 76.9% | 77.8% | 67.9% | 69.2% | 68.3% | 68.9% | 72.4% | 71.8% |
| | West | 73.9% | 76.4% | 73.8% | 76.3% | 77.8% | 78.8% | 73.9% | 76.6% | 73.9% | 76.3% | 77.0% | 77.8% | 68.2% | 69.6% | 68.6% | 69.2% | 72.5% | 72.0% |
| High glazing | South | 72.7% | 75.7% | 72.8% | 75.7% | 76.8% | 77.9% | 72.8% | 76.2% | 72.9% | 75.8% | 75.8% | 77.0% | 67.3% | 70.0% | 67.0% | 69.1% | 70.3% | 70.3% |
| | North | 73.1% | 76.0% | 73.1% | 75.9% | 77.0% | 78.3% | 73.0% | 76.3% | 73.2% | 75.9% | 76.2% | 77.2% | 67.4% | 69.2% | 67.4% | 68.7% | 71.0% | 70.7% |
| | East | 73.8% | 76.3% | 73.8% | 76.3% | 77.8% | 78.7% | 73.7% | 76.9% | 73.7% | 76.5% | 77.0% | 78.0% | 68.7% | 70.5% | 68.8% | 70.1% | 72.7% | 72.6% |
| | West | 73.8% | 76.4% | 73.9% | 76.3% | 77.8% | 78.7% | 73.8% | 76.9% | 73.9% | 76.6% | 77.0% | 78.0% | 69.1% | 70.9% | 69.1% | 70.4% | 72.8% | 72.6% |

Table 7: Discomfort Hours for City of Chongqing (Shapingba) with PMV>+1 or PMV<-1 (percentage of hours in the year)

| Discomfort hours summary | | | | Shapingba, Chongqing | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Heavy walls | | | | | | Lightweight walls | | | | | | Lightweight insulated walls | | | | | |
| | | 0.25 ACH | | 0.5 ACH | | 1 ACH | | 0.25 ACH | | 0.5 ACH | | 1 ACH | | 0.25 ACH | | 0.5 ACH | | 1 ACH | |
| | | Ground | 1st floor | Ground | 1st floor | Ground | 1st floor | Ground | 1st floor | Ground | 1st floor | Ground | 1st floor | Ground | 1st floor | Ground | 1st floor | Ground | 1st floor |
| Low glazing | South | 75.5% | 77.1% | 74.8% | 76.7% | 75.1% | 77.9% | 75.0% | 77.0% | 74.4% | 76.5% | 75.0% | 77.8% | 73.2% | 74.4% | 71.9% | 73.6% | 71.4% | 73.6% |
| | North | 75.4% | 77.1% | 74.8% | 76.7% | 75.0% | 77.9% | 75.0% | 77.0% | 74.4% | 76.5% | 75.0% | 77.9% | 73.3% | 74.6% | 71.8% | 73.7% | 71.3% | 73.9% |
| | East | 75.6% | 77.3% | 75.0% | 76.8% | 75.4% | 78.1% | 75.4% | 77.2% | 74.7% | 76.8% | 75.3% | 78.2% | 74.3% | 75.4% | 72.8% | 74.6% | 72.5% | 74.7% |
| | West | 75.6% | 77.4% | 75.0% | 76.9% | 75.4% | 78.2% | 75.3% | 77.3% | 74.7% | 76.9% | 75.2% | 78.3% | 74.4% | 75.6% | 72.9% | 74.8% | 72.6% | 74.7% |
| | | | | | | | | | | | | | | | | | | | |
| Medium glazing | South | 75.6% | 77.3% | 75.0% | 76.8% | 75.3% | 78.0% | 75.0% | 77.1% | 74.4% | 76.7% | 75.1% | 78.0% | 74.0% | 75.2% | 72.7% | 74.2% | 72.5% | 74.4% |
| | North | 75.6% | 77.3% | 75.0% | 76.9% | 75.2% | 78.0% | 75.1% | 77.1% | 74.4% | 76.6% | 75.1% | 78.0% | 74.3% | 75.4% | 72.9% | 74.3% | 72.6% | 74.5% |
| | East | 75.9% | 77.6% | 75.2% | 77.3% | 75.7% | 78.3% | 75.5% | 77.5% | 74.9% | 77.0% | 75.5% | 78.4% | 75.1% | 76.6% | 73.9% | 75.7% | 73.8% | 75.6% |
| | West | 75.9% | 77.6% | 75.3% | 77.3% | 75.7% | 78.3% | 75.5% | 77.6% | 74.9% | 77.0% | 75.5% | 78.5% | 75.2% | 77.0% | 74.0% | 76.0% | 73.8% | 76.0% |
| | | | | | | | | | | | | | | | | | | | |
| High glazing | South | 75.4% | 77.5% | 75.0% | 76.9% | 75.4% | 77.9% | 75.1% | 77.3% | 74.5% | 76.7% | 75.0% | 78.2% | 74.6% | 76.2% | 73.4% | 75.2% | 73.3% | 75.2% |
| | North | 75.6% | 77.5% | 75.1% | 76.8% | 75.4% | 78.1% | 75.2% | 77.3% | 74.6% | 76.8% | 75.0% | 78.2% | 74.8% | 76.4% | 73.6% | 75.3% | 73.4% | 75.3% |
| | East | 76.0% | 77.8% | 75.4% | 77.3% | 75.9% | 78.3% | 75.7% | 77.8% | 74.9% | 77.4% | 75.5% | 78.7% | 75.9% | 77.7% | 74.5% | 76.7% | 74.5% | 76.8% |
| | West | 75.9% | 78.0% | 75.4% | 77.5% | 75.9% | 78.5% | 75.9% | 78.0% | 75.2% | 77.5% | 75.7% | 78.9% | 76.2% | 78.2% | 74.7% | 77.0% | 74.8% | 77.2% |

# Overheating and passive cooling interventions on low-income residential houses in Abuja, Nigeria.

**Michael U. Adaji[1], Timothy O. Adekunle[2] and Richard Watkins[3]**

[1] Department of Architecture and Visual Arts, University of East London, Docklands Campus, London, E16 2RD, UK, m.adaji@uel.ac.uk; utenwojo.adaji@southessex.ac.uk;
[2] Department of Architecture, College of Engineering, Technology, and Architecture (CETA), University of Hartford, 200 Bloomfield Avenue, West Hartford, CT 06117, USA;
[3] Kent School of Architecture and Planning, University of Kent, Canterbury, UK.

**Abstract:** This paper discusses the results of the monitoring and comfort surveys conducted at different locations in Abuja, Nigeria. The study aims to evaluate the performance of residential houses in the city, during the dry season and interventions to improve occupants' comfort. The results revealed overheating occurred in all the living rooms. In the bedrooms, 100% and 80% exceeded the Cat. II and III thresholds respectively. The study also explored passive cooling interventions to improve indoor environmental conditions by modifying the roof and shading device. At each location, two buildings were simulated as naturally ventilated and air-conditioned for one-week (30/April–06/May), and the entire warm/dry season (01/February–06/May). The interventions (75mm roof and 450mm shading device) have a significant effect in reducing the maximum living room temperatures by 5°C in the naturally ventilated building. The night-time bedroom temperatures were reduced by 3.8°C. The study showed the interventions would improve occupants' comfort during night-time. In the living rooms, the air-conditioned model revealed a 100% reduction (25kWh-0kWh) in the cooling load when the passive interventions were applied. The cooling load in the bedrooms was also reduced by 100% (7kWh-0kWh) when the interventions were introduced. The interventions contributed to the cooling load reduction as the maximum temperatures remain at 28°C for most of the time. For the entire dry season, the percentage of temperatures >28°C for the naturally ventilated living rooms was reduced by 23% and 43% during the daytime and evening period respectively. The percentage of temperatures >28°C dropped by 17% in the bedrooms during the night-time. The study showed that the most effective passive cooling interventions for the naturally ventilated model include the application of roof insulation and shading device. The investigation showed the effectiveness of reducing temperatures in dry season using passive interventions to improve occupants' comfort in hot-humid weather conditions.

**Keywords:** Overheating; passive cooling interventions; dynamic thermal simulation; thermal comfort; low-income residential buildings.

## 1. Introduction

Current studies have mentioned the possibility of high temperatures within the indoor environment of different buildings (Lomas and Kane, 2013; Adekunle and Nikolopoulou, 2014, 2016; Adaji et al, 2019), particularly in residential buildings in various locations in sub-Saharan region (Ealiwa et al, 2001; Ogbonna and Harris, 2008; Akande and Adebamowo, 2010; Djongyang et al, 2010; Djongyang et al, 2012; Adunola and Ajibola, 2012; Nematchoua et al, 2014; Koranteng et al, 2015; Adaji et al, 2015) such as Abuja in Nigeria (Adaji, 2018). High temperatures in residential buildings in different regions can make occupants of such buildings thermally uncomfortable for a substantial period (Adunola and Ajibola, 2012; Akande and Adebamowo, 2010; Adekunle and Nikolopoulou, 2014, 2016; Adaji et al, 2015). Higher temperatures in buildings in moderate (Lomas and Kane, 2013; Adekunle and Nikolopoulou, 2016), tropical (Nicol, 2004; Al-Tamimi et al, 2011), hot and humid climates

(Akande and Adebamowo 2010; Adaji et al,  2015, 2016) can affect thermal comfort and overall well-being of people. Various factors such as housing condition and quality (Jolaoso et al,  2012), thermal mass of building envelopes (Kendrick et al,  2012; Adekunle and Nikolopulou, 2016, 2019), regional climates (Nematchoua et al,  2014; Adekunle, 2019, Adaji et al,  2016, 2019), design parameters like orientation (Al-Tamimi et al,  2011; Adekunle and Nikolopoulou, 2019) as well as non-integration of low-energy solutions (Nicol and Humphreys, 2002) to mitigate the effect of overheating can contribute to elevated temperatures in buildings.

### 1.1. Thermal comfort studies in tropical regions

Many investigations on thermal comfort have been carried out in tropical regions and hot-humid climates with most results showing a wide range of temperatures at which people feel comfortable (comfort or neutral temperature) measured in air-conditioned (AC) and naturally ventilated (NV) buildings, see table 1. These studies also showed that neutral temperatures of naturally ventilated buildings were higher compared to the recorded temperatures in air-conditioned buildings. Buildings in hot-humid climates develop thermal discomfort conditions due to their location and other factors such as access to control, energy cost, etc. Feasibly, air-conditioning is often used to improve indoor comfort and reduce internal temperatures, but then again this is a process that requires energy and money, resources which most people in developing countries cannot afford (Zain et al,  2007). However, if this problem is not taken care of it often leads to serious indoor environmental conditions like heat stress, lack of comfort and poor indoor air quality which are highly linked with low-income family units in developed and developing countries (Santamouris et al,  2007).

Table 1: Summary of thermal comfort research in tropical region and humid climates with reported neutral and acceptable comfort range for comparison

| Year | Study | Location (Climatic zone) | Type of Building/Space | Season | Key findings |
|---|---|---|---|---|---|
| 2019 | Adaji et al. | Abuja (Hot-humid) | Residential (NV and AC) | Dry Season | 1. Neutral temp. = 28.0°C - 30.4°C<br>2. Combined preferred temp. = 27.5°C – 29.4°C<br>3. Overall mean temp = 31.7°C |
| 2016 | Efeoma and Uduku | Enugu (Hot-humid) | Office (AC) | | 1. Neutral temp. = 28°C |
| 2012 | Adunola A. O. | Ibadan (Hot-humid) | Residential (NV) | April | 1. Regression equation: Y = 0.483*X – 15.59(TSENS with respect to TOP*)<br>2. Neutral temp. = 32.3°C TOP* |
| 2012 | N. Djongyang et al | Ouagadougou Dry-tropical sub-Saharan Africa region. | Bedrooms (AC) | Dry Season | 1. Neutral temp. range = 29°C – 32°C |
| 2010 | N. Djongyang, & R. Tchinda | Ngaoundere & Kousseri, (Cameroon) Harmattan season | Residential | November 2008 to January 2009. | 1. Neutral temp. (Ngaoundere) = 24.69°C<br>2. Neutral temp. (Kousseri) = 27.32°C |
| 2010 | Akande & Adebamowo | Bauchi (Hot Dry) | Residential (N.V.) | Rainy and Dry Season | 1. Regression equation: Y = 0.357*X – 10.2 (Dry Season)<br>2. Regression equation: Y = 0.618*X – 15.4 (Rainy Season) |

| Year | Study | Location (Climatic zone) | Type of Building/Space | Season | Key findings |
|---|---|---|---|---|---|
| 2019 | Adaji et al. | Abuja (Hot-humid) | Residential (NV and AC) | Dry Season | 1. Neutral temp. = 28.0°C - 30.4°C<br>2. Combined preferred temp. = 27.5°C – 29.4°C<br>3. Overall mean temp = 31.7°C |
| | | | | | 3. Combined neutral temp. = 28.4°C TOP*<br>4. Acceptable comfort range = 25.5 – 29.5°C TOP* |
| 2008 | Ogbonna & Harris | Jos (Temperate Dry) | Residential (N.V.) | July & August (Rainy Season) | 1. Regression equation: Y = 0.3589*X – 9.4285<br>2. Neutral temp. = 26.270C TOP*<br>3. Acceptable comfort range = 25.5 – 29.50C TOP* (-0.5 ≤ TSENS ≤ +0.5)<br>4. PMV neutral temp. = 25.06°C |
| 2007 | Adebamowo et al | Lagos (Warm humid) | Residential (N.V.) | | 1. Neutral temp. = 28.2 °C |
| 1988 | Ojosu et al. | Hot Dry<br>Temperate Dry<br>Hot-humid<br>Warm humid | | | 1. Acceptable comfort zone = 21 – 26°C<br>2. Acceptable comfort zone = 18 – 24°C<br>3. Acceptable comfort zone = 21 – 26°C<br>4. Acceptable comfort zone = 21 – 26°C |
| 1955 | Ambler H. R. | Port Harcourt (Warm humid) | Office (A.C.) | | Office 1. Neutral temp. = 23.13°C ET* |

Note: ET* (Effective Temperature), TOP* (Operative Temperature), TSENS (Thermal Sensation Vote). N.V. (Naturally Ventilated), A.C. (Air-conditioned)

As a result of these recorded high temperatures shown in Table 1, various studies have been conducted to examine the most effective sustainable strategy that will improve indoor thermal and reduce overheating. One of the strategies includes passive cooling applications. Passive cooling as described by Givoni (2011), is a process that does not use energy for operation i.e. indoor cooling and minimizing internal heat gain. Givoni (2011) discussed the consideration of elements of proper architectural and urban design responsive to climate as a way of treating the building by aiming to improve comfort in hot periods even if the building is not mechanically conditioned or by reducing the equipment size and an air-conditioned building's energy consumption. In this interpretation, passive cooling enhances heat loss from buildings. There has been extensive research on passive cooling by applying methods and techniques from traditional buildings (Singh et al, 2009; Singh et al, 2010; Indraganti, 2010; Dili et al, 2009; Dili et al, 2010). In Dili et al. (2011), research comparing traditional and modern buildings in Kerala, India, showed that the minimum temperature recorded in the bedrooms of the two types of the building was the same, but the maximum temperature of the modern-day building was higher by 2.5°C. The study (Dili et al, 2011) also observed that the internal environmental conditions were more stable and comfortable than those of the modern-day building. These residential buildings need cooling and with the power, economic crisis and high-energy cost, the only option remaining is the adoption of low-cost passive cooling techniques. Research in passive cooling techniques is given in Givoni (1991) who presents some of the known techniques for passive cooling, insulated roofs and walls (Asan, 2008; Kumar et al, 1989 and Shariah et al, 1997). In Sodha et al. (1978, 1986), roof ponds were considered as a passive cooling strategy while the earth-air tunnel was considered in (Mihalakakou et al, 1995) and ventilation (Hamdy and Firky, 1998).

### 1.2. Design strategies for passive cooling for hot-humid tropical climate

Passive cooling systems do not eliminate the use of a fan or a pump when their application boosts performance (Givoni, 1994). Several studies on the tropics such as Al-Obaidi et al. (2014b, 2014c) in Malaysia, enhance passive cooling with hybrid systems. Passive cooling strategies generally consist of all the preventive measures against overheating in the interior of buildings (Asimakopoulos, 1996). Passive cooling systems are energy-efficient and eco-friendly techniques used to improve the thermal comfort with no or little power consumption, as described later in this study (Section 6.0). The cooling systems work either by removing heat from the building to a natural heat sink or by preventing heat from entering the living space from external heat sources. Several passive cooling concepts vary widely in working principle and performance. The practicability of these techniques depends greatly on the local climate. Further, ambiguities about their performance among stakeholders lead to non-practice of these techniques even in favourable locations. Some of the design strategies for hot-humid tropical climates include the following studies. For natural ventilation (Gao and Lee, 2011; Ai, et al, 2011), phase change materials (PCM) (Benard et al. 1981; Chou et al. 2013), reflective roof paints (Santamouris, 1990; Al Yacouby et al, 2011; Al-Obaidi et al, 2014d; Oberndorfer et al. 2007; Aubrey, 2010; and Matthews, 2012), radiant cooling (Omidreza et al. 2013; Stetiu, 1999; Al-Obaidi et al, 2014d); roof insulation (Alvarado and Martınez, 2008; Jun Han et al, 2013), green roofs (Morau, et al, 2012; Omidreza et al, 2013; Spala et al, 2008; Ascione et al, 2013; Peri et al, 2012); and solar chimneys (Chungloo and Limmeechokchai, 2007; Khedari et al, 2000a; Rodrigues, et al, 2000; Letan, et al, 2003).

From the various studies considered on tropical climate passive cooling strategies above, the literature revealed the importance of polyurethane insulation on the building envelope, and this will be further explored in this study. The study will also consider passive interventions by modifying the roof, ceiling, wall and shading device on naturally ventilated and air-conditioned base models. Moreover, the study will consider the effects of each intervention on the daytime and evening temperatures in living rooms and the sleeping time temperatures in bedrooms temperature for the naturally ventilated model. Likewise, the effect of each intervention on the mechanical cooling load in the living room during the daytime and evening period and the bedroom when mechanical cooling is enabled will be evaluated.

## 2. Case study description

The study area Abuja is located at latitude 9° 04’ N and longitude 7° 29’ E, at an elevation of 840 m (2760 ft.) above sea-level. The area now designated the Federal Capital Territory (F.C.T.), Abuja, Nigeria’s capital, falls within the Savannah Zone vegetation of the West African sub-region with Patches of rain forest. As it is in the tropics, Abuja experiences two weather conditions annually; the rainy season ranging from 305 to 762 mm (12 – 30 in.) which begins in April and ends in October and the dry season (the equivalent of summer in a temperate climate) which begins in November and ends in March. However, within this period, there is a brief interlude of Harmattan. A period when the North-East Trade Wind moves in with the main feature of dust haze intensified coolness and dryness. Fortunately, the high altitudes and undulating terrain of the FCT act as a moderating influence on the weather of the territory. Temperatures can rise to 40°C during the dry season with dry winds lowering the temperature to as low as 12°C (Abubakar, 2014).

The dry season surveys considered in this paper were carried out in two locations (Lugbe and Bwari) in Abuja. Post-occupancy evaluation was carried out in different residential buildings at the two locations. Environmental monitoring of variables and respective thermal comfort surveys during the dry season were conducted at the selected buildings in each of the locations. Due to the approval required from the occupants to evaluate the buildings and willingness to participate in the comfort surveys, physical measurements and comfort surveys were only considered in four buildings in the study locations to investigate the thermal comfort of occupants. The buildings were selected based on their overall representation of the typical type of housing in the area, means of ventilation (natural ventilation and air conditioning), purpose of construction (for low-income group) and building type (low rise building). The mean U-value of 2.03 W/m2K is computed for the external walls of all the case study buildings. Table 2 below summarises the main features of the case study buildings in different study locations within Abuja. This section discusses the selected case study dwellings for the comfort survey for this study.

Table 2: Main features of the case study buildings evaluated in the two locations in Abuja

| **Case study** | **Designation area/purpose of construction** | **Location** | **Means of ventilation** | **Building type and additional information** | **Floor plan, elevation, and U-values of building components** |
|---|---|---|---|---|---|
| Case Study 1, Lugbe (LGH1) | Designated low-income area/developed for low-income earners | Located within the Light Gold Estate in Lugbe, Abuja | Naturally ventilated | Low-rise construction, 3-bedroom, north facing, detached bungalow built with sandcrete blocks, covered with aluminium roofing sheets with no insulation. | <br><br>External walls: 230mm, U-values of 2.028 W/m$^2$K;<br>Internal walls: U-values of 1.025 W/m$^2$K;<br>Roof: U-values of 7.142 W/m$^2$K; Cement plaster ceiling board: 20mm, U-values of 2.532 W/m$^2$K |
| Case Study 2, | Designated low-income area/built for | Located within the Trade | Air conditioned | Low-rise construction, 2-bedroom, | |

| Case study | Designation area/purpose of construction | Location | Means of ventilation | Building type and additional information | Floor plan, elevation, and U-values of building components |
|---|---|---|---|---|---|
| Lugbe (LGH2) | low-income earners | Moore Estate in Lugbe, Abuja | | north-east facing, semi-detached bungalow built with sandcrete blocks, covered with longspan aluminium roofing sheets with no insulation. | <br><br>External walls: 230mm, U-values of 2.028 W/m$^2$K;<br>Internal walls: U-values of 1.025 W/m$^2$K;<br>Roof: U-values of 7.142 W/m$^2$K; Cement plaster ceiling board: 20mm, U-values of 2.532 W/m$^2$K |
| Case Study 3 Bwari (BWH1) | Designated low-income and high-density area/built for low-income earners | Located in Bwari, Abuja | Naturally ventilated | Low-rise construction, 2-bedroom flat, south-west facing, semi-detached bungalow built with sandcrete blocks, covered with zinc iron roofing sheets with no insulation. | <br> |

| Case study | Designation area/purpose of construction | Location | Means of ventilation | Building type and additional information | Floor plan, elevation, and U-values of building components |
|---|---|---|---|---|---|
| | | | | | External walls: 230mm, U-values of 2.028 W/m$^2$K;<br>Internal walls: U-values of 1.025 W/m$^2$K;<br>Roof: U-values of 7.142 W/m$^2$K; Cement plaster ceiling board: 20mm, U-values of 2.532 W/m$^2$K |

## 3. Methodology

The methodology for the study includes environmental monitoring, post-occupancy and thermal comfort surveys. Since the period of the monitoring was not an extended one, the study also considered building simulation to capture more data for data analysis. The research methodology also provides the opportunity to compare both measured and simulated data on an equal basis as well as over an extended period. Existing studies have explored some of the research techniques considered in the paper (Ogbonna and Harris, 2008; Akande and Adebamowo, 2010; Adekunle and Nikolopoulou, 2014; Adaji et al, 2015, 2019). A few studies have explored all the research methods outlined in the study at the same time to improve the quality of data presented in the published work (Adekunle and Nikoloupou, 2016; Adaji, 2018, Adaji et al, 2019).

The surveys were aimed at obtaining a comprehensive understanding of occupants' thermal comfort sensation within the buildings and occupant's energy demands and use. For the monitoring, sensors were installed to measure environmental variables within the thermal environment. The building simulation was considered to understand the thermal behaviour of the case study buildings. As stated in the existing research, post-occupancy studies are crucial for evaluating the thermal condition in buildings (Nicol and Roaf, 2005); while the thermal comfort surveys help to understand as well as analyse the nature and occurrence of occupants' complaints of experiencing warmth or sensation through the day that cannot be achieved with environmental monitoring (Nicol and Roaf, 2005; Adekunle and Nikolopoulou, 2014).

The passive cooling methodology strategy explored a range of fabric passive intervention strategies and shading device projection for a week to align with the simulation periods. For any intervention, the sensitivity of the model is tested by increasing the thickness of the insulation from 25-500mm. The second strategy tested the sensitivity of shading device projection from 150-1050mm on the base model. From each sensitivity study, an optimum thickness is chosen. These strategies were selected based on their availability in the Nigerian construction market and their real-life application. The third strategy looked at the effect of insulation on daily cooling loads for a week in the living room and bedroom spaces. The study then looked at the effect of the optimum passive intervention over the dry season. The roof, external walls and ceilings were selected for modification in the base model, as this is a significant route where heat enters the building. The high fabric U-Values Roof: 7.1 W/m2K, Ceiling 2.5 W/m2K and Wall 2.0 W/m2K) were a source of concern and the interventions were aimed at reducing these U-Values considerably and thus lessen the cooling load for the air-conditioned model. The use of shading devices was also explored to test the potential for reducing solar gain.

## 4. Data analysis: comparison of modelled and measured data

The results from the simulations were compared using the results obtained from the indoor monitoring of the spaces. The one week of the monitoring was considered for the comparison. The simulated hourly data was compared with hourly averages of the 15 minutes monitored data. This range was adopted as a calibration criterion which is the maximum peak difference between the external recorded temperatures and the weather file temperature throughout the dry season period. The comparison of the simulated and monitored temperatures showed the predicted peak temperatures align mostly with the measured peaks recorded during the monitoring. The differences between the maximum simulated and monitored temperature peaks were usually within a range of 2 – 3°C for most of the period.

### 4.1. Indoor (measured and predicted) and weather file temperatures

The predicted temperatures show consistency with the measured temperatures in Lugbe and Bwari, with average temperatures around 30°C in Lugbe and 29°C in Bwari (Tables 3 and 4). The external temperatures in Lugbe show the weather file had a maximum temperature above 40°C, which agrees with the measured temperature at 40°C. In Bwari, the measured outdoor temperature had a maximum of 38.6°C, which is consistent with the weather file temperature (38°C) for the same period. The weather file temperatures for Lugbe are warmer than those for Bwari, as is the case for the measured external temperature.

### 4.2. Measured and predicted indoor temperatures at Lugbe

The mean monitored living room temperature in the naturally ventilated dwelling in Lugbe was 32°C which is very close to the predicted temperature of 31°C. The model predicted a maximum temperature of 37.7°C, around 1.5°C more the monitored temperatures (Table 3). The maximum predicted living room temperatures were higher than the predicted bedroom temperatures by more than 1°C but was no significant difference between the measured maximum and average living room and bedroom temperatures though the living room reported a minimum temperature that is around 2°C higher than the bedroom space. The comparison between the measured and simulated internal temperatures for the naturally ventilated spaces at Lugbe shows the occupants have high adaptation potential when exposed to longer hours of high temperatures above 28°C.

Table 3: Maximum, minimum and average measured and predicted Living room and bedroom temperatures at the naturally ventilated dwellings (H1) and the air-conditioned dwellings (H2) at Lugbe

| Lugbe | Ext. Temp. (°C) | Weather file Temp. (°C) | Average measured and predicted Living room and bedroom temperatures at the naturally ventilated dwellings (H1) | | | | Average measured and predicted Living room and bedroom temperatures at the air-conditioned dwellings (H2) | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Measured Living room Temp. (°C) H1 | Living room PDT Temp. (°C) H1 | Measured Bedroom Temp. (°C) H1 | Bedroom PDT Temp. (°C) H1 | Measured Living room Temp. (°C) H2 | Living room PDT Temp. (°C) H2 | Measured Bedroom Temp. (°C) H2 | Bedroom PDT Temp. (°C) H2 |
| **MAX** | **41.1** | **44.0** | **36.2** | **37.7** | **34.9** | **36.6** | **32.7** | **34.6** | **32.9** | **36.0** |
| **MIN** | **23.5** | **20.8** | **28.4** | **27.7** | **29.5** | **28.3** | **29.8** | **26.1** | **27.0** | **26.2** |
| **AVG.** | **31.1** | **30.2** | **32.0** | **31.0** | **32.4** | **31.7** | **31.6** | **29.3** | **31.0** | **30.4** |

PDT = Predicted, NV = Naturally Ventilated

### 4.3. Measured and predicted indoor temperatures at Bwari

The average measured living room temperatures in the naturally ventilated dwelling in Bwari was 31.9°C compared to 29.3°C in the simulated model while the maximum monitored temperature was 36°C compared to around 34°C in the model. Table 4 shows that the monitored living room and bedroom space was warmer than the corresponding simulated spaces. The average living room temperatures in the air-conditioned dwelling in Bwari had temperatures around 29°C for the monitored dwelling which agrees with the temperature simulated (28.6°C) for the same space. However, the maximum measured temperature of 31.5°C contrasts with the 34.2°C reported in the simulated living space. The maximum predicted bedroom temperatures were 1°C higher than the monitored bedroom temperatures, though the difference between them was not more than 1°C (Table 4).

Table 4: Maximum, minimum and average measured and predicted living room and bedroom temperatures at the naturally ventilated dwellings (H1) and air-conditioned dwellings (H2) at Bwari

| Bwari | Ext. Temp. (°C) | Weather file Temp. (°C) | Average measured and predicted living room and bedroom temperatures at the naturally ventilated dwellings (H1) | | | | Average measured and predicted living room and bedroom temperatures at the air-conditioned dwellings (H2) | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Measured Living room Temp. (°C) H1 | Living room PDT Temp. (°C) H1 | Measured Bedroom Temp. (°C) H1 | Bedroom PDT Temp. (°C) H1 | Measured Living room Temp. (°C) H2 | Living room PDT Temp. (°C) H2 | Measured Bedroom Temp. (°C) H2 | Bedroom PDT Temp. (°C) H2 |
| **MAX** | **38.6** | **38.0** | **36.0** | **33.7** | **35.4** | **33.5** | **31.5** | **34.2** | **33.2** | **34.3** |
| **MIN** | **22.2** | **22.4** | **27.3** | **26.1** | **28.0** | **25.0** | **26.9** | **25.2** | **26.8** | **26.1** |
| **AVG.** | **30.1** | **28.2** | **31.9** | **29.3** | **31.7** | **28.8** | **29.3** | **28.6** | **30.2** | **29.3** |

PDT = Predicted, NV = Naturally Ventilated

## 5. Neutral temperatures and overheating analysis.

Linear regression analysis was used to calculate neutral and preferred temperatures, and the results showed the temperatures were in a range of 28°C to 30°C. The results suggest occupants in LGH1 (NV) showed more adaptation potential, with a higher neutral temperature of 29.5°C and preferred temperature of 28.3°C, compared to a recorded neutral temperature of 28.8°C and a lower preferred temperature of 28.1°C in LGH2 (AC). The results suggest occupants in BWH1 (NV space) showed more adaptation potential, with a higher neutral temperature of 30.4°C and preferred temperature of 28.2°C, compared to a recorded neutral temperature of 29.4°C and a lower preferred temperature of 27.5°C in BWH2 (AC). Overall, the finding showed that occupants in this region can adapt to elevated temperatures. The results revealed that the residents in Lugbe indicated a higher neutral and preferred temperature compared to the occupants in Bwari with a lower neutral and preferred temperature. As a result of these reported high neutral temperatures, the study further explored the potential for overheating in the indoor spaces.

The overheating analysis of the monitored and simulated temperatures in the indoor spaces at Lugbe and Bwari for one week were analysed below using the static CIBSE criteria of 1% of hours above 28ºC for the living rooms. However, 1% of hours above 28ºC was considered for the bedroom spaces. Furthermore, findings from the evaluation of the overheating risk at the internal spaces at the case studies using the approved dynamic thermal comfort criteria (EN16798-1) are discussed below with 5% of hours above and below the Cat. III upper, Cat. II upper and lower indicators to identify warm discomfort and cold discomfort in all the spaces considered at the two case studies. In this study, LGH1, LGH2, BWH1 and BWH2 represented the monitored dwellings, while LG-PDT-H1, LG-PDT-H2, BW-PDT-H1 and BW-PDT-H2 represented the simulated dwellings. The results of the evaluation of the risk of overheating are presented below.

### 5.1. The Static CIBSE comfort model for monitored and simulated data

Considering the CIBSE comfort model, extreme overheating occurs during the dry season in 100% of the spaces (living rooms and bedrooms) during the monitoring period at Lugbe and Bwari. A similar result was obtained for the simulation as overheating also occurs in 100% of the spaces (Figures 1 and 2). Figures 1 and 2 below show the analysis of the risk of overheating at Lugbe and Bwari. The figures explain the percentage of hours above 28ºC for the living rooms during the daytime and evening period and there night time in the bedroom spaces. For Lugbe and Bwari, the analysis shows that 100% of the living areas simulated were above 28ºC for more than 1% of the time. The analysis also suggests that 100% of the bedrooms exceeded 28ºC above 1% of the time for Lugbe and Bwari.

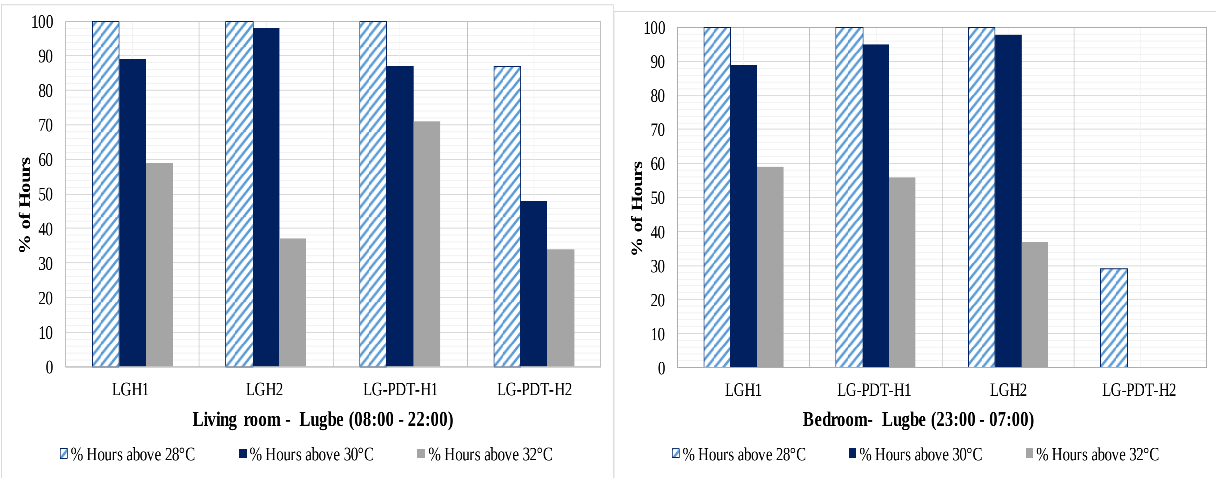


Figure 1: The static CIBSE comfort model - comparison between monitored and predicted temperatures in the living rooms and bedrooms at Lugbe.

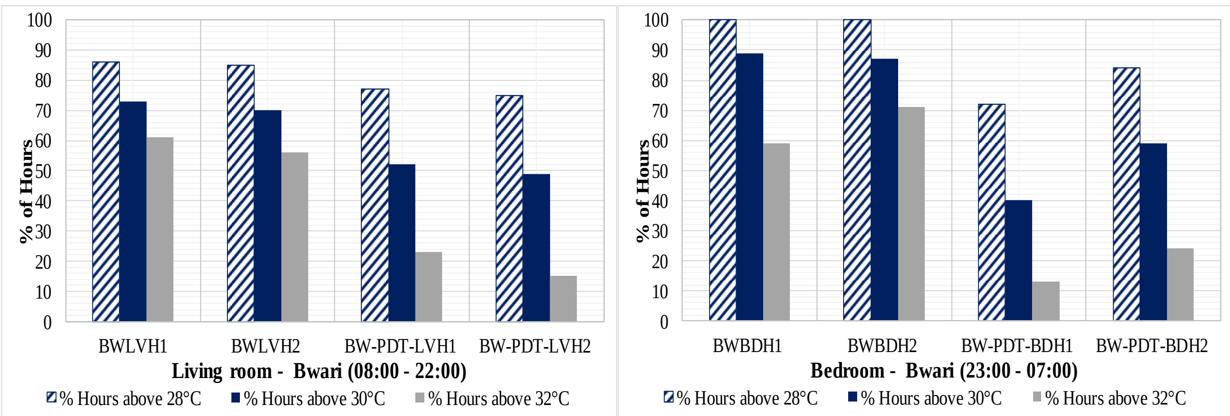


Figure 2: The static CIBSE comfort model - comparison between monitored and predicted temperatures in the living rooms and bedrooms at Bwari.

### 5.2. The EN16798-1 dynamic adaptive comfort model for monitored and predicted temperatures

The predicted temperatures during the daytime and evening period in the naturally ventilated living room at Lugbe exceed the Cat. II upper threshold and exceed the Cat. III upper threshold for a similar percentage of the time when compared with the results obtained from the monitored data (Figure 3). The result aligns with the findings on the assessment of the risk of overheating over the same period when monitored temperatures were evaluated. The results also showed the monitored spaces are warmer than predicted and occupants are prone to warm discomfort for longer hours during the dry season. The findings also revealed extreme indoor thermal conditions during the daytime and evening period in Lugbe (Figure 3a). The night-time adaptive overheating analysis in Lugbe showed temperatures exceed the Cat. II upper threshold for more than 5% of the time. The results also agree with the assessment of the measured data when the Cat. II upper and the Cat. III upper limits were considered (Figure 3b).

In comparison to the predicted indoor temperatures for Lugbe, the findings revealed extreme indoor thermal conditions during the daytime and evening period. The night-time adaptive overheating analysis in Lugbe showed temperatures exceed the Cat. II upper threshold for more than 5% of the time. The results also agree with the assessment of the measured data when the Cat. II upper and the Cat. III upper limits were considered. The results also suggest warm discomfort in the bedroom which agrees with the results obtained during the monitored temperatures in the bedroom. The naturally ventilated living room in Bwari showed predicted temperatures rose above 5% of hours over the Cat. II upper threshold for more than 5% of the time and was above 1% of hours over the Cat. III marker for more than 1% of the time (Figure 4a). The predicted naturally ventilated living room temperature during the daytime and evening periods in Bwari, exceeded 5% of hours above the Cat. II upper threshold which agrees with the monitored temperatures during the same period (Figure 4a). The monitored temperatures in Bwari showed more hours above the Cat. II upper and Cat. III upper thresholds compared to the predicted temperatures indicating warm discomfort occurs in the naturally ventilated living room space. In the bedroom, the temperature rose above the Cat. IEQ II upper threshold for more than 5% of the time indicating warm discomfort at night. The results agree with the assessment of the measured data when the Cat. II upper threshold limit was considered (Figures 4b). The results also suggest warm discomfort in the bedroom which agrees with the results obtained during the monitored temperatures in the bedroom at Bwari.

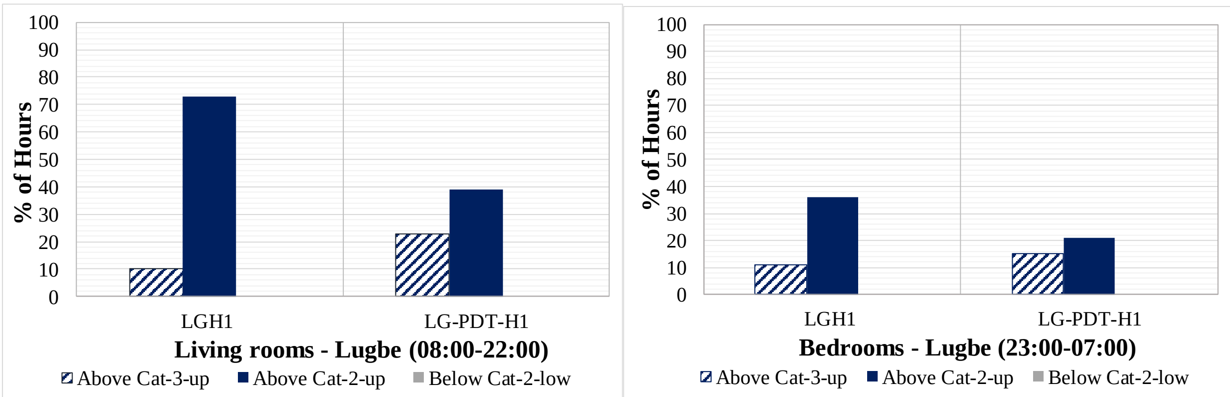


Figure 3: Comparison between monitored and predicted temperatures in the living rooms and bedrooms at Lugbe using the dynamic EN16798-1 adaptive comfort model.

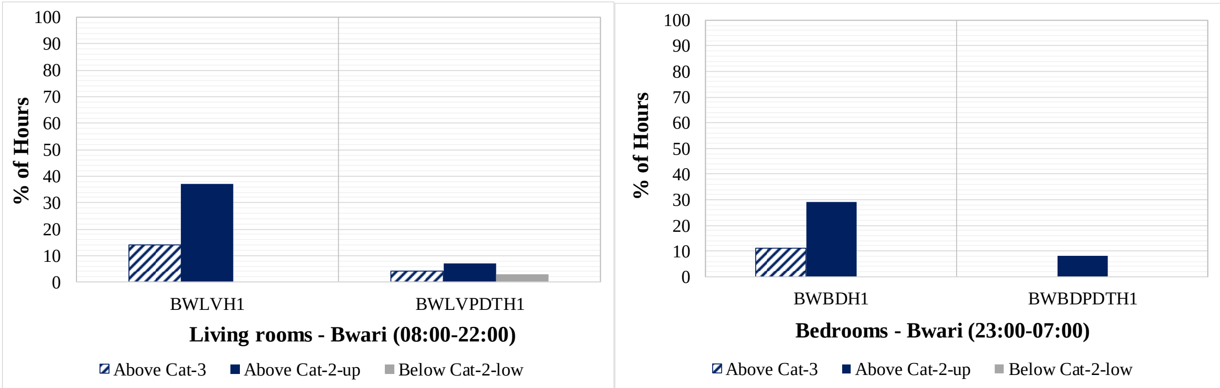


Figure 4: Comparison between monitored and predicted temperatures in the living rooms and bedrooms at Bwari using the dynamic EN16798-1 adaptive comfort model.

## 6. Passive cooling strategy and application

To improve the indoor environment and reduce the risk of overheating reported in this paper, the study considers some passive interventions that will be adopted on a base model to reduce external heat gain and indoor heat in residential buildings in Abuja. For the passive intervention simulations, two single-story base models were selected: the naturally ventilated model (BWPDTH1) and the air-conditioned model (BWPDTH2), representing a building in Bwari chosen because these reflected the real conditions when compared to the measured data. The passive interventions considered in this study included modifying the roof, ceiling, wall and shading device application on a naturally ventilated and air-conditioned base model. For each intervention, the simulations show the effects on the daytime and evening living room temperatures and the sleeping time, bedroom temperatures for the naturally ventilated model. For the air-conditioned model, it shows the effect on the mechanical cooling load in the living room during the daytime and evening period and the bedroom when mechanical cooling is enabled.

### 6.1. Design optimisation: roof modifications

Polyurethane (PUR) roof insulation board was applied underneath the metal roof at thicknesses from 25-500mm. A large range was used to find the most appropriate thickness for roof insulation in a naturally ventilated and air-conditioned building. The effect of the insulation on the cooling load for the air-conditioned building is revealed in the simulation results.

#### 6.1.1.Naturally ventilated model: Living room and bedroom – roof insulation

The roof insulation board reduced the predicted indoor temperatures, from a maximum of 33.7°C to 30.6°C, a 3.1°C drop when 75mm roof insulation board was applied in the naturally ventilated living room space from 08:00 – 22:00 (Table 5). The predicted average temperature reduced by 1.5°C drop 30.0°C to 28.5°C using the same insulation thickness. Table 5 summarizes the effects of the different roof insulation thickness on the base model. When considering the percentage of hours above 28°C, Table 6 shows a drop-in percentage from 84% for the base model to 66% when using 75mm roof insulation board.

Table 5 also shows the maximum base model bedroom temperature during the sleeping period reduced 2°C (from 30.4°C to 28.4°C) when 75mm roof insulation was applied to the bedroom space during the sleeping period (Table 8). When considering the percentage of hours above 28°C for the same period, while Table 7 shows a drop from 33% for the base model to 10% when using 75mm roof insulation board.

Table 5: Summary of roof insulation intervention in the naturally ventilated living room space model occupied 08:00 – 22:00, and bedroom space model occupied 23:00 – 07:00 showing the predicted indoor temperatures.

| PUR Roof Insulation thickness (mm) | Roof insulation intervention in the naturally ventilated living room space model occupied 08:00 – 22:00 | | | Roof insulation intervention in the naturally ventilated bedroom space model occupied 23:00 – 07:00 | | |
|---|---|---|---|---|---|---|
| | Max Temp. (°C) BWPDTLVH1 | Min Temp. (°C) BWPDTLVH1 | Avg. Temp. (°C) BWPDTLVH1 | Max Temp. (°C) BWPDTH1 (Simulated) | Min Temp. (°C) BWPDTH1 (Simulated) | Avg. Temp. (°C) BWPDTH1 (Simulated) |
| 500 | 29.9 | 26.1 | 28.1 | 28.0 | 25.3 | 26.4 |
| 400 | 29.9 | 26.1 | 28.2 | 28.0 | 25.3 | 26.5 |
| 300 | 29.9 | 26.1 | 28.2 | 28.1 | 25.3 | 26.5 |
| 200 | 30.0 | 26.1 | 28.2 | 28.2 | 25.3 | 26.5 |
| 100 | 30.4 | 26.1 | 28.4 | 28.3 | 25.3 | 26.6 |
| 75 | 30.6 | 26.1 | 28.5 | 28.4 | 25.5 | 26.7 |
| 50 | 30.7 | 26.1 | 28.6 | 28.6 | 25.4 | 26.7 |
| 25 | 31.2 | 26.2 | 28.9 | 28.8 | 25.4 | 26.8 |
| 0 | 33.7 | 26.3 | 30.0 | 30.4 | 25.0 | 27.4 |

Table 6: Summary of the predicted effects of roof insulation intervention on indoor temperatures above 28°C in the naturally ventilated living room model naturally ventilated from 08:00 – 22:00.

| | Base Roof | Roof PUR 25 mm | Roof PUR 50 mm | Roof PUR 75 mm | Roof PUR 100 mm | Roof PUR 200 mm | Roof PUR 300 mm | Roof PUR 400 mm | Roof PUR 500 mm |
|---|---|---|---|---|---|---|---|---|---|
| Hours above 28°C | 88 | 77 | 73 | 69 | 67 | 61 | 61 | 61 | 61 |
| % of Hours above 28°C | 84 | 73 | 70 | 66 | 64 | 58 | 58 | 58 | 58 |

Table 7: Summary of the predicted effects of roof insulation intervention on indoor temperatures above 28°C in the naturally ventilated living room model, occupied from 23:00 – 07:00.

| | Base Roof | Roof PUR 25 mm | Roof PUR 50 mm | Roof PUR 75 mm | Roof PUR 100 mm | Roof PUR 200 mm | Roof PUR 300 mm | Roof PUR 400 mm | Roof PUR 500 mm |
|---|---|---|---|---|---|---|---|---|---|
| Hours above 28°C | 21 | 8 | 6 | 6 | 4 | 3 | 2 | 2 | 1 |
| % of Hours above 28°C | 33 | 13 | 10 | 10 | 6 | 5 | 3 | 3 | 2 |

### 6.1.2. Air-conditioned model: Living room and bedroom – roof insulation

In the air-conditioned model when mechanical cooling was enabled in the living room from 18:00-22:00, there was a significant change in the cooling load. Table 8 shows a reduction of 11kWh in the living room cooling load when it was occupied for 08:00-22:00. This reduction occurred when 75mm roof insulation was applied in the air-conditioned model. In the air-conditioned model, when mechanical cooling was enabled in the bedroom from 21:00-23:00,

Table 8 shows a reduction of 5Wh from the base model bedroom cooling load (7kWh) when 75mm roof insulation was applied on the air-conditioned model.

Table 81: Summary of predicted cooling loads (sensible + latent) when using roof insulation intervention in a modelled air-conditioned living room, occupied from 08:00 – 22:00. and air-conditioned is enabled from 18:00-22:00 and bedroom, cooled from 21:00 – 23:00.

| PUR Insulation thickness (mm) | Modelled air-conditioned living room, occupied from 08:00 – 22:00. and air-conditioned is enabled from 18:00-22:00 | Modelled air-conditioned bedroom cooled from 21:00 – 23:00. |
|---|---|---|
| | Cooling load kWh (Roof) | Cooling load kWh (Roof) |
| 500 | 11 | 1 |
| 400 | 11 | 1 |
| 300 | 12 | 2 |
| 200 | 12 | 2 |
| 100 | 13 | 2 |
| 75 | 14 | 2 |
| 50 | 15 | 3 |
| 25 | 17 | 4 |
| 0 | 25 | 7 |

## 6.2. Design optimisation: ceiling modifications

The ceiling was modified by using polyurethane (PUR) insulation boards on the default cement plasterboards generally used in Nigeria. The PUR board thickness was varied from 25 to 500mm in the simulations on the base model, to find the most appropriate thickness for ceiling insulation in a naturally ventilated and air-conditioned building. The effect on the cooling load for the air-conditioned building is also discussed in this section.

### 6.2.1.Naturally ventilated model: Living room and bedroom – ceiling insulation

Considering the naturally ventilated living room space from 08:00-22:00 in Bwari, the ceiling insulation boards reduced the predicted maximum internal temperatures, from 33.7°C to 30.4°C, a 3.3°C drop when 75mm ceiling insulation board was applied (Table 9). Table 9 also shows the summary of the effects of the various ceiling insulation thickness on the indoor temperature. When considering the percentage of hours above 28°C, Table 10 shows this reducing from 84% for the base model to 63% when using 75mm ceiling insulation board.

Table 9 shows a 1.2°C from the maximum base model temperature (30.4°C) to 29.2°C when 75mm ceiling insulation is applied to the bedroom space during the sleeping period. When considering the percentage of hours above 28°C for the same period, Table 11 shows a drop from 33% for the base model to 10% when using 75mm ceiling insulation board.

Table 9: Summary of ceiling insulation intervention in the naturally ventilated living room space model occupied 08:00 – 22:00, and bedroom space model, occupied 23:00 – 07:00 showing the predicted indoor temperatures.

| PUR Ceiling Insulation thickness (mm) | Ceiling insulation intervention in the naturally ventilated living room space model occupied 08:00 – 22:00 | | | Ceiling insulation intervention in the naturally ventilated bedroom space model occupied 23:00 – 07:00 | | |
|---|---|---|---|---|---|---|
| | Max Temp. (°C) BWPDTLV-H1 | Min Temp. (°C) BWPDTLV-H1 | Avg. Temp. (°C) BWPDTLV-H1 | Max Temp. (°C) BWPDTLVH1 | Min Temp. (°C) BWPDTLVH1 | Avg. Temp. (°C) BWPDTLVH1 |
| 500 | 29.9 | 26.0 | 28.1 | 29.2 | 24.8 | 26.6 |
| 400 | 29.9 | 26.0 | 28.1 | 29.2 | 24.8 | 26.6 |
| 300 | 30.0 | 26.0 | 28.1 | 29.2 | 24.8 | 26.6 |
| 200 | 30.1 | 26.0 | 28.2 | 29.2 | 24.8 | 26.6 |
| 100 | 30.3 | 26.0 | 28.3 | 29.2 | 24.8 | 26.6 |
| 75 | 30.4 | 26.0 | 28.3 | 29.2 | 24.8 | 26.6 |
| 50 | 30.6 | 26.0 | 28.5 | 29.2 | 24.9 | 26.6 |
| 25 | 31.1 | 26.0 | 28.7 | 29.3 | 24.9 | 26.7 |
| 0 | 33.7 | 26.3 | 30.0 | 30.4 | 25.0 | 27.4 |

Table 10: Summary of the predicted effects of roof insulation intervention on indoor temperatures above 28°C in air-conditioned living room model, occupied from 08:00 – 22:00.

| | Base Ceil. | Ceil. PUR 25 mm | Ceil. PUR 50 mm | Ceil. PUR 75 mm | Ceil. PUR 100 mm | Ceil. PUR 200 mm | Ceil. PUR 300 mm | Ceil. PUR 400 mm | Ceil. PUR 500 mm |
|---|---|---|---|---|---|---|---|---|---|
| TEMP>=28°C | 88 | 76 | 68 | 66 | 64 | 59 | 60 | 59 | 59 |
| % Hours above 28°C | 84 | 72 | 65 | 63 | 61 | 56 | 57 | 56 | 56 |

Table 11: Summary of the predicted effects of roof insulation intervention on indoor temperatures above 28°C in naturally ventilated bedroom model, occupied from 23:00 – 07:00.

| | Base Ceil. | Ceil. PUR 25 mm | Ceil. PUR 50 mm | Ceil. PUR 75 mm | Ceil. PUR 100 mm | Ceil. PUR 200 mm | Ceil. PUR 300 mm | Ceil. PUR 400 mm | Ceil. PUR 500 mm |
|---|---|---|---|---|---|---|---|---|---|
| TEMP>=28°C | 21 | 8 | 8 | 7 | 7 | 7 | 7 | 7 | 7 |
| % Hours above 28°C | 33 | 13 | 13 | 11 | 11 | 11 | 11 | 11 | 11 |

### 6.2.2.Air-conditioned model: Living room and bedroom – ceiling insulation

Table 12 shows a reduction of 11kWh in the living room occupied from 08:00-22:00, considering the cooling load from 18:00-22:00 when 75mm ceiling insulation was applied to the air-conditioned model. The table shows a reduction of 2kWh from the base model bedroom cooling load (7kWh) when 75mm roof insulation was applied to the air-conditioned model.

Table 12: Summary of predicted cooling loads (sensible + latent) when using ceiling insulation intervention in a modelled air-conditioned living room, occupied from 08:00 – 22:00 with cooling enabled from 18:00 – 22:00, and bedroom model cooled from 21:00 – 23:00.

| PUR insulation thickness (mm) | Modelled air-conditioned living room, occupied from 08:00 – 22:00 with cooling enabled from 18:00 – 22:00 | Modelled air-conditioned bedroom space model cooled from 21:00 – 23:00. |
|---|---|---|
| | Cooling loads kWh (ceiling) | Cooling load kWh (Ceiling) |
| 500 | 12 | 4 |
| 400 | 12 | 4 |
| 300 | 12 | 4 |
| 200 | 13 | 5 |
| 100 | 14 | 5 |
| 75 | 14 | 5 |
| 50 | 15 | 5 |
| 25 | 17 | 5 |
| 0 | 25 | 7 |

### 6.3. Design optimisation: Wall modifications

The walls were modified by applying polyurethane (PUR) insulation boards on the default sandcrete modelled exterior wall used in Nigeria. The board thickness varied from 25 to 500mm which was simulated in the base model to find the most appropriate thickness for wall insulation in a naturally ventilated and air-conditioned building. The effect of this passive cooling intervention on a naturally ventilated model and an air-conditioned model is shown in this section.

#### 6.3.1.Naturally ventilated model: Living room and bedroom – wall insulation

Considering the naturally ventilated living room space from 08:00-22:00, the wall insulation board reduced the predicted maximum internal temperatures, from 33.7°C to 33.0°C, a 0.7°C fall when 75mm ceiling insulation board was applied (Table 13). Table 13 also summarizes the effects of the various wall insulation thicknesses on the indoor temperature. When considering the percentage of hours above 28°C, Table 14 reveals a drop-in percentage from 84% for the base model to 80% when using 75mm wall insulation board. Table 13 shows a 1.6°C drop in temperature from the maximum base model temperature (30.4°C) to 28.8°C when 75mm wall insulation is applied to the air-conditioned bedroom space during the sleeping period. When considering the percentage of hours above 28°C for the same period, Table 15 shows a drop from 33% for the base model to 13% when using 75mm wall insulation board.

Table 13: Summary of wall insulation intervention in the naturally ventilated living room space model occupied 08:00-22:00, and bedroom space model occupied 23:00 – 07:00 showing the predicted indoor temperatures.

| PUR Wall Insulation thickness (mm) | Wall insulation intervention in the naturally ventilated living room model occupied 08:00-22:00 | | | Wall insulation intervention in the naturally ventilated bedroom model occupied 08:00-22:00 | | |
|---|---|---|---|---|---|---|
| | Max Temp. (°C) BWPDTLVH1 | Min Temp. (°C) BWPDTLVH1 | Avg. Temp. (°C) BWPDTLVH1 | Max Temp. (°C) BWPDTLVH1 | Min Temp. (°C) BWPDTLVH1 | Avg. Temp. (°C) BWPDTLVH1 |
| 500 | 32.8 | 26.3 | 29.6 | 28.6 | 25.3 | 26.7 |
| 400 | 32.8 | 26.3 | 29.6 | 28.6 | 25.3 | 26.7 |
| 300 | 32.9 | 26.3 | 29.6 | 28.6 | 25.3 | 26.7 |
| 200 | 32.9 | 26.3 | 29.7 | 28.6 | 25.3 | 26.7 |
| 100 | 33.0 | 26.3 | 29.7 | 28.8 | 25.4 | 26.8 |
| 75 | 33.0 | 26.3 | 29.7 | 28.8 | 25.4 | 26.8 |
| 50 | 33.1 | 26.3 | 29.7 | 28.9 | 25.4 | 26.9 |
| 25 | 33.2 | 26.3 | 29.8 | 29.1 | 25.4 | 27.0 |
| 0 | 33.7 | 26.3 | 30.0 | 30.4 | 25.0 | 27.4 |

Table 14: Summary of the predicted effects of wall insulation intervention on indoor temperatures above 28°C in naturally ventilated living room model, occupied from 08:00-22:00.

| | Base Wall | Wall PUR 25 mm | Wall PUR 50 mm | Wall PUR 75 mm | Wall PUR 100 mm | Wall PUR 200 mm | Wall PUR 300 mm | Wall PUR 400 mm | Wall PUR 500 mm |
|---|---|---|---|---|---|---|---|---|---|
| Hours above 28°C | 88 | 86 | 84 | 84 | 84 | 84 | 84 | 84 | 84 |
| % Hours above 28°C | 84 | 82 | 80 | 80 | 80 | 80 | 80 | 80 | 80 |

Table 15: Summary of the predicted effects of wall insulation intervention on indoor temperatures above 28°C in naturally ventilated bedroom model, occupied from 23:00 – 07:00

| | Wall Roof | Wall PUR 25 mm | Wall PUR 50 mm | Wall PUR 75 mm | Wall PUR 100 mm | Wall PUR 200 mm | Wall PUR 300 mm | Wall PUR 400 mm | Wall PUR 500 mm |
|---|---|---|---|---|---|---|---|---|---|
| Hours above 28°C | 21 | 9 | 8 | 8 | 6 | 6 | 6 | 6 | 6 |
| % Hours above 28°C | 33 | 14 | 13 | 13 | 10 | 10 | 10 | 10 | 10 |

### 6.3.2. Air-conditioned model: Living room and bedroom – wall insulation

Table 16 reveals a reduction of 16Wh from 25kWh in the cooling load for the base model in the living room occupied from 08:00 – 22:00 with cooling enabled from 18:00 – 22:00. Considering the cooling load from 21:00-23:00, Table 16 shows a reduction of 2kWh from the base model (7kWh) when 75mm wall insulation was applied to the air-conditioned model.

Table 16: Summary of cooling loads (sensible + latent) when using wall insulation intervention in a modelled air-conditioned living room space, occupied from 08:00 – 22:00 with cooling enabled from 18:00 – 22:00, bedroom space model cooled from 21:00 – 23:00.

| PUR Insulation thickness (mm) | Modelled air-conditioned living room space, occupied from 08:00 – 22:00 with cooling enabled from 18:00 – 22:00 | Modelled air-conditioned bedroom space model cooled from 21:00 – 23:00. |
|---|---|---|
| | Cooling load kWh (Wall) | Cooling load kWh (Wall) |
| 500 | 7 | 4 |
| 400 | 7 | 4 |
| 300 | 7 | 5 |
| 200 | 8 | 5 |
| 100 | 8 | 5 |
| 75 | 9 | 5 |
| 50 | 9 | 5 |
| 25 | 11 | 5 |
| 0 | 25 | 7 |

### 6.4. Design optimisation: Shading device modifications

On the exterior living rooms and bedrooms windows on the naturally ventilated and air-conditioned models, shading devices were applied using an exterior projection varying from 150 to 1050mm to find the most suitable projection that would reduce indoor temperatures. In the simulations, the naturally ventilated building had bedroom windows orientated towards the North-East and South-East, while the living room had an exterior window oriented towards the South-East. Sunlight entered the building during the simulated period especially the air-conditioned model, because it has windows on three sides of the house. In the air-conditioned model, the living room had one of its windows oriented to the east and the other to the south while the bedroom had one of its windows oriented towards the west and the other to the north. The shading device was made up of 50mm thick concrete horizontal overhang and vertical side fins, offset 100mm from the window (Figure 5). This study applies a horizontal and vertical shading device. This section will discuss the effects of the shading devices on the naturally ventilated model and air-conditioned model.

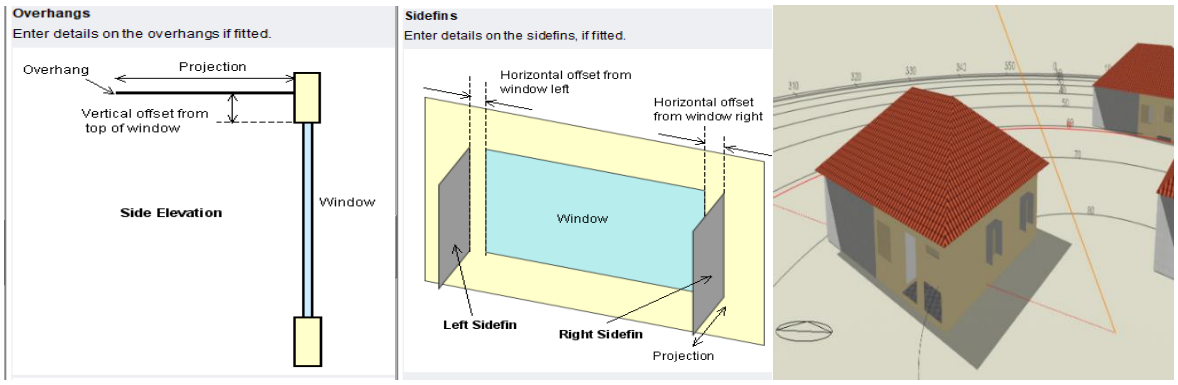


Figure 5: Views of 450mm thick concrete horizontal overhang (left), vertical side fins (middle), and shading device on the naturally ventilated model at 14:00 (right)

### 6.4.1. Naturally ventilated model: Living room and bedroom – shading device

Considering the effects on the indoor daytime period from 08:00-22:00 when using shading devices (Table 17), shows a 1.1°C reduction from the base model temperature (33.7°C) was achieved when a 1050mm projection shading device was applied. When considering the percentage of hours above 28°C for the daytime period, Table 18 shows a drop from 84% for the base model to 81% when using 150-1050mm shading device extension. Considering the effects on the indoor sleeping period from 23:00-07:00 when applying shading devices (Table 17), shows a 0.7°C reduction from the maximum base model temperature (30.4°C) was predicted when a 300mm projection shading device extension was applied. When considering the percentage of hours above 28°C for the daytime period, Table 19 shows an 11 percentage points drop in temperature from 33% for the base model to 22% when applying a 300mm shading device projection.

Table 17: Summary of shading device intervention in the naturally ventilated living room space model, occupied 08:00 – 22:00, and bedroom model, occupied 23:00 – 07:00 showing the predicted indoor temperatures.

| Shading Device Extension | Shading device intervention in the naturally ventilated living room model occupied 08:00 – 22:00 | | | Shading device intervention in the naturally ventilated bedroom model occupied 23:00 – 07:00 | | |
|---|---|---|---|---|---|---|
| | Max Temp. (°C) BWPDTLVH1 | Min Temp. (°C) BWPDTLVH1 | Avg. Temp. (°C) BWPDTLVH1 | Max Temp. (°C) BWPDTLVH1 | Min Temp. (°C) BWPDTLVH1 | Avg. Temp. (°C) BWPDTLVH1 |
| **1050** | **32.6** | **25.9** | **29.3** | **29.7** | **25.2** | **27.0** |
| **900** | **32.7** | **25.9** | **29.3** | **29.7** | **25.2** | **27.0** |
| **750** | **32.8** | **25.9** | **29.4** | **29.7** | **25.2** | **27.0** |
| **600** | **32.9** | **25.9** | **29.4** | **29.7** | **25.2** | **27.0** |
| **450** | **33.1** | **25.9** | **29.5** | **29.7** | **25.2** | **27.0** |
| **300** | **33.3** | **26.0** | **29.7** | **29.7** | **25.2** | **27.0** |
| **150** | **33.5** | **26.1** | **29.8** | **29.8** | **25.2** | **27.0** |
| **0** | **33.7** | **26.3** | **30.0** | **30.4** | **25.0** | **27.4** |

Table 18: Summary of the effects of shading device intervention on indoor temperatures above 28°C in naturally ventilated living room model, occupied from 08:00 – 22:00.

| | Shading device Base | SD 150 mm | SD 300 mm | SD 450 mm | SD 600 mm | SD 750 mm | SD 900 mm | SD 1050 mm |
|---|---|---|---|---|---|---|---|---|
| **Hours above 28°C** | **88** | **85** | **85** | **85** | **85** | **85** | **85** | **85** |
| **% Hours above 28°C** | **84** | **81** | **81** | **81** | **81** | **81** | **81** | **81** |

SD-Shading Device

Table 19: Summary of the effects shading device intervention for indoor temperatures above 28°C in naturally ventilated bedroom model, occupied from 23:00 – 07:00.

| | Shading device Base | SD 150 mm | SD 300 mm | SD 450 mm | SD 600 mm | SD 750 mm | SD 900 mm | SD 1050 mm |
|---|---|---|---|---|---|---|---|---|
| **Hours above 28°C** | 21 | 14 | 14 | 13 | 13 | 13 | 12 | 12 |
| **% Hours above 28°C** | 33 | 22 | 22 | 21 | 21 | 21 | 20 | 20 |

### 6.4.2. Air-conditioned model: Living room space and bedroom – Shading device

Considering the cooling load from 08:00-22:00, Table 20 shows a reduction of 13kWh from the base model (25kWh) when a 450mm shading device was applied to the air-conditioned model. Considering the cooling load from 21:00-23:00, Table 20 highlights a reduction of 2kWh from the base model (7kWh) when 1050mm shading device extension was applied to the air-conditioned model.

Table 20: Summary of cooling loads (sensible + latent) when applying shading device intervention on an air-conditioned Living room space model, occupied from 08:00 – 22:00 with cooling enabled from 18:00 – 22:00 and bedroom space model cooled from 21:00 – 23:00.

| Shading Device Extension (mm) | Air-conditioned living room space model, occupied from 08:00 – 22:00 with cooling enabled from 18:00 – 22:00 | Air-conditioned bedroom space model cooled from 21:00 – 23:00. |
|---|---|---|
| | Cooling Load kWh (Shading device) | Cooling Load kWh (Shading device) |
| **1050** | 7 | 5 |
| **900** | 7 | 6 |
| **750** | 8 | 6 |
| **600** | 9 | 6 |
| **450** | 12 | 6 |
| **300** | 16 | 6 |
| **150** | 18 | 6 |
| **0** | 25 | 7 |

## 6.5. Daily cooling load for the various passive cooling (insulation) interventions in the living room and bedroom

The cooling load for the air-conditioned model when cooling was enabled during the daytime, i.e. 18:00-22:00, showed a large drop from 66kWh for the base model to 14 and 16kWh respectively when 75-500mm roof or ceiling insulation was applied in the living rooms (Table 21). The wall insulation led to a 29kWh cooling load reduction when 75 – 500mm insulating boards were applied. The roof and ceiling insulation were more effective than the wall insulation during the daytime and evening period. The bedroom space also had cooling loads reduced to 11kWh and less when 75mm insulation was applied on the roof and ceiling, but the wall insulation gave only a 3kWh reduction when 75mm insulation was applied (Table 21).

Table 21: Summary of cooling loads when applying roof, ceiling and wall insulation on an air-conditioned Living room model cooled from 18:00 – 22:00 and bedroom model cooled from 23:00 – 07:00.

| PUR Insulation thickness (mm) | Air-conditioned living room model cooled from 18:00 – 22:00 | | | Air-conditioned bedroom model cooled from 23:00 – 07:00 | | |
|---|---|---|---|---|---|---|
| | Cooling load kWh Roof insulation | Cooling load kWh Ceiling insulation | Cooling load kWh Wall insulation | Cooling load kWh Roof insulation | Cooling load kWh Ceiling insulation | Cooling load kWh Wall insulation |
| 500 | 11 | 11 | 11 | 1 | 4 | 4 |
| 400 | 12 | 11 | 11 | 1 | 4 | 4 |
| 300 | 12 | 12 | 11 | 2 | 4 | 5 |
| 200 | 13 | 12 | 11 | 2 | 5 | 5 |
| 100 | 13 | 13 | 12 | 2 | 5 | 5 |
| 75 | 14 | 14 | 12 | 2 | 5 | 5 |
| 50 | 15 | 14 | 13 | 3 | 5 | 5 |
| 25 | 17 | 16 | 14 | 4 | 5 | 5 |
| 0 | 25 | 25 | 25 | 7 | 7 | 7 |

## 6.6. Comprehensive optimum passive cooling interventions

The results from the simulation of the various PUR insulation applications to the roof, ceiling and external walls showed how effective the insulation is. However, since the effect of the roof and ceiling insulation were identical, i.e., either could be cheaper, the ceiling insulation was no longer pursued as an intervention in this study, only the roof and wall insulation were incorporated into the optimum passive intervention. A selection of the various insulation thicknesses applied on the roof and walls was simulated to reduce the maximum indoor temperatures to 28°C from a daytime maximum temperature of 33.7°C. This is the lowest comfortable temperature reported and discussed earlier in (Adaji 2017; Adaji et al, 2019). Although shading devices showed smaller indoor temperature reductions and based on the orientation of the building, they were significant and included in the passive application. Some simulation was run here to explore the potential of including thermal mass into the optimum passive interventions. A 20% thermal mass was adopted as a passive cooling intervention to help reduce the indoor temperature to the comfortable temperature range. This section discusses the comprehensive, combined passive cooling interventions chosen for a naturally ventilated and air-conditioned model.

### 6.6.1. Impact of passive cooling interventions on naturally ventilated living room model and bedroom model

Figures 9 show the effect of passive cooling interventions on the maxima and minima naturally ventilated living room temperature during the daytime and evening period for a week. The passive intervention analysis of the living room space occupied from 08:00-22:00, showed a 5°C reduction from the predicted base model maximum air temperature of 33.7°C to 28.8°C. This was achieved when 75mm roof and wall insulation was applied together with 450mm external shading device projection on the window and 20% thermal mass made of 100% concrete (Table 22 and Figure 6a). Table 22 also shows a 2.5°C reduction in the average temperature from the base model (30.5°C) with the same passive application.

Figure 6b shows the effect of passive cooling interventions on the maxima and minima of the naturally ventilated bedroom temperature during the night-time (23:00-07:00) for a week. The passive intervention analysis of the bedroom showed a 3.8°C drop from the predicted base model maximum air temperature of 30.4°C to 26.6°C. This was achieved when 75mm roof and wall insulation were applied together with 450mm external shading device extension on the window and 20% thermal mass. The table also shows a 1.7°C reduction in the average temperature from the base model (27.4°C) with the same passive application over the same period.

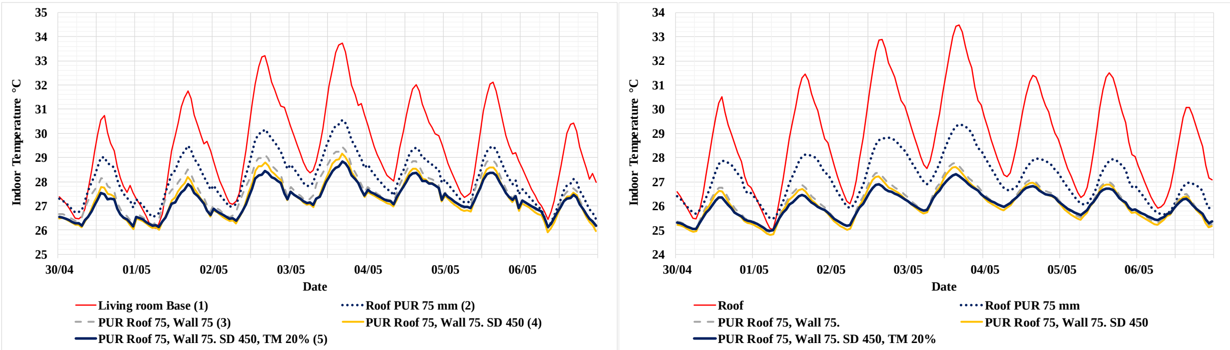


Figure 6: Summary of the proposed passive intervention on the living room space in naturally ventilated model during the daytime and evening time, 08:00 – 22:00 (left) and night-time, 23:00 – 07:00 (right), showing the effect on indoor predicted temperatures.

Table 22: Summary of insulation intervention in a naturally ventilated living room occupied from 08:00 – 22:00 and bedroom from 23:00 – 07:00, showing the effect on predicted indoor temperatures.

| | Passive Cooling Intervention | Insulation intervention in a naturally ventilated living room occupied from 08:00 – 22:00 | | | Insulation intervention in a naturally ventilated bedroom occupied from 23:00 – 07:00 | | |
|---|---|---|---|---|---|---|---|
| | | Max Temp. BWPDTLVH1 | Min Temp. BWPDTLVH1 | Avg. Temp. BWPDTLVH1 | Max Temp. BWPDTBDH1 | Min Temp. BWPDTBDH1 | Avg. Temp. BWPDTBDH1 |
| 1 | Living room Base | 33.7 | 26.3 | 30.0 | 30.4 | 25.0 | 27.4 |
| 2 | Roof PUR 75 mm | 30.6 | 26.1 | 28.5 | 28.4 | 25.5 | 26.7 |
| 3 | PUR Roof 75, Wall 75. | 29.5 | 26.1 | 27.9 | 26.8 | 24.9 | 25.7 |
| 4 | PUR Roof 75, Wall 75. SD 450 | 29.1 | 25.9 | 27.6 | 26.6 | 24.8 | 25.6 |
| 5 | PUR Roof 75, Wall 75. SD 450, TM 20% | 28.7 | 26.1 | 27.5 | 26.6 | 25.0 | 25.7 |

Note: SD - Shading Device, TM – Thermal Mass.

### 6.6.2. Passive cooling application on air-conditioned model living room model and bedroom model

Considering the daytime and evening period when mechanical cooling was enabled (18:00-22:00), Table 23 show a summary of the various passive cooling interventions on the cooling load. The cooling load dropped from 25kWh to 0 when 75mm roof and wall insulation, 450 mm shading device and 20% thermal mass were applied on the model. Also, there was a reduction in the cooling load from 7kWh to 0kWh when 75mm roof and wall insulation was applied together with 450mm shading device on the living room windows and 20% thermal mass on the base model. (Table 23).

Table 23: Summary of cooling loads (sensible + latent) for selected passive cooling interventions in a modelled air-conditioned living space cooled from 18:00 – 22:00 and 21:00 – 23:00.

| | Passive Cooling Intervention | Air-conditioned living space cooled from 18:00 – 22:00 | Air-conditioned living space cooled from 21:00 – 23:00 |
|---|---|---|---|
| | | Total cooling load kWh | Total cooling load kWh |
| 1 | Living room Base Model | 25 | 7 |
| 2 | Roof PUR 75 mm | 17 | 3 |
| 3 | PUR Roof 75, Wall 75 | 0 | 0 |
| 4 | PUR Roof 75 Wall 75, SD 450 | 0 | 0 |
| 5 | PUR Roof 75 Wall 75, SD 450, TM 20% | 0 | 0 |

## 6.7. Overall Dry season comparison between base model and optimum passive intervention in a naturally ventilated and air-conditioned model

The passive interventions discussed in section 6.6 show that for the naturally ventilated model, the passive intervention combination with 75mm roof and wall insulation, 450 mm exterior window shading devices and 20% thermal mass was the most effective intervention. For the air-conditioned model, 75mm roof and wall insulation, 450 mm exterior window shading devices and 20% thermal mass was also the most effective intervention. These interventions were adopted to form the optimum passive cooling interventions for the naturally ventilated and air-conditioned models during the daytime, evening period and night-time and now form the proposed optimum passive interventions for this study. This section discusses the effects of the optimum passive intervention for the dry season period considered from 01/February – 06/May for simulation, on a naturally ventilated base and a model that was cooled during the daytime and evening (08:00 – 22:00) and night-time (21:00 – 23:00).

### 6.7.1. Overall Dry season comparison between the naturally ventilated base model and optimum passive cooling model.

The model simulated the naturally ventilated living room space ventilated from 08:00 – 22:00 throughout the dry season. It showed the maximum predicted air temperatures reduced by 5.5°C from 36.2°C to 30.7°C when the optimum passive intervention was applied (Table 24). For the night-time period, the maximum air temperature reduced from 31.4°C for the predicted base model to 27.7°C, a 3.7°C drop when the optimum passive intervention was applied. Table 24 also shows a summary average and minimum temperatures for the effects of the optimum passive intervention on the base model during the dry season.

Table 24: Summary of predicted temperature comparison between the base model and optimum passive cooling intervention in a naturally ventilated living room space during the dry season period at different periods

| | Base Model - Living room (08:00 – 22:00) | Living room - Optimum passive cooling interventions (08:00 – 22:00) | Base Model - Living room (23:00 – 07:00) | Living room - Optimum passive cooling interventions (23:00 – 07:00) |
|---|---|---|---|---|
| MAX | 36.2 | 30.7 | 31.4 | 27.7 |
| MIN | 25.0 | 26.2 | 23.2 | 24.3 |
| AVG. | 30.4 | 28.3 | 27.8 | 26.4 |

### 6.7.2. Overall Dry season cooling load comparison between the air-conditioned base model and optimum passive cooling.

The cooling loads when air-conditioning was enabled from 18:00-22:00 showed a significant drop from 525kWh for the base model to 0kWh when the optimum passive interventions were applied (Table 25). There was also a significant drop in the cooling load during the evening period from 525kWh for the base model to 0kWh when the optimum passive interventions were applied. During the night cooling period (21:00-23:00), there was also a significant drop in the cooling load from 345kWh to 8kWh when the optimum passive interventions were applied (Table 39).

Table 25: Summary of cooling load (sensible + latent) comparison between the base model and optimum passive cooling intervention in a modelled air-conditioned living room cooled from 18:00 – 22:00, and 21:00 – 23:00.

| Optimum passive cooling intervention in a modelled air-conditioned living room (18:00 – 22:00) | | Optimum passive cooling intervention in a modelled air-conditioned living room (21:00 – 23:00) | |
|---|---|---|---|
| Cooling load, Base Model Living room (kWh) | Cooling load, Optimum passive interventions Living room (kWh) | Cooling load, Base Model Living room (kWh) | Cooling load, Optimum passive interventions Living room (kWh) |
| 525 | 0 | 345 | 8 |

When considering the percentage of hours above 28°C in the living room for the dry season (01/Feb. – 06/May), Table 26 shows this reducing from 57% for the base model to 48% when the optimum passive intervention is applied for the dry season. Also, the temperature was further reduced from 45% for the base model to 3% when the optimum passive intervention is applied when considering the percentage of hours above 30°C. When considering the percentage of hours above 28°C in the bedroom for the dry season, Table 26 shows a drop from 38% to zero when the optimum passive cooling intervention is applied. Figures 7 and 8 show the effect of the optimum passive cooling application for a year on the living room and bedroom temperatures.

Table 26: Summary of the effects of optimum passive interventions on the indoor temperatures above 28°C and 30°C in the naturally ventilated Living room and bedroom occupied at different periods during the dry season.

| | Base Model - Living room (08:00 – 22:00) | Living room - Optimum passive cooling interventions (08:00 – 22:00) | Base Model - Living room (23:00 – 07:00) | Living room - Optimum passive cooling interventions (23:00 – 07:00) |
|---|---|---|---|---|
| Hours above 28°C | 1308 | 1086 | 3335 | 0 |
| % Hours above 28°C | 57 | 48 | 38 | 0 |
| Hours above 30°C | 1031 | 57 | 0 | 0 |
| % Hours above 30°C | 45 | 3 | 0 | 0 |

Figure 7 shows the reduction in the effect of outdoor temperature on the naturally ventilated indoor temperatures throughout the dry season. For the living room base model, there was a strong relationship between the indoor and outdoor temperature ($r^2$ = 0.655). This reduced substantially when the optimum passive interventions were applied to the living room spaces ($r^2$ = 0.511) (Figure 7a). Similarly, the relationship between the external temperature and the base model bedroom space ($r^2$ = 0.564) reduced when the optimum passive interventions were applied ($r^2$ = 0.486) (Figure 7b). Figure 8 shows the effect of the optimum passive cooling application for a year on the living room and bedroom temperatures.

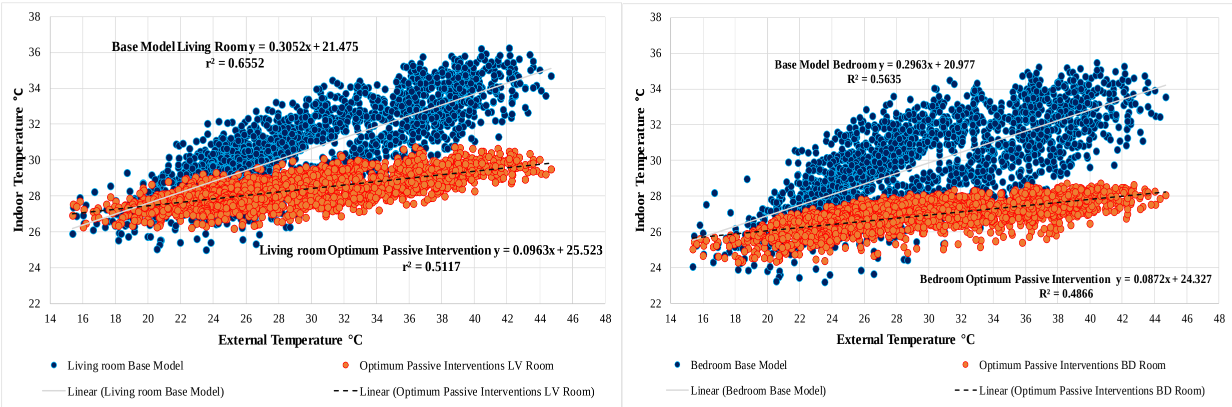


Figure 7: Relationship between the predicted naturally ventilated living room air temperature, the predicted living room optimum passive intervention air temperature at Bwari and the external temperature using Abuja TMY3

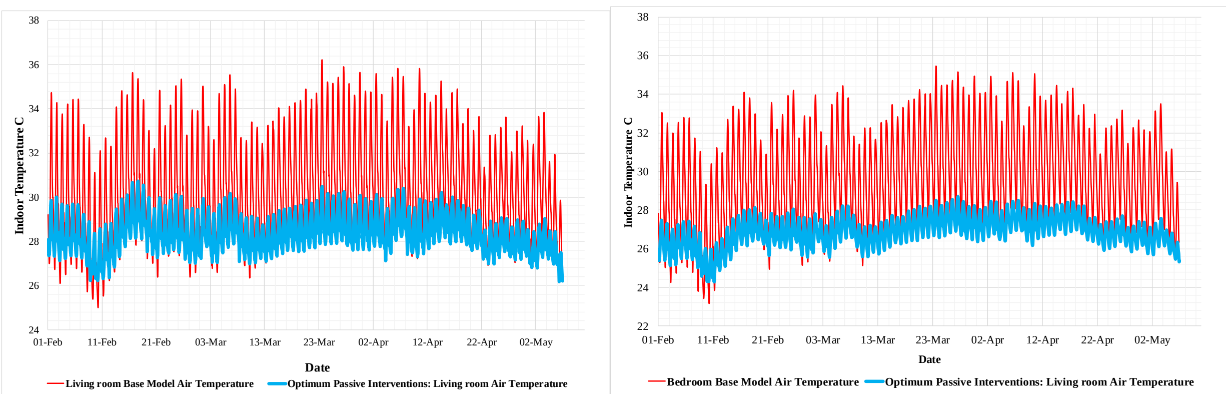


Figure 8: Relationship between the predicted naturally ventilated living room air temperature and the predicted optimum passive intervention air temperature at Bwari

## 7. Conclusion

The paper presented the results from the application of passive interventions on the base model using dynamic thermal simulations and compared the findings with the base model temperatures for Lugbe and Bwari in Abuja, Nigeria. The study considered passive interventions by modifying the roof, ceiling, wall and shading device on a naturally ventilated and air-conditioned base model. For each intervention, the simulated results showed the effects on the daytime, evening and sleeping time temperatures in living rooms and bedrooms, respectively for the naturally ventilated model. For the air-conditioned model, the findings revealed the effect on the mechanical cooling load in the living room during the daytime and evening period and the bedroom when mechanical cooling is enabled.

Two case study buildings at each location were simulated as naturally ventilated and air-conditioned for the periods considered which included one-week (30/April – 06/May) and dry season (01/February – 06/May) for the naturally ventilated model. The results showed that applying the recommended optimum passive interventions (75mm roof and wall insulation, 450mm shading device and 20% thermal mass) during the daytime and evening periods for a week had a significant effect in reducing the maximum living room temperatures by 5°C. The night-time bedroom temperatures were reduced by 3.8°C from the base model air temperature when the optimum passive interventions were applied. This strategy would improve the sleeping period for occupants at night. The air-conditioned model saw a 100% reduction (25kWh to 0) in the cooling load from the base model cooling loads when the optimum passive interventions were applied to the living room (75mm roof and wall insulation, 450mm shading device and 20% thermal mass) during the daytime and evening period. The bedroom cooling load was reduced by 100% (7kWh to 0kWh) when the optimum passive interventions were applied. The reduction in the cooling load was possible because the optimum passive interventions alone maintained the maximum indoor temperatures at 28°C for most of the time. During the dry season simulations, the percentage of temperatures above 28°C for the naturally ventilated living room space dropped by 23% during the daytime and for the sleeping period in the bedroom, the percentage of temperatures above 28°C was reduced by 17%.

This investigation revealed that the most effective passive cooling application for the naturally ventilated model is the application of 75mm roof and wall insulation, 450mm shading device and 20% thermal mass as an optimal passive cooling intervention. This strategy is effective in reducing indoor temperatures throughout the dry season. The results showed that indoor temperatures can be reduced significantly in line with the comfort range reported in this study which can also reflect in the overall financial savings during the dry season period. The results also revealed that the optimum passive interventions were effective in providing an alternative form of indoor cooling during the hot, dry season and save energy and mechanical cooling cost.

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# The pursuit of thermal comfort in residential buildings in Khartoum

**Huda Z.T. Elsherif[1], Professor Marialena Nikolopoulou[2] and Dr. Henrik Schoenefeldt[3]**

[1]Kent School of Architecture & Planning, University of Kent, Canterbury CT2 7NR, UK, hzte3@kent.ac.uk
[2]Kent School of Architecture & Planning, University of Kent, Canterbury CT2 7NR, UK, M.Nikolopoulou@kent.ac.uk
[3]Kent School of Architecture & Planning, University of Kent, Canterbury CT2 7NR, UK, H.Schoenefeldt@kent.ac.uk

**Abstract:** Air conditioning (AC) use is on the rise across the world, even in developing countries. Beyond global warming implications there is an additional concern, electricity scarcity. Understanding the underlying thermal comfort issues is vital to reduce electric consumption. This study focused on residential buildings in the capital state (Khartoum) as it alone consumes 70% of the country's electric production. To identify the broader thermal comfort issues, a questionnaire was distributed in Khartoum. 56% of the participants found their thermal environment unacceptable, while an overwhelming majority of 81.1% of participants set their AC setpoint below the recommended 25ºC. A sample of 6 houses were monitored for two months to give a more detailed insight. The monitoring showed that the AC type impacted both the internal diurnal temperature variations and the usage patterns. Naturally ventilated spaces in Khartoum were found to be uncomfortable most of the time regardless of the house type. However, in AC spaces, the building fabric impacted how long the space stayed cool after the AC was turned off. This implies that although using an AC is inevitable to achieve thermal comfort, improving the building fabric can reduce its usage.

**Keywords:** Thermal comfort, Sudan, Adaptive behavior, Air-conditioner, electric consumption

## 1. Introduction:

### 1.1. Context

Increased reliance on air conditioning is a global trend as urbanism increases worldwide. Air conditioning consumes vast amounts of energy to cool buildings, which contributes to global warming and climate change (Rodrigueza & D'Alessandrob, 2019). To reduce this dependency, increasing environmental performance in buildings and encouraging adaptive thermal comfort is crucial (Moore, et al., 2017).

This study focuses on Sudan, a sub-Saharan country located south of Egypt. Only 45% of Sudanese homes have electricity (Statistics, 2015). The capital state, Khartoum, has a higher percentage at 81.6% (Abdulhadi, 2016). Consequently, it consumes 70% of the country's electric production even though its residents make up only 12% of the population (Statistics, 2008). The pattern of increased AC reliance has also emerged in Sudan, as the total number of AC units imported grew from 12,000 units in 2004 to 150,000 in 2019 (CTC group records). The energy deficit between supply and demand is growing and the country started importing electricity from Ethiopia (Rabah, et al., 2016). The areas connected to the electricity grid suffer from a 40% electricity shortage, which forces the National Authority of Electricity to schedule regular power cuts (Ghandour, 2016). It has also recommended reducing consumption to enable it to provide electricity to more people and reduce these power cuts (Ministry of Energy, 2015). This emphasizes the link between the supply/demand gap and power cuts. The combination of these factors has also led to a substantial yearly increase of electricity prices (JEM, 2018). This highlights that for Sudan, reducing consumption is not only an environmental issue, but a social equality one as well.

The Arab oil boom in the 1970s attracted many Sudanese, who later returned to Sudan carrying the modern building ideals common in the Arabian gulf (Elkhier, 2014), e.g. modern Mediterranean style villas rather than vernacular one-story verandah houses (Bashier, 2008). The author has observed that this also led to a change in people's lifestyles and behaviors. For example, people no longer spend most of their time outdoors as documented by Merghani (2006) and Osman (2004). Karmel summarizes the change in residential buildings into the replacement of the verandah by the enclosed living hall, the tendency towards more compact forms, the inclusion of the kitchen and bathroom with the main building and the excessive use of concrete, glass and air-conditioning (Osman, 2016).

With a single thermal comfort study ever conducted in Sudan (Rodrigueza & D'Alessandrob, 2019), it is critical to evaluate the current thermal performance of Sudanese houses along with the problems that have led to this accelerated increase of AC use. This paper addresses this research gap, aiming to reveal the factors that influence thermal performance and comfort conditions of the housing sector in Khartoum, focusing on the hottest months in the year, May-June.

The objectives of this study for residential houses in Khartoum are:

1. To identify if there are thermal comfort problems in modern and traditional houses.
2. To understand how the lifestyle change from traditional to modern has affected adaptive behaviors and daily patterns especially the relationship with the outdoors.
3. To identify AC usage patterns and what influences them.

### 1.2. Geography and climate

The geographic coordinates of Khartoum state are 15.5007° N, 32.5599° E. In the Koppen classification, the climate is as BWh (Hot desert climate) (Rodrigueza & D'Alessandrob, 2019). Winters are cool and dry with daily temperatures ranging from 5$^{o}$C to 25$^{o}$C, while the Summers are hot and dry and can exceed 45$^{o}$C in late May (Perry, 1991).

## 2. Methodology

To identify the broad issues, a study across the population was conducted through questionnaires. Targeted building monitoring provided insight into the details considered in the questionnaire.

### 2.1. Questionnaire

A cross-sectional questionnaire was distributed in July and had 99 respondents. The questionnaires were distributed to people in companies to be completed at home and an online version was also used. Having access to the internet or being a professional implies that most respondents are most likely from the middle or upper class, with the results likely reflecting this demographic. This demographic consumes the most energy per capita, hence excluding lower classes does not greatly affect the study. However, this distinction is important when comparing results from other surveys which included lower classes.

The questionnaire was written in Sudanese Arabic and had three main parts: (i) surveying the building materials and construction types and the reasons users chose them; (ii) thermal comfort survey based on the ISO 7730 and other studies; (iii) documenting behaviors and habits, including mechanic cooling and electric consumption habits.

### 2.2. **Monitoring**:

Six houses were fitted with internal temperature data loggers, one in a conditioned space and in an unconditioned space. They each recorded the internal temperature and relative humidity every 15 minutes for one month from May 5th till May 30th for three of the houses (H1-H3) then from June 1st to July 1st for the other three houses (H4-H6). The sampled houses were chosen based on logistical and security preferences. The users also recorded their AC use, except for H5 which lost their log.

## 3. Results and analysis

An external datalogger was placed in the balcony of the first floor of H3. The data collected show that the temperatures in May were slightly hotter than June but the period between 16/5/2019-23/5/2019 and 14/6/2019-21/6/2019 had the most similar weather with the largest difference being 7K. As such, these two weeks were used for comparison between the six houses.

### 3.1. Survey results

From the surveys, 69% of the houses were modern and 31% traditional courtyard houses. This paper will focus on results of the thermal comfort, adaptive habits and AC use of the survey.

#### 3.1.1. Building services:

Mixed mode buildings are popular in developing hot countries as they cannot afford to install air conditioning in all the spaces (Honnekeri, et al., 2014). Only 3 respondents did not own an AC in any room.

The most conditioned space was usually the bedroom, as 93% of respondents indicated compared to 83% in the living room as shown in figure 2. This is because Sudanese people prioritize night comfort (Merghani, 2006). Only 5 respondents (4%) had an AC in the kitchen.

Split units were more common in bedrooms at 33.1% compared to 20% in living room as shown in Figure 10. The same trend shows with window units that are 8.9% in the bedroom and 5.8% in the living room. This further proves that the ability to cool efficiently is more important in bedrooms than living rooms.

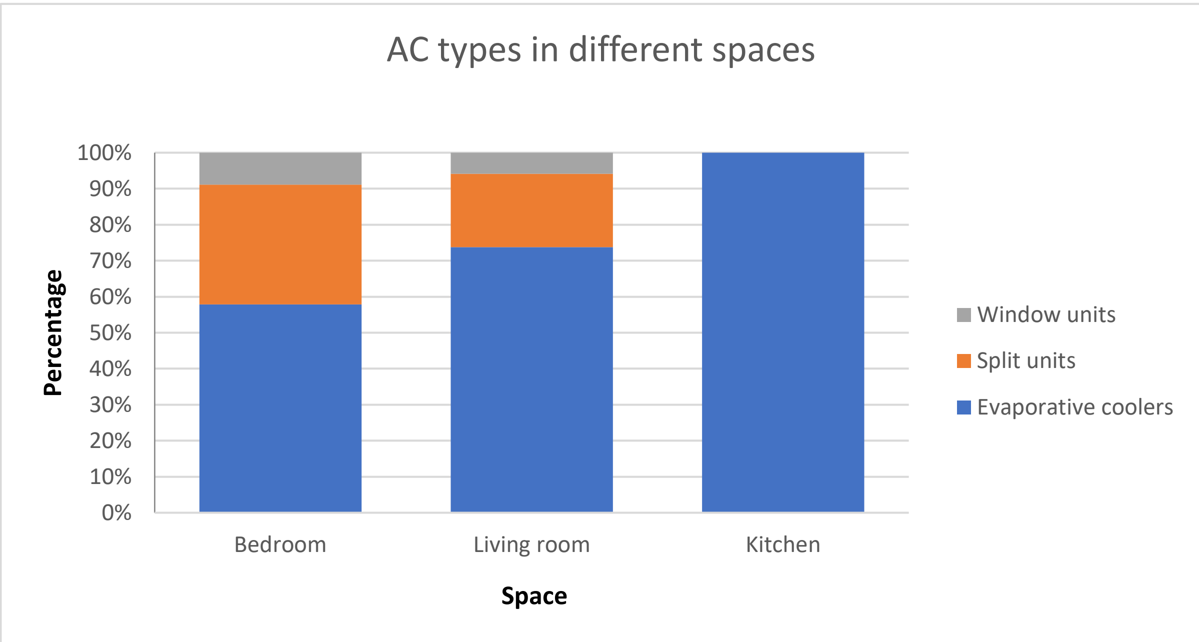


Figure 2 AC types in different spaces

The choice of AC depended on several factors, but the most cited reason for evaporative coolers was electric consumption (44.4%) and cost (23.8%). For split units and window units it was the ability to cool efficiently at (77%) and (92%) respectively. This shows that AC choice depends largely on the budget, those with budget restrictions chose evaporative coolers. However, when the budget was larger, the ability to cool becomes the priority over cost efficiency. This implies that if more people become wealthier, the number of split units will increase.

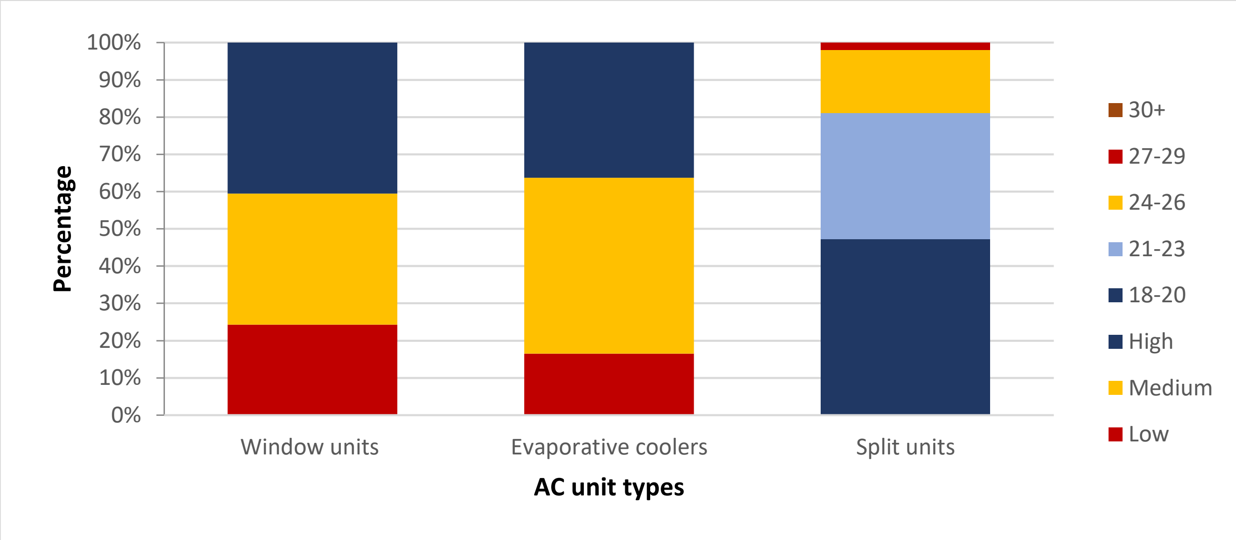


Figure 3 Setting points for different types of AC units

Figure 3 shows that the most common set temperatures were (18-20$^oC$) in split units (47%), medium in evaporative coolers (47.3%) and high (40.5%) in window units. The National Authority of Electricity recommends setting the AC at medium or 25$^oC$ which only 18.9% of split unit users adhered to. 76.2% of respondents said they always leave their AC on, 15.4% only during the day and 8.3% only during the night. This means that most people feel the need to set the AC at the lowest setting possible for long periods to achieve thermal comfort. This could be because they feel their houses are too hot or because their expectations have changed and living in cold air-conditioned spaces has become the social norm. It could also be a combination of both.

This section shows that in the middle and upper classes of Khartoum, intensive AC use is predominant. Given the results shown above, a pattern of AC acquirement could be forecasted. It can be assumed that If a poor family enters middle class, the first AC they will buy will be an evaporative cooler for the bedroom. As the budget increases other bedrooms become included and then the living room. The next budget increase will encourage upgrading to a split unit in the bedroom and then other spaces will follow.

### 3.1.2. Thermal comfort

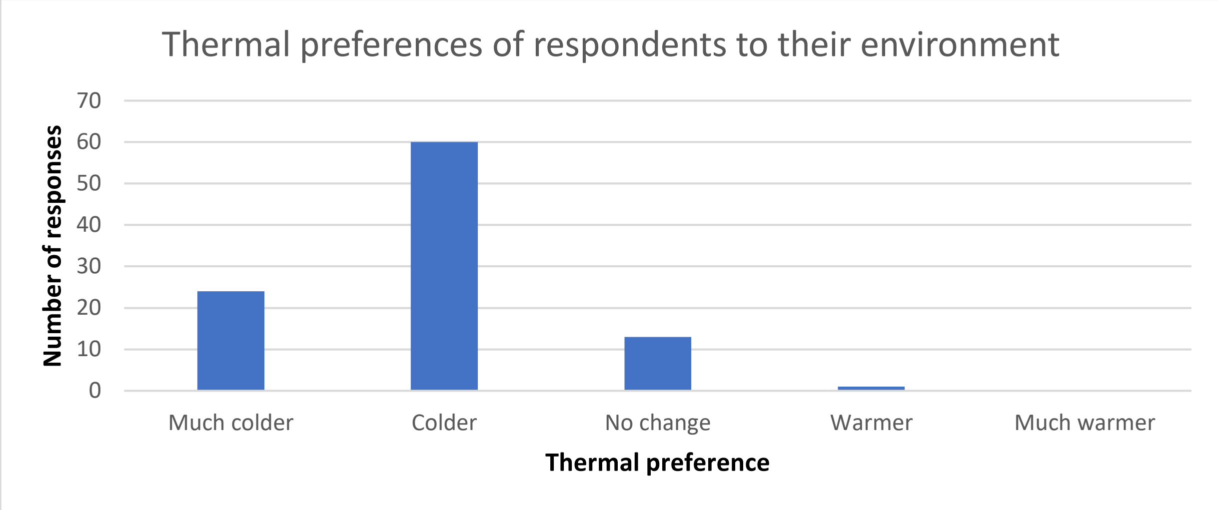


Figure 4 Thermal preference responses of the questionnaire held in Khartoum on July 2019

Only 13% of respondents said they prefer to keep their environment as it is (Figure 4) even though 56% found their thermal environment acceptable. This coincides with Toe's (2013) finding that people in hotter climates prefer colder conditions but have come to accept the current situation. 61% preferred it to be colder, while 24% preferred it to be much colder.

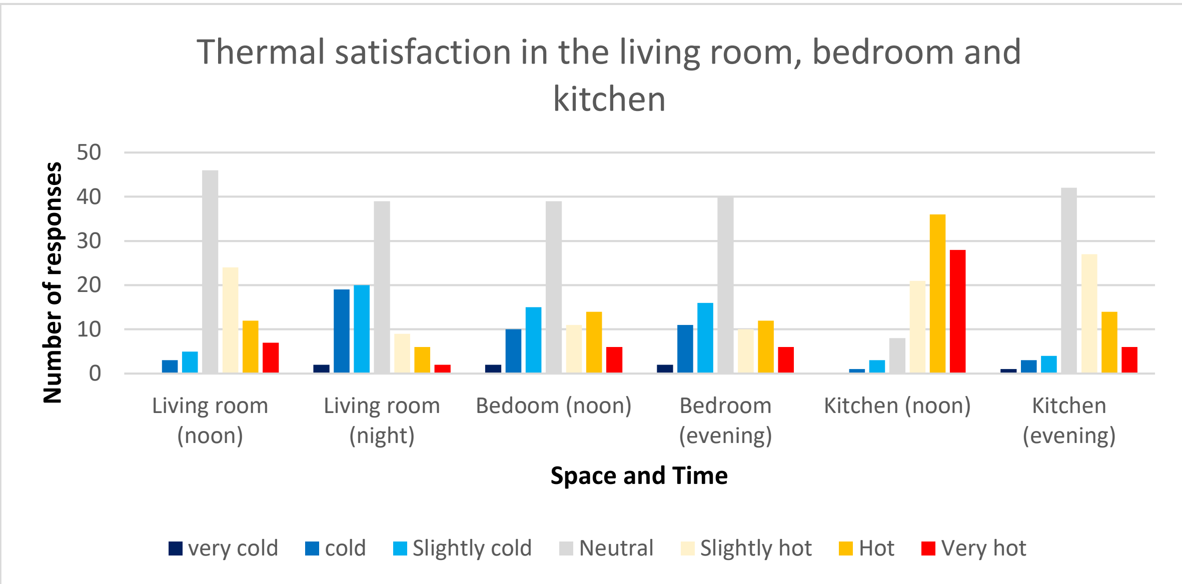


Figure 5 Thermal satisfaction in the living room, bedroom and kitchen

Figure 5 shows that the most problematic space is the kitchen at noon with most responses being slightly hot (22%), hot (37%) and very hot (29%). 44.3% of respondents described their living room as slightly hot, hot or very hot compared to just 31.8% for bedrooms. This coincides with the priority hierarchy established in section 3.1.1 where the bedroom receives the best AC followed by the living room and then the kitchen. As cooking produces a lot of heat, in addition to the heat coming from outside, it's likely that occupants believe that attempting to condition the kitchen would consume far too much energy and therefore experience more challenges to achieving thermal comfort in this space.

### 3.1.3. Adaptive behaviors:

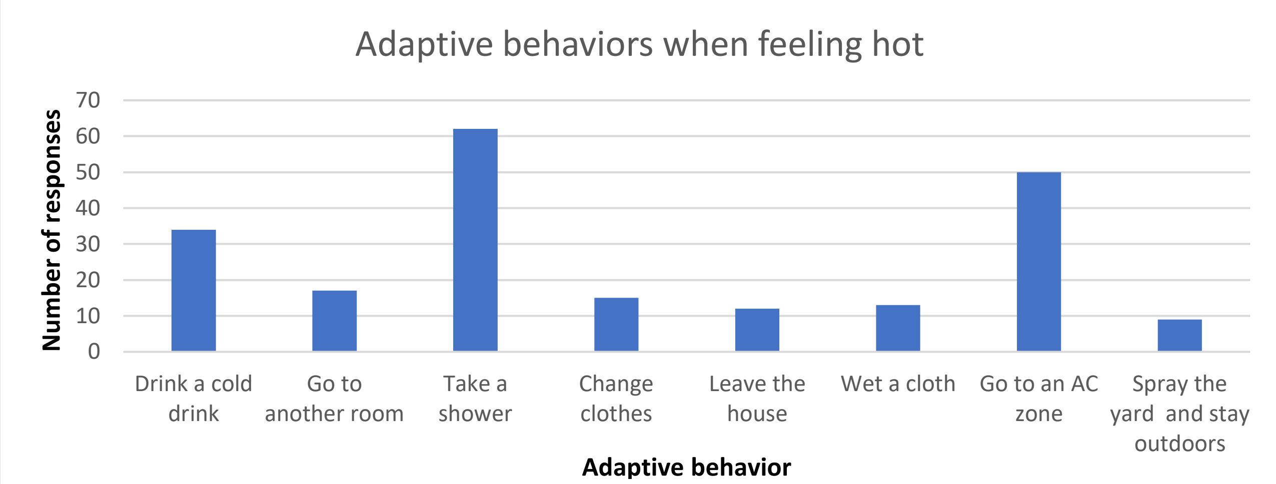


*Figure 6 Adaptive behaviors when feeling hot*

The most common adaptive behavior(Figure 6) was taking a shower (29.2%), followed by moving to an AC zone (23.6%) and drinking a cold drink (16%). The least used method was spraying the yard (4.25%). This is emphasized by the fact only 7.8% always spray their yards and 7.8% usually sprayed their yards. This could be because people no longer spend as much time outdoors as only 21% said they always or usually spend their evenings in the yard and 46% said they rarely or never spend their evenings there. This could be part of the trend towards modernism. Only 14.8% had shade trees in their yard and 41% had a verandah, both of which could have improved the microclimate in the yard to encourage spending evenings outdoors. Most people (46%) didn't have the space for a shade tree while 36.1% believed having trees planted in the street in front of the yard was enough. Similarly, 63% said they lack the space for a verandah, while 27% thought they do not need one. Therefore, it can be concluded that the reduced amount of space available and lifestyle change are key drivers to reduced time spent outdoors. The DHS (1990) survey showed that urban households have more members than rural ones, and with the trend of rapid urbanism in the capital, the reduced space could be a result of increased density per household.

Only 14% still slept outside at night and another 14% sleep in the living room, while the rest sleep in their bedrooms. The main deterrent to sleeping outdoors was mosquitos (31%) followed by the heat (26%) and privacy (9.6%) and security (9%). Only 8.6% of respondents said they do not frequently use the bedroom during the daytime and 10% said they also entertain guests in them. This shows that achieving thermal comfort is important in bedrooms both day and night, especially since only 11% of houses were empty during office hours, while 18% had only one occupant left.

The most common reason to open the window was a power cut event (39%), followed by the morning window opening (28%) and when cleaning the house (17%). It should be noted that cleaning is usually done in the mornings so there could be a large overlapping between the two periods. Only 9.7% opened windows at night to cool the house, which is probably because people now use AC units rather than natural ventilation to cool at night.

### 3.1.4. Discussion:

This survey has highlighted the environmental impact of modernization in Khartoum. For example, in the past, cooking outdoors in verandahs would have solved the excessive heat problem in indoor kitchens.

However, many people no longer have enough space for a verandah. The lack of outdoor spaces shaded by verandahs or trees could be a contributor to the modern trend of reduced time spent outdoors. Sleeping outdoors is no longer prevalent because of mosquitos and because people think it is too hot outside. Since the temperatures now are only slightly warmer than 15 years ago, it could be speculated that people's expectations have changed, and they now prefer to sleep in the cooler temperature of the AC. The prioritization of the bedroom combined with its extensive use both day and night mean that efforts to improve the building fabric should be focused there to achieve the maximum benefit. Window opening patterns show that most people no longer open their windows at night to cool the building naturally. In sum, it can be implied that people used to adapt their behavior whenever they felt the building was uncomfortable but now resort to the AC as a convenient alternative. This means that to address the current prevalent dissatisfaction with the thermal environment, the building needs to change as the occupants are no longer willing to adapt to it.

### 3.2. Building monitoring:

#### 3.1.1. Overview:

*Table 1: details of the monitored buildings*

| | **Building features** | | | | **Occupant details** | | |
|---|---|---|---|---|---|---|---|
| | **Topography** | **Wall type** | **Roof type** | **No. of floors** | **Class** | **Family type** | **No. of occupants** |
| **H1** | Traditional courtyard | Composite brick/adobe mix | Wood/ straw/ earth mix | 1 | Lower middle | Extended | 9 |
| **H2** | Modern | 20cm brick | Reinforced concrete | 3 | Upper middle | Extended | 6 |
| **H3** | Modern | 30cm brick | Reinforced concrete | 2 | Upper middle | Nuclear | 3 |
| **H4** | Modern | 20cm concrete block | Reinforced concrete | 2 | Upper middle | Nuclear | 2 |
| **H5** | Traditional courtyard | 40cm brick | Corrugated metal with false ceiling | 1 | Lower middle | Nuclear | 4 |
| **H6** | Traditional courtyard | 50cm stone in room 1 & 20cm brick in room 2 | Corrugated metal with false ceiling | 1 | Lower middle | Extended | 6 |

H1, H5 and H6 are single-story courtyard houses with families from the lower middle class and rely on evaporative coolers. H2, H3 and H4 are modern houses with families from the upper middle class and mainly use the split units. H2, H3 and H4 houses have a ground floor for the main family and an upper floor for their children except for H4 that has two apartments on the first, one rented and the other for the daughter. Due to these differences, they will be grouped into a 'traditional' and 'modern' group during the discussion. The houses were chosen with different construction types to identify if there is a general thermal comfort problem in middle class houses or if it is only in certain types.

### 3.1.2. Thermal comfort:

**Traditional group:**

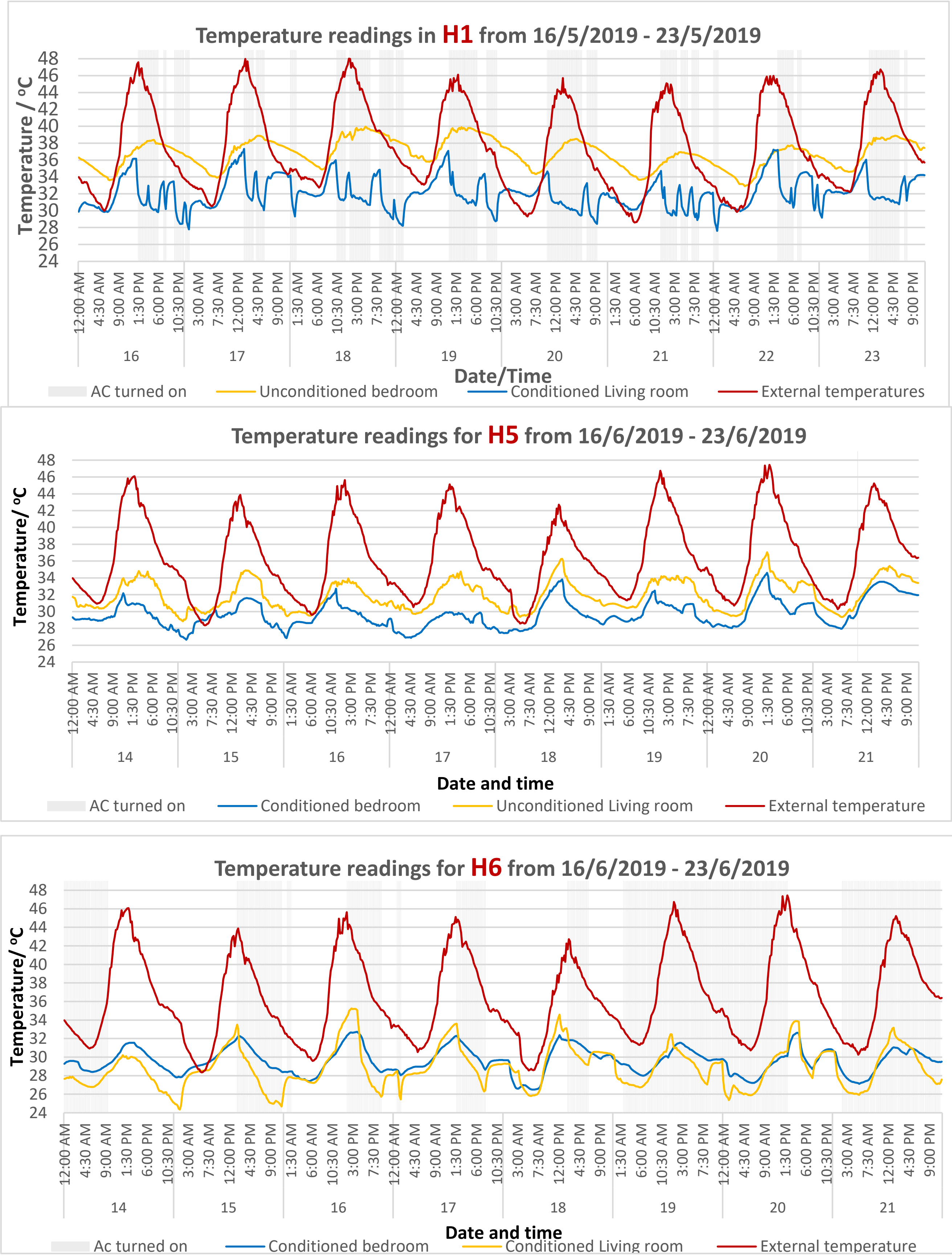


*Figure 7 Temperature variations for H1, H5 and H6*

The occupants in H1 have a budget that limits their use of the evaporative cooler to nine hours. They chose to use the AC during the day and sleep outdoors at night. There are three users who occupy the living room and are at home during different times of the day which is why the AC use in H1 shows frequent turning on and off of the AC as people enter and leave the room. These factors resulted in an irregular temperature pattern within the space. It took 8 hours for the air-conditioned living room to become as hot as the unconditioned bedroom when the AC was turned off on the 17$^{th}$ of May. The occupants complained the bedroom is too hot, so they only use it for storage. The daytime temperatures in the bedroom range between 32$^{o}$C -41$^{o}$C.

Occupants in H5 positioned the evaporative cooler opposite to the door and kept it open in order to use it for both spaces. This is clearly reflected in the readings as both spaces follow the same pattern with the bedroom being colder as the cooler was located there. It also compromised the ability to use the unconditioned space as a reference. The occupant said that the AC was usually turned on from midnight till 6-9pm the next day and only turned off for 6-8 hours per day. Temperatures ranged from 26.6$^{o}$C-34.8$^{o}$C in the bedroom and 28$^{o}$C-37$^{o}$C in the living room. The occupants spend most of their time in the living room because the bedroom was too humid at times. The occupants said that they

In H6, both the living room and bedroom have evaporative coolers. The bedroom is made of stone and the living room is made of 20cm thick brick. Temperatures ranged between 25.1$^{o}$C-33.2$^{o}$C in the bedroom and 24.3$^{o}$C-36.1$^{o}$C in the living room. The readings show the spaces share similar thermal patterns despite the difference in construction with the mean temperature being 29.2$^{o}$C in the bedroom and 28.9$^{o}$C in the living room. The AC was turned on average for six hours/day in the bedroom and 12 hours/day in the living room. This coincides with observations that the living room is used both day and night while the bedroom was only used at night.

All 3 houses left the door open and frequently turned the AC on/off to release moisture built up from the evaporative coolers. It is observed that turning the AC on cooled the spaces slowly reaching up to 6K temperature difference in 6 hours. However, when turned off the temperatures didn't suddenly increase, which could be because of the moist air still lingering in the space. Another reason could be because the evaporative cooler didn't cause a large drop in temperature compared to the outdoors. The smaller temperature difference ($\Delta T$) means that the rate of heat entering the building is less which slows internal temperature rise. When the AC was turned on all day (as in H6 on the 19$^{th}$) the temperature rose and fell with the external temperature rather than keep declining with prolonged use. H1 used the AC during the day while H5 and H6 used it all day whenever they were home. Only H1 used the yard at night to sleep due to economic restrictions. H5 used to always spend their evenings and nights outdoors to socialize and sleep when the multi-generation family lived in the house. However, since modern life dictated each nuclear family move to a separate house, only 4 occupants were left, so they no longer see the need to sleep outdoors. H6 does not use the yard even during power cuts because a high-rise building built recently nearby invades their privacy. H5 and H6 emphasize the impact of social drivers on environmental decisions.

**Modern Group:**

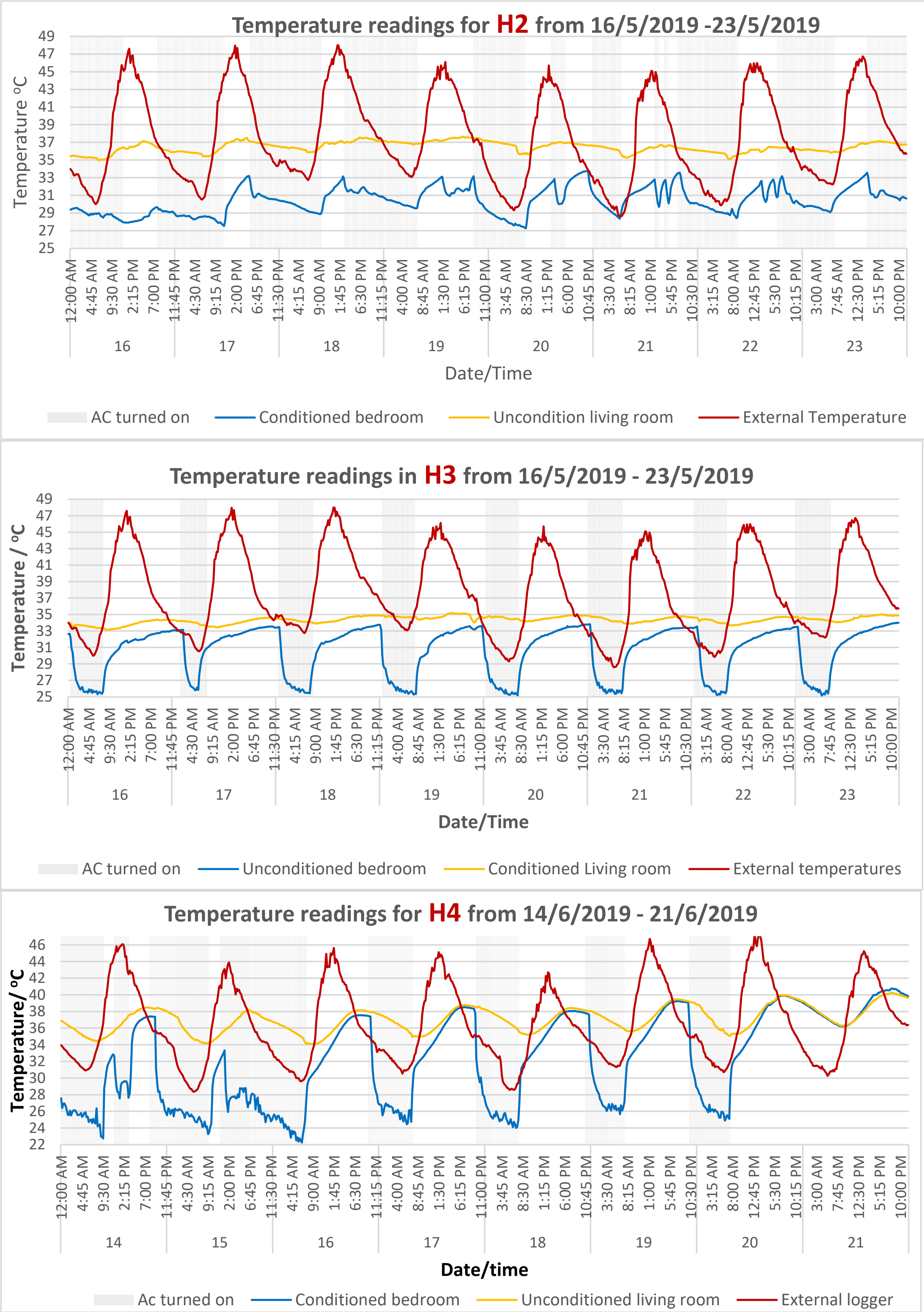


Figure 8 Temperature variation for H2 from 16/5/2019 -23/5/2019

The occupants in H2 turned on the AC and fan whenever they were in the bedroom with an average of 14 hours per day. The set point was 27°C which would explain why it was turned on for so many hours. This kept the indoor temperatures between 27°C-33°C which is lower than the living room's temperature which was between 35°C-37°C.

The occupant in H3 turned the split unit on at the same time every night from 12am – 8am, including weekends, this is reflected in the regular pattern depicted. The living room in H3 was the only unconditioned space in the 6 monitored houses where occupants were satisfied with just a fan. The temperatures ranged between 24°C-35.4°C in the bedroom and 31°C-35.8°C in the living room. They set the split unit AC at 25°C. The occupants in this house expressed satisfaction with their thermal environment.

In H4, the occupants used the lowest setting possible 18°C as their set point. Temperatures ranged from 22.1°C-40.7°C in the bedroom and from 30.5°C-40.2°C in the living room. The occupants have mentioned that guests always complain the living room is too hot. June 15$^{th}$ was a weekend and the AC was turned on for 22 hours because of how fast the room heats up.

Looking at the temperature drops in figure 8 shows that the split units achieved up to 16k temperature difference very quickly. However, H4 kept that coolth for only 5 hours while H3 kept it for 16 hours before the temperatures reached the same as the unconditioned spaces. This highlights the impact of the building fabric. Turning the split units off had a stronger immediate impact on internal temperature rise compared to evaporative coolers. This is evident in the sharp vertical temperature rise in all 3 houses in the first hour after the AC is turned off. This could be because of the higher temperature difference the split units reach compared to evaporative coolers which speeds up the heat infiltration rates. This means that the lower the temperature the split unit is set on, the more energy it must consume, not only to cool the space, but to also mask the increased heat infiltration caused by the larger temperature difference.

All 3 unconditioned living rooms in the modern group were rarely used and none of the occupants use the yard. H2 complained that it was due to privacy issues from the surrounding multi-story buildings. H3 said they live a modern lifestyle that does not include staying outdoors and that they felt their house was cool even during power cuts. H4 did not have access to the yard as they are renting unlike the other tenant on the floor who is related to the family. H5 explained that because of this, during power cuts, she only has access to a small balcony and frequently stays in the car to use the AC, because her baby cannot tolerate the 40°C temperature indoors. This highlights the impact of social norms on the building and emphasizes the difference between apartment houses that are built as a vertical extension for the same family compared to commercial apartment houses where tenants are not related.

### 3.1.3. Temperature distribution throughout the monitoring period

Table 1 Summary of the measured performance from monitored houses' (May and June 2019), the grey rows are NV spaces

| | Internal temperatures | | | | Percentage of hours above certain degrees/ % | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Min /°C | Max /°C | Mean /°C | Standard deviation | < 28 /°C | 28-30.9 /°C | 31-33.9 /°C | 34-36.9 /°C | 37-39.9 /°C | >40 /°C |
| H1-B | 32.1 | 41.9 | 36.7 | 1.7 | 0 | 0 | 5.2 | 50.8 | 41.6 | 2.4 |
| H1-L | 27.3 | 41.2 | 32.5 | 2.1 | 0.4 | 23.4 | 56.1 | 17.2 | 1.78 | 1.1 |
| H2-B | 25.6 | 35.1 | 29.9 | 1.8 | 14.6 | 57.5 | 27 | 0.8 | 0 | 0.1 |
| H2-L | 31.2 | 37.8 | 35 | 1.7 | 0 | 0 | 31 | 58.9 | 10 | 0.1 |
| H3-B | 24 | 34.8 | 30.9 | 3 | 23 | 14 | 55.2 | 7.8 | 0 | 0 |
| H3-L | 33 | 35.9 | 34.6 | 0.6 | 0 | 0 | 18.8 | 81.2 | 0 | 0 |
| H4-B | 22.1 | 40.7 | 33.7 | 4.7 | 20.2 | 6.2 | 11.8 | 32.1 | 27.8 | 1.8 |
| H4-L | 30.5 | 40.2 | 36.6 | 1.6 | 0 | 0.6 | 2.6 | 54.3 | 42 | 0.5 |
| H5-B | 26.7 | 34.8 | 30.3 | 1.7 | 8.3 | 59.5 | 30.4 | 11.8 | 0 | 0 |
| H5-L | 28.1 | 37.1 | 31.8 | 1.8 | 0 | 37.4 | 48 | 14.1 | 0.03 | 0 |
| H6-B | 25.1 | 33.3 | 29.2 | 1.6 | 23.3 | 60.6 | 16.1 | 0 | 0 | 0 |
| H6-L | 24.3 | 36.1 | 28.9 | 2.1 | 37.4 | 43.9 | 17.6 | 0.8 | 0 | 0 |

Table 2 shows that the mean temperature in NV spaces was between 34.6-36.7°C except in H5-L which benefited from the cool air escaping from the bedroom with a mean temperature of 31.8°C. which explains why it is also the only NV space that was regularly used by its occupants. Comparing the different NV spaces helps evaluate how the building fabric is performing without mechanical aid (except for fans). The standard deviation in H4-B was the highest at 4.7, this is due to wide range of temperatures inside the space that range from 22.1-40.7°C. This shows that the space has very poor heat insulation. The lowest mean temperatures were 28.9°C and 29.2°C in H6-B and H6-L respectively. Even though it seems the two spaces function similarly because of the similar temperatures, it is known that these adjacent spaces have the same evaporative cooler that was turned on for only six hours in H6-B, compared to 12 hours in H6-L. Therefore, it can be deduced that the stone walls preserved the coolth better than the 20cm brick walls.

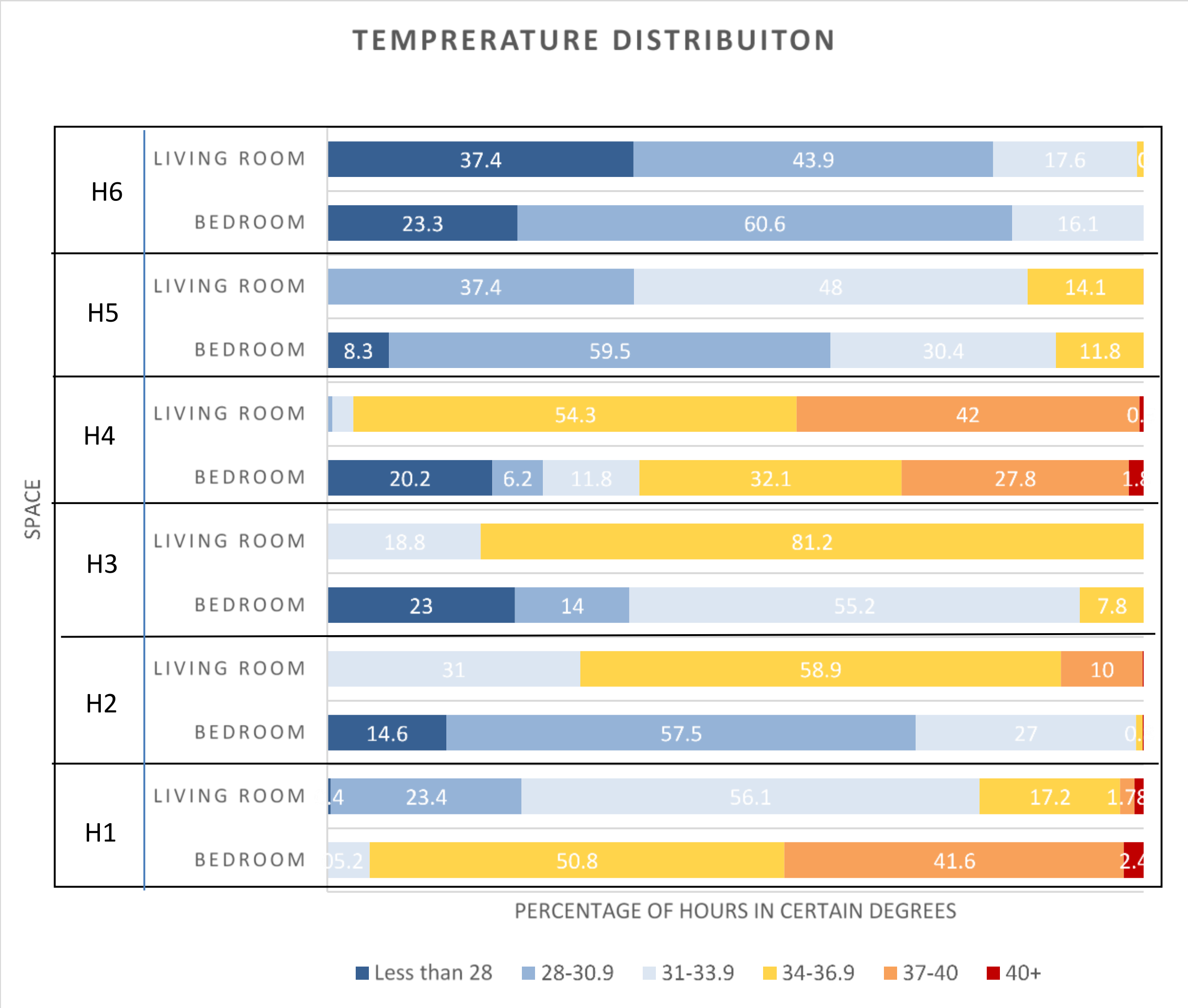


Figure 9 Temperature distribution in the 6 monitored houses, The blues are within the comfort range (up to 34 °C) and the oranges are outside the comfort range

Figure 9 shows that H5 and H6 had the highest percentage of temperature readings below 34°C. NV spaces in H1, H2 and H3 had only 5.2-31% of temperatures below 34°C compared to 79.9%-99.1% in the AC spaces. The hottest house was H4 with only 38.2% of readings below 34°c in H4-B and 3.2% in H4-L.

### 3.1.4. Adaptive thermal comfort

The weather station in Khartoum airport was used to calculate the daily running mean during May and June. The outdoor running mean in Khartoum is higher than the range limits in all three comfort standards BSEN 15251, Toe (2013) and Indraganti (2014). Therefore, to estimate occupants' thermal comfort outside these limits, Indraganti's upper and lower limits were extended (dotted line in figure 10) and capped with the horizontal line representing the 34.12°C which is the estimated maximum internal comfortable temperature regardless of the temperature outside.

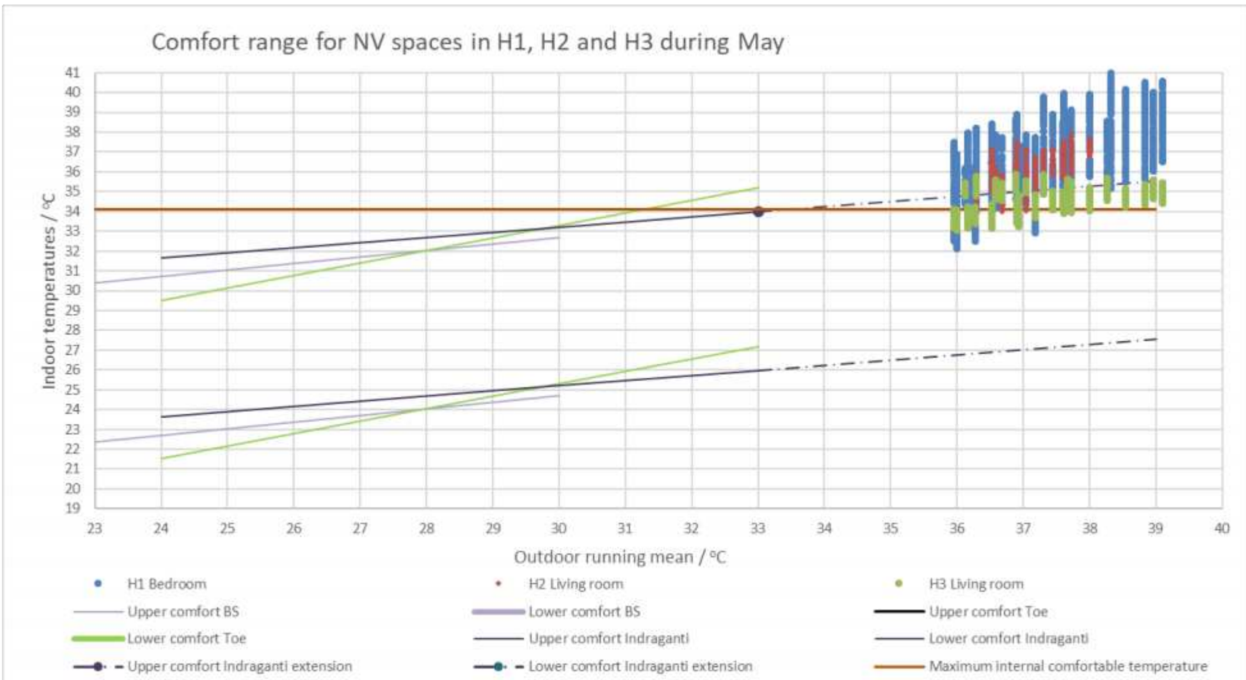


Figure 10 Comfort range for H1-B, H2-L and H3-L during May 2019 using the adaptive thermal comfort method

Only 1% of H2 living room fell within the comfort zone followed by 6.3% for H1-bedroom and 23% for H3-L. H1-B has a standard deviation of 2.1 compared to only 1.7 in H2-L. This means the internal temperatures have a larger diurnal swing which although heats up rapidly during the day, it also cools quickly during the night. This explains why H1-B has more instances within the comfort range even though its mean temperature is higher than H2-L.

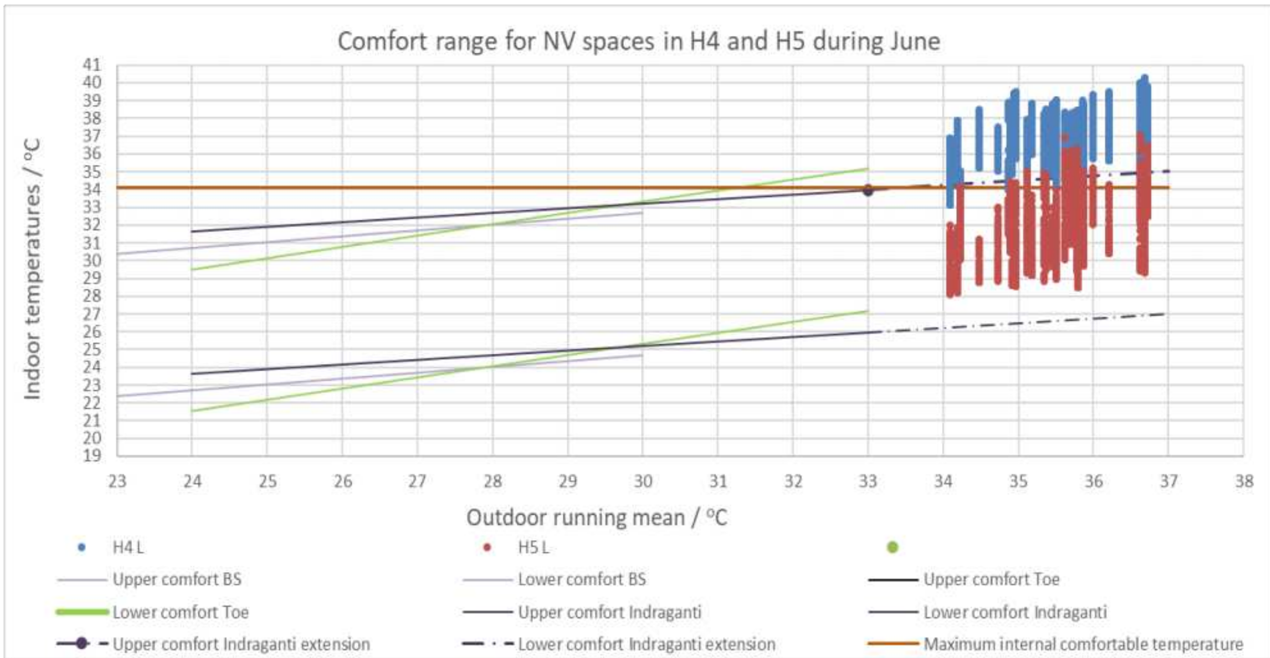


Figure 11 Comfort range for NV spaces in H4 and H5 during June

H6 has been excluded in this graph because both spaces had evaporative coolers. The graph shows that 87% of the H5-L temperature distribution was in the extended comfort zone compared to 3.8% of H4-L. This is due to the fact that the evaporative cooler in the bedroom leaks cool air into the space, not just due to the fabric.

### 3.1.5. Evaluation of AC zones using the adaptive thermal comfort method:

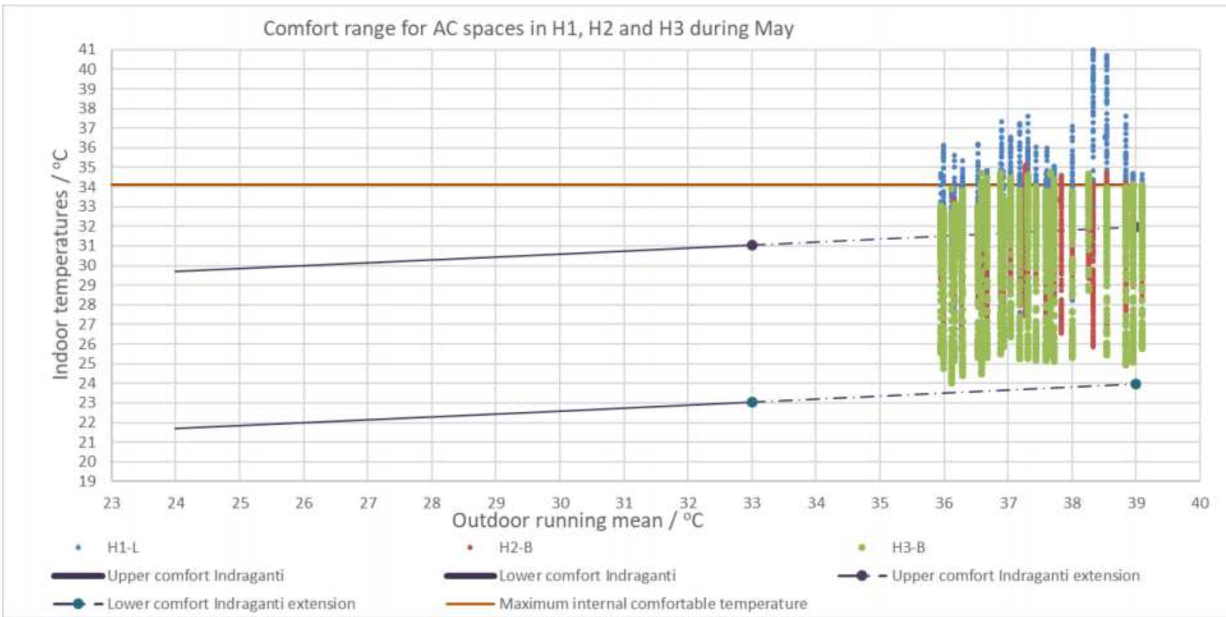


Figure 12 Comfort range for AC spaces in H1, H2 and H3 during May

Though the adaptive model is used for NV spaces, Indraganti developed an equation for AC zones as well. Figure 12 shows that the temperature was within the comfort zone for H1-L for only 37.4% of the time, followed by 43.2% in H3-B and 81% in H2-B. H3 performed better than H2 in the NV spaces because even though they share the same roof type the walls in H3 are 10cm thicker. H3 turns on the AC for 14 hours though, compared to just eight hours in H2 which is probably why H3 performed better in the AC zones. It could be speculated that H1 performs poorly because it is very leaky and all the coolth leaks through the windows and doors or because their evaporative cooler is not working properly.

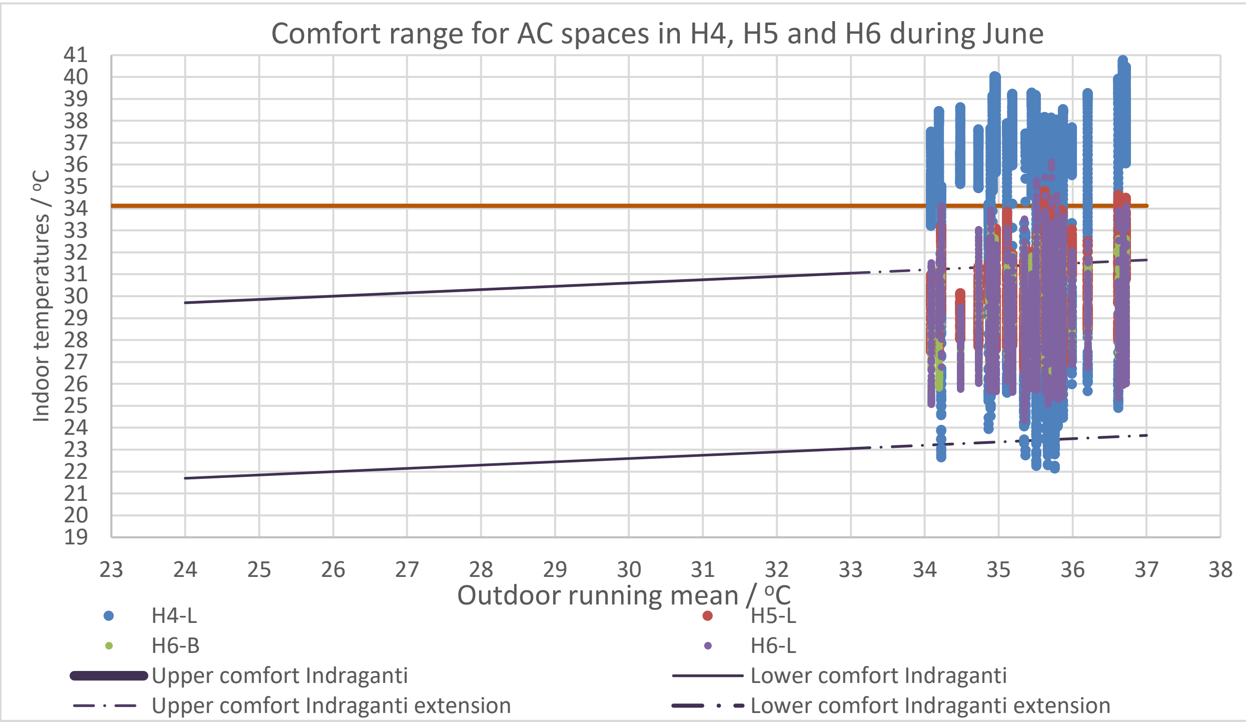


Figure 13 Comfort range for AC spaces in H4, H5 and H6 during June

Figure 13 shows that the temperature readings in H4 were in the comfortable range for only 27.1% of the monitored period followed by 74.2% in H5, 85.5% in H6-L and 89.6% for H6-B. The absence of occupants on H4 for several days meant the AC was not turned on for those days which explains why only 27.1% of the readings are within the comfort range, but the house still performs very poorly as it quickly heats up when the AC was turned off.

### 3.1.6. Analysis

The analysis of the thermal performance in the six houses show that NV spaces in Khartoum during the summer are very uncomfortable regardless of their construction. Occupants rarely use them because of this. However, when factoring the AC, two patterns emerged. The first pattern emerges in well-sealed multi story houses with split units. The split units created a sharp drop in temperatures followed by an increase in temperatures once the AC was turned off. This increase was gradual in brick houses and rapid in cement block houses. This emphasizes that even though installing AC units is inevitable to achieve thermal comfort in Sudan, improving the fabric has a drastic impact on reducing usage time. The second pattern was prevalent in courtyard houses that were leaky and had evaporative coolers. Evaporative coolers had to be turned on for longer periods as they cooled the spaces more slowly and users kept the doors open to reduce humidity levels which also caused the cool air to escape. This excess moisture made occupants uncomfortable in H5 even though the readings showed the spaces were supposed to be comfortable 74%-87% of the time.

In terms of performance, **Error! Reference source not found.** shows that H1, H3 and H4 were the least comfortable, even though the occupant in H4 expressed satisfaction with the space. It also shows that the stone walls in H6-B provided 85% comfortable temperatures despite only having the AC on for only six hours.

Table 2 Thermal performance comparison of AC spaces in the houses monitored

| | Services | Behavior | Building | | | Thermal performance |
|---|---|---|---|---|---|---|
| Space | AC type | Number of hours turned on | Wall type | Roof type | No. of floors | Percent of time comfortable |
| H1-L | Evaporative cooler | 9 | 40cm Brick/Mud | Traditional | 1 | 37.4 |
| H2-B | Split unit | 14 | 20cm Brick | Concrete | 3 | 81 |
| H3-B | Split unit | 8 | 30cm Brick | Concrete | 2 | 43.2 |
| H4-B | Split unit | 11 | 20cm Concrete block | Concrete | 2 | 27.1 |
| H5-B | Evaporative cooler | 18 | 40cm Brick | Corrugated metal w/false ceiling | 1 | 74.2 |
| H6-B | Evaporative cooler | 6 | 40cm Stone | Corrugated metal w/false ceiling | 1 | 85.5 |
| H6-L | Evaporative cooler | 12 | 20cm Brick | Corrugated metal w/false ceiling | 1 | 89.6 |

### 3.1.7. Conclusions:

Houses in Khartoum have a major thermal comfort problem. NV spaces were comfortable for only 1%-23% of the time. Which is why, in the past, people in Khartoum used to spend a large portion of their time outdoors. Modernism introduced the AC, which provided a more convenient solution to the high indoor temperatures. Thus, using an AC has become inevitable, however, reducing the number of hours its used is possible. This can be achieved with several different approaches.

Firstly, the building layout and design needs to adapt to the increasing density in Khartoum. The lack of space was the main contributor to the lack of verandahs and trees. Therefore, there is a need to find alternative methods to shade buildings without consuming too much space. Shading of the yard could encourage people to return to spending more time outdoors. The frequent and irregular power cuts mean that providing a cool external space is essential and not a luxury. Balconies need to be larger to allow users to sleep far away from the hot building walls. They also need to be covered with nets to protect from mosquitos. This is because these two factors were the largest deterrent to sleeping outdoors.

Secondly, adaptive behaviors should be encouraged as a first response to feeling hot rather than turning the AC on. For example, awareness campaigns could show the public that they could open the windows during the evening then close them and turn the AC on at night. This could reduce the cooling load on the AC and allow for a higher set point.

Finally, the type of AC installed in a building impacts the temperature patterns inside the space because split units cause a faster drop in temperatures compared to evaporative coolers, which is why they were preferred in bedrooms. Evaporative coolers were favored with people who had lower budgets which indicates that if more income becomes available, more people will install the colder and more energy intensive split units. This further emphasizes that instead of trying to eliminate AC use, it is more efficient for future designs to focus on optimizing it. In the monitored houses, AC spaces were comfortable for 27.1%-89.6% of the time. Split units and evaporative coolers were on both sides of this spectrum. This means that you cannot say that one type is more comfortable than the other, but rather that the environment they are in impacts their performance. More research needs to be done to deduce the best design practices for each AC type in order to improve their efficiency. For example, in evaporative coolers, finding a way to expel excess moisture without losing the cool air could solve the moisture build up problem. For split units on the other hand, it's more important to prevent temperatures from rapidly increasing after the AC is turned off. For both types, a fabric first approach can also reduce the amount of heat entering the building thus reducing the cooling load.

This study concludes that because people's behaviors and expectations in Khartoum have changed, the buildings need to change as well in order to adapt to this new lifestyle.

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# Adaptive model and the adaptive mechanisms for thermal comfort in Japanese offices

**Hom B. Rijal[1], Michael A. Humphreys[2] and J. Fergus Nicol[3]**

[1] Department of Restoration Ecology & Built Environment, Tokyo City University, Japan, rijal@tcu.ac.jp;
[2] Centre for Religion and Culture, Regent's Park College, University of Oxford, UK, mahumphreys4@gmail.com
[3] Department of Architecture, Oxford Brookes University, UK, jfnicol@brookes.ac.uk

**Abstract:** To quantify seasonal differences of comfort temperature, to develop an adaptive model, and to explore the adaptive mechanisms in offices in the Kanto region of Japan, we conducted monthly transverse and daily longitudinal surveys of the occupants, and measured the thermal environment in 23 office buildings. The thermal comfort and occupant behaviour surveys, together with the measurements, took place over a period of more than a year. We collected some 7297 thermal comfort votes. The data show that the residents were highly satisfied with the thermal environment in their offices, and they adapted well to the prevailing thermal conditions, even when the outdoor temperature had a large seasonal variation. By analysing the relationship between indoor and outdoor temperature, an adaptive model for offices was developed for the prediction and control indoor temperature. This adaptive model is strongly supported by the various adaptive actions reported by the office workers.

**Keywords:** Office building; Field survey; Comfort temperature; Adaptive model, Occupant behaviour

## 1. Introduction

Adaptive thermal comfort depends on behavioural, physiological and psychological adaptations (Brager and deDear 1998, Humphreys and Nicol 1998). Office workers use a variety of 'adaptive opportunities' to regulate their indoor thermal environment and secure their thermal comfort. We explored these adaptive mechanisms, and show that they give robust support to the adaptive model set out in this paper.

We previously proposed an adaptive model for Japanese offices (Rijal et al. 2017). The regression coefficient was 0.21, significantly lower than the coefficients in the CEN (0.33) and ASHRAE (0.31) standards. The coefficients also were lower than those found for Japanese dwellings (0.48) (Rijal et al 2019a). We also confirmed that the adaptive model was strongly supported by the occupants' behaviour both in dwellings and in offices (Rijal et al. 2019a, 2019b). However due to the small quantity of data from Japanese office buildings, there was a need for further investigation and confirmation.

In this study the thermal measurement, thermal comfort and occupant behaviour surveys have been conducted over more than two years in 23 office buildings in the Tokyo and Yokohama areas of Japan. The objectives are to explore seasonal differences in the comfort temperature and perhaps develop a more solidly founded adaptive model for Japanese offices, and to explain the adaptive behaviours.

## 2. Methods

### 2.1. Investigated buildings

For this paper we have used two surveys. In survey 1, 11 office buildings were investigated in the Tokyo and Kanagawa areas of Japan from August 2014 to October 2015 (Rijal et al. 2017, Rijal et al. 2019b). In survey 2, 16 office buildings were investigated in the same areas from August 2017 to November 2018. These contemporary buildings which we got permission for the field survey are broadly typical of those available in the investigated areas (Figure 1). The numbers of HVAC and mixed mode buildings are 6 and 17 respectively (four mixed mode buildings were in both surveys). The mixed mode buildings are of the change-over type (CBE, 2016). So, the building can be free running mode or air-conditioning mode by season or day or time of day. All mixed mode buildings have openable windows, and most of them (B4 ~ B8) are university office buildings. Generally, people open and close windows in spring and autumn to control the room temperature. In summer people close the windows and use cooling. In winter they close the windows and use heating. Two of the HVAC buildings have both manual and automatic natural ventilation openings. The surveyed floors were selected on the availability of the occupants to take part in the surveys, and on permission given by the building managers.

Figure 1. Example of the investigated buildings.

### 2.2. The measurements, thermal comfort survey and occupant behaviour survey

The indoor air temperature, globe temperature, relative humidity and air movement were measured 1.1m above floor level, away from direct sunlight, using a data logger. Outdoor air temperature and relative humidity were obtained from the nearest meteorological station.

The thermal comfort survey was conducted in Japanese. The thermal sensation scale used is shown in Table 1. We distributed a paper questionnaire for survey 1, while a web-based survey was used for survey 2. We conducted both transverse and longitudinal surveys but in this paper we analyse only the data from the transverse surveys.

Table 1. Scale used for the thermal comfort surveys

| No. | Modified thermal sensation vote (mTSV) |
|---|---|
| 1 | Very cold |
| 2 | Cold |
| 3 | Slightly cold |
| 4 | Neutral (neither hot nor cold) |
| 5 | Slightly hot |
| 6 | Hot |
| 7 | Very hot |

Transverse surveys were conducted one day each month by researchers visiting each building with measurement instruments and with questionnaires for the subjects. On each visit, one set of responses was collected from each subject. The instruments were set up on an office table, and questionnaire responses were requested from subjects seated near the instruments (within 2-3 metres). While people were responding to the questionnaire, the researcher recorded the common environmental controls and the thermal environmental data for them. After completing the data collection for that group, the instruments were moved to the next group, and so on. This process was repeated for all groups each month. A few people did not provide responses because of their busy schedule, and some were not in the office at the time of the visit. Window opening, heating use and cooling use were recorded in binary form at the time of completing the questionnaire (0 = window closed or heating/cooling off, 1 = window open or heating/cooling on). We collected 4,660 votes in survey 1 and 2637 votes in survey 2.

**2.3. Calculation methods**

**2.3.1 Griffiths method**

The comfort temperature is estimated by using the Griffiths' method (Griffiths 1990, Nicol et al. 1994, Rijal et al. 2008, Humphreys et al. 2013, Rijal et al. 2019a).

$$T_c = T_g + (4 - C) / a \tag{1}$$

$T_c$: The comfort temperature by Griffiths' method (°C); $T_g$: Globe temperature (°C); C: Thermal sensation vote; a: The rate of change of thermal sensation with room temperature.

When the thermal sensation vote is 4 (neutral) the comfort temperature equals the globe temperature, otherwise it differs from it. The comfort temperature was estimated using a value of 0.50 for the rate of change (a).

**2.3.2 Running mean outdoor temperature**

The exponential running mean outdoor temperature is calculated using the following equation (McCartney & Nicol, 2002).

$$T_{rm} = \alpha T_{rm-1} + (1-\alpha) T_{od-1} \tag{2}$$

Where, $T_{rm-1}$ is the running mean outdoor temperature for the previous day (°C), $T_{od-1}$ is the daily mean outdoor temperature for the previous day (°C). So, if the running mean has been calculated (or assumed) for one day, then it can be readily calculated for the next day, and so on. α is a constant between the 0 and 1 which defines the speed at which the exponential running mean responds to the outdoor air temperature. ASHRAE standard (2013) recommends using a value of α between of 0.60 to 0.90. The correlation between comfort temperature and outdoor temperature is almost constant in this range (McCartney & Nicol, 2002), so the value chosen is not critical. We have chosen α to be 0.8, as evaluated by McCartney & Nicol and as used in the derivation of the CEN standard (CEN 2007).

**2.3.3 Logistic regression analysis**

To predict the proportion of windows open, heating and cooling use, logistic regression analysis was conducted (see, for example, Nicol & Humphreys 2004). The relationship between the probability (p) of that control being used, and the outdoor temperature ($T_o$) is of the form:

$$\text{logit}(p) = \log \{p/(1-p)\} = bT_o + c \tag{3}$$

$$p = \exp^{(bT_o + c)}/\{1 + \exp^{(bT_o + c)}\} \tag{4}$$

where exp (exponential function) is the base of the natural logarithm, b is the regression coefficient for $T_o$, and c the constant in the regression equation.

## 3. Results and discussions

Data was divided into three groups for analysis. If heating was in use at the time of the survey visit, the data were classified as being in the heating mode (HT). If cooling was in use at the time of the visit, the data were classified as being in the cooling mode (CL). If neither heating nor cooling were in use, the data were classified as being in the free-running mode (FR). The CL and HT modes are distinct groups of data (generally CL occurs in summer and HT in winter), and they need to be analysed separately. This classification differs from that used in the CIBSE Guide (CIBSE, 2006), and in ASHRAE Standard 55. In CIBSE guide, the data was combined for the heating and cooling mode. In ASHRAE standard, the building was classified as the naturally ventilated building.

### 3.1. Outdoor and indoor temperature

The Köppen climate classification of the investigated areas is the humid subtropical climate (Cfa). The mean outdoor air temperatures at the time of the survey-visit for survey 1 were 20.7 °C, 10.4 °C and 24.9 °C and for FR, HT and CL modes respectively. The values were the same for survey 2.

As shown in the Figure 2 the indoor globe temperature correlates strongly with the indoor air temperature in both surveys, and so the results can be presented using the globe temperature alone. The mean globe temperatures during the voting for survey 1 were 25.0 °C, 23.8 °C and 25.9 °C for FR, HT and CL modes which are 0.1°C, 0.2 °C and 0.7°C lower than survey 2. The Japanese government recommended that indoor temperature should be 20 °C in winter (HT) and 28 °C in summer (CL) respectively (Nakashima, 2013) (In 2005, they recommended the temperature setting and later they recommended the indoor temperature). The results show that the mean indoor temperatures during heating and cooling were quite different from those recommended. The seasonal range of the indoor temperature was quite small, while there was a wide seasonal range of outdoor temperature.

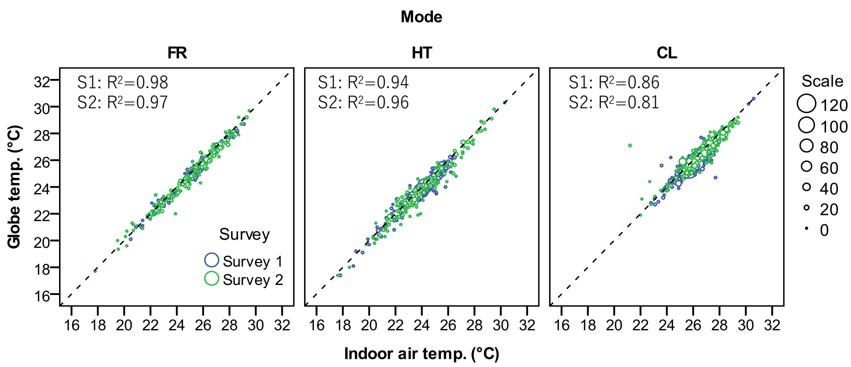


Figure 2. Relation between the globe temperature and indoor air temperature.

### 3.2. Adaptive thermal comfort

#### 3.2.1 Distribution of thermal sensation

The percentage of thermal sensation is shown in the Figure 3. The distributions were much the same in both surveys. Occupants sometimes felt hot (greater than 5) in CL mode and sometimes felt cold (less than 3) in HT mode, despite the use of heating or cooling. Perhaps because of the small monthly variations of temperature in the offices, and the tendency of people to adapt to the temperatures they encounter, there are many '4 neutral' votes in each mode (55 ~ 58%). It is conventional to consider as comfortable responses that fall in categories 3, 4 and 5. These percentages are very high (95%). Thus it can be said that occupants were generally satisfied in the thermal environment of their offices.

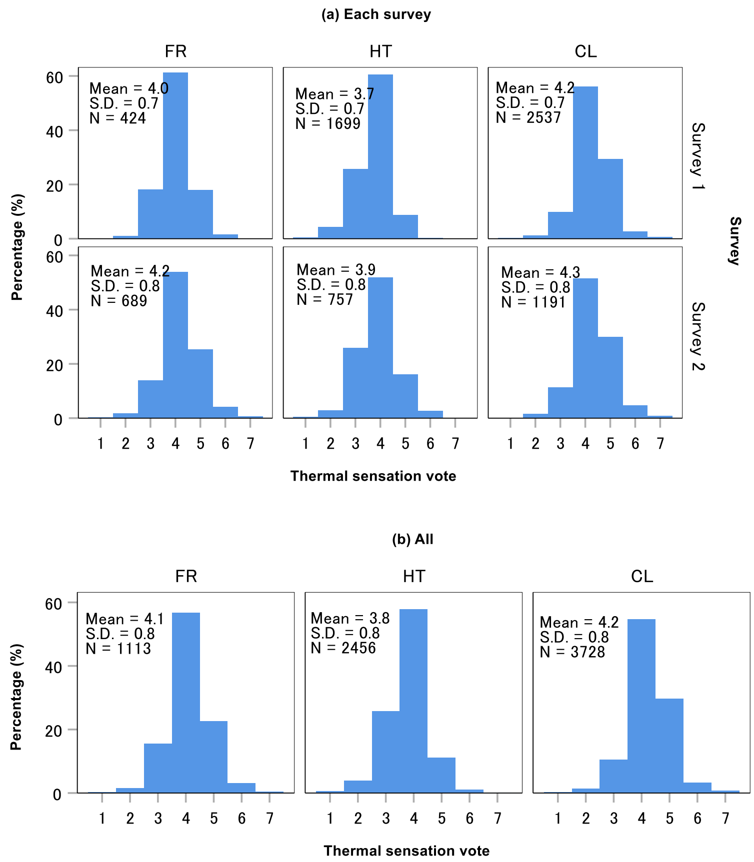


Figure 3. Percentage of thermal sensation vote

### 3.2.2 Comfort temperature

Figure 4 shows the percentage of comfort temperature as calculated by the Griffiths' method. The distributions for the two surveys are similar. We calculated the comfort temperature for each thermal sensation vote. Each value is of low accuracy, but is unbiased. (The low accuracy of the individual values contributes to the quite large standard deviations of the distributions. Nevertheless, the standard errors of the means on Figure 4 are all less than 0.1 K.) The mean comfort temperature obtained from both surveys is 24.9°C (FR mode), 24.3°C (HT mode) and 25.6°C (CL mode) which are very similar to indoor globe temperature. We found that in these buildings the comfort-temperature was 4.3°C higher in HT mode and 2.4 °C lower in CL mode than the recommended values by Japanese government (Nakashima, 2013).

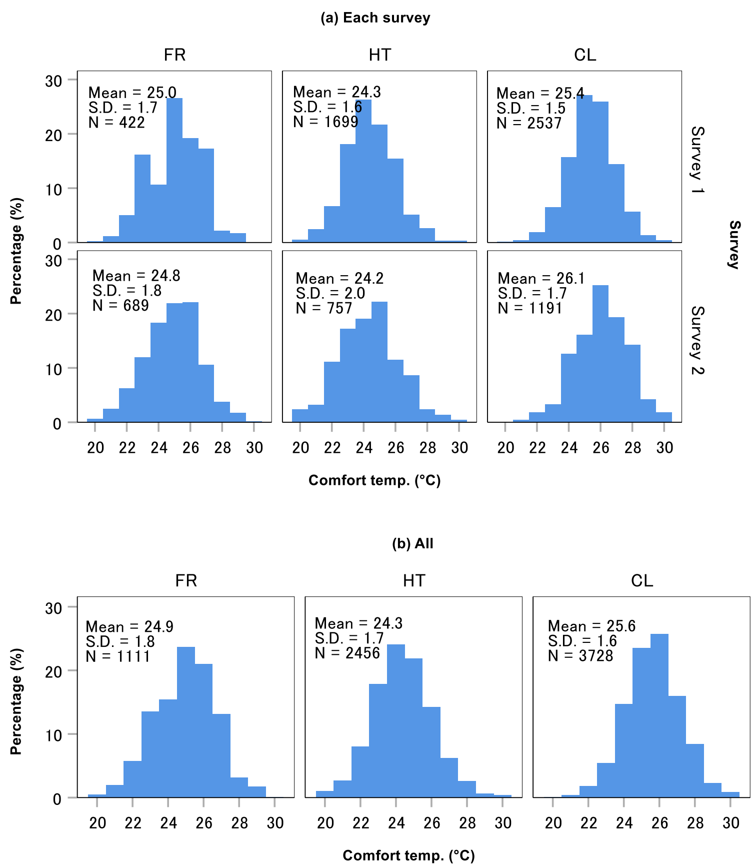


Figure 4. Percentage of comfort temperature

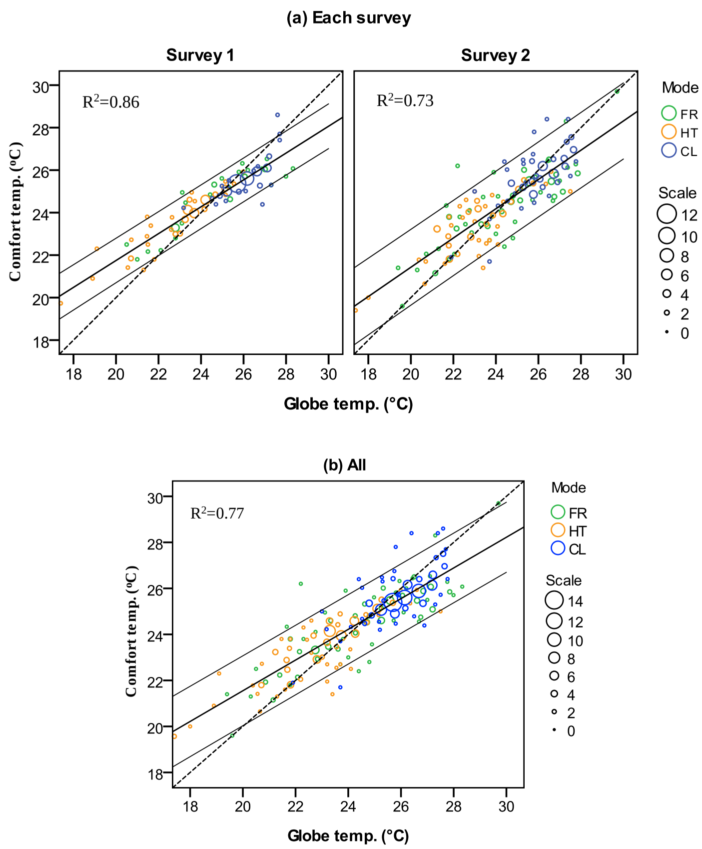


Figure 5. Relation between the comfort temperature and globe temperature. Each point indicates the monthly mean temperature.

The correlation between comfort temperature and globe temperature is quite high (Figure 5), showing that fundamentally the people had adapted to a large extent to the temperatures that were provided. Had more seasonal drift of indoor temperature been provided, it is likely that people would have adapted to it (see Humphreys, Nicol & Roaf (2016) chapter 27).

### 3.2.3 Monthly and seasonal differences in temperature

Figures 6 and 7 show the monthly and seasonal variation of the comfort temperature. The results are similar for both surveys. It is evident that the comfort temperature closely tracks the mean indoor globe temperature over the year, the difference between them being about 1K in any month or season. The comfort temperature and the indoor globe temperature both show rather little monthly and seasonal variation. The comfort temperature is 22.1 °C in January, 25.9 °C in August and September in FR mode. Thus the monthly variation of the mean comfort temperature is 3.8 K (Figure 6). The comfort temperature is 24.9 °C in spring, 25.7 °C in summer, 24.7 °C in autumn and 23.6 °C in winter in FR mode, and thus seasonal difference in comfort temperature is 2.1 °C (Figure 7). These seasonal variations are smaller than we had found for dwellings: 9.4 °C (Rijal et al. 2019a).

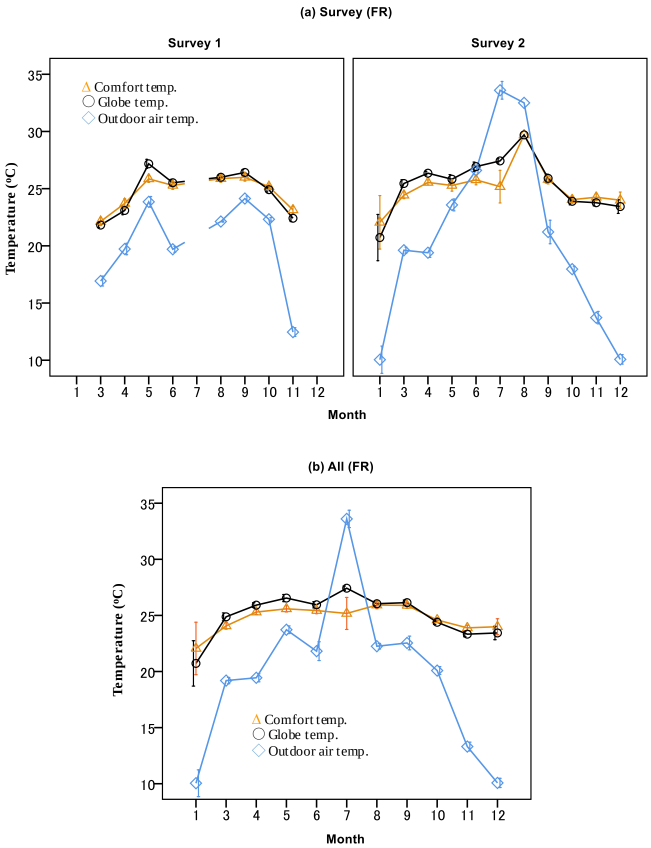


Figure 6. Monthly mean comfort temperatures and globe temperatures, with 95% confidence intervals. (The mean outdoor temperature is also shown.)

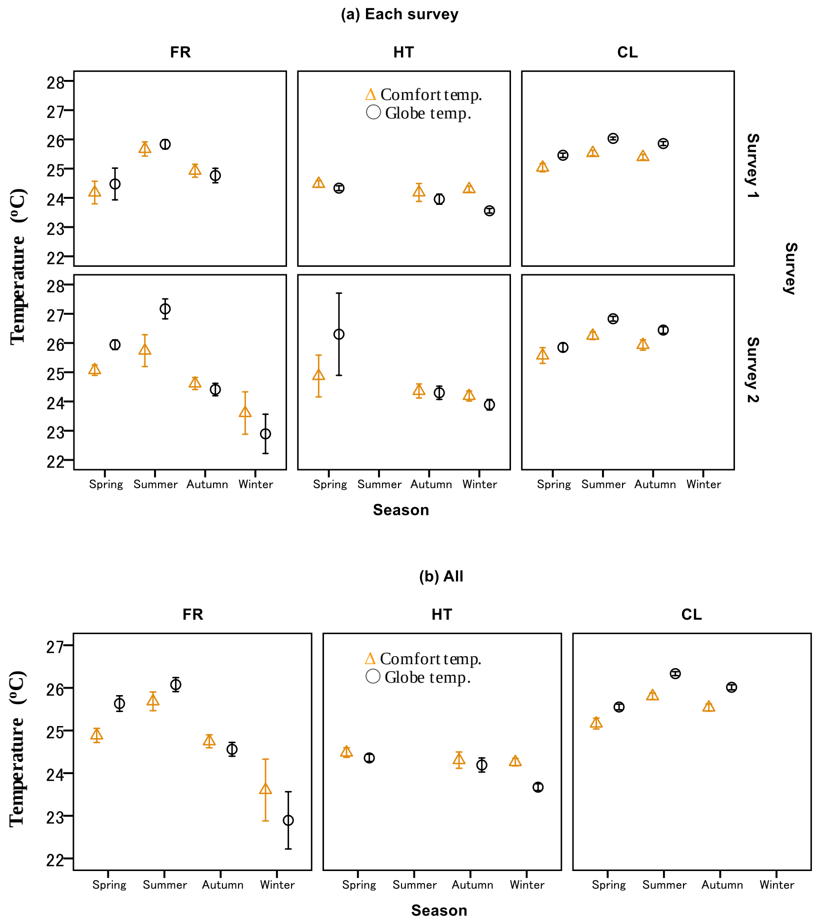


Figure 7. Seasonal variation of comfort temperature and globe temperature with 95 % confidence intervals.

### 3.2.4 The adaptive model

An adaptive model relates the indoor comfort temperature to the outdoor air temperature (Humphreys, 1978; Humphreys & Nicol, 1998; ASHRAE, 2004; CEN, 2007). Figure 8 shows the relation between the comfort temperature (calculated by the Griffiths' method) and the running mean outdoor temperature. However, the mean comfort temperatures in the HT and CL mode were not very different (see Figure 4), and thus we have combined them, as is done in the CIBSE guide. The regression equations are given below.

Survey 1

FR mode $T_c$=0.21$T_{rm}$+20.8 (n=422, $R^2$=0.42, S.E.=0.012, p<0.001) (5)

CL & HT mode $T_c$=0.07$T_{rm}$+23.9 (n=4,236, $R^2$=0.10, S.E.=0.003, p<0.001) (6)

Survey 2

FR mode $T_c$=0.15$T_{rm}$+22.5 (n=689, $R^2$=0.14, S.E.=0.014, p<0.001) (7)

CL & HT mode $T_c$=0.10$T_{rm}$+23.5 (n=1,948, $R^2$=0.20, S.E.=0.005, p<0.001) (8)

All

FR mode $T_c$=0.15$T_{rm}$+22.3 (n=1,111, $R^2$=0.21, S.E.=0.009, p<0.001) (9)

CL&HT mode $T_c$=0.10$T_{rm}$+23.5 (n=6,184, $R^2$=0.14, S.E.=0.003, p<0.001) (10)

n: Number of samples, $R^2$: Coefficient of determination, S.E.: Standard error of the regression coefficient, p: Significance level of regression coefficient.

We found broadly similar trends in both surveys. The relations are useful despite their low $R^2$ values, because the regression lines indicate a substantial rise in the temperature for comfort indoors with rising outdoor temperature, over the range for which heating or cooling is likely to be used.

The regression coefficient and the correlation coefficient in the FR mode are higher than in the HT and CL modes. As shown in Table 2, the regression coefficient is lower than that in the CEN standard (FR=0.33) and it is similar to the CIBSE guide (CL&HT=0.09). It is lower than found for Japanese dwellings (Rijal et al. 2013, 2019a).

It is probable that the low gradients which we find for these 'adaptive models' just reflect the small seasonal trends of the indoor temperatures in our sample of office buildings. 85% of data of this study is from the CL&HT mode, and thus we need to increase the sample size of the FR mode to obtain a reliable estimate. In view of the climatic variation across Japan, we also need to conduct the field survey in various parts of Japan.

The equations can be used to predict the indoor comfort temperature for these buildings. For example, when the running mean outdoor temperature is 25 °C in the equation (9), the comfort temperature would be 26.1 °C for the FR mode. Similarly, when the running mean outdoor temperature is 10 °C and 28 °C in the CL&HT mode (equation 10), the comfort temperature would be 24.5 °C and 26.3 °C respectively. The results indicate that the range of the mean comfort temperature for CL&HT mode is small – less than 2K – probably because the occupants adapted to the small seasonal variation of the temperature in these particular offices. (Had the government-recommended temperatures been provided, the occupants would perhaps have adapted to the summer or winter environment of the office without compromising comfort or productivity, but further surveys would be needed to explore the question.)

Table 2. Regression equations in this study and previous studies

| References | Buildings | Mode | Equation |
|---|---|---|---|
| Rijal et al. (2017) | Offices | FR | $T_c$=0.21$T_{rm}$+20.8 |
| | | CL&HT | $T_c$=0.07$T_{rm}$+23.9 |
| CIBSE (2006) | Offices | CL&HT | $T_c$=0.09$T_{rm}$+22.6 |
| CEN (2007) | Offices | FR | $T_c$=0.33$T_{rm}$+18.8 |
| ASHRAE (2004) | Offices | NV | $T_c$=0.31$T_{om}$+17.8 |
| Humphreys (1978) | All types | FR | $T_c$=0.534$T_{om}$+11.9 |
| Rijal et al. (2019a) | Dwellings | FR | $T_c$=0.480$T_{rm}$+14.4 |
| | | CL | $T_c$=0.180$T_{rm}$+22.1 |
| | | HT | $T_c$=0.193$T_{rm}$+18.3 |
| | | All | $T_c$=0.432$T_{rm}$+15.4 |
| Rijal et al. (2013) | Dwellings | FR | $T_c$=0.531$T_{rm}$+12.5 |
| | | CL | $T_c$=0.297$T_{rm}$+18.8 |
| | | HT | $T_c$=0.307$T_{rm}$+16.5 |

FR: Free running, CL: Cooling, HT: Hearing, NV: Naturally ventilated, $T_c$: Comfort temp. (°C), $T_{rm}$: Daily running mean outdoor air temp. (C), $T_{om}$: Monthly mean outdoor air temp. (°C).

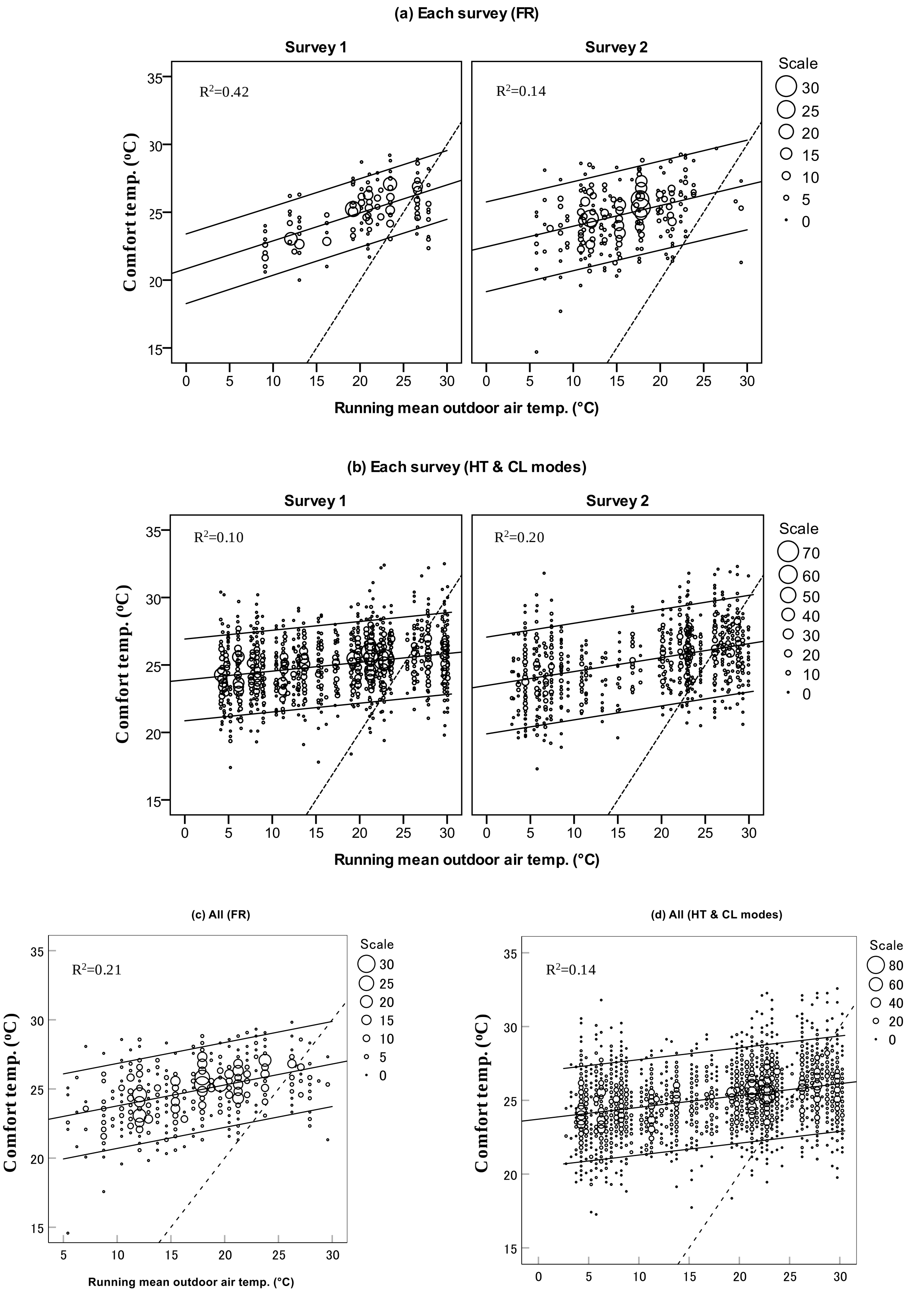


Figure 8. Relation between the comfort temperature and the running mean outdoor temperature (The dashed lines indicate equality of indoor comfort temperature and outdoor running mean temperature.)

### 3.3. Adaptive mechanisms

As we discussed in the previous section, the comfort temperature varies with the outdoor temperature. The reason might be that the people are adapting well in their offices using various behavioural, physiological and psychological adaptations (Brager & de Dear 1998, Humphreys & Nicol 1998). This section of the paper focuses on adaptive mechanisms the occupants used to regulate their thermal comfort.

#### 3.3.1 Window opening behaviour

The overall mean value of 'open window' for all data is 0.17 (n=2918). When we compared by building, the mean value ranged from 0.00 to 0.45. The mean window opening is 0.42 (n=949), 0.03 (n=944) and 0.07 (n=1025) for FR, HT and CL modes respectively. Interestingly, the mean window opening in UK office buildings was 0.70 in naturally ventilated (NV) mode and 0.04 in air conditioned (AC) mode (Rijal et al. 2007). The mean windows open in Pakistan office and commercial buildings was 0.33 in NV mode (Rijal et al. 2008). As the window opening is very low in the CL and HT modes, we shall limit the analysis to the FR mode.

We now derive equations that predict the window opening behaviour in these Japanese offices. Such predictions are needed for the thermal simulation of buildings. The following regression equations were obtained for all data in between the windows open and the outdoor air temperature:

Survey 1 $\quad \mathrm{logit}(p) = 0.507T_o\text{-}10.0 \quad (n = 399, R^{2*} = 0.27, S.E. = 0.059, p < 0.001)$ (11)

Survey 2 $\quad \mathrm{logit}(p) = 0.251T_o\text{-}6.4 \quad (n = 550, R^{2*} = 0.17, S.E. = 0.030, p < 0.001)$ (12)

All $\quad \mathrm{logit}(p) = 0.350T_o\text{-}7.6 \quad (n = 949, R^{2*} = 0.26, S.E. = 0.027, p < 0.001)$ (13)

where $R^{2*}$ is Cox and Snell $R^2$. The regression coefficient of the survey 1 is higher than that of survey 2. Surveys in Kyoto (Majima et al. 2007) and in the UK (Rijal et al. 2007) returned regression coefficients of 0.119 and 0.181 respectively, so the regression coefficient of this research is higher than previously found. Perhaps window opening behaviour varies widely from building to building, depending how easy it is to open window. As shown in the Figure 9, the proportion of the windows open rises as the outdoor temperature rises.

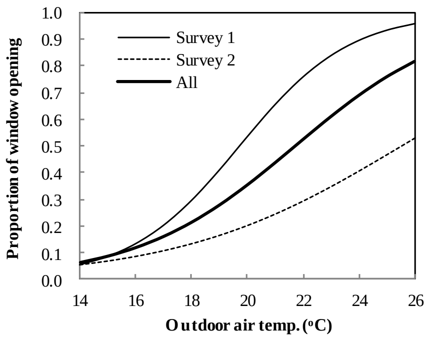


Figure 9. Relation between the window opening and outdoor air temperature

#### 3.3.2 Clothing adjustments

The mean clothing is 0.73 clo, 0.89 clo and 0.60 clo in FR, HT and CL modes respectively. The results show that people adjusted their clothing considerably in each mode. In order to predict the clothing insulation, regression analysis of the clothing insulation and outdoor air temperature was conducted. Figure 10 shows the relation between the clothing insulation and outdoor air temperature with the 95% confidence interval of the individual clo-values. The following regression equations were obtained between the clothing insulation ($I_{cl}$, clo) and outdoor air temperature.

FR

Survey 1 $I_{cl} = -0.030T_o + 1.2$ (n=419, $R^2$=0.27, S.E. = 0.002, $p<0.001$) (14)

Survey 2 $I_{cl} = -0.025T_o + 1.2$ (n=676, $R^2$=0.23, S.E. = 0.002, $p<0.001$) (15)

All $I_{cl} = -0.027T_o + 1.2$ (n=1095, $R^2$=0.27, S.E. = 0.001, $p<0.001$) (16)

HT & CL

Survey 1 $I_{cl} = -0.014T_o + 0.9$ (n=4180, $R^2$=0.30, S.E.<0.0001, $p<0.001$) (17)

Survey 2 $I_{cl} = -0.017T_o + 0.9$ (n=1922, $R^2$=0.44, S.E.<0.001, $p<0.001$) (18)

All $I_{cl} = -0.015T_o + 1.0$ (n=6102, $R^2$=0.35, S.E.<0.0001, $p<0.001$) (19)

We have found similar results for both surveys. The regression coefficients are negative for all equations. It shows that the clothing insulation decreases when outdoor air temperature is increased.

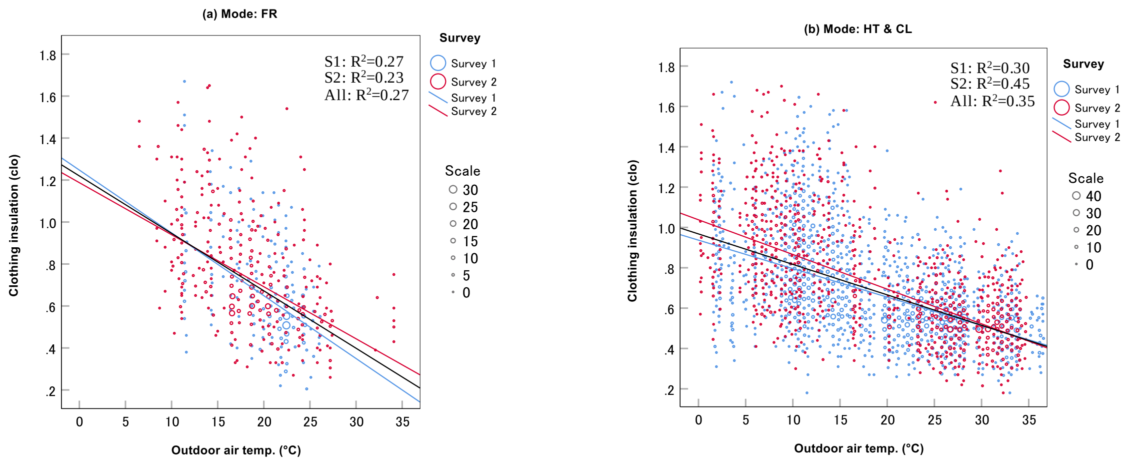


Figure 10. Relation between the clothing insulation and outdoor air temperature

### 3.3.3 Heating and cooling use

In this section we analyse heating and cooling use. These behaviours are needed for the thermal simulation of buildings. The following regression equations were obtained for heating use or cooling use and the outdoor air temperature:

Heating use

Survey 1 logit(p)=-0.839$T_o$+13.6 (n=1241, S.E.=0.055, $R^{2*}$=0.66, $p<0.001$) (20)

Survey 2 logit(p)=-0.497$T_o$+6.8 (n=1688, S.E.=0.028, $R^{2*}$=0.54, $p<0.001$) (21)

All logit(p)=-0.589$T_o$+8.8 (n=2929, S.E.=0.024, $R^{2*}$=0.59, $p<0.001$) (22)

Cooling use

Survey 1 logit(p)=0.359$T_o$-8.5 (n=1241, S.E.=0.024, $R^{2*}$=0.37, $p<0.001$) (23)

Survey 2 logit(p)=0.499$T_o$-11.7 (n=1698, S.E.=0.026, $R^{2*}$=0.59, $p<0.001$) (24)

All $\text{logit}(p)=0.437T_o-10.3$ (n=2939, S.E.=0.017, $R^{2*}$=0.52, p<0.001) (25)

The regression coefficient for heating use for survey 1 is higher than for survey 2. There is less difference between the coefficients for cooling use. These equations are presented in the Figure 11. The proportion of the heating use rises as the outdoor temperature decreases, and the proportion of the cooling use rises as the outdoor temperature increases.

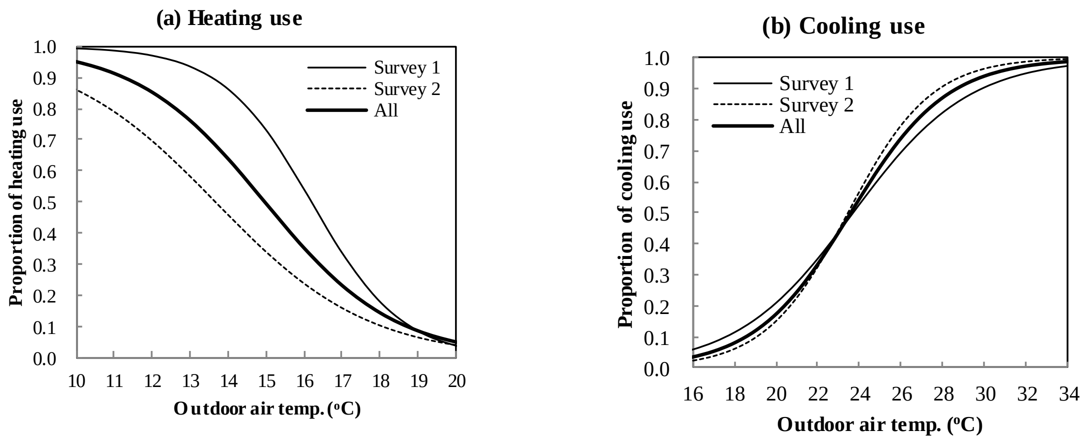


Figure 11. Relation between the heating use or cooling use and outdoor air temperature.

## 4. Discussion and conclusions

This research project has again demonstrated the power of human adaptation to provide comfortable conditions for the occupants of offices. People secured their comfort by choosing clothing suitable to the temperature, by opening or closing windows (if the building had openable windows), by turning heating on or off, and by switching on cooling when desired. The result of these processes ensured that the comfort temperature tracked the indoor temperature month by month throughout the year, so achieving a high level of thermal comfort, such that 95% of the subjective responses were within the central three categories of the scale (the 'comfort zone').

However, the results from the two surveys included in the project differed in some respects, although showing the same broad trends. In survey 1 the use of heating increased more steeply as the temperature fell (Figure 11), the window opening increased more steeply as the temperature rose (Figure 9), and the comfort temperature (in the free-running mode) rose more steeply as the outdoor temperature rose. These differences are not entirely unexpected, because adaptation rests on the interaction between the building and its occupants, and is further influenced by social constraints. But the differences mean that it is not possible to provide a single definite relation between, say, window opening and outdoor temperature. Relations of this kind are averages from the buildings included in the survey. This limits their usefulness for the thermal simulation of buildings.

We summarise the principal findings of these surveys of comfort and occupant behaviour in Tokyo and Kanagawa (Japan) as follows:

1. The occupants were highly satisfied with the thermal environment of their offices, as indicated by the high proportion of 'neutral' responses, and the large proportion of thermal sensation votes in the three central categories of the scale.
2. Cooling and window opening were increasingly used when the outdoor temperature rose above about 20°C and heating when the outdoor temperature dropped below 17°C. The average comfort temperature was found to be 25.6 °C when cooling was used, 24.3 °C when heating was used, and 24.9 °C when neither heating nor cooling were used (the Free Running mode). The comfort temperature for heating mode is surprisingly high.
3. The seasonal difference in comfort temperature in offices (2.1°C) is significantly less than had been found for Japanese dwellings (9.4°C). The comfort–temperatures tracked the concurrent mean indoor globe temperatures.
4. Adaptive models are given to estimate the probable comfort temperature from outdoor air temperature.
5. Behavioural adaptations (window opening, clothing adjustments, heating/cooling use) are related to the outdoor air temperature.

## 5. Acknowledgements

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# Post-occupancy evaluation of occupants' satisfaction with the indoor environment in five commercial buildings in Singapore

**Toby Cheung[1], Stefano Schiavon[2], Lindsay Graham[2], Kwok Wai Tham[3]**

[1] Berkeley Education Alliance for Research in Singapore (BEARS), Singapore, toby.cheung@bears-berkeley.sg;
[2] Centre for the Built Environment (CBE), University of California Berkeley, US, schiavon@berkeley.edu; lindsaytgraham@berkeley.edu;
[3] School of Design and Environment, National University of Singapore, Singapore, bdgtkw@nus.du.sg;

**Abstract:** Using a web-based survey tool, originally developed by the Centre for the Built Environment, we surveyed five air-conditioned commercial buildings (540 responses) in Singapore. We used a 7-point scale to evaluate subjects' satisfaction on 18 indoor environmental quality (IEQ) aspects including temperature, lighting level and overall privacy. We also asked follow up questions on the reason(s) of dissatisfaction. We found that majority of the IEQ parameters cannot reach the 80% satisfaction target suggested in Green Mark (Singapore green building standard) in workspaces. The percentage of dissatisfied exceeded 20% on sound privacy (43%), personal control (32%), temperature (31%), air movement (27%), overall privacy (26%) and noise level (21%). However, the percentage of occupants who expressed satisfaction with their overall workspace environment reached 78%, similar to what we found in US commercial buildings. We found that the major contributors to thermal dissatisfaction were insufficient air movement and overcooled workspaces. Higher temperature set-points and elevated air speed could be an alternative solution. Also, occupants in open plan office were unhappy with the noise produced by their nearby colleagues. These survey results indicate the needs to review existing IEQ satisfaction targets in Singapore's green building standard and potentially in other countries.

**Keywords:** Commercial buildings, Indoor environmental quality (IEQ), Occupants' satisfaction, Post-occupancy evaluation, Web-based survey

## 1. Introduction

Sustainable buildings should aim to achieve substantial energy saving and greenhouse gases emission reduction, while also providing good indoor environmental quality (IEQ) that satisfies building occupants. IEQ affects occupants' health, comfort, well-being and productivity. Conducting a subjective survey with a reliable and valid survey tool could provide valuable information in understanding subject satisfaction of the built environment and identify areas in need of improvement.

To this aim, the Centre for the Built Environment (CBE) at the University of California, Berkeley, has been developing and maintain an effective and reliable occupant survey to appraise occupant satisfaction for more than 20 years (Huizenga et al., 2002; Zagreus et al., 2004). The latest version of IEQ survey tool has been implemented in over 1000 buildings with over 100000 individual occupant responses. The core survey collects information about characteristics of the target building and information from building occupants on their perceptions and satisfaction with the indoor environment and related features.

Using the CBE Indoor Environmental Quality (IEQ) Occupant Survey database, different studies examining occupant satisfaction with the built environment become possible. For instance, responses within the CBE database have been compared in regards to occupant satisfactions in LEED versus non-LEED certified buildings (Altomonte et al., 2019; Altomonte and Schiavon, 2013; Schiavon and Altomonte, 2014); Kim and de Dear (2012) and Frontczak et al. (2012) have examined the relationships between individual IEQ factors and overall workspace satisfaction. Further, Karmann et al., (2017) compared the acoustic and temperature satisfaction between radiant and all-air buildings; and Wargocki et al. (2012) explored occupant satisfaction and self-estimated performance in relation to IEQ parameters in buildings. Despite the large sample size and building type variety available in the CBE database, the building samples are mainly located in the US. Occupant satisfaction with the indoor built environment could be different in countries with tropical climate, especially with regards to satisfaction with the thermal environment (Cheung et al., 2019; Lee et al., 2019).

Singapore is located at 1.3° N, 103.8° E and belongs to the tropical rainforest climate "Af" based on the Köppen Climate Classification. In Singapore, post-occupancy evaluation assessment of occupant satisfaction with a building's environment is obtained via a local green certification scheme called Green Mark (BCA, 2017). To gain certification, Green Mark requires a building to obtain less than 20% dissatisfied occupant responses (or 80% satisfaction). This standard basically follows similar criteria found in other standards, such as the definition of an acceptable indoor air quality and thermal environment being achieved when a substantial majority (80% or more) of people do not express dissatisfaction (ASHRAE Standard 62.1 (2016) and Standard 55 (2017)). It should be noted though that one study examining IEQ satisfaction in buildings in Singapore showed that satisfaction with many indoor environment parameters failed to achieve the 80% level, even in Green Mark certified buildings (Lee et al., 2019). The CBE survey tool offers an opportunity to examine whether or not these standards are achievable in tropical spaces (like found in Singapore), where environmental factors may differ in buildings compared to those located in non-tropical climates. By expanding the CBE database to include more buildings in Singapore, we can begin addressing these questions and better determine whether or not it is suitable to apply one satisfaction rate target to all IEQ factors in all spaces.

Here, we surveyed occupant satisfaction in five commercial buildings using a survey adapted from the CBE IEQ Occupant Survey. This study's objectives are to identify (i) the occupant satisfaction level of different IEQ aspects; (ii) the reason(s) of environmental dissatisfaction; and (iii) the contributing factors to occupants' overall thermal comfort in workspaces in Singapore.

## 2. Methodology

We modified the CBE IEQ Occupant Survey to fit building characteristics found in Singapore (i.e., there is no space heating in Singaporean buildings, so these items were removed). The resulting survey mainly aimed to assess occupant satisfaction with the space. Each satisfaction question is structured on a seven-point Likert scale and asks "How satisfied are you with …" followed by the environmental factors in question. As shown in Figure 1, the scale ranged from "very satisfied" (+3) to "very dissatisfied" (-3) with a midpoint of "neither satisfied nor dissatisfied" (0). The 18 parameters assessed included temperature, humidity, air movement, flexibility of dress code, electrical lighting, natural lighting, glare, views from windows, stuffiness, odors, noise level, sound privacy, cleanliness, amount of available space, furnishings, degree of personal control, overall privacy and overall environment. In this study, the dissatisfaction rate (D) and satisfaction rate (S) are estimated by Equations 1 and 2. The average satisfaction score in each IEQ category is calculated using Equation 3 (where $n$ is the total response count for that IEQ parameter).

$$Dissatisfaction\ rate, D\ (\%) = \frac{Very\ dissatisfied\ count + Dissatisfied\ count + Somewhat\ dissatisfied\ count}{Total\ sample\ count} \quad (1)$$

$$Satisfaction\ rate, S\ (\%) = \frac{Very\ satisfied\ count + Satisfied\ count + Somewhat\ Satisfied\ count}{Total\ sample\ count} \quad (2)$$

$$Average\ satisfaction\ score\ = \frac{1}{n}\sum Satisfaction\ score\ in\ particular\ IEQ\ category \quad (3)$$

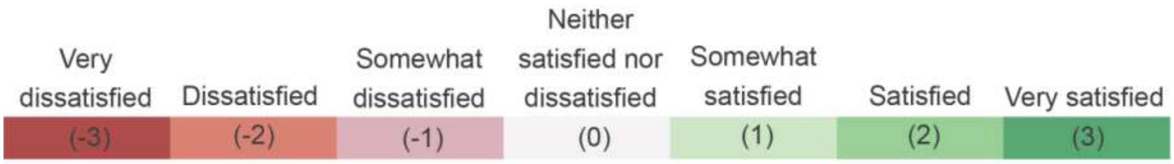


Figure 1. Satisfaction answer using a 7-point Likert scale.

Further, if a "dissatisfied" response was recorded by the occupant, follow-up questions were asked to identify the source of dissatisfaction. The possible sources of dissatisfaction are categorized into four core indoor environmental related aspects, namely, thermal environment, air quality, lighting and sound. An "others" option is provided for each category so that occupants can list any other source of dissatisfaction not included in the response set. The questionnaire also collects background information from respondents including sex, age group, working hour, workspace types, and proximity of workstation to windows and external walls.

Five Green Mark certified air-conditioned office buildings in Singapore were surveyed resulting in 540 individual responses. We only included staff who were performing office work and had personal workstations, and excluded any non-office working floors or areas within the same building. Each participating building had a survey response rate for at least 10% of the total occupancy.

## 3. Results

### 3.1. Description of the dataset

Table 1 summarizes respondent and workspaces characteristics. 58% of respondents were male, mainly between 21 and 50 years old, and occupants report spending more than 30 hours per week in their workspace. Most of the occupants were located in open plan offices with low (< 1.5 m height) or no partitions. The majority of respondents were located near (within 3 m) an external wall and window.

Table 1. Respondents and workspaces characteristics

| Parameters and descriptions | | Responses rate |
|---|---|---|
| | | |
| Sex | Female | 203 (38%) |
| | Male | 314 (58%) |
| | n.a. | 23 (4%) |
| Age group | 21 – 30 | 148 (27%) |
| | 31 – 40 | 178 (33%) |
| | 41 – 50 | 107 (20%) |
| | 51 – 60 | 68 (13%) |
| | 61 above | 14 (3%) |
| | n.a. | 25 (5%) |
| Working hour (hour) | Less than 10 | 61 (11%) |
| | 10 – 30 | 68 (13%) |

| | | |
|---|---|---|
| | More than 30 | 388 (72%) |
| | n.a. | 23 (4%) |
| Workspace type | Cubicle with low or no partitions (<1.5 m) | 314 (58%) |
| | Cubicle with high partitions (>1.5 m) | 82 (15%) |
| | Enclosed / private office | 56 (10%) |
| | Others | 49 (9%) |
| | n.a. | 39 (7%) |
| Distance from external wall | Within 3 m | 273 (51%) |
| | Further than 3 m | 222 (41%) |
| | n.a. | 45 (8%) |
| Distance from external window | Within 3 m | 334 (62%) |
| | Further than 3 m | 167 (31%) |
| | n.a. | 39 (7%) |

### 3.2. Occupants' IEQ satisfaction distribution

Figure 2 shows the distribution of satisfaction responses for each IEQ factor. Overall, respondents were more satisfied with the flexibility of dress code (S = 86%), electric light (S = 84%) and cleanliness (S = 82%) of their workspace. Factors where dissatisfaction rates exceed 20% were sound privacy (D = 43%), personal control (D = 32%), temperature (D = 31%), air movement (D = 27%), overall privacy (D = 26%) and noise level (D = 21%). These results raise an important question: Are these environments surveyed poorly performing commercial spaces or is it common to have large variation on satisfaction responses in different IEQ factors within buildings in Singapore?

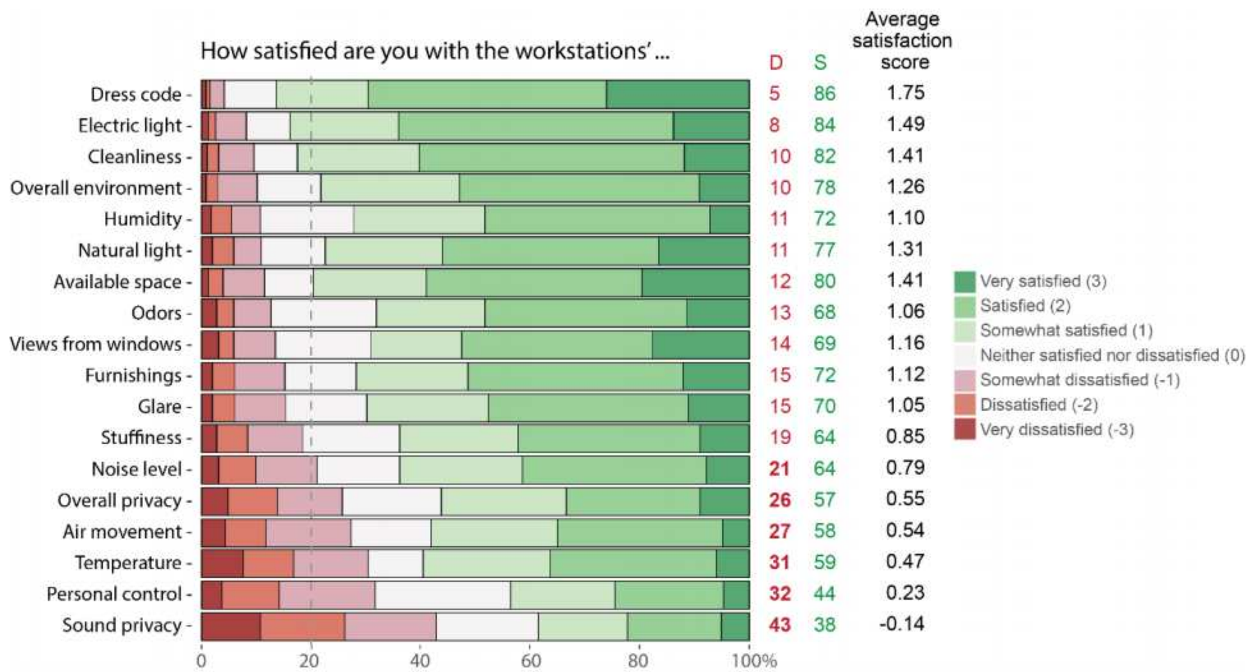


Figure 2. Distribution of occupant satisfaction responses for all IEQ categories. Calculation of dissatisfaction rate (D), satisfaction rate (S) and the average satisfaction score is presented in Equation (1), (2) & (3). The grey dotted line indicates a 20 % target.

To answer this question, we compared the satisfaction distribution patterns in Figure 2 to another study conducted by Karmann et al. (2017) examining 60 commercial buildings in US using the original CBE survey tool. Despite some variations on the selected IEQ parameters, the satisfaction distribution trend is comparable between the two studies. For instance, dissatisfaction rate for sound privacy (D = 59%), temperature (D = 32%) and noise level (D = 42%) were also found exceeding 20% in Karmann et al.'s study. In addition, sound privacy was the category with the highest dissatisfaction in both studies. This brief comparison shows that the IEQ satisfaction survey results of commercial buildings in Singapore are not worse when compared with the US counterparts. A more important outcome from the results is that achieving a high occupant satisfaction is much harder for some IEQ factors compared to others. For example, it is harder to achieve 80% satisfaction with sound privacy than for electric light. Therefore, instead of one target rate criteria (i.e., 80% satisfaction), we think we should have different satisfaction target rate for each IEQ factor. The target rates should be based on occupant satisfaction responses from a large database to achieve reliability and representativeness. For example, the target rates could be based on the average satisfaction score or some other effective rating systems based on the distribution of satisfaction responses. The average satisfaction scores in Figure 2 confirm the spread in values of satisfaction levels across the IEQ factors. Current values may not be reliable to represent office buildings in Singapore due to small sample database and the selection process. Nevertheless, we proved that a fairer definition of the satisfaction target rates is needed. Future work should expand the database and explore possible methods for target rates development.

Despite lower satisfaction rates found in some IEQ parameters (i.e. temperature, air movement or noise level), building occupants were generally satisfied with the overall workspace environment (S = 78%). It suggests that the IEQ parameters assessed may have a smaller influence on the subject's overall environment satisfaction.

### 3.3 Sources of dissatisfaction

Figure 3 summarizes the sources of occupants' IEQ dissatisfaction in the workspace. Among the four major IEQ categories, higher dissatisfaction was observed with the thermal environment (349 votes), followed by sound (276 votes), lighting (220 votes) and air quality (154 votes). Each IEQ category has a different sample count because (i) the follow-up questions only pop-up when a dissatisfaction response is captured, and (ii) each respondent can vote more than one reason of dissatisfaction for each IEQ category. In this work, we calculated the percentage as the ratio of sample count for each dissatisfaction reason over the total sample size, excluding the "other(s)" option, within the corresponding IEQ category. In doing so, we lose 2 % to 10 % of dissatisfied responses, depending on IEQ category. The reasons for excluding the "other(s)" option is that these dissatisfaction responses are (i) too diversely dispersed (i.e. cannot be grouped into meaningful categories), or (ii) associated with only one particular building (e.g. there is no greenery near building X).

We found that occupants were dissatisfied with the workplace thermal environment mainly because of weak air movement (30%), followed by their workstation being too cold (24%) and too hot (19%). It should be noted that some contradictory results are observed. For example, occupants' indicated a desire for more air movement, while also reporting that a space was too cold. Further analysis (see Figure 4) suggests that only 10% of the respondents reported dissatisfaction with weak air movement while also reporting that they felt cold in their workspace. More occupants expressed a desire for higher air speed because they were too hot (38%), or simply some amount of air movement despite satisfaction with temperature (46%). Interestingly, 6% of the occupants who expressed dissatisfaction with too little air movement also reported being both too cold and too hot in their workspace.

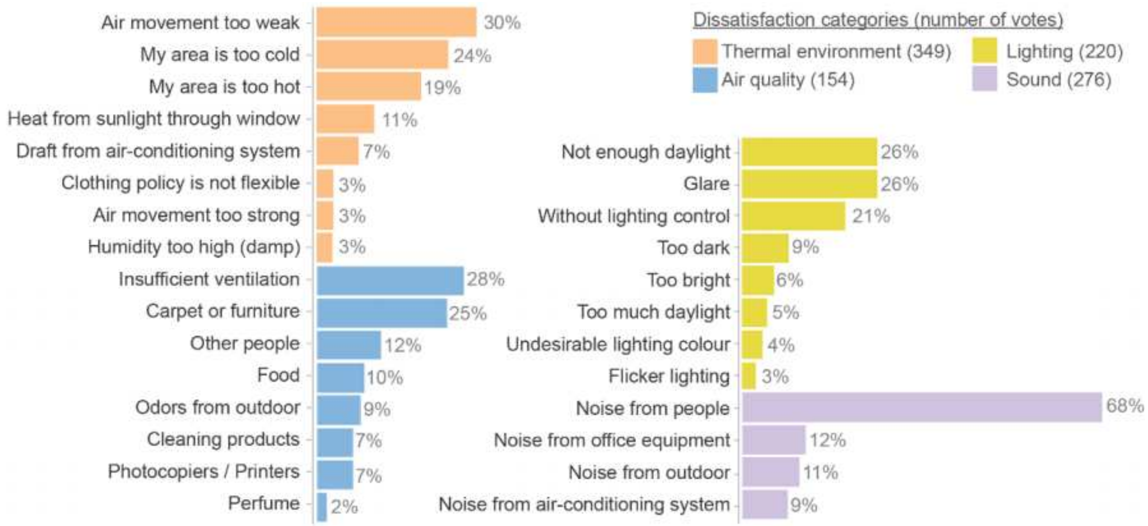


Figure 3 Source of dissatisfaction of different indoor environmental quality (IEQ) categories (the percentage is calculated within the same IEQ category)

Existing building design criteria of air velocity in air-conditioned occupied space required in Singapore Standard-553 (Singapore Standard, 2016) is not to exceed 0.3 m/s. Perhaps providing flexibility on air velocity in the Standard can reduce dissatisfaction on insufficient air movement in workspace. Increasing indoor air speed by using either ceiling or desk fans enhances cooling effect perceived by the occupants, thus restoring thermal comfort in a warm environment (Schiavon and Melikov, 2009). The effectiveness of this elevated air speed cooling strategy had been confirmed in both chamber experiment (Schiavon et al., 2017; Xu et al., 2017) and real office (Lipczynska et al., 2018) spaces in Singapore. This strategy does not only reduce cooling energy demand but simultaneously enhance occupant's thermal satisfaction.

An over cooling problem is observed in some of the air-conditioned workspaces in this study. In Figure 3, despite 19% of the respondents indicating that they were too hot, a quarter of the total dissatisfied count is reflective of occupants being too cold. This finding aligns with a former study of over cooling in other air-conditioned commercial buildings in Singapore (Sekhar et al., 2003).

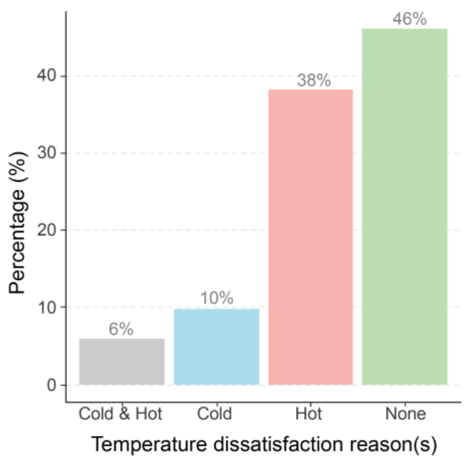


Figure 4 Percentage of dissatisfied reason(s) with temperature for the occupants who were dissatisfied with too weak air movement in workspace

Among the four IEQ categories, air quality received the least dissatisfied responses from occupants (154 votes). Occupants' main sources of dissatisfaction was due to "insufficient ventilation" (28%), smell from "carpet or furniture" (25%) and "other people" (12%). Elevated air movement enhances air mixing in a space, therefore increasing air movement may be effective in diluting unpleasant odors and may also increase real (Pantelic et al., 2019) and perceived air quality (Melikov and Kaczmarczyk, 2012; Zhang et al., 2011). In this case, a strategy to increase air movement in workspace does not only enhance the thermal environment, but also improves satisfaction with air quality.

In terms of lighting dissatisfaction, the major source of dissatisfaction come from "not enough daylight" (26%) and "glare" (26%), followed by lack of control (21%). We found that up to 75% of the occupants who reported glare in the workspace were seated near (<3 m) a window. Surprisingly, among the "not enough daylight" dissatisfaction responses, 45% of the occupants were also located near a window. This could be due to the fact that occupants are closing blinds to protect themselves from glare. Incorporation of effective design that includes light shelves and shading devices to maximize daylight while reducing glare, could be a solution to minimize lighting dissatisfaction (Freewan, 2010). In addition, providing simple manual control of lighting (e.g., a desk lamp) can enhance occupant acceptability of lighting in office space (Galasiu and Veitch, 2006).

The most dissatisfaction reported came from "noise from people" (68%). It is also a major contributor to the of dissatisfaction in sound privacy (D = 43%) and noise level (D = 21%) (Figure 2). Expectedly, 92% of dissatisfaction for "noise from people" was reported in open plan offices, and 75% of these respondents were those housed in cubicles with low (<1.5 m) or no partitions. Providing private office to everyone may not be possible, meanwhile having high partitions (>1.5 m) could partially reduce noise from people and improve sound privacy, but its effectiveness has been challenged as this design may also reduce the ease of communication between colleagues (Jensen et al., 2005). In fact, the dissatisfaction rate of "sound privacy" from occupants working in spaces with high partition (>1.5 m) was still high (D = 28%). Alternatively, having several easily-available temporary quiet offices could provide employees with a quiet place for times when deep focus is needed, while still affording space for collaborative environments within the whole workspace (Haapakangas et al., 2018).

## 4. Thermal comfort satisfaction contributors

Apart from the specific 18 IEQ factors measured (Figure 1), we also surveyed occupants' satisfaction on overall thermal comfort. Despite the term thermal comfort being frequently mentioned in building design standards, it can be very abstract and difficult to understand as a lay person. Therefore, we aim to identify which thermal comfort parameter is most related to "overall thermal comfort" using the occupant's satisfaction responses.

Figure 5 presents scatter plots depicting the linear relationship (orange line) of the satisfaction score with overall thermal comfort and the other thermal comfort parameters including temperature, humidity, air movement and flexibility of dress code. The contour is also provided to visualize data density. Among the four thermal comfort parameters, satisfaction with temperature is highest ($R^2$ = 0.77, MAE = 0.42) with the overall thermal comfort satisfaction, followed by air movement ($R^2$ = 0.48, MAE = 0.79), humidity ($R^2$ = 0.45, MAE = 0.67) and the least relationship is found with dress code ($R^2$ = 0.23, MAE = 1.06). This means when occupants are satisfied with the temperature in workspace, they are also likely to be satisfied with the overall thermal environment; and vice versa when dissatisfied.

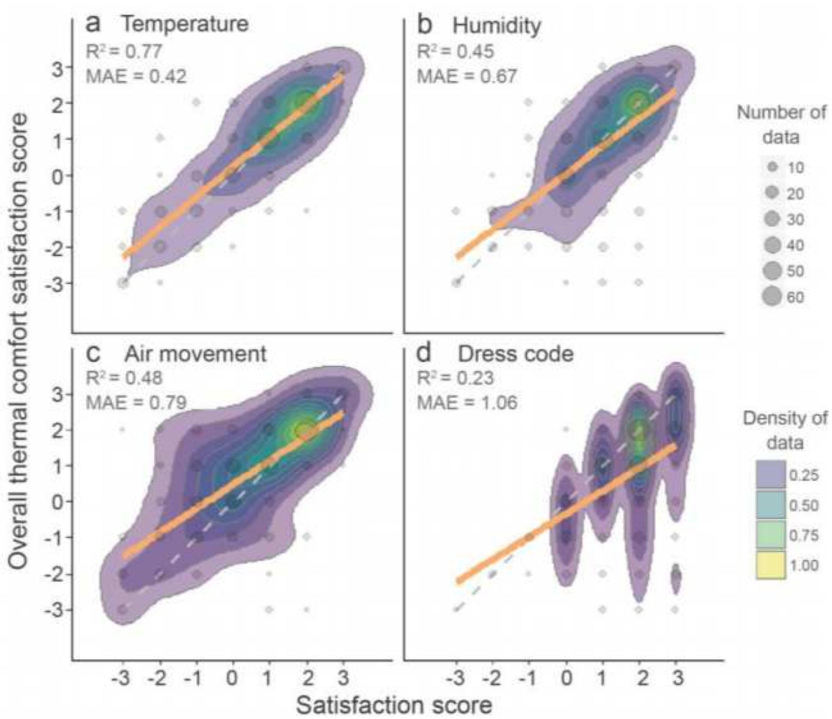

Figure 5 Scatter plot with linear relationship (orange line) between overall thermal comfort and others satisfaction score: (a) Temperature, (b) Humidity, (c) Air movement and (d) Dress code.

Table 2 summarizes multiple linear regression prediction results of overall thermal comfort satisfaction with the satisfaction score of each of the four thermal comfort parameters. The full model (Case 1) shows that the major components in predicting overall thermal comfort satisfaction in the workspace are satisfaction with temperature, followed by dress code and air movement, while the lowest contribution is from humidity. The results here are different from that presented in Figure 5.

Table 2 Multiple linear regression analysis on overall thermal comfort satisfaction (p-value: 0 < *** < 0.001 < ** < 0.01 < * <0.05)

| | Estimate | | | | Intercept | Residual standard error | Adjusted $R^2$ |
|---|---|---|---|---|---|---|---|
| **Cases** | **Temperature** | **Humidity** | **Air movement** | **Dress code** | | | |
| 1 | 0.70 *** | 0.04 | 0.11 ** | 0.13 ** | 0.03 | 0.71 | 0.79 |
| 2 | 0.71 *** | - | 0.13 ** | 0.14 ** | 0.03 | 0.71 | 0.79 |
| 3 | 0.74 *** | - | 0.15 *** | - | 0.24 | 0.72 | 0.78 |
| 4 | 0.79 *** | - | - | 0.16 *** | -0.01 | 0.72 | 0.78 |
| 5 | - | - | 0.59 *** | 0.31 *** | 0.00 | 1.08 | 0.52 |
| 6 | 0.84 *** | - | - | - | 0.24 | 0.74 | 0.77 |

We found that occupant satisfaction with temperature has a stronger relationship with air movement ($R^2$ = 0.51, MAE = 0.74) and humidity ($R^2$ = 0.51, MAE = 0.64) compared to flexibility of dress code ($R^2$ = 0.19, MAE = 1.19). When we computed a multiple linear regression on the relationships between overall environment satisfaction score and air movement or humidity satisfaction scores, the effects are masked by satisfaction with temperature, and thus the correlations become less significant. Only the true relationship between temperature and overall environment satisfaction remains.

By removing humidity in Case 2, prediction performance of the overall thermal comfort satisfaction remains the same. Dependent variables are further reduced in Cases 3 – 6. Using only satisfaction with temperature (Case 6) this variable is able to explain 77% of the variance in the overall thermal comfort satisfaction. Adding satisfaction with air movement and dress code enhance the prediction performance slightly (Cases 3 & 4), but the difference is negligible. These findings suggest that occupants' satisfaction with overall thermal comfort seems to be mainly related to air temperature satisfaction. Results suggest that instead of surveying all four parameters, asking occupants to only report their satisfaction with temperature could act as a reliable proxy for their satisfaction with overall thermal comfort.

## 5. Limitations and further studies

A major limitation of current study is the small building sample size (5 buildings and 540 respondents). We are planning to survey more buildings in the near future with the aim of developing an IEQ benchmarking system for Singaporean commercial buildings using our surveyed database. This benchmark will help inform building owners, facility management and government agencies on what reliable occupant satisfaction target rates, could be especially beneficial to update the existing Green Mark certification scheme.

In addition, this study did not fully explain the confounding effect on occupant satisfaction from different IEQ factors, or the impacts on building or workspace characteristics. Performing generalized linear mixed model (GLMM) with propensity score analysis or factor analysis may provide deeper insights into the underlying reasons for occupant satisfaction with the environmental parameters. These analyses will be undertaken in subsequent work.

## 6. Conclusions

We modified the CBE IEQ Occupant Survey to conduct IEQ satisfaction assessments in 5 commercial buildings in Singapore (540 respondents). Overall satisfaction with the environment was 78%. We found dissatisfaction rates higher than 20%, for sound privacy (D = 43%), personal control (32%), temperature (31%), air movement (27%), overall privacy (26%), and noise level (21%). The highest satisfaction was found for flexibility on dress code (S = 86%), electric light (84%) and cleanliness (82%). These results suggest that achieving a high occupant satisfaction for some IEQ factors is harder than others. Developing reliable satisfaction target rates by different IEQ factors could provide a more effective measure of occupant satisfaction of IEQ parameters. We also found that occupants are dissatisfied with the thermal environment in workspaces mainly because of weak air movement and the space being too cold. Meanwhile, the most prominent source of dissatisfaction in a workspace comes from noise generated from other people. Additional analysis showed that satisfaction with temperature can be a proxy for satisfaction with overall thermal comfort in Singaporean commercial buildings. Future surveys could be shortened by eliminating less important questions as is the case when assessing thermal comfort.

## Acknowledgment

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# Exploring current and future thermal comfort practices in shared workspaces

**Kathy New[1], Adrian Friday[1], Alexandra Gormally[2], Adam Tyler[1] Mike Hazas[1]**
[1] Lancaster University, School of Computing and Communication
[2] Lancaster University, Lancaster Environment Centre

**Abstract:**
In 2018, the UK service sector consumed 20,222 ktoe energy (24% of the UK total, excluding transport). Education is a major consumer within this sector, with Higher Education Institutions (HEIs) being particularly energy intensive. Space heating accounts for the highest use of energy in UK offices, and whilst more energy efficient buildings are being designed and constructed, around 80% of the buildings we will be using by 2050 have already been built. Many offices provide little data for energy managers to effectively control buildings, resulting in spaces that are often overheated and inefficient.

Emerging technologies have great potential to deliver energy reduction, by controlling heating and cooling in more precise and targeted ways. We have designed a bespoke system to be retrofit to existing buildings to allow enable energy managers to control heating on a room-by-room or even finer basis. In this paper, we use a mixed-methods observation and measurement approach to observe existing offices to understand the current thermal comfort practices and particularly how comfort is governed in shared environments. We identify some of the barriers for successful adoption of our system and make the case for the co-evolution of policy and technology to promote greater personal responsibility for thermal comfort in a warming world.

**Key words:** Energy, thermal comfort, policy, higher education, HCI

## 1.0 Introduction

Energy used for space heating and cooling is the second most energy demand-intensive activity in the UK, after transport (GOV.UK, 2018). By far the greatest use of energy in office buildings goes into space heating and cooling, and these buildings generally operate within a narrow, static band of temperature (19-21$^{\circ}$C) all year round, despite significant differences in year-round external temperature and occupant dress. Education is a high consumer of energy in the UK service sector (employing 80% of the UK workforce (ONS 2011)), with Higher Education being especially energy intensive (Royston et al. 2018). The work is relevant as the UK is legally bound to cut its emissions to 80% below 1990 levels by 2050, and to comply with the Paris agreement (United Nations 2015). As Cass (2018) points out, despite a focus on improving standards (in terms of regulation, assessment and certification), this has not succeeded in producing more efficient buildings in the non-domestic sector. Whilst more energy efficient buildings are being designed and constructed, 80% of the buildings we will be using in 2050 have already been built (CIBSE 2013), calling for solutions that address the energy demands of heating and cooling in existing buildings.

Space heating technology has the potential to significantly reduce energy use and support carbon reduction, and we believe, encourage comfort over a wider range of principles according to adaptive thermal comfort principles (Nicol et al, 2012). We are in the process of creating a system to help energy managers and existing building occupants to manage thermal comfort, and promote such personal adaptivity. The system provides fine-grained data on a room-by-room basis, and links with other sensors and information to allow us to precisely control heating policy and enable different users to interact with the system using a flexible web-based platform. Our system is designed to be scalable to an enterprise context of over 10,000 water-filled radiators with minimal maintenance using passively powered thermostatic radiator valves.

This study explores interactions between office occupants and this emerging class of interactive thermal comfort technology. Specifically, using Lancaster University as a case study, we take a socio-technical approach to deploy a prototype of our system in a shared office environment. Using data logging, ethnographic observation and interviews, we uncover how office occupants thermal comfort practices are currently configured, and identify potential barriers and enablers for the adoption of systems like ours. In our paper, we 1) reveal the complexities of introducing smart heating control systems into a workplace, especially in shared offices, and 2) make the case for co-ordination of policy, people and technology to encourage more adaptive behaviour and reduce energy consumption in existing buildings.

**2.0 Related work**

The study draws on a range of interdisciplinary work on thermal comfort, including human computer interaction (Milenkovic et al. 2013. Clear et al. 2018), practice theory (Shove, 2003, 2014), building design (Leaman and Bordass, 1993), and environmental policy and governance (Curtis et al. 2017, Royston et al, 2018). Sustainable design aims to reduce the negative environmental impact of products and services by putting sustainability as a core principle during the design phase (Poel, 2017, Blevis, 2007). HCI considers this both from the technological point of view, and the human perspective in terms of the context and situations in which those products and services are used.

Thermal comfort has been studied widely since Fanger (1972). Leaman and Bordass (1993) describe the problem of complexity in building design leading to issues with comfort, and advocate for simplicity and clarity when it comes to the technical interfaces which support this. They suggest 'robust, adaptive procedures usually work best' in terms of providing thermal comfort. Leaman et al. (2010) also note that evaluations of completed buildings are usually so poor, organisations are reluctant to publish them, meaning lessons are not learned and the same mistakes are perpetuated. They discuss the importance of buildings as 'contexts' where human practices and behaviours take place, however they claim that buildings are 'adapted' to a certain extent, by their situation (e.g. more insulation in cold countries, and better draught prevention on windy sites). However, on large evolving campuses such as universities, buildings can emerge at different points over hundreds of years, and adaptations are not always suitable for their current use or occupant preferences (Brand 1997).

The importance of personal adaptivity in thermal comfort has long been recognised. Research has shown that clothing choices correlate more closely with outdoor temperature when there is a flexible dress code (Morgan and De Dear 2003) so in order to promote adaptability, a range of supportive policies would have to be in place. One successful example of this comes from Japan and the Cool Biz initiative, introduced in 2005, where public buildings were not cooled below 28°C in summer (Shove 2014).

In order to support these initiatives, the government introduced the Cool Biz dress code and workers were encouraged to wear short sleeved shirts without jackets and ties, along with light trousers in breathable fabrics. All government leaders took part, including the Prime

Minister, and the fashion industry embraced the campaign by designing appropriate lightweight clothing. The campaign mainly focused on men, as women working in offices did not tend to wear full business suits in the same way, and were already able to wear lighter clothing in the office. In addition to the dress code, since 2012, the government have called for "Cool Sharing" to encourage people to share cool places rather than use individual air conditioning units (Japanese Environment Quarterly 2013). After an earthquake and tsunami ravaged the northeast coast of Japan in 2011, damaging Fukushima, the Japanese government upgraded this to 'Super Cool Biz' fearing energy shortages. This included further relaxing dress codes, and suggested alterations to working practices such as starting work earlier in the morning when it is cooler, and taking longer summer holidays (The Japanese Times, 2014).

Advances in technology have changed the landscape of thermal comfort in the home, e.g. through the ability to control heating systems remotely via your phone or tablet (Ayan and Turkey 2018), and these systems are now being introduced to the workplace. However, this type of system has different needs to those in a domestic setting, with different building structures, social dynamics, and expectations of what constitutes appropriate thermal comfort levels. Office temperatures have long been a source of conflict and displeasure, and developments in social media have resulted in new ways to share this, including dedicated channels on Twitter and Facebook. With technology and access transferring from the domestic sphere to the non-domestic, there are questions about how this impacts workers in shared offices, and whether comfort levels actually improve. Does it increase individual control and agency, or can it introduce new complexities around how thermal comfort is negotiated and disrupt office relationships and practices? Within the workplace are questions of agency and control which do not exist in a domestic setting, as temperature is often controlled by a facilities manager or decided by a subset of managers, and limited control sits with the individual (Goulden and Spence, 2015).

In the workplace, there is also an inherent tension between giving people more control, and reducing energy use. How the ambient room temperature is decided in shared workplaces poses further questions. Thermal comfort is often portrayed as a product to be provided *to* building occupants, rather than something they can achieve, and much work has been done on voting systems (Jazizadeh et al. 2012). Shumann et al. (2010) believe maximising thermal comfort in buildings leads to increased productivity, and should therefore be a desired goal, without really looking into the complexities of how this can be achieved. Shin et al. (2017) discuss the need for mechanisms to determine room temperature where diverse thermal comfort preferences co-exist: they look at different decision-making methods (e.g., majority, mean, trimmed mean and median) concluding that these methods may be unfair to some of the occupants, instead presenting a method to *evenly distribute* the unfairness. However in all these studies, the building and its mechanisms are seen as responsible for thermal comfort, and little responsibility is placed with the occupants themselves. We argue an alternative approach could be to provide a lower set back temperature and place more responsibility on the occupants to adapt via their clothing levels and behaviour.

Digital technology means that the very way in which we interact with thermal comfort (such as visibly turning radiators on or off, opening windows, using energy-intensive electric heaters, fans or portable air conditioners etc.), is changing. Unlike overt physical actions, interactions can be invisible, risking the creation of new tensions in the workplace. Balancing local control and accountability with energy saving is delicate and under-researched.

**3.0 Case study: Lancaster University**

UK Higher Education Institutions' (HEIs) energy consumption increased by 3% from 2005-06 to 2015-16, which Royston (2018) links to increases in high-energy services such as 24-hour libraries and en-suite student accommodation, fuelled by the introduction of student fees and the wider financialisation of Universities. This has also lead to differences in expectations with regard to facilities and services, with the Higher Education Policy Institute (HEPI 2019) student academic experience survey highlighting that a high-quality campus environment is a key factor in student satisfaction, and emphasising the importance of Universities investing in the development and modernisation of their estates.

This paper examines some of the emerging issues from deploying a retrofittable system to enable energy managers in large organisations to control buildings on a room-by-room basis. The aim of the system is to provide more granular data, enabling better control and more end-user reflection and engagement in order to reduce energy consumption. However, in order to be effective, there are considerable technical and human factors to be overcome.

We use offices on Lancaster University campus as a case study: the University occupies a 560-acre parkland site outside Lancaster, in the North West of England. Building on the current site began in 1966, and the estate now comprises 250 buildings. According to the Higher Education Statistics Agency (HESA) in 2018, the University has 14,000 students, and 4,000 staff. Energy consumption at the University has increased by 13.4% from 2009-10 to 2017-18. During this time, the campus has seen great change with original buildings modified, replaced and adapted several times since 1966, depending on the financial ebb and flow of this dynamic sector (McClintock, 2011).

**4.0 Methodology**

To understand the thermal environment, how it changes throughout the day, and how the occupants maintained their thermal comfort, we chose a triangulation of methods including i) data logging, ii) thermal imaging, iii) ethnographic observation and iv) interviews with individuals. We uncover the current range of thermal comfort behaviours that exist, and the impact of our new technology on these existing behaviours. Whilst our findings are, by their nature very specific to our participants, time and location of the study, and are not meant to be representative, we believe there are useful lessons to be learnt for those considering similar technologies for existing buildings, estates and campuses. Our methods are also consistent with a human centred approach to sustainability through design; Pink et al. 2013 argues we need to understand the socio-cultural contexts in which practices are situated. This view is further supported by Kuijer and de Jong (2011) who describe the need to first understand practices that consume energy, before introducing systems to reduce this.

**4.1 Phase 1: Thermally challenging individual offices**

An initial pilot study was carried out with two female participants in individual offices at Lancaster University. In contrast to studies focusing on comfort voting (e.g. Ricciardi et al. 2012), our methods focus on gaining insights as to the kind of thermal comfort related practices that were taking place. The participants were i) interviewed at the beginning and end of the study, ii) asked to wear temperature logging devices (DS1921G iButtons) and iii) had three further iButtons placed around their office at different locations, as well as a Lascar Easylogger EL-USB-1. They were also provided with pen-and-paper thermal comfort diary and asked to log their activity whilst at work for three days during the study period, which took place over a week in May 2018. The office temperature continued to be logged for 3 weeks after this period. During the second round of interviews, the participants were shown traces of the temperatures logged during the study, which was cross-referenced with the diary entries to gain a deeper understanding of their practices and experiences during at this time. This method builds on previous work by Clear et al (2013).

Given the relatively modest outdoor temperatures at our latitude at this time, the initial study revealed some surprising findings: one of the offices we logged between 5 and 12 June 2018 *never fell below* 30°C at any point (see Figure 3), exceeding 36 degrees.

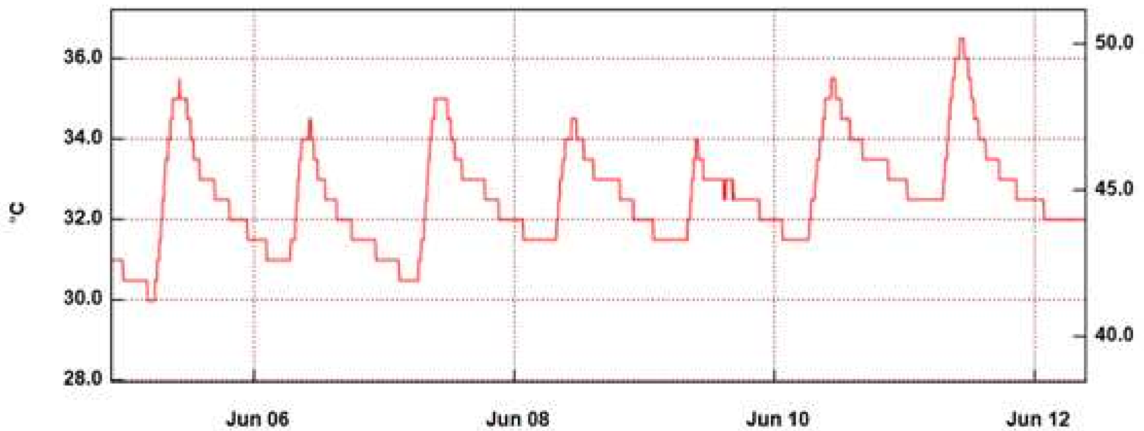



Figure 1: *Temperature trace from a single occupancy office in June 2018. Note the clear diurnal patterns, but also the gradual build-up of baseline heat throughout the week. Temperature is over 30 degrees even after cooling off overnight.*

In this case, the participant described some surprising adaptive behaviours she used in order to cope with the temperature, including regularly spraying her feet, legs and upper body with water, as well as placing her feet in a bowl of water under the table when extremely hot.

**4.2 Phase 2: Regulating temperature in shared offices**

Two themes that emerged from the pilot study were that of agency and control with regard to thermal comfort, and the control of shared spaces. To explore this further, and in order to develop a successful roll-out programme for our system from testbed to building level, we needed to understand more about thermal comfort issues in shared office spaces. With this in mind, we sought advice from facilities staff with regards to shared spaces with 'problematic' temperature, and approached a busy shared office for 'a follow up investigation'.

This second phase of the study (February 2019) used participant observation, with the researcher spending two hours a day over a two-week period working in the office to observe thermal comfort behaviours. Data loggers (DS1921G iButtons) were also installed on all desks, and Lascar data loggers (EL-USB-1) were also used to provide data from the centre of the room. After the initial two weeks observation, the research team installed a testbed of remote controllable thermostatic radiator valves (iTRVs) in the office shown above, adjacent meeting rooms and communal areas, and trained the occupants on how to use them.

Figure 2 shows the room layout, with the occupant's desks in yellow and the observer in orange. Table 1 details gender and age data for the occupants.

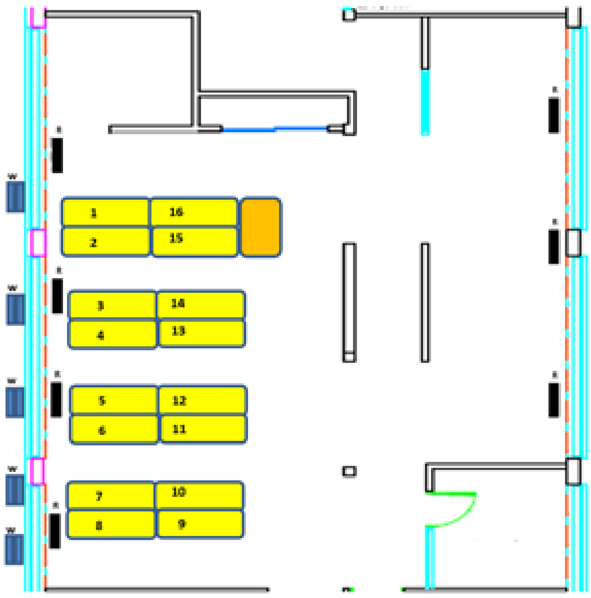



Figure 2: *Layout of the shared office study site. The orange desk marks the observer position, and the yellow desks are the occupants.*

Table 1: *Shared office demographic data*

| Gender | Under 45 | Over 45 | Total |
|---|---|---|---|
| M | 4 | | 4 |
| F | 8 | 4 | 12 |

After this period, a group interview was then carried out over a lunch time, where occupants were presented with some of the temperature data logged, as a prompt for further discussions around their thermal comfort practices. A thermal imaging camera was also used with the occupants, enabling them to visualise the office environment in a different way.

## 5.0 Findings

We now focus on the experience and themes that emerged from our data and participant interviews.

## 5.1 Temperature and adaptation strategies

As with our first phase study, the temperature logging from the second phase in shared offices during winter also showed that it was substantially overheated, rarely getting below 23°C.

However, the experience was far from uniform, with several observable 'microclimates' within the same room (*Figure 3*).

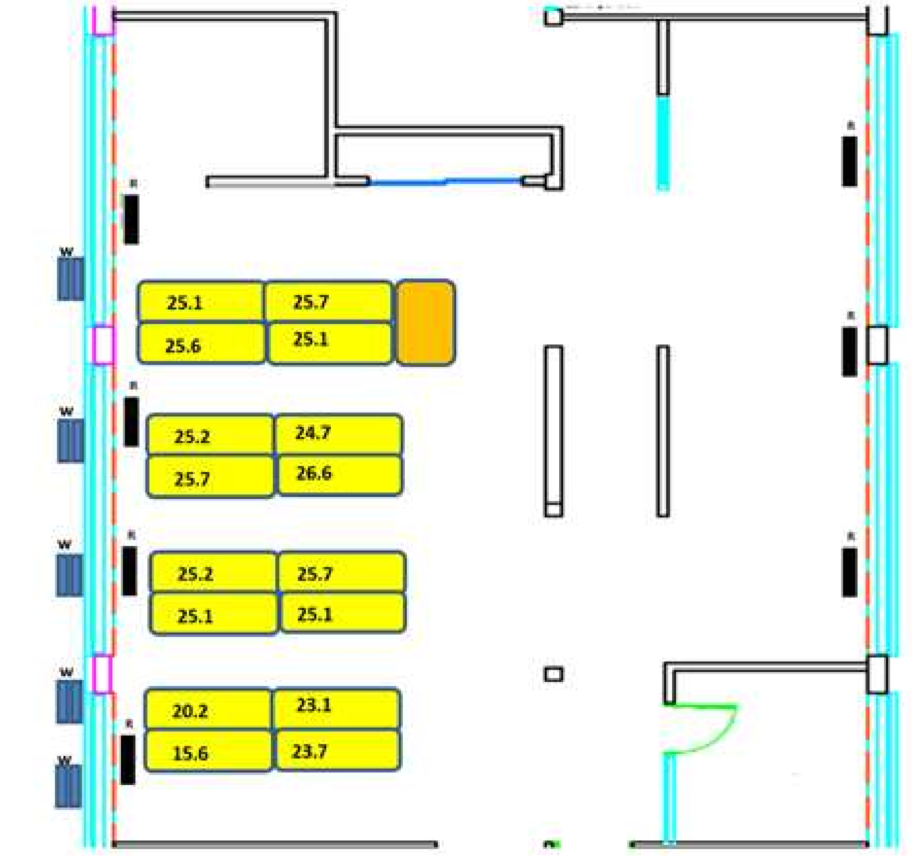



Figure 3: *Temperature variation by desk, snapshot taken 16.43pm 28/02/2019. Note due to different use of windows and fans desk 8 is over 10 degrees colder than desk 1, although this effect is surprisingly localised given the temperatures on adjacent desks.*

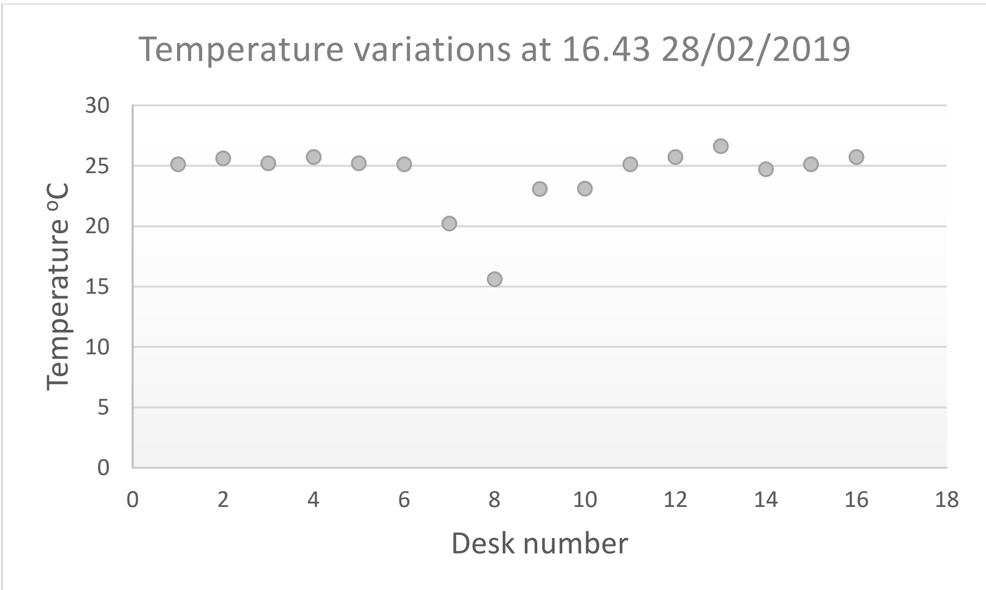



Figure 4: *Plot graph to show temperature variation by desk, snapshot taken 16.43pm 28/02/2019, highlighting the difference in localised temperature across the room.*

The data above shows the temperature variations at a single point in time, with desk 8 at 15.6°C and desk 13 at 26.6°C. The occupant of desk 8 has a range of adaptive strategies for managing her thermal comfort. They sit next to a window which was *open* throughout the observation period, uses a desk fan, dresses in light clothing and keeps sandals at work. The occupant is female, over 45, and has a preference for cooler temperatures. The observation found that there is a distinct 'zoning' to the office, with one end occupied by older women who struggle with the heat, and the other end occupied by a younger, gender-mixed population.

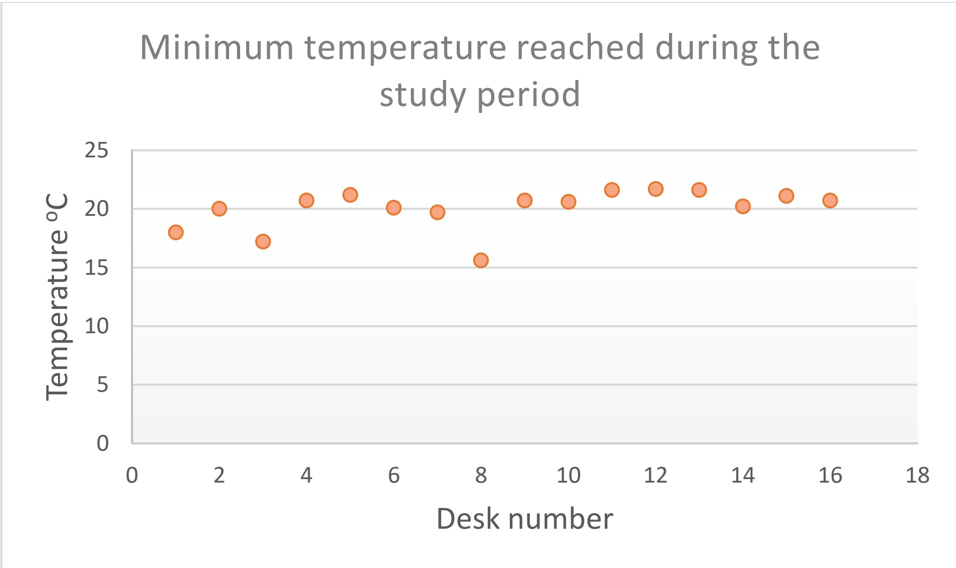



Figure 5: *Minimum temperature variation by desk, reached during the study period, with a difference of 6.1°C between desks*

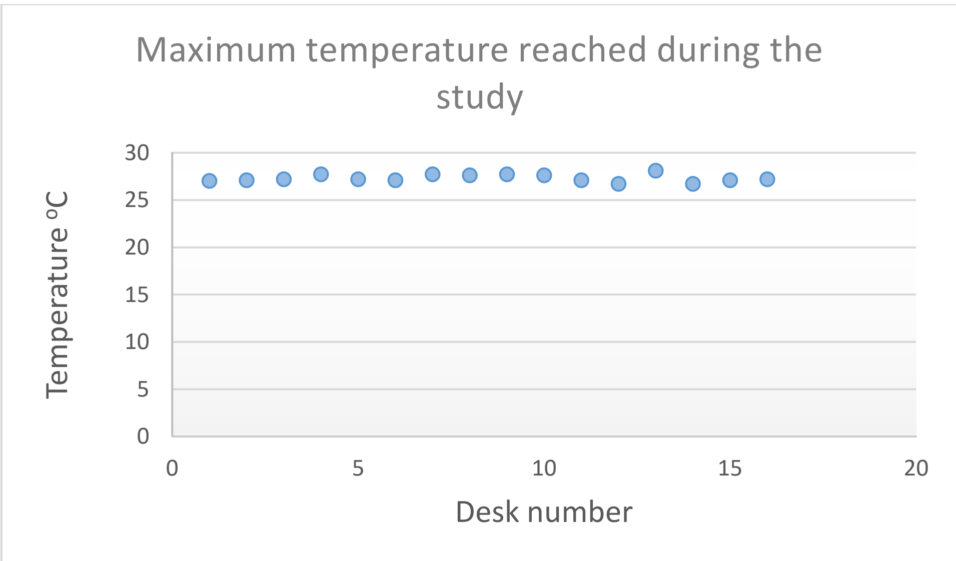



Figure 6: *Maximum temperature variation by desk, reached during the study period, showing very little difference. Note the maximum temperature recorded in the office was 28.1 degrees.*

Figure 5 and 6 show the variation in maximum and minimum temperature across the office. The larger variations in minimum temperature were achieved through adaptive methods such as opening windows and using desk fans.

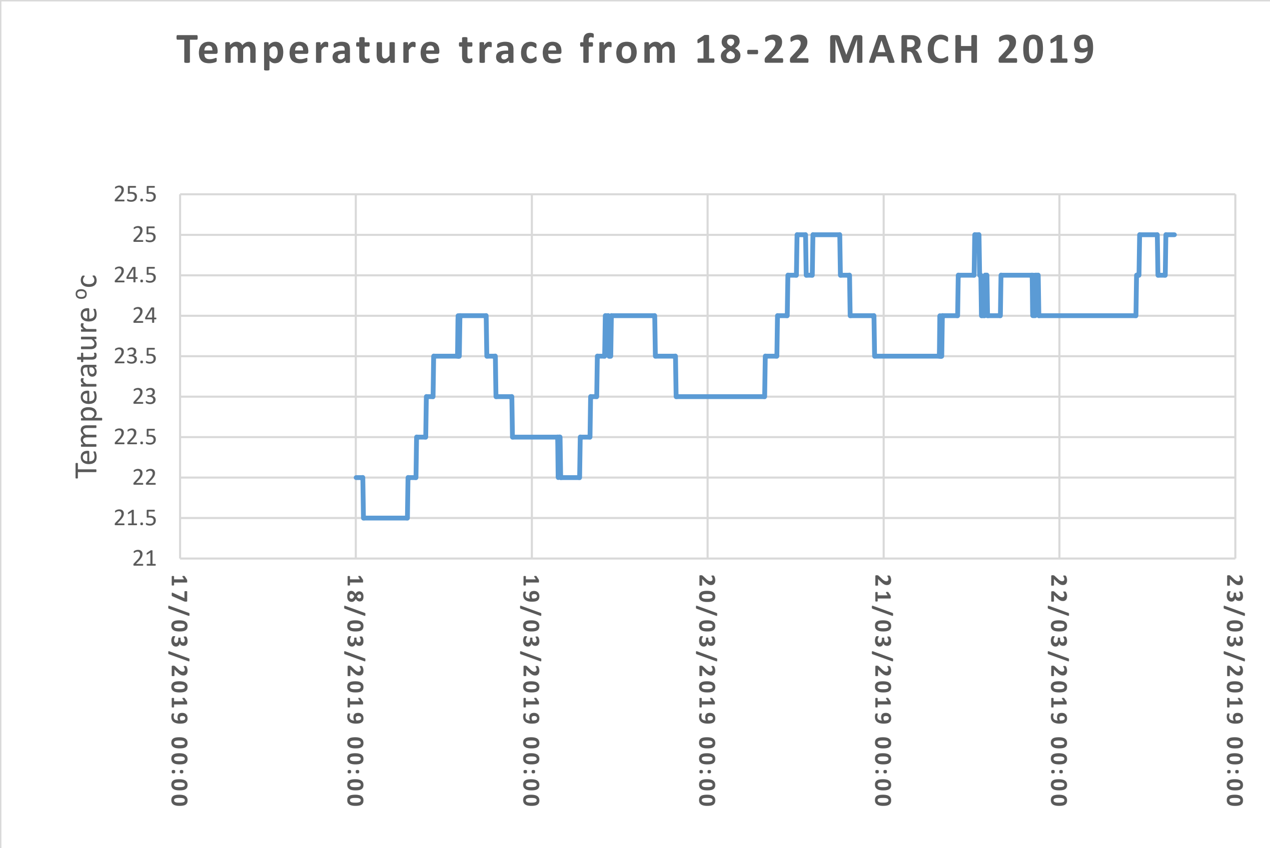
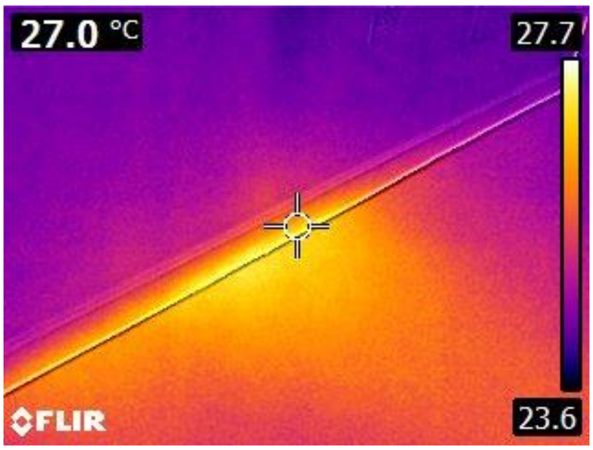
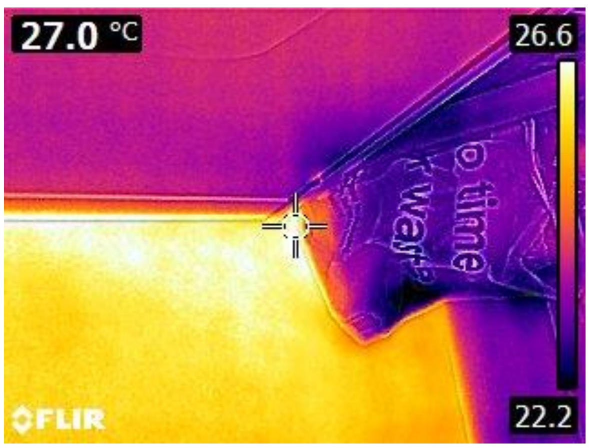



Figure 7: *Temperature logged from 18-22 March, in the centre of the room using Lascar data logger (EL-USB-1 Note the increasing base temperature as the week continues.*

Figure 7 illustrates the increasing morning temperatures as the week moves from Monday to Friday, highlighting the 'rhythm' of the week in terms of temperature change, as the building is unable to adequately vent heat overnight. This was due to a combination of factors including windows that were unable to be left open overnight due to security concerns, and their sideways opening mechanisms, risking rain ingress.




Figures 8 and 9: *Thermal imaging photographs identifying the floor as a source of heat in the office*

Figures 8 and 9 show thermal images of the intersection between the floor and a wall in the shared office, highlighting how much heat is entering the room through the floor. Making this data visible to the occupants, along with the temperature traces of the room, enables them to understand their thermal environment in a more comprehensive and nuanced way. We argue that this has potential benefits in terms of supporting effective adaptive behaviour.

These studies have highlighted a significant issue with trialling the system: managing to change the temperature at all, given all the other heat sources in the room including the IT and people themselves. Our iTRV controlled radiators are designed not to come on until the room temperature goes below a certain set point ambient temperature. Anything below 23 °C (the upper limit setpoint) resulted in the valves remaining closed all of the time. As many offices are chronically overheated (Nicol 2013), this proved to be an issue also for our testbed.

**5.2 Temperature and adaptation strategies**

One participant in the individual office study reflected that the extreme temperature adversely affected her health and performance:

> *'I always feel very drained in the summer . . . I think I get very tired and I think I don't focus on things'.*

Other health issues mentioned were headaches, swollen ankles, feeling lethargic and difficulty breathing. There was a perception that the lack of humidity caused by the heat also affects breathing and health generally.

Occupants of the shared office reported often feeling dizzy, tired and having aching eyes, as well as headaches. There were particular concerns over the previous summer (2018) which was one of the hottest summers the UK had experienced (BBC News, 3/09/2018).

> *'Last summer you know it was exceptional, but it could be the same this summer. I think we need to prepare for it.'*

> *'Some people were going home ill. Passing out, being sick, someone was sick at their desk.'*

As temperatures increase, and records continue to be broken, these issues will become even more of a concern. Our study was helpful in recognising the temperature rhythms of the day in spaces, affording people the opportunity to reconfigure their working practices in order to minimise their discomfort (or optimise their comfort, depending on the conditions). This data and knowledge therefore empower people in terms of increasing their competence in managing their own thermal comfort. However, it was noted that opportunities for adaptation (such as working elsewhere during peak temperature times, adapting clothing, reconfiguring their space in terms of window and door openings) can be limited by other factors such as institutional policies and procedures.

**5.3 Agency in shared offices**

Opportunity for adaptation can be quite limited, both in shared and single offices. Snow et al. (2016) discuss the idea of window 'ownership' whereby whoever sits next to the window has control over when that is open or closed. This behaviour was observed in the shared office, and also mentioned in interviews (‘*I don’t have a window*’). Instead, occupants all had individual desk fans which were used as their own element of control.

In single offices, the ability to open and close doors and windows both in personal office space and shared corridors and spaces (which provided much-needed through-draughts) was limited by a number of factors. These included the need to maintain privacy or confidentiality, as well as accommodating other building users who chose to configure these spaces in different ways. With regard to shared spaces, one participant stated:

> *‘I guess round here I’m the most senior colleague, so I get to do what I want.’*

The nature of the work done, and the way teams are organised can also mean that people have limited opportunity to move and rearrange their workspace:

> ‘*I need to do a certain amount on my phone, and a certain amount on the computer, other people need to know where to find me… students can pop in to find me the constraints of being in a department and being part of an organisation mean that it’s harder to be somebody who hot desks somewhere . . . it’s not a case of working regularly anywhere else.*’

In the shared office, one of the factors affecting window opening was the possibility of insect ingress:

> *‘there is one or two people in here who are frightened of insects so we have to take that as a fact. . .some people say don’t open the window or they’ll come in.’*

It is clear that working practices will need to change and workplaces will need to find different ways of operating to accommodate these constraints (e.g. the installation of insect screens).

**5.3 The role of radiators**

As this was a trial testbed deployment phase, one of our main goals was to be responsive to any complaints in case it was due to a failure of our prototype. If an occupant reported an issue with the heating system at any point, we tried to resolve it as soon as possible. In order to maintain confidence in the valves, and due to manufacturing issues and unknown failure rates, if a valve proved unreliable, we removed it and replaced it with a standard TRV.

On one occasion, we received a telephone call asking for help as the office was ‘freezing’, and the valve could not be turned on: the valves are designed so that if the room temperature is below the set point, the valve will not open and the radiator will not come on. During this complaint, on examining the data from the independent temperature logger in the room, we determined that the room temperature was 23°C and had not fallen below this at all.

However, further discussion and observation revealed that it was raining outside, and the occupant had wet outer garments from the rain, and wanted to dry them off. This highlighted one of the limitations with the technology, as the valves will not turn on if the room temperature is above the maximum setpoint (23°C). Previous interviews with the single occupancy participants revealed that radiators are commonly used to dry swimming costumes and towels (and presumably a range of other sports gear) as well as outer garments. For successful adoption of the technology, alternative solutions for drying clothing should be identified to avoid this kind of radiator use.

**5.4 The role of policy**

One of the key questions we are considering with the introduction of new heating technology is how to encourage a lower set back temperature, with more emphasis on personal adaptation (based on adaptive thermal comfort principles), and make this acceptable to building occupants. An important tool we can use to help drive this is a suitably agreed guidance policy, co-designed by stakeholders, which specifically identifies individual responsibility for thermal comfort, and make it clear that some personal adaptation may be necessary. In the example above, if the temperature of the room was 23°C, and the policy supported a lower base line temperature (e.g. 19°C) there is no requirement from the building to increase the room temperature, and energy savings are possible. Heating policy also needs to prevent adaptations which introduce energy intensive personal heating devices to avoid rebound effects.

Our study uncovered a range of 'invisible' thermal comfort policies which, as side effects, unintentionally influenced peoples' thermal comfort.

The current Lancaster University heating policy is short and general, and states that:

> *The University heating controls are set to heat buildings to maintain an ambient temperature in occupied buildings and residences during heating operational hours.*

Data protection and confidentiality meant that windows and doors which might otherwise be left open to allow air circulation and breeze have to be closed.

> *'I might be chatting to a particular student…so I'll have to shut the door for that. I might have meetings . . . where we're discussing confidential matters, the door has to be shut.'*

Whilst the university does not have a formal dress code, office-based staff mentioned:

> *'there's a smart casual dress code for most of the staff'*
>
> *'There isn't an official dress code but we are an office. . . there's an expectation that we dress for the office . . . and it's not written down and it's never actually needed to be said, it's just been respected.'*

When referring to her clothing a female occupant mentioned:

> *'I wouldn't want to wear less than this though. I would feel uncomfortable in strappy stuff at work'.*

Whilst no formal dress code exists, there are social expectations which put limits on adaptation in the University work environment.

Another unexpected effect of University policy was transport, which provides incentives for car sharing, such as cheaper parking permits. This is a laudable, as it supports carbon reduction in transport to and from the University. However, one of the shared office occupants mentioned how this constrains their ability to take an hour for lunch, and go out for some exercise (increasing metabolism) as they need to ensure their working pattern fit with their co-driver.

It is clear from these examples that a range of policies can affect thermal comfort, and the ability to adapt in the workplace. More research is needed in this area to unpack this further, but it is clear that indoor temperature policy should not be looked at in isolation from other policies.

**6.0 Discussion and conclusion**

Our study has identified that there are many challenges to implementing new heating systems in the workplace. Technological acceptance can also be problematic, and the technology we introduced initially increased 'friction' in the system by using an online interface which needs to be logged into, to request a different temperature. Plainly, further trials are necessary to gain a clear idea of the energy savings achievable through implementing the technology at a whole building scale.

Many of the buildings at Lancaster University are multi-use, consisting of offices, residences and teaching spaces such as lecture theatres and seminar rooms, all of which have different occupancy patterns. If heating needs to be supplied to a building from 6am to 11pm, (for example if residential accommodation is included), any manual TRVs that have been turned up during the day will continue to release heat and consume energy until 11pm. This would result in the heating being on for a considerable time, despite many spaces possibly only being occupied for a few hours, if at all. This can result in overheated buildings and considerable wasted heat energy.

Using the Coolbiz example cited earlier, changes in dress code would be an essential part of introducing a more adaptive heating system and transferring comfort responsibility from the building to the person. Whilst it is recognised in the literature (Morgan and De Dear 2003) that work clothing correlates more closely to outdoor temperatures when there is a supportive policy, we found that 'invisible' and unstated dress codes exist which prevent this, even in the relatively progressive environment of a University.

Identifying the role of radiators in drying clothing at work is an important finding for the design of the system, and highlight the value of stakeholder engagement in developing a system that meets user needs.

In conclusion, we propose that to be most effective in promoting adaptive behaviour, a new sustainable technology cannot be introduced in isolation. Matters that affect thermal comfort are situated in a range of non-temperature policies, and the people responsible for thermal comfort (usually energy managers) have no control over these policies. Different thermal preference is widely documented in the literature, and we have demonstrated the gulf in microclimates in a shared office. There needs to be more personal responsibility for thermal comfort in order to begin to reconcile these differences.

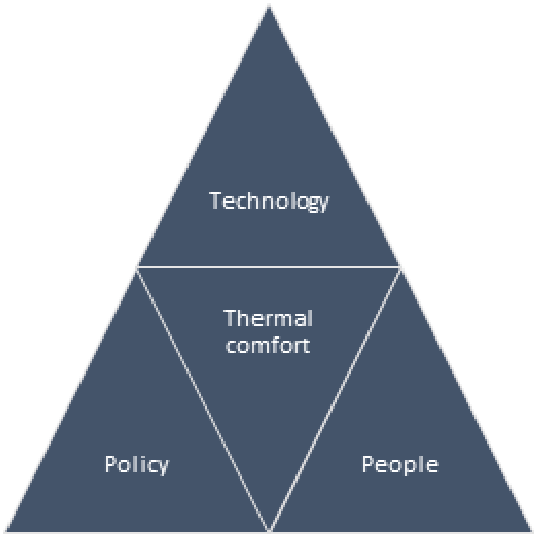



Figure 10: *The relationship between technology, people and policy*, in shaping thermal comfort

Importantly, while we might focus on thermal comfort in isolation, as we've seen, often other workplace demands or practices ('invisible policies', see further Royston 2016) such as data protection and transport policies can have an effect on thermal comfort. We believe that through a data-driven and mixed methods approach, a nuanced understanding of the workplace can lead to better informed and more effective low energy thermal comfort policies and systems.

These changes would inevitably involve a radical rethinking of the way we organise our work spaces, as well as considerable bravery on the part of the policy makers in the institution. With the current climate situation, and many of our local governments and institutions declaring climate emergencies, now is the time for radical action rather than business-as-usual approaches.

Future work intends to extend the testbed, and integrate the iTRV admin system into the building management system. This would enable links to occupancy data through the room booking system, and WiFi association (occupancy) data to assist with scheduling different temperature setpoints, further optimising heating and reducing energy use.

**Acknowledgements**

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# Investigating occupant's thermal disposition in mixed-mode offices: A field study on thermal comfort in a Brazilian subtropical climate

**Ricardo Forgiarini Rupp[1, 2], Jørn Toftum[2] and Enedir Ghisi[1]**

[1] Laboratory of Energy Efficiency in Buildings, Department of Civil Engineering, Federal University of Santa Catarina, Florianópolis/SC, Brazil, ricardorupp@gmail.com

[2] International Centre for Indoor Environment and Energy, Department of Civil Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark

**Abstract:** In this work, we aim to investigate occupant's thermal disposition in mixed-mode offices. Thermal disposition can be described as a person's self-assessment of his/her own thermal sensitivity. Classic field studies on thermal comfort were conducted in mixed-mode offices located in the city of Florianópolis (Brazil). Occupants manually controlled the mixed-mode strategy through the operation of both operable windows and unitary air-conditioning system for cooling. Occupants were asked to assess their thermal perception through a questionnaire while air temperature, globe temperature, air velocity and relative humidity were measured in situ. Statistical analysis was performed separating the data by occupant's thermal disposition. Thermal disposition was also investigated according to gender, age, body mass index and prior exposure to air-conditioning in relation to thermal discomfort. More than two thousand seven hundred questionnaires were collected during the field campaign that took a year. Results indicated that there is an agreement between thermal sensation and thermal disposition, i.e., occupants that are more sensitive to heat presented a higher thermal sensation under equivalent thermal conditions and vice-versa. Results from this study have shown an interesting way of categorising occupants according to their thermal disposition, which could be used to improve the design of personalised conditioning systems.

**Keywords:** thermal comfort; field study; mixed-mode; personalised conditioning systems.

## 1. Introduction

There are several factors that affect human thermal comfort in indoor spaces, including physiological, psychological and cultural aspects. Gender, age, body composition, metabolism, thermal history (previous thermal exposure) and adaptive opportunities available have been studied by different researchers in various climatic contexts, highlighting individual differences in thermal comfort (e.g., Byrne et al., 2005; Karjalainen, 2012; Kingma et al., 2012; Rupp et al., 2018). Despite thermal comfort has generally been described as a mental/psychological state and thermal comfort studies ask subjects about their thermal perception (i.e., sensation, preference, acceptability, comfort), other psychological variables still need to be addressed in the context of thermal comfort research.

A psychological variable, called "perceived coldnaturedness" by Howell and Kennedy (1979) and Howell and Stramler (1981) and, later called "thermal disposition" by Healey and Webster-Mannison (2012), has been associated with discrepancies in individual's thermal comfort. Thermal disposition can be described as a person's self-assessment of his/her own thermal sensitivity, i.e., being more sensitive to heat, cold, both or neither, in relation to his/her perception of the thermal sensitivity of his/her co-workers.

Howell and Kennedy (1979) conducted field studies on thermal comfort in different building typologies in Houston (USA) to validate, in actual buildings, Fanger's model, the

Predicted Mean Vote (PMV)/Predicted Percentage of Dissatisfied (PPD) model. They measured the thermal environment and applied questionnaires to occupants. Amongst the questions, they asked users about their self-perceived coldnaturedness. Results showed that clothing, air temperature and relative humidity accounted for 7-8% of the variance in thermal sensation vote in classrooms and offices, while psychological variables (perceived temperature and coldnaturedness) accounted for 10.5% and 31.2% of the variance, respectively. Howell and Kennedy (1979) stated that a narrow range of environmental conditions was find during the field studies, which can partially explain why the physical predictors accounted for so little variance in thermal sensation. Authors concluded that Fanger's model might be a valid representation of physical variables on thermal sensation, but the model is not valid for real-spaces as psychological variables play an important role and users are able to adapt to shifts in physical conditions. Howell and Stramler (1981) performed new field studies in offices and classrooms and confirmed the achievements of Howell and Kennedy (1979), i.e., the psychological variables were more important for individual's thermal sensation than non-psychological variables.

A pilot field study was performed in a small office in Brisbane, Australia, using a mixed-methods approach (thermal comfort assessment methods and structured qualitative methods) (Healey and Webster-Mannison, 2012). During the interviews, users were asked about their thermal disposition and most of them were able to identify themselves as being more sensitive to cold and/or heat. Based on the pilot study, Healey (2014) conducted a field study on thermal comfort in a mixed-mode office in Gold Coast (hot and humid climate of Australia) and interviewed the participants. Occupants more sensitive to cold presented a higher neutral temperature than those more sensitive to heat. Healey (2014) concluded that occupants adjusted the indoor thermal environment according to their thermal disposition.

Other studies are found in the literature (Nagashima et al., 2002; Yasuoka et al., 2012; Jacquot et al., 2014) that investigated individual differences in thermal sensitivity, although they do not call it thermal disposition. Young Japanese women were studied in a climate chamber regarding their body core and skin temperatures and thermal comfort (Nagashima et al., 2002). After an interview with the subjects, which included ten questions (e.g., do you feel colder than others?), researchers separated the women in two groups: group C (people that complained of persistent coldness, which is commonly called Cold Syndrome in Japan) and group N (women not suffering from coldness). Each subject was exposed to two different experimental protocols: a control session at 29.5°C and a cold session at 23.5°C. Results pointed out that group C subjects felt colder than group N subjects in the cold session (body core and skin temperature were similar between both groups, but the metabolic rate was lower in group C). Authors concluded that such higher thermal sensitivity to cold may be associated to low thyroid function (T4) in group C subjects, which can explain the lower metabolism in group C (Nagashima et al., 2002). Another two climate chamber experiments were carried out with young Japanese female subjects (Yasuoka et al., 2012). Subjects were asked whether they feel generally colder than others in the same space. In the first experiment, participants were allowed to adjust room temperature according to their preferences. Based on the results, participants were separated into two groups: group H (preferred higher temperatures, ≥29 °C) and group M (preferred medium temperatures, <29 °C). Then, the second experiment took place where subjects were exposed to variations in air temperature between 33 °C and 25 °C. Group H subjects reported colder thermal sensation than group M and no differences in mean skin temperature were found between the two groups.

Most of these studies recruited a few participants. Therefore, more studies considering a larger sample are needed to explore the impact of occupant's thermal disposition on thermal comfort. In this work, we aim to investigate occupant's thermal disposition in actual mixed-mode offices.

## 2. Method

Field studies on thermal comfort were conducted during a year in a mixed-mode office building. The building is in the humid subtropical climate of Florianópolis, Brazil (latitude -27°36' and longitude -48°33'). Offices have no heating, and cooling systems are installed in all spaces – the mixed-mode strategy is manually operated by users who decide when windows should be opened/closed, or the air-conditioning system turned on/off. Some characteristics of the building and its occupants can be seen in Table 1. The building is a public building located in the city centre. All occupants of the building were invited to participate as volunteers in the study.

Table 1. Characteristics of the mixed-mode building and its occupants.

| | |
|---|---|
| **General features** | |
| Construction year | 1990 |
| Retrofit | 2012 |
| Total floor plan area ($m^2$) | 3,090 |
| Number of blocks | 1 |
| Number of floors | 5 |
| Shape | Rectangular |
| Construction | Concrete |
| External walls | Apparent concrete |
| Windows | Clear single glass with applied reflective film |
| Shading devices | Facade elements |
| **Indoors** | |
| Offices | Open plan with lightweight partition materials |
| Indoors height (m) | 2.6 |
| **Occupation** | |
| Number of occupants (approximately) | 250 |
| Working hours (approximately) | 8am - 6pm |
| **Air-conditioning and natural ventilation system** | |
| Natural ventilation system | Operable windows |
| Air-conditioning system | Split system |
| Mixed-mode operation | Changeover controlled by users |
| **Comfort surveys** | |
| Period | 2015 - 2016 |
| Season | All seasons |
| Questionnaires | 2,741 (Male: 1,480, Female: 1,261) |

## 2.1. Data collection

Thermal comfort questionnaires were applied to building occupants while instrumental measurements of environmental variables were carried out in the offices. Clothing, activity, demographic (age and gender) and anthropometric (height and weight) information about occupants were collected through the questionnaires. Clothing and activity levels were estimated in accordance with ASHRAE 55 (2017). Questionnaires also included questions about thermal perception (sensation, preference, acceptability and comfort), thermal disposition and occupant's dependence on air-conditioning (AC) outside the studied offices – Table 2. Four categories were adopted, according to Healey (2014), in order to ask users about their thermal disposition. Occupant's dependence on AC was grouped in four categories according to the frequency and daily usage of air-conditioning outside the workspace, i.e., the higher the frequency and daily usage of AC, the higher the dependence on AC. This criterion was adopted in a previous work (Rupp et al., 2018).

Microclimate stations recorded the indoor air temperature, globe temperature, air velocity ($V_{ar}$) and relative humidity (RH). Measurements were performed according to ASHRAE 55 (2013). Outdoor thermal conditions were collected from a meteorological station located near the building.

Table 2. Scales adopted in the questionnaires.

| Scale | -3 | -2 | -1 | 0 | +1 | +2 | +3 |
|---|---|---|---|---|---|---|---|
| Thermal sensation | Cold | Cool | Slightly Cool | Neutral | Slightly Warm | Warm | Hot |
| Thermal preference | - | - | Cooler | No change | Warmer | - | - |
| Thermal acceptability | - | - | - | Acceptable | Unacceptable | - | - |
| Thermal comfort | - | - | - | Comfortable | Uncomfortable * | - | - |
| Thermal disposition | - | - | - | Not Sensitive | Sensitive to Heat and Cold | Sensitive to Heat | Sensitive to Cold |
| Dependence on AC | - | - | - | None | Light | Moderate | Heavy |

* Occupants that answered "uncomfortable" in the thermal comfort question must indicate if the discomfort was due to heat or cold sensation.

## 2.2. Data analysis

Statistical analysis was performed in R statistical software environment (R Core Team, 2019).

The operative temperature and the prevailing mean outdoor air temperature ($T_{pma(out)}$) were calculated following ASHRAE 55 (2017). For the latter, we estimated the mean daily outdoor temperature and adopted a value of 0.6 for the constant α (weighting method). PMV, PPD and Standard Effective Temperature (SET) were calculated in R software – scripts developed by Silva et al. (2016).

Neutral temperatures were estimated for each thermal disposition group category. The body mass index (BMI) was calculated by dividing the weight by the square of the body height.

As our field campaign took a year to be completed, users could have experienced different thermal conditions. In order to adjust such differences in thermal history prior to the survey-day, we adopted a relative temperature scale (Equation 1): the temperature offset from neutrality ($T_{diff}$), which has been used in other studies (Nicol and Humphreys, 2007; Indraganti et al., 2014; Rupp et al., 2018).

$$T_{diff} = T_o - T_{comf} \qquad \text{(Eq. 1)}$$

where: $T_{diff}$ is the temperature offset from neutrality (°C); $T_o$ is the indoor operative temperature (°C); $T_{comf}$ is the indoor neutral (comfort) temperature estimated through the adaptive thermal comfort model from ASHRAE 55 (2017) (°C).

In order to investigate the influence of occupant's thermal disposition on the thermal perception, we conducted linear regressions and logistic regressions. Linear regression was performed between indoor operative temperature and thermal sensation vote for each thermal disposition category.

Multiple logistic analyses were carried out considering key variables: $T_{diff}$, gender, age, BMI, dependence on AC, and thermal disposition as independent variables. BMI values were separated in two groups: overweight (BMI > 25.0 kg/m$^2$) and non-overweight (BMI < 25.0 kg/m$^2$). We also separated the occupant's age in two groups (younger than 50 years and over 50 years). The dependent variable was based on the user's thermal comfort vote (Table 2). Thus, two sets of analyses were performed in order to predict warm and cold discomfort. Equation 2 shows the probability of occupants to express warm or cold discomfort as a function of the independent variables. Wald chi-square test was employed to evaluate the statistical significance of each *b* coefficient for the predictor in the logistic regression models, i.e., when a coefficient of an independent variable in the model is significantly different from 0 (zero), that variable contributes significantly to the prediction of the outcome. We also used the Odds Ratio (OR) to estimate the likelihood of the occupants reporting warm discomfort and cold discomfort in comparison with the reference group (OR = 0).

$$P(discomfort) = (1 + e^{-(b0+b1.X1+b2.X2+\ldots+b6.X6)})^{-1} \qquad \text{(Eq. 2)}$$

where: *P(discomfort)* is the probability of cold/warm thermal discomfort occurring; *e* is the base of natural logarithms; *b0* is the constant of the logistic regression model; *b1* is the regression coefficient of the variable *X1*; *b2* is the regression coefficient of the variable *X2*; and so on. Six predictors were adopted ($T_{diff}$, gender, age, body mass index, dependence on air-conditioning and thermal disposition) for multiple logistic analysis and a single predictor was used ($T_{diff}$) for the simple logistic regressions.

We also performed simple logistic regression for each thermal disposition category by using $T_{diff}$ as the independent variable and warm or cold discomfort as the dependent variable (Equation 2). This way we obtained two curves (warm and cold discomfort), which were summed into one curve in order to show the total percentage of dissatisfied, an approach similar to the derivation of the PMV-PPD curve (Fanger, 1970). The 80% comfort ranges were determined by localising in both sides of the curve the 20% cold and heat dissatisfied (Y-axis) and their intersections with the temperature offset from neutrality (X-axis).

## 3. Results

Data collection resulted in a sample of 2,741 answers to the questionnaires (54% of males and 46% of females) with 52% of data collected during air-conditioning operation and 48% in natural ventilation mode (Table 3).

### 3.1. Characteristics of the building and its occupants

Table 3 presents an overview of indoor and outdoor thermal conditions, human variables, user's responses and calculated indices during field studies in both modes of operation of mixed-mode offices. Indoor thermal conditions were similar between both modes of operation while the prevailing mean outdoor air temperature was significantly lower during natural ventilation operation since occupants opened windows mainly in winter and intermediate seasons. Because of this, clothing was higher during natural ventilation operation. A heterogeneous sample of occupants participated in the study. Thermal responses and PMV pointed out to near-neutral sensations in both modes of operation. User's thermal acceptability and thermal comfort were high.

Table 3. Overview of indoor and outdoor thermal conditions, human variables, user's responses and calculated indices during field studies in both operation modes of mixed-mode offices. Values are shown as mean ± S.D.

| Variable category | Variable name | Air-conditioning (n=1,425) | Natural ventilation (n=1,316) |
|---|---|---|---|
| Indoors | To (°C) | 24.2 ± 1.1 | 24.0 ± 1.2 |
| | Va (m/s) | 0.11 ± 0.02 | 0.12 ± 0.09 |
| | RH (%) | 60 ± 6 | 67 ± 9 |
| Outdoors | $T_{pma(out)}$ (°C) | 22.6 ± 2.5 | 19.4 ± 1.7 |
| Human variables | Metabolism (met) | 1.19 ± 0.15 | 1.18 ± 0.14 |
| | Clothing (clo) | 0.61 ± 0.11 | 0.74 ± 0.20 |
| | Age (years) | 37.2 ± 10.7 | 38.4 ± 11.0 |
| | Weight (kg) | 75.2 ± 15.5 | 72.0 ± 15.0 |
| | Height (m) | 1.70 ± 0.10 | 1.69 ± 0.09 |
| | Body mass index (kg/m$^2$) | 25.7 ± 3.9 | 25.1 ± 3.9 |
| User's responses | Thermal sensation (TSV) | 0.0 ± 0.8 | 0.1 ± 0.7 |
| | Thermal preference | 0.1 ± 0.5 | 0.1 ± 0.5 |
| | Thermal acceptability | 0.1 ± 0.3 | 0.0 ± 0.2 |
| | Thermal comfort | 0.2 ± 0.4 | 0.1 ± 0.3 |
| | Thermal disposition | 1.6 ± 1.0 | 1.9 ± 1.0 |
| | Dependence on AC | 1.3 ± 1.1 | 1.3 ± 1.1 |
| Calculated indices | $T_{comf}$ (°C) | 24.8 ± 0.8 | 23.8 ± 0.5 |
| | $T_{diff}$ (°C) | -0.6 ± 1.2 | 0.2 ± 1.0 |
| | PMV | 0.0 ± 0.5 | 0.2 ± 0.4 |
| | PPD (%) | 10 ± 6 | 10 ± 5 |
| | SET (°C) | 25.4 ± 1.9 | 26.3 ± 2.0 |

### 3.2. Investigating occupant's thermal disposition and thermal perception

Considering all data, 38% of occupants reported being more sensitive to heat, while 27% stated being more sensitive to cold and the remaining 35% of occupants expressed being more sensitive to both heat and cold (21%) or not sensitive (14%).

Linear regression analyses were performed between thermal sensation vote and indoor operative temperature with the intention to assess whether occupants with different thermal dispositions also have distinct thermal sensations. Figure 1 presents the results of the linear regression analyses, where it may be observed that users more sensitive to heat demonstrated a higher thermal sensation vote than those more sensitive to cold, under equivalent thermal conditions. Users sensitive to both cold and heat and those who were not sensitive to either cold or heat showed thermal sensations somewhere in between users more sensitive to cold or more sensitive to heat, except for some data points in lower temperatures, where less data was collected and, because of that, a wider confidence interval can be noticed.

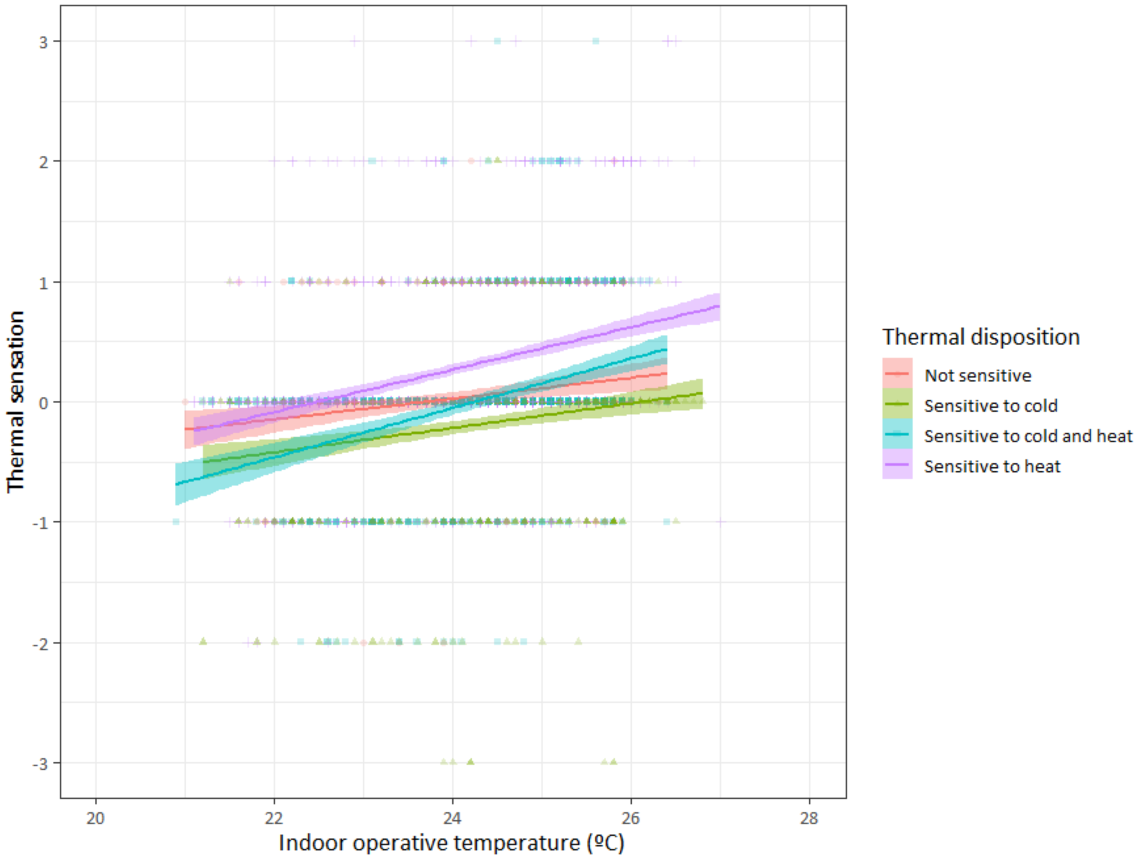



Figure 1. Linear regression between indoor operative temperature and thermal sensation vote for each thermal disposition category. Confidence intervals of 95% are shown in bands along the regression lines. Density of data may be observed by lighter/darker coloured points.

Table 4. Linear regression equations between indoor operative temperature and thermal sensation vote for each thermal disposition category and, neutral temperatures (solving equations with TSV=0).

| Thermal disposition category | Linear regression equation | Neutral temperature (°C) |
|---|---|---|
| Not sensitive | TSV = 0.09To – 2.05 (n=391, $R^2$=0.03, p<0.001) | 23.7 |
| Sensitive to cold and heat | TSV = 0.21To – 4.98 (n=583, $R^2$=0.10, p<0.001) | 24.2 |
| Sensitive to heat | TSV = 0.18To – 3.98 (n=1031, $R^2$=0.09, p<0.001) | 22.5 |
| Sensitive to cold | TSV = 0.10To – 2.67 (n=732, $R^2$=0.03, p<0.001) | 26.1 |

The resulting linear regression equations (Table 4) reveals that users sensitive to both cold and heat and those sensitive to heat have a higher thermal sensitivity (i.e., a higher gradient of the linear regression equation) than users more sensitive to cold or not sensitive. Thus, the latter two groups have a wider tolerance to temperature variations when considering their thermal sensation vote. Neutral temperatures, derived by solving the equations with a thermal sensation vote equal to 0 (zero), showed that, in fact, occupants more sensitive to cold have the highest neutral temperature (26.1 °C) and, those more sensitive to heat have the lowest neutral temperature (22.5 °C) – a significant difference of 3.6 °C. People sensitive to cold and heat presented a similar neutral temperature than those not sensitive.

In order to further investigate occupants' thermal disposition and examine if, indeed, this variable is a significant contributor to thermal comfort predictions, we performed multiple regression analyses considering also other known variables, from a previous study (Rupp et al., 2018), that affect thermal discomfort, i.e., temperature offset from neutrality, gender, age, body mass index and prior exposure to air-conditioning (i.e., dependence on AC). Tables 5 and 6 present the results of multiple logistic regression analyses for user's warm and cold discomfort, respectively. The strongest predictor of thermal discomfort was the temperature offset from neutrality as may be observed by the Wald test results (45.15 for warm discomfort and 51.55 for cold discomfort), followed by thermal disposition (Wald = 22.63 for warm discomfort and 25.09 for cold discomfort). Overall, gender and age were insignificant (NS) to predict thermal discomfort ($p>0.05$). For warm discomfort, in addition to $T_{diff}$, the body mass index, the dependence on AC and the thermal disposition (except by users more sensitive to cold) were associated with occupant's warm discomfort. Overweight occupants are 1.48 times more likely to express warm discomfort than non-overweight occupants, and those who use AC more heavily are 1.24 times more likely to express warm discomfort than light users of AC – both values are similar to the ones we got in our previous study (Rupp et al., 2018) in office buildings in Florianópolis. Regarding thermal disposition, occupants more sensitive to heat and those sensitive to both cold and heat are respectively 5.97 times and 2.92 times more likely to express warm discomfort than users not sensitive to either cold or heat.

Table 5. Results of multiple logistic regression model considering user's warm discomfort.

| Predictors | b | Wald | Sig. | Odds Ratio (OR) |
|---|---|---|---|---|
| Temperature offset from neutrality | 0.42 | 45.15 | p<0.001 | 1.52 |
| Gender | - | - | NS | - |
| Age | - | - | NS | - |
| Body mass index | 0.39 | 6.06 | p<0.05 | 1.48 |
| Dependence on air-conditioning | 0.22 | 11.22 | p<0.001 | 1.24 |
| Thermal disposition [Sensitive to heat and cold] | 1.07 | 22.63 | p<0.001 | 2.92 |
| Thermal disposition [Sensitive to heat] | 1.79 | | p<0.001 | 5.97 |
| Thermal disposition [Sensitive to cold] | - | - | NS | - |

Note: N=2,741. $R^2$=0.73(Nagelkerke). Model $\chi^2(6)$=211.37, $p<0.001$. Reference group: female, ≤50 years, non-overweight, none (dependence on AC), not sensitive.

Table 6. Results of multiple logistic regression model considering user's cold discomfort.

| Predictors | b | Wald | Sig. | Odds Ratio (OR) |
|---|---|---|---|---|
| Temperature offset from neutrality | -0.55 | 51.55 | p<0.001 | 0.57 |
| Gender | - | - | NS | - |
| Age | - | - | NS | - |
| Body mass index | - | - | NS | - |
| Dependence on air-conditioning | - | - | NS | - |
| Thermal disposition [Sensitive to heat and cold] | - | - | NS | - |
| Thermal disposition [Sensitive to heat] | -1.53 | 25.09 | p<0.001 | 0.21 |
| Thermal disposition [Sensitive to cold] | 1.75 | | p<0.001 | 5.74 |

Note: N=2,741. $R^2$=0.84(Nagelkerke). Model $\chi^2(6)$=210.02, $p<0.001$. Reference group: female, ≤50 years, non-overweight, none (dependence on AC), not sensitive.

For cold discomfort, our multiple logistic regression analysis showed that only $T_{diff}$ and two categories of thermal disposition (users more sensitive to cold and users more sensitive to heat) were associated with occupant's cold discomfort. Users more sensitive to cold are 5.74 times more likely to express cold discomfort than users not sensitive to either cold or heat. Occupants not sensitive to cold or heat are 4.76 times (OR=0.21 for users more sensitive to heat, i.e., OR=1.00/0.21 for those not sensitive) more likely to express cold discomfort than users more sensitive to heat.

Intending to better understand the differences in thermal comfort between occupants more sensitive to heat and users more sensitive to cold, we separated our database to consider only those two thermal disposition categories. Then, we performed multiple logistic regression following the same logic as in Tables 5 and 6. The results are shown in Tables 7 and 8. For warm discomfort (Table 7), $T_{diff}$ was the strongest predictor (Wald = 38.59) of thermal discomfort closely followed by thermal disposition (Wald = 31.51). Apart from $T_{diff}$ and thermal disposition, only the dependence on AC associated with thermal discomfort. Occupants more sensitive to heat are 4.55 times (OR=0.22 for users more sensitive to cold) more likely to express warm discomfort than their counterparts. Occupants that use AC more heavily are 1.21 times more likely to express warm discomfort than light occupants of AC, which is similar to the results obtained using our entire database (Table 5).

Table 7. Results of multiple logistic regression model considering user's warm discomfort for occupants sensitive to cold and sensitive to heat.

| Predictors | b | Wald | Sig. | Odds Ratio (OR) |
|---|---|---|---|---|
| Temperature offset from neutrality | 0.45 | 38.59 | p<0.001 | 1.56 |
| Gender | - | - | NS | - |
| Age | - | - | NS | - |
| Body mass index | - | - | NS | - |
| Dependence on air-conditioning | 0.19 | 6.44 | p<0.05 | 1.21 |
| Thermal disposition | -1.50 | 31.51 | p<0.001 | 0.22 |

Note: N=1,765. $R^2$=0.17(Nagelkerke). Model $\chi^2(6)$=162.94, $p<0.001$. Reference group: female, ≤50 years, non-overweight, none (dependence on AC), sensitive to heat.

Table 8. Results of multiple logistic regression model considering user's cold discomfort for occupants sensitive to cold and sensitive to heat.

| Predictors | b | Wald | Sig. | Odds Ratio (OR) |
|---|---|---|---|---|
| Temperature offset from neutrality | -0.57 | 33.42 | p<0.001 | 0.56 |
| Gender | - | - | NS | - |
| Age | - | - | NS | - |
| Body mass index | - | - | NS | - |
| Dependence on air-conditioning | - | - | NS | - |
| Thermal disposition | 3.37 | 54.55 | p<0.001 | 28.94 |

Note: N=1,765. $R^2$=0.27(Nagelkerke). Model $\chi^2(6)$=182.10, $p<0.001$. Reference group: female, ≤50 years, non-overweight, none (dependence on AC), sensitive to heat.

Considering cold discomfort (Table 8), the Wald test results indicated that the strongest predictor of thermal discomfort was thermal disposition (Wald = 54.55) followed by $T_{diff}$ (Wald = 33.42) and, those two variables were the only ones associated with cold discomfort – the same trend observed in Table 6. Users more sensitive to cold are 28.94 times more likely to express cold discomfort than people more sensitive to heat. In fact, it is harder that users more sensitive to heat complain about cold discomfort, as can be seen in Figure 2b.

Gender was not associated with thermal discomfort in any of our analysis, which is against the outcomes of our previous research (Rupp et al., 2018) that did not consider the thermal disposition variable. Perhaps, this is due to the fact that it is the thermal disposition (also known as coldnaturedness), a psychological variable, and not the gender that is associated with thermal perception, as Howell and Kennedy (1979) stated:

> sex is also consistently related to the cognitive "coldnaturedness" variable. Apparently, women tend to perceive themselves as more "coldnatured" than do men, and it is this difference, rather than sex per se, that contributes to the slight difference in thermal sensation judgments (Howell and Kennedy, 1979, p. 236).

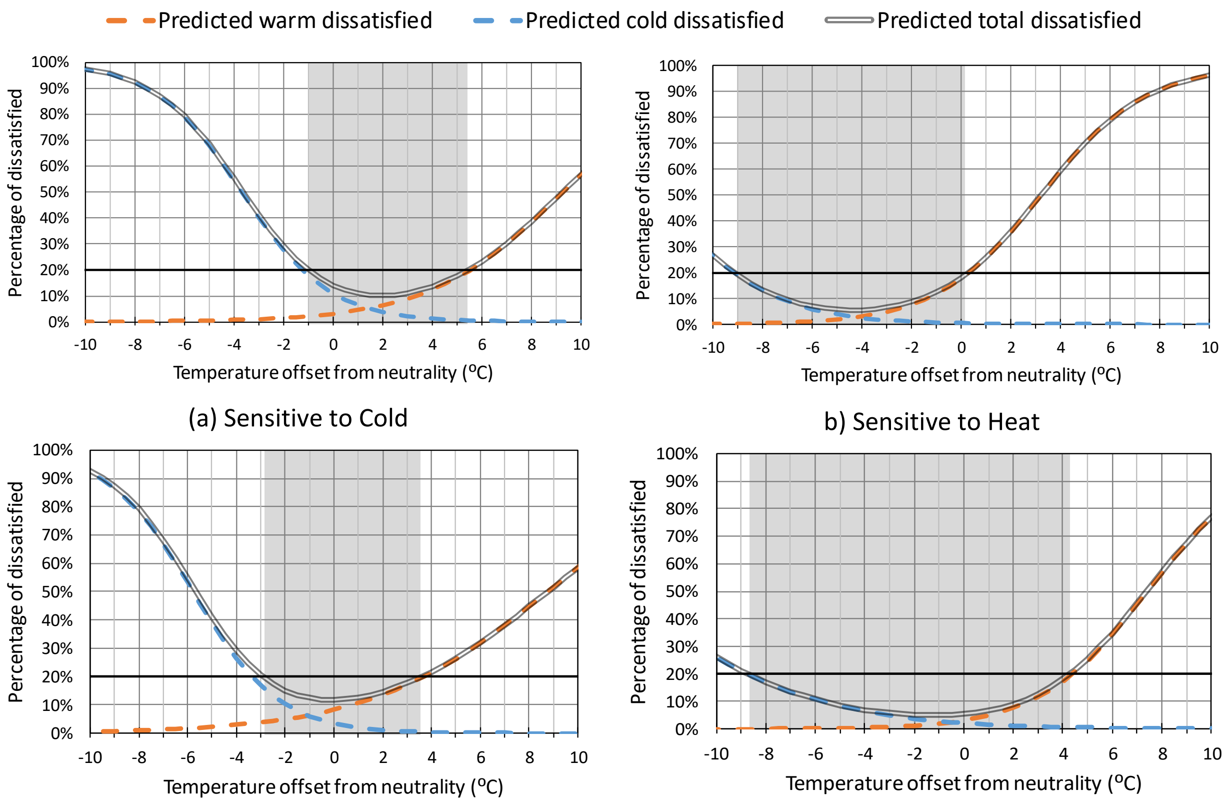
In our analyses, we also found that women tend to perceive themselves more sensitive to cold than do men (48% of women answered they were more sensitive to cold, against 9% of men). The opposite was observed regarding occupants more sensitive to heat, where 54% of men said they were more sensitive to heat while 18% of women stated the same.

**3.3. Exploring ranges of thermal comfort by occupant's thermal disposition**

As one of the most influential variables to affect thermal discomfort was thermal disposition, we conducted further analysis to explore the widths of the thermal comfort ranges for each thermal disposition category. We used simple logistic regression to build prediction curves relating the temperature offset from neutrality and the percentage of dissatisfied, in order to define 80% thermal comfort ranges. Figure 2 presents the thermal comfort ranges and the predicted percentage of thermal discomfort as a function of the temperature offset from neutrality for the four thermal disposition categories. The curves can be interpreted like the classic Fanger's PMV/PPD curve, but instead of considering PMV on the x-axis, we used the temperature offset from neutrality calculated from the adaptive thermal comfort model of ASHRAE 55. This way, the curves showed a minimum PPD of 5% (like Fanger's model) for users not sensitive to either cold or heat (Figure 2d). However, this happened when $T_{diff}$ was equal to -1.5 °C. The minimum PPD was higher (12%) for occupants sensitive to both cold and heat (Figure 2c) when $T_{diff}$ was equal to 0.0 °C, which coincides with the indoor comfort temperature from ASHRAE 55 adaptive thermal comfort model. People more sensitive to cold and those more sensitive to heat presented a minimum PPD of 10% and 6% when $T_{diff}$ was equal to 2.0 °C and -4.5 °C, respectively (Figures 2a e 2b). This suggests that a different indoor comfort temperature than prescribed by ASHRAE 55 model is demanded depending on user's thermal disposition, i.e., users more sensitive to cold require a higher temperature than the adaptive model from ASHRAE 55 and users more sensitive to heat need a lower temperature.

It is also interesting to notice that the ranges of thermal comfort are related to occupants' thermal disposition (Figure 2). Users more sensitive to cold showed a thermal comfort range tending to the warm side of $T_{diff}$ scale (from -1.0 to 5.5 °C, a range of 6.5 °C), while occupants more sensitive to heat presented a thermal comfort range tending almost entirely to the cooler side of $T_{diff}$ scale (-9.1 to 0.2 °C, a range of 9.3 °C). Also, a more similar distribution of thermal comfort ranges on both sides of $T_{diff}$ scale was achieved for users sensitive to both cold and heat (between -2.9 to 3.6 °C, a range of 6.5 °C). A wider range of thermal comfort (12.9 °C) from -8.7 to 4.2 °C was obtained for occupants not sensitive to either cold or heat. The adaptive model of thermal comfort from ASHRAE 55 (2017) established a universal (for all people) valid indoor comfort temperature range of 7.0 °C, evenly distributed from the midpoint (zero – neutrality). Considering our data from mixed-mode buildings in a Brazilian subtropical climate, we may highlight some differences and similarities in relation to the ASHRAE's model:

- ASHRAE's range of 7.0 °C was similar to the ranges derived for users more sensitive to cold and those sensitive to both cold and heat. However, a wider range of up to 12.9 °C (people not sensitive to cold or heat) was obtained for the other two thermal disposition categories.
- The evenly distributed range (± 3.5 °C) of ASHRAE 55's model looks a bit like the range calculated for occupants sensitive to both cold and heat. However, for the other three thermal disposition categories, the 80% comfort ranges were unevenly distributed from the midpoint, as mentioned before, which indicates that the comfort ranges do change depending on occupant's thermal disposition.




(a) Sensitive to Cold

b) Sensitive to Heat

(c) Sensitive to both Cold and Heat

(d) Not Sensitive

Figure 2. Predicted percentage of thermal discomfort as a function of the temperature offset from neutrality according to thermal disposition. The grey bands show the 80% comfort range.

## 4. Conclusions

A psychological variable, known as thermal disposition, was explored in this work. Occupants in mixed-mode offices were investigated regarding their thermal perception in the subtropical climate of Brazil. Field studies involving simultaneous measurements of environmental variables with the application of questionnaires were performed during a year, which resulted in more than two thousand seven hundred valid questionnaires. Data were submitted to statistical analyses, and the main contributions are:

- An agreement between thermal sensation and thermal disposition was observed in this work. Under equivalent thermal conditions, occupants that were more sensitive to heat showed a higher thermal sensation than occupants more sensitive to cold, which also reflected in their neutral temperatures (a 3.6 °C lower neutral temperature was estimated for users more sensitive to heat in relation to users more sensitive to cold).
- Thermal disposition was found to be associated with thermal discomfort and along with the temperature offset from neutrality ($T_{diff}$) were the most influential variables to predict both warm and cold discomfort. Occupants more sensitive to heat are more likely to express warm discomfort than users more sensitive to cold while the latter is more likely to manifest cold discomfort than their counterparts. In addition to thermal disposition and the temperature offset from neutrality, the body mass index and the degree of dependence on air-conditioning systems outside the workplace were associated with occupant's warm discomfort. Overweight occupants are more likely to express warm discomfort than non-overweight occupants, and people that use air-conditioning more frequently are more likely to register warm discomfort than light users of air-conditioning.
- User's thermal disposition also affects the range of indoor temperatures people find comfortable (the thermal comfort range). Occupants more sensitive to cold presented a trend to the warm side of the temperature offset from neutrality scale while the thermal comfort range from users more sensitive to heat tended nearly entirely to the cooler side of the relative temperature scale. A wider range of $T_{diff}$ was estimated for users not sensitive to either cold or heat and a thermal comfort range more evenly distributed from the neutral temperature based on the adaptive model of thermal comfort from ASHRAE 55 (2017) was predicted to users sensitive to both cold and heat. The minimum predicted percentage of dissatisfied (PPD) varied between 5% and 12% for users not sensitive to either cold or heat and for users sensitive to both cold and heat, respectively. Overall, the minimum PPDs were achieved when $T_{diff}$ was different from neutrality (i.e., $T_{diff} \neq 0$); the only exception was the minimum PPD from users not sensitive to either cold or heat that occurred when $T_{diff}$ was equal to zero.

The analyses conducted in this work did not find an association between gender and thermal discomfort while our previous study (Rupp et al., 2018) showed the contrary. However, we did not consider the thermal disposition variable in the previous research. In our current work, we also found that women tend to perceive themselves more sensitive to cold than do men, while men tend to perceive themselves more sensitive to heat. Thus, because of this and based on the research of Howell and Kennedy (1979), maybe it is not the gender but this psychological variable (thermal disposition) that should be considered when addressing individual differences on thermal comfort. An in-depth analysis could be performed in future studies to support or not such achievements. Another point that requires further investigation is regarding a possible reporting bias as occupants reported on both their thermal sensation and their thermal disposition.

This work also highlighted the importance of categorising users according to their thermal disposition in order to improve thermal comfort predictions, supporting other studies in this subject (Howell and Kennedy, 1979; Howell and Stramler, 1981; Healey and Webster-Mannison, 2012) and further research that also categorised people according to different variables (Nagashima et al., 2002; Yasuoka et al., 2012; Jacquot et al., 2014). Further research may explore such categorisation to improve the design of personalised conditioning systems.

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# Office workers' stress level; The impact of IEQ, Control and Personal factors

**Azadeh Montazami[1] and Chris Lunn[1]**

[1] Centre for the Built and Natural Environment (BNE), Coventry University, 3 Gulson Road, CV1 2JH, UK; azadeh.montazami@coventry.ac.uk

**Abstract:** Indoor Environmental Quality (IEQ) has a significant impact on office workers' productivity levels, however, the extent to which IEQ affects general stress is understudied. This study aims to determine the impact of the physical office environment on office workers' stress levels based on data obtained from a questionnaire. The questionnaire was developed based on the combination of Building Use Studies (BUS) method and Crisis Inventory - 93 scale which is used to evaluate physiological stress symptoms. In total, 93 occupants from 45 offices participated in this survey. In this study, occupants' perceptions about various aspects of comfort, their sensitivity and level of control over IEQ and also their physiological stress symptoms were questioned. For this study, an ES (Environmental Stress) score based on the occupants' vote on physiological stress in relation to IEQ was developed. The results show that the ES score is significantly affected by aggregated scale comfort dissatisfaction. Thermal comfort over the summer and air quality over the winter have the main influence on ES score. The greater usability of control over IEQ significantly correlated with a lower ES score. This study also highlights that individual sensitivity level toward the various aspects of comfort is an influential factor on stress symptoms.

**Keywords:** Stress symptom, Indoor Environmental Quality, Office, Control, Individual Sensitivity

## 1. Introduction

The reduction of stress from the physical office would be beneficial to workers and offer large economic incentives for employers to provide optimal work environments. Offices are important to the global economy; in the UK for example, over 11 million people, just above 1/3 of all the UK workforce, work in offices (Hampton, 2015). Office-based employment has grown rapidly, adding one million jobs between mid-2010 and 2015 (Hampton, 2015). The number of UK office workers has increased, with an additional 90,000 in 2016 and 74,000 in 2017 (CBRE Research, 2016). Due to this growth, significant financial investment has been made in offices (Hampton, 2015).

Ensuring offices are of good quality is important, as poor environment negativity affects the health and performance of workers (Burge, 2004). The World Health Organization (WHO) (1995) states that one-third of an adult's life is spent at work and conclude that the work environment affects physical and psychological health (Leka and Jain, 2010). Another WHO report estimates "3.6% of the total burden of disease was directly related to the work environment" in 2004 in many Western European countries (Whitehead and Dahlgren, 2006). Though this relates to all work environments rather than just offices, many of the major hazards identified are still present in offices, such as "physical factors, adverse ergonomic conditions, allergens and varied psychosocial factors" (Whitehead and Dahlgren, 2006). Property specialist Savills found 40% of office workers believe their office is positive for their health, although 30% stated they thought it was detrimental (Lang *et al.,* 2016). Mental health can also be affected by office layout: 48% of respondents thought that the office layout supported their wellbeing (Lang *et al.,* 2016). This shows that the public already understands the connection between the work environment and their wellbeing and health.

**1.1. Stress and office environment:**

Stress has large economic and societal costs (The Sainsbury Centre for Mental Health, 2007). The reduction of stress can yield significant returns on investment, with improved health and productivity of society. The initial definition of stress was set broadly by Hans Selye (1976) as the "nonspecific response of the body to any demand". Therefore, the concept of stress has been widely applied to physical and psychological burdens and work-based psychological stresses have been extensively studied. The European Agency for Safety and Health at Work (2009) states that stress is the second most common health condition from the 'work environment', though in other fields the 'work environment' is often used to describe the organisation factors as well as physical conditions. The European Agency for Safety and Health at Work (2009) estimates that in the UK, 12% of the working population is suffering from stress from work. It has been estimated by the Sainsbury Centre for Mental Health (2007) that the cost of mental health problems to UK employers is nearly £26 billion per year. Additionally, stress can contribute to long-term health conditions such as heart disease, depression and musculoskeletal problems (Leka and Jain, 2010, McEwen, 2008).

Studies of stress in the 'work environment' have often overlooked the physical work environment (Vischer, 2007), often focusing on job strain, organisational management or interpersonal relationships (Blaug, 2007; Leka and Jain, 2010). The physical environment is often seen as having little influence on the stress of workers. However, theoretical frameworks connecting IEQ and overall stress have been proposed by Rashid and Zimring (2008) and by Vischer (2007, 2008) and Wineman (1982)

**1.2. Stress and body reaction:**

The body tries to maintain a favourable internal environment to continue living. This involves many physiological systems, for example, temperature, fluid pressure and pH, which is collectively known as homeostasis. Therefore a "stressor is anything that knocks homeostasis out of balance" (Sapolsky, 2004: 6). Although homeostasis is physiological, it can be maintained through physiological or behavioural change. Stressors can be of three types; acute physical, chronic physical and psychological, affecting the autonomic nervous system and hormones. The effect on the autonomic nervous system, which branches out to nearly every organ in the body, affects organ functioning, enabling the body to respond to emergencies. Additionally, when the brain perceives a stressful situation, it responds by releasing hormones, triggering the release of other stress hormones that, through the circulatory system, spread through the entire body. These two pathways of the stress reaction mean that stressors can have direct effects on physiology or can be activated through the brain's appraisal of stressors. The stress-response can be modulated by the psychological appraisal. "Psychological stress occurs when an individual perceives that environmental demands tax or exceed his or her adaptive capacity." (Cohen et al, 2007). Strong psychological moderators of stress are "outlets for frustration", social support, predictability, control or "perception of things worsening" (Sapolsky, 2004)

Studies have shown aspects of IEQ correlate with raised stress biomarkers of office occupants (Jung *et al.,* 2014; Kristiansen *et al.,* 2009; C.-Y. Lu *et al,.* 2007; J. F. Thayer *et al.,* 2010), however, many of these studies are from a medical background and fail to adequately describe the built environment. Whereas, built environmental research studies into stress often examine architectural elements, rather than IEQ and examine singular physiological markers of stress. Additionally, occupant studies related to IEQ do not directly look at stress, however, these studies mainly look at environmental dissatisfaction, productivity, absenteeism, or individual health complaints.

The built indoor environment is known as a stressor to office workers, however, little research has quantified the effect of the quality of offices on occupants' overall stress. This study aims to evaluate how the quality of office environments influences revealing stress symptoms among office workers.

## 2. Methods:

This paper is focused on assessing the quality of the office environment on revealing stress symptoms among office workers. This study was carried out in 45 offices of eight university buildings in the West Midlands during the academic year of 2016-2017. The five main steps carried out in this methodology are Stage 1) Developing a self-reported questionnaire that can collect reliable data about the occupant's stress symptoms with relation to the office-working environment; Stage 2) Sample selecting concerning buildings and occupants; Stage 3) Transformation and overview of the data. Stage 4) Developing two indices of 'Dissatisfaction' and 'Environmental Stress Score Index to carry out analysis. Stage 5) Developing an Environmental Stress (ES) Score for carryout analysis. The properties of light, sound, temperature and air of a building are collectively called Indoor Environmental Quality (IEQ).

### 2.1. Development of the Questionnaire:

For this study, a new questionnaire was developed by combining the developed version of BUS (Building Usability Survey) method with the 'Stress and Crisis Inventory-93 (SCI-93)' questionnaire as a reliable method to record stress symptoms. Following are detailed explanations about the components of each questionnaire and how they were developed.

#### 2.1.1. BUS Methods expansion:

The Building User Survey (BUS) method has been used for the last three decades in building use studies to evaluate the Indoor Environmental Quality. The BUS Methodology helps to capture as much of this complexity as possible without overwhelming occupants with too many questions. It highlights both good and less favourable building performance. The Building User Survey (BUS) provided a snapshot record of occupant perception of their working environments during summer and winter (BUS Methodology, 2018).

- **Perceiving control and IEQ factors:** The BUS method only asks about availability of control over the IEQ factors by the questioning respondent about their level of control . This is the easiest and most common measure of personal control, However, in this study, the BUS method was developed considering perceived control. To assess perceived control, respondents were questioned about the usability and frequency of use of the controls, which is suggested by Stevenson et al. (2013) are added to the BUS questionnaire. According to Piman et al. (2018) availability of control does not necessarily translate into occupants feeling effectively satisfied with IEQ.

- **Personal factors and IEQ factors:** Here evidence about acceptable comfortable temperature (Schweiker et al., 2018; Shipworth et al., 2016) partly depends on personal factors. For this reason, to have a more realistic answer about occupants perceptions regarding IEQ,the BUS survey was also developed by asking the Sensitivity and Rumination of the participant on various aspect of IEQ. Sensitivity) Sensitivity of participants to the IEQ has been assessed with a bespoke scale. The scale is intended to record if participants believe that they are sensitive to environmental conditions. Self-reported sensitivity scales are often used in research into noise annoyance, these can be simple single scales, for example, “I am sensitive to noise” (Lercher and Widmann, 2013; Sygna et al., 2014) or multiple statement Likert scales (Weinstein 1978; Schutte et al., 2007). This study used the following question “[I]n general, do you consider yourself sensitivity to the following qualities…?”, for the following variables “Heat”, “Cold”, “Air Quality”, “Light” and “Noise”. The qualities were assessed with 1 - 7 scale, with 1 (“No”) to 7 (“Very”). Rumination) Individuals’ responses to environmental stressors vary, as a personal trait could explain part of the variation, it has been suggested tendency to worry could be of interest to IEQ research (Bluyssen et al., 2011: 2636). Worry and rumination, closely connected related concepts, are characterized as prolonged thought about the source of one's own distress. For this paper we will refer to both concepts as rumination. Rumination and worry are assessed with self-reported Likert scales examining the frequency of thoughts (Meyer et al. 1990; Nolen-Hoeksema and Morrow, 1991; Trapnell and Campbell, 1999), to gage general rumination or worry style. Research has been conducted to examine responses to events with bespoke questions regarding worry or rumination (Nolen-Hoeksema and Morrow, 1991; Zoccola et al., 2010). For brevity, we used a used single question combining rumination and worry asking directly related to their office IEQ. Phrased as “Do you give much thought to or worry about the following aspects of your working environment…?”, for the following variables “Heat”, “Cold”, “Air Quality”, “Light” and “Noise”. The scale has a range of 1 (“Never”) to 7 (“Always”). This scale’s wording was intended to gauge their perceived frequency of the thoughts, rather than the valence (pleasantness).

**2.1.2. The Stress and Crisis Inventory-93 (SCI-93)**:

This scale was designed to assess the severity of symptoms that are primarily related to the autonomous nervous system. .This scale designed by physicians in Sweden, is a validated instrument for measuring clinical indications of stress symptoms related to the autonomous nervous system (Ericsson *et al.,* 2015; Krafft and Nyström, 2002; Krafft *et al.,* 2004; Nystöm and Nyström, 1996 ). The scales are designed to measure stress responses in crisis situations, however, the scale has been used to assess urban and indoor access to vegetation effects on stress (Grahn and Stigsdotter, 2003; Grahn and Stigsdotter ,2010; Lottrup *et al.,* 2013). This study used the full symptom questionnaire (Ericsson *et al.,* 2015), the scale is worded “[I]n my everyday life I am affected by”, followed by 35-items, for example “[R]educed memory”, “[R]educed appetite”, etc. The response scale has been extended to 0 - 6, to detect subtle interactions with the environment the range and is coded 0 - “Not at all”, 1/2 - “Little”, 3 - “Moderately”, 4/5 - “Often”, 6 - “Very often”. Responses on the Likert scale are summed with the range of 0 - 210, to provide a single score for each individual.

**2.2. Sample selection:**

- **Participants:** The filed study started after receiving research ethics certificates. The participant consent form was obtained before filling out the questionnaires and it was agreed that no clinical diagnosis was performed based on the collected data and the participants could opt-out from participating in this study by contacting the authors. In this study, 476 printed surveys were distributed to staff and PhD students, within 8 buildings at Coventry University city-centre campus, during the academic year of 2016-2017. The response rate was twenty-six per cent, with 124 returned. The distribution of the participants based on their role is gathered in Table 1. As it can be seen, the majority of responses were from clerical staff within offices shared by more than eight others. PhD students (n = 20) were excluded from the database, due to no compulsory hours in the building. Participants who had no variation in response to the stress questioners, defined as zero standard deviation, were also excluded as unreliable data.

Table 1. Job role of the respondents based on their age and gender

| Jobs' roles | Male < 30 | Male >= 30 | Female < 30 | Female >= 30 | Unspecified gender < 30 | Total |
|---|---|---|---|---|---|---|
| Clerical | 3 | 14 | 20 | 33 | 1 | 71 |
| Lecturer | 0 | 8 | 1 | 2 | 1 | 12 |
| Technician | 0 | 5 | 0 | 0 | 0 | 5 |
| Librarian | 0 | 1 | 1 | 9 | 0 | 11 |
| Total | 3 | 28 | 22 | 44 | 2 | 99 |

**Buildings:** To have a more reliable answer, data was collected from 45 offices located in eight buildings constructed from 1910 to 2012 with various means of IEQ control. Offices selected were cellular offices and open-plan offices that accommodate two to more than eight office workers. Following are the distribution of participants based on their office size collected from different buildings.

Table 2. Numbers of respondents from each building

| Building code | Built | One | Two | Two - Four | Five - Eight | ≥ Eight | Total |
|---|---|---|---|---|---|---|---|
| AB | 1963 | 0 | 1 | 4 | 4 | 14 | 23 |
| ECB | 2012 | 1 | 0 | 8 | 1 | 8 | 18 |
| FL | 2001 | 0 | 0 | 0 | 3 | 9 | 12 |
| Hub | 2011 | 1 | 2 | 1 | 4 | 7 | 15 |
| JL | 1970 | 4 | 4 | 4 | 1 | 3 | 16 |
| PH | 1973 | 0 | 0 | 0 | 0 | 1 | 1 |
| SC | 2006 | 1 | 0 | 0 | 0 | 7 | 8 |
| WM | 1910 | 0 | 0 | 1 | 0 | 4 | 5 |
| other | | 0 | 0 | 0 | 0 | 1 | 1 |
| | Total | 7 | 7 | 18 | 13 | 54 | 99 |

**2.3. Transformation of the data:** The procedure of data transformation for the analysis is explained as follow:

**2.3.1. IEQ data transformation and indices**: The quality of office spaces should be studied from individual viewpoints. Therefore, the collected data from the BUS survey are transformed to the following four indices which were suggested by George Baird in 2010 and 2015. The total dissatisfaction index suggested by the authors is based on the existing indices.

- **Individual Comfort Index:** The scale in this index runs from '1' to '7', with '1' being uncomfortable and '7' most comfortable. Individual comfort index was calculated for each individual using Eq.1 below:

$$\boldsymbol{Ind\ Comf\ Index} = \frac{(\boldsymbol{Comfort} + \boldsymbol{Light} + \boldsymbol{Noise} + \boldsymbol{Temp\ winter} + \boldsymbol{Temp\ summer} + \boldsymbol{Air\ winter} + \boldsymbol{Air\ summer})}{\boldsymbol{Total\ questions\ answered}}$$

- **Individual Satisfaction Index:** This index combines the user's ratings of design, needs, health and productivity using Eq.2. The design, needs, health scales '-3' to '+3', with '0' being the midpoint, '+3' is considered the best 'score and -3 as the worst score. The productivity scale is rated on a 1-9 scale, with the range of '-40% or less' to '+40% or more' productivity, in 10% increments. The range for Individual Satisfaction Index is therefore: -3.25 to + 3.25 using Eq.2:

$$\boldsymbol{Individual\ Satisfaction\ Index} = \frac{(\boldsymbol{Design + Needs + Health + Productivity})}{\boldsymbol{Total\ questions\ answered}}$$

- **Dissatisfaction index:** This index has been performed for temperature and air quality in summer and winter, light and noise which calculate the mean of the absolute distance from the ideal score for each scale. The noise dissatisfaction equation has an extra component suggested by authors, which is related to the noise from internal sources.

Eq3: Winter Temp dissat

$$\boldsymbol{Temp\ Winter\ Dissat} = \frac{(\,|TWOVER - 7| + 2\times|TWHOT - 4| + 2\times|TWSTABLE - 4|)}{\boldsymbol{Total\ questions\ answered}}$$

Eq 4: Summer Temp dissat

$$\boldsymbol{Temp\ SummerDissat} = \frac{(\,|TSOVER - 7| + 2\times|TSHOT - 4| + 2\times|TSSTABLE - 4|)}{\boldsymbol{Total\ questions\ answered}}$$

Eq 5: Winter Air dissat

$$\boldsymbol{Air\ WinterDissat} = \frac{\begin{pmatrix}2\times|AIRWSTIL - 4| + 2\times|AIRWDRY - 4| + |AIRWFRESH - 1| \\ + |AIRWODOURL - 1| + |AIRWOVER - 7|\end{pmatrix}}{\boldsymbol{Total\ questions\ answered}}$$

Eq 6: Summer Air dissat

$$\boldsymbol{AirSummerDissat} = \frac{\begin{pmatrix}2\times|AIRSSTIL - 4| + 2\times|AIRSDRY - 4| + |AIRSFRESH - 1| \\ + |AIRSODOURL - 1| + |AIRSOVER - 7|\end{pmatrix}}{\boldsymbol{Total\ questions\ answered}}$$

Eq 7: Light dissat

$$\boldsymbol{Light\ Dissat} = \frac{\begin{pmatrix}|LTOVER - 7| + 2\times|LTNAT - 4| + |LTARTNGL - 1| \\ + 2\times|LTART - 4| + |LTARTNGL - 1|\end{pmatrix}}{\boldsymbol{Total\ questions\ answered}}$$

Eq 5: Noise dissat

$$\boldsymbol{NoiseDissat} = \frac{\begin{pmatrix}|NSEOVER - 7| + 2\times|NSECOLL - 4| + 2\times|NSEPEOPLE - 4| \\ + 2\times|NSEINSIDE - 4| + 2\times|NSOTHERROOMS - 4| \\ + 2\times|NSEOUTSIDE - 4| + |NSEINTERRUPTION - 1|\end{pmatrix}}{\boldsymbol{Total\ questions\ answered}}$$

An index of total dissatisfaction has been calculated from a mean of all of the above IEQ dissatisfaction, using equation 6 below: Total dissatisfaction which is suggested by authors.

$$\boldsymbol{Total\ dissatisfaction} = \frac{\begin{pmatrix}TempSummerDissat + TempWinterDissat + AirWinterDissat \\ + AirSummerDissat + LightDissat + NoiseDissat\end{pmatrix}}{\boldsymbol{6}}$$

### 2.4. Developing Environmental Stress (ES) Scale:

There is no questionnaire available to collect stress symptoms with relation to IEQ. Therefore, to study the impact of IEQ on office workers' stress level, the first step is to evaluate the relation of office IEQ dissatisfaction level to each of the stress symptoms and investigate which stress symptom (collected by 1-7 Stress Crisis Inventory 93 scale) is mostly triggered by environmental factors. Figure 1 shows the stress symptoms that are related to the IEQ factors highlighted in black. The highlighted symptoms in the figure below are the symptoms that are triggered by IEQ reported by occupants.

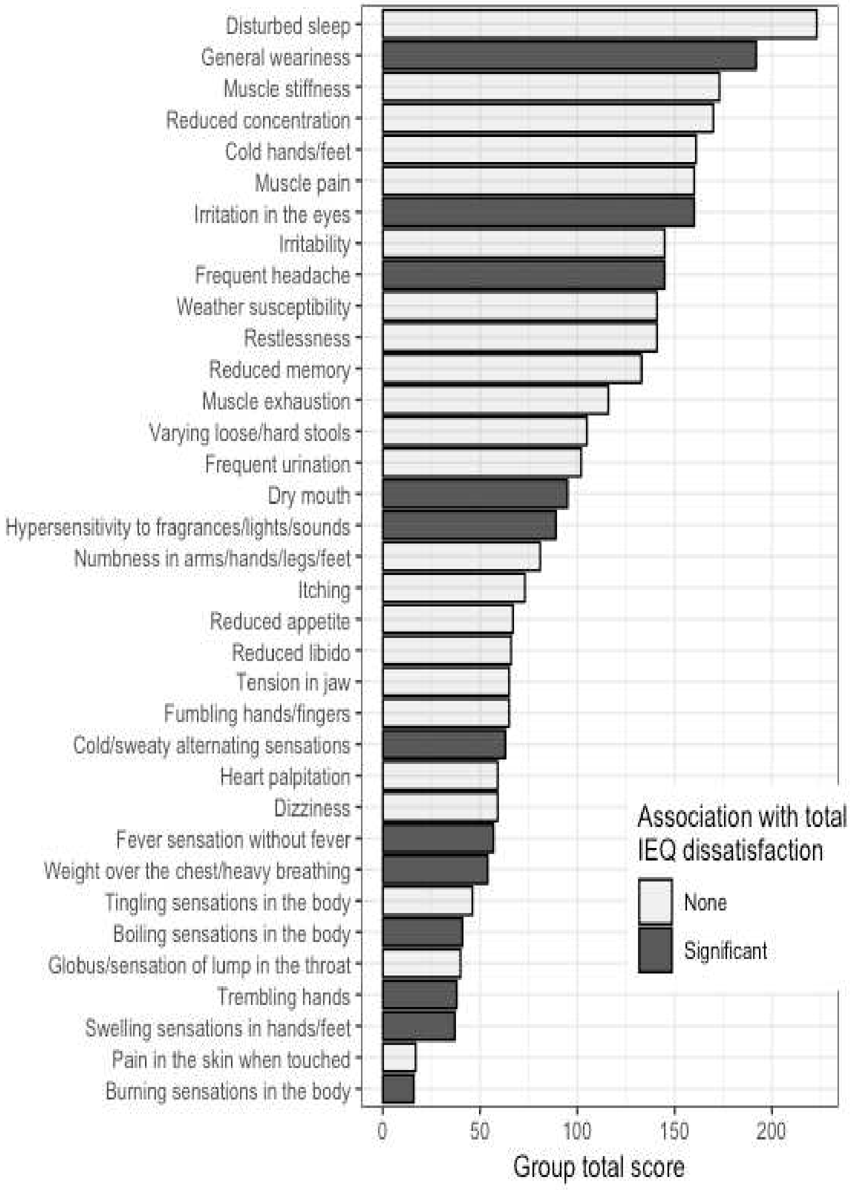



Figure 1. The cumulated Stress Crisis Inventory 93 scale for each stress symptom

At this stage, a new stress score which contains all the triggered symptom by IEQ is generated which is called Environmental Stress (ES) Scale. This score is used for further analysis.

## 3. Analysis:

In this section, various factors that could influence the office workers' stress levels are discussed. In the first part of this analysis, the office workers' stress levels are evaluated in relation to Indoor Environmental Qualities. In the second part, the influence of availability and perceived of control on office workers stress level on ES Score are evaluated. In the third part of this analysis, the impact of personal factors such as sensitivity level, gender and age are evaluated. The last part of this analysis evaluates the impact of office size on office workers' stress level.

### 3.1. The impact office IEQ qualities on Stress level:

To evaluate the impact of IEQ level on office workers' stress level, there is a need to tailor Stress Crisis Inventory 93 scale to the new scale that represents the symptoms that are triggered by IEQ. Therefore, the first step is generating the Environmental Stress (ES) scale. The second and third steps are to evaluate the impact of individual dissatisfaction and control on the Environmental Stress (ES) Scale. In order to study the impact of the Indoor Environmental Quality on office workers stress level, firstly, Environmental stress (ES) score is calculated for each individual using their response to the questionnaire. Secondly, individual total dissatisfaction of the office Indoor Environmental Quality, and individual comfort index and dissatisfaction from each of the IEQ variables (i.e. temperature, air quality, noise and light) are calculated. Thirdly, the relation between (ES) score and the index of comfort and dissatisfaction index are evaluated. Figure 2 shows the relation between Environmental stress score to comfort index and individual total dissatisfaction. There is a significant relationship between the ES scale and 'individual comfort index' and 'individual total dissatisfaction'. These graphs show that when an individual is more comfortable and less dissatisfied with the office IEQ levels, they are less stressed and vice versa. As can be seen, the individual dissatisfaction level is a stronger predictor on Environmental stress score ($R^2$= 0.23, $p < 0.001$) compared to individual comfort index ($R^2$= 0.092, $p < 0.01$) and this is related to the fact that dissatisfaction index considers all the sub variables of the IEQ while comfort index only considers an overview of the IEQ variables.

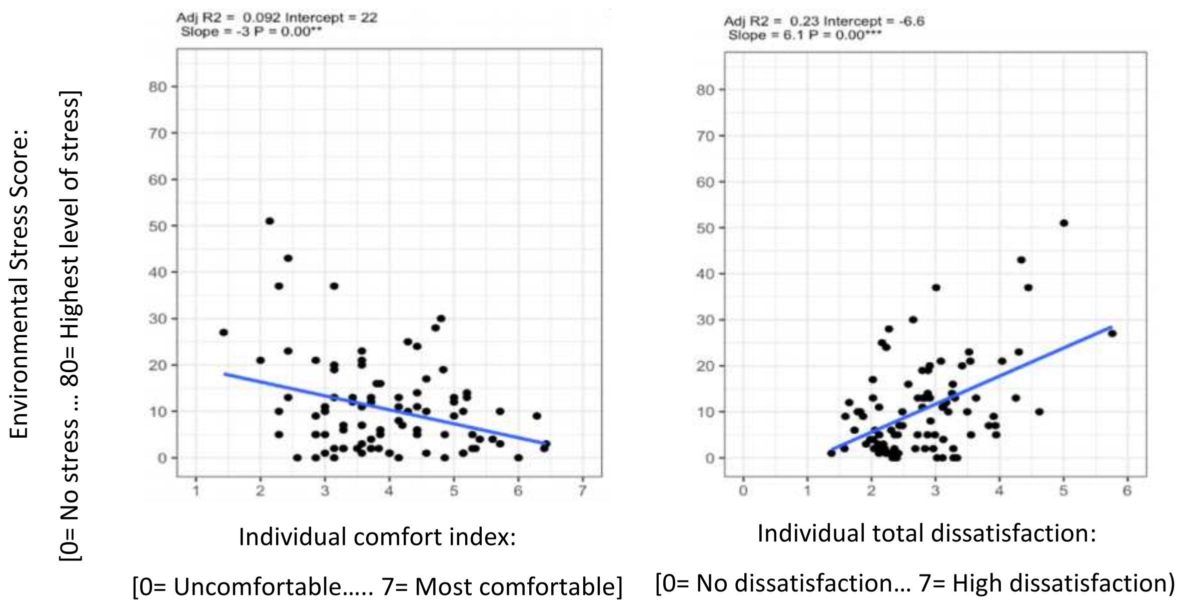



Figure 2. Relation between (ES) Score and individual comfort index (Left) individual dissatisfaction (Right)

To study how each of the IEQ variables has an impact on Environmental Stress score (ES), the correlation between each IEQ individual dissatisfaction with ES score is evaluated. As can be seen in Table 3, the quality of air in winter influence on ES score is significantly higher ($r$= 0.39, $P < 0.001$) than other IEQ factors. The temperature in both summer and winter and the air quality in summer are the second most influential factors on ES score after air quality in winter with ($P < 0.01$). The dissatisfaction from noise and light influence on ES score, however, is lower compared to the other IEQ variables. This variation of influence is more related to the quality of offices for each of their IEQ variables.

Table 3. Correlation of Stress score with environmental variables (p < 0.001 = ***, p < 0.01 = **, p < 0.05 = *)

| IEQ variables | | r | df | P Value |
|---|---|---|---|---|
| Dissatisfaction of | Temp winter | 0.25 | 91 | 0.01 * |
| | Air winter | 0.39 | 91 | 0.00 *** |
| | Temp summer | 0.29 | 84 | 0.01 ** |
| | Air summer | 0.30 | 84 | 0.00 ** |
| | Light | 0.26 | 91 | 0.01 * |
| | Noise | 0.27 | 91 | 0.01 * |
| | Total | 0.49 | 91 | 0.00 *** |

## 3.2. The impact of control on Environmental Stress (ES) Score

There is evidence that both availability and perception of control play an important role in occupants' satisfaction level. For this reason, in this study we specifically asked about the availability of control, the frequency of use of control and also the usability of control as part of the survey. Occupants were asked to vote using a Seven Point Likert scale from Unsatisfactory to Satisfactory to the question of *"How useable do you find the environmental controls (if you have them)…?"* to show how they are satisfied with the usability of the control systems. To check if the friendliness of the control systems influences the frequency of use of the control system, respondants are asked to vote using a Seven Point Likert scale from *Never to Constantly* to the question *"How often do you use the environmental controls…?"* to show how often they use the control system. Table 4 shows Regression analysis between 'Environmental Stress Score' and 'Total IEQ dissatisfaction' with the availability of control, frequency of using control and the usability of control.

Table 4. Availability, frequency of use and usability of control with relation to ES score and Total IEQ dissatisfaction

| | | Availability of control 1= No Control….7= Full Control | | | | | Frequency of control use 1= Never ….7=Constantly | | | | | Usability of control 1=Un Satisfactory …7=Satisfactory | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Heating | Cooling | Ventilation | Light | Noise | Heating | Cooling | Ventilation | Light | Noise | Heating | Cooling | Ventilation | Light | Noise |
| Environmental Stress (ES) Score | 0= No stress… 80= Highest stress | -0.21* | -0.14 | -0.15 | 0.01 | -0.04 | -0.02 | 0.13 | 0.06 | 0.06 | 0 | -0.26* | -0.21 | -0.23* | -0.08 | 0 |
| Total IEQ Dissatisfaction | 0= No dissatisfaction…7= High dissatisfaction | -0.11 | 0.08 | -0.17 | 0.06 | 0.09 | 0.15 | **0.41*** | **0.27*** | -0.1 | -0.05 | -0.27* | -0.22 | -0.23* | -0.19 | -0.02 |

As can be seen from Table 4, the availability of control over ventilation does not have any impact on Environmental Stress (ES) score or IEQ dissatisfaction while the usability of control over ventilation has a significant impact on both Environmental Stress Score and IES dissatisfaction level. Those who are more satisfied with the usability of control over ventilation have reported a lower ES score (R2= -0.23, P<0.5) and lower dissatisfied with their office environment (R2= -0.23, P<0.5).

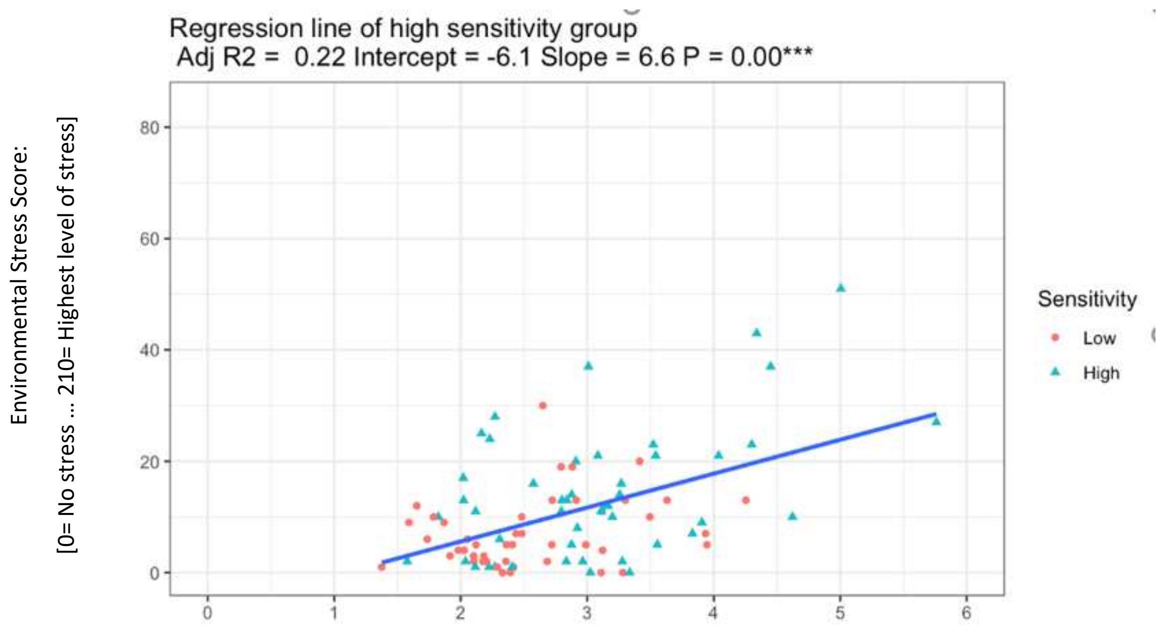
The availability of control to stop overheating can have a significant impact on reducing the ES score; however, it does not have a significant impact on the satisfaction of IEQ. According to Table 4, the frequency of use of control has a negative impact on IEQ dissatisfaction level. This proves that the availability and interaction with the control system would not be helpful and could have a negative impact on occupants' satisfaction level. The frequency of use of control may be related to a design issue and lack of adaptation of the individual to the environment and therefore, there is greater use of control to achieve comfort. However, the usability and friendliness of the control system have a positive influence on IEQ and improve the ES Score.

### 3.3. The impact of individual factors on Environmental Stress (ES) score

In this part of the analysis, the influence of individual variables, such as individual sensitivity and demographics (i.e. age, gender), on Environmental Stress score are evaluated.

#### 3.3.1. Environmental Stress (ES) score and individual sensitivity level toward IEQ

To evaluate how the sensitivity of office workers has an impact on their ES score, office workers were asked to vote about their sensitivity to Heat, Cold, Air quality, Light and Noise from 1=No to 7=Very. High sensitivity individuals have been defined as those above the group median, low sensitivity as below the median, from the sensitivity index. The figure below shows the level of ES score in relation to High and Low sensitivity of the office workers. The result shows that ES score is affected by IEQ dissatisfaction among high- sensitivity office workers (R2= 0.22 and P<0.001) while it is not the case for low-sensitivity office workers (P>0.05). The groupings of participants based on above-average sensitivity show different relations between IEQ and stress compared to those with below average sensitivity. These differences could indicate perceived sensitivity is an important moderator of IEQ on stress score. According to this study, there is a strong relationship between sensitivity and rumination r(92) = .67,*p*=.00***.




Individual total dissatisfaction:

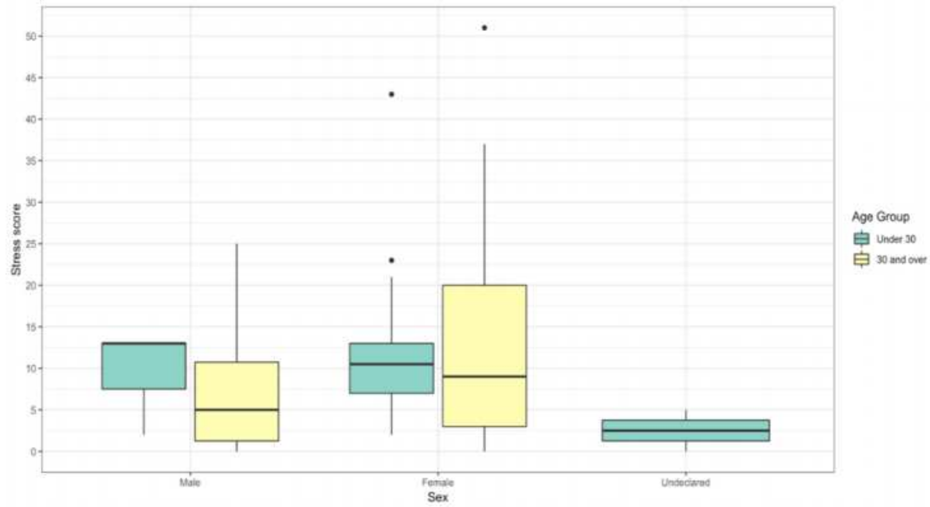
[0= No dissatisfaction… 7= High dissatisfaction)

Figure 3. Stress score dichotomised into high and low sensitivity

### 3.3.2. Environmental Stress (ES) score in various demographics

The following figure shows the overview of ES score in relation to age and gender of respondent.

Environmental Stress Score:
[0= No stress ... 210= Highest level of stress]




Gender and Age

Figure 4. Stress score dichotomised into gender and age

The result of Welch Two Sample t-test shows that there is a significant difference in ES score between Females and Males ($P<0.05$) . According to this test, females are more affected by poor environment rather than men. However, no significant difference was found for ES score in the two age groups of below and above 30 years old.

Table 5. Comparing *stress* symptoms base on gender using Welch Two Sample t-test

| | **Male** | | **Female** | | df | tvalue | p.value | Pearson's r |
|---|---|---|---|---|---|---|---|---|
| | mean | sd | Mean | sd | | | | |
| Gender | 7.93 | 6.37 | 12.8 | 11 | 85 | -3 | 0.01 * | 0.27 |

Table 6. Comparing stress symptoms base on age using Welch Two Sample t-test

| | **Under 30** | | **30 and over** | | df | tvalue | p.value | Pearson's r |
|---|---|---|---|---|---|---|---|---|
| | mean | sd | mean | sd | | | | |
| Age | 11.08 | 8.76 | 11.27 | 10.47 | 50 | 0 | 0.93 | 0.01 |

### 4. Conclusion:

This paper was focused on the impact of indoor environmental quality (IEQ), the element of control and personal factors on developing stress symptoms among office workers. For the purpose of this study, a questionnaire was developed based on the combination of the BUS questionnaire and a reliable questionnaire of Stress and Crisis Inventory-93 (SCI-93) which records the severity of physical stress symptoms. In this study, the BUS methodology was developed asking the friendliness and frequency of use of the control systems and also the level of disturbance from noise from internal sources. In this questionnaire, the sensitivity of occupants towards the different elements of IEQ (i.e. thermal comfort, lighting comfort, acoustic comfort and air quality) was also questioned.

This study for the first time introduces the Environmental Stress Score (ES Score) that represents stress symptoms in relation to IEQ. This score is a suitable indicator to assess the wellbeing of office workers in relation to their working environment. This study highlights dissatisfaction with Office Indoor Environmental Quality (IEQ) is associated with a higher ES score. In addition, sensitivity of the office workers toward the IEQ plays a significant role in the severity of developing ES Score. This study highlights that reviling the stress symptom among female and male are significantly different and females are more affected by poor IEQ than males. Therefore, an organisation needs to have a strategy to consider the sensitivity and gender of the office workers when designing and allocating office accommodation.

According to this study, poor air quality in winter is the main reasons for developing stress symptoms (ES Score) among office workers. After that, the thermal comfort in both seasons and air quality during summer were the main reasons for developing stress symptoms. Quality of noise and light has a lower influence on developing stress symptoms compared to other elements of IEQ.

This study confirms the control over the IEQ of the working environment and having a user-friendly control system can moderate stress symptom prevalence among office workers. Therefore, this study urges designers to take extra care in designing user-friendly aspects of IEQ control.

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# Differences in thermal comfort and satisfaction in offices based on gender

**Madhavi Indraganti**

Qatar University, Doha, Qatar
email madhavi@qu.edu.qa; Madhavi.indraganti@fulbrightmail.org

**Abstract:** Women's labor force participation in Asia remains low and shows a downward trend despite improved female education and significant economic growth. Several factors contribute to increased female labor force participation. Providing comfortable indoor environments to female employees is a necessary step in that direction. Are our offices inclusive for women? This study investigates the gender differences in environmental satisfaction in offices in Qatar, Japan and India from the thermal comfort and indoor environmental surveys the author conducted collecting 12,192 sets of data. Further, wider comparisons are drawn with the office environments in other Asian countries relying on the ASHRAE Database I and II containing 10,551 sets of data from seven more countries. Except in Japan and South Korea, women are more dissatisfied than men with their thermal environments in all other countries investigated. In Qatar, female dissatisfaction is significantly lower in all the other environmental parameters studied (thermal, air movement, humidity, indoor air quality, noise and lighting levels). For example, the gender differences as noted through odds ratios indicated that female subjects in Asia are 37.3 % ($p<0.001$, N = 22,343) more likely to be dissatisfied with their thermal environments than are their male counterparts. Similar consistent trend is noted for other environmental variables as well.

**Keywords:** Thermal comfort Field study; Age; gender; Office buildings; user satisfaction

## 1. Introduction

Gender equality is 'smart economics' (de Mattos & Chaudhary, 2016). Reduced gender discrimination and women in the workforce positively impact the economic development of a nation. However, women's labor force participation in Asia remains low and shows a downward trend despite improved female education and significant economic growth (de Mattos & Chaudhary, 2016). For example, in India female employment rate is lower than in any big economy barring Saudi Arabia and is falling (The Economist, 2018). A report says, India would be 27% richer if more women there worked (The Economist, 2018). This is majorly due to lack of suitable jobs and conducive job environments (de Mattos & Chaudhary, 2016).

Thermal comfort is a subjective feeling and is not a temperature set-point. Several thermal and non-thermal factors contribute to it, such as air quality, lighting and noise levels etc. Many researchers across a wide range of building and climate types recorded marked differences in occupant comfort perceptions of both sexes (Kim, de Dear, Cândido, Zhang, & Arens, 2013), (Indraganti, Ooka, & Rijal, 2015) (Karyono, 2000). Therefore, there cannot be a one-size fits all solution that is totally acceptable to both men and women.

The rentier states in the Gulf Cooperation Council (GCC) Countries have abundantly available fuel as a main source of revenue. A plethora of petrol and natural gas is leading to extravagant energy consumption patterns in these states. Moreover, their unique socio-political obligations compel them to have subsidized and cheap energy tariffs, which further exacerbate the energy use (Rodriguez, Pant, & Flores, 2015) (Fattouha & El-Katiria, 2013). While increasing population and consumerism transformed the Gulf states into key energy users (Clemente, 2015). The ecological footprint of this region is changing very rapidly. This is a major challenge. Qatar ranks highest in electricity consumption per capita in the world (International Energy Agency (IEA), 2017).

Thermal comfort reports from the real-life office buildings from the affluent GCC nations are few and far in between. A yearlong field study in offices in Qatar and presented an adaptive thermal comfort model for GCC (Indraganti & Boussaa, 2018). However, the gender differences in comfort perception in GCC offices have not been investigated yet.

In this context, this paper aims to

(1) Study the effect of age, gender and body mass index on indoor environmental satisfaction and comfort temperature in offices in Qatar
(2) Compare the same with other office environments in India, Japan and other Asian countries.

## 2. Methods and field survey

This paper relies on the thermal comfort field study data collected in offices in Doha (Indraganti & Boussaa, 2018), India (Indraganti M. , Ooka, Rijal, & Brager, 2014), Japan (Indraganti, Ooka, & Rijal, 2013). For drawing larger comparisons, the paper makes use of the thermal comfort field data from offices in Asia made available through ASHRAE Database I and II (Ličina, Cheung, Zhang, Dear, & et.al., 2018).

Doha (N25◦ 17′ and E51◦ 32′ ) is the capital of Qatar, a small peninsula in the Arabian Sea. It has hot desert climate and long hot-humid summer (May- September). Winter is mild (December–February) while Spring (March, April) and Autumn (October, November) are warm. The field study was conducted in 10 air-conditioned office buildings in Doha during 01-2016 to 01-2017 resulting in 3742 sets of comfort data. Five of these buildings are government office buildings and the rest are buildings for private companies. Each dataset consisted of occupant responses to a detailed paper questionnaire and simultaneous measurements of environmental parameters.

The data from Indian offices was collected from 28 office buildings located in two cities Chennai (N13°04' and E80° 17', warm humid wet land coastal climate) and Hyderabad (N17°27' and E78° 28' with composite climate) during 01-2012 to 02-2013. We collected 6042 datasets during the survey. The survey was done in naturally ventilated (NV), mixed mode (MM) and fully air-conditioned buildings. A total of 1352 sets of data were collected when the buildings were run in naturally ventilated mode and 4310 sets in air-conditioned (AC) mode. About 6 % data (N: Males = 270, Females: 116) was collected during power outages when ACs were off and windows were closed ($AC_{outage}$).

The data from 4 office buildings in Japan was collected in a paper based thermal comfort field survey done in Tokyo (N35°41' 22.22" and E139° 41' 30.12") in humid subtropical climate during 07-2012 to 09-2012. A total of 2402 sets of data were collected (432 in NV mode and 1979 in AC mode).

All the questionnaires consisted of three sections: (1) personal identifiers such as code name, age and gender (2) thermal comfort responses such as current thermal sensation, preference, acceptability (3) response to other environmental parameters such as air movement; humidity, etc.

While the subjects filled the questionnaires, the field surveyor simultaneously measured the following using calibrated digital instruments: (1) air temperature, (2) relative humidity, (3) globe temperature, (4) air velocity (5) $CO_2$ concentration. These were at a height of 1.1m following ASHRAE Class II protocols. The methods, instrument details and sensitivities are elaborated in Doha (Indraganti & Boussaa, 2018), India (Indraganti M. , Ooka, Rijal, & Brager, 2014), Japan (Indraganti, Ooka, & Rijal, 2013).

### 2.1. The subject sample

The subject sample consisted of acclimatized subjects working in the surveyed buildings within the age group of 18 to 70 years. In all the surveys, a larger sample size was collected from males. Females provided 31.6% of total data in Doha, 29.9% in Chennai, 23.8% in Hyderabad and 48.8% of the data in Tokyo. Mean age of male sample varied from 30 t0 38 years. The average age of female sample varied from 29.3 to 40.8 years. The mean clothing insulation of female subjects was generally higher in all the surveys except in Tokyo. The descriptive statistics of the investigated sample is shown in Table 2.

Table 1. Descriptive statistics of the investigated subject sample (s.d. : Standard deviation)

| Survey | Gender | Sample size | Age (years) | | Body surface area ($kg/m^2$) | | Clothing insulation (clo) | |
|---|---|---|---|---|---|---|---|---|
| | | (N) | Mean | s.d. | Mean | s.d. | Mean | s.d. |
| Doha | Male | 2558 | 36.0 | 8.3 | 1.88 | 0.15 | 0.75 | 0.14 |
| | Female | 1184 | 31.3 | 7.7 | 1.65 | 0.14 | 0.95 | 0.31 |
| Chennai | Male | 2037 | 29.6 | 8.6 | 1.79 | 0.14 | 0.67 | 0.04 |
| | Female | 870 | 31.3 | 9.5 | 1.56 | 0.13 | 0.81 | 0.11 |
| Hyderabad | Male | 2394 | 32.5 | 9.2 | 1.79 | 0.14 | 0.68 | 0.04 |
| | Female | 747 | 29.3 | 8.2 | 1.59 | 0.13 | 0.74 | 0.11 |
| Tokyo | Male | 1231 | 38.0 | 12.8 | | | 0.63 | 0.06 |
| | Female | 1171 | 40.8 | 11.6 | | | 0.62 | 0.09 |

### 2.2. Measurement of other environmental parameters

Thermal comfort is a multi-dimensional paradigm as it may be influenced by several other environmental variables in addition to the four prime variables, such as air and radiant temperatures, air velocity and relative humidity. Therefore, measuring the occupant sensation and preferences for other environmental parameters is also important. With this objective, alongside these major physical variables, we measured the sensation and preference for various other environmental parameters in these three surveys using the scales as shown in the following Table 2. The table also shows the subjective thermal comfort scales used for measuring thermal sensation (in response to the question "how do you feel the temperature now?"), thermal preference (in response to the question "how do you prefer to feel?") and thermal acceptability (in response to the question "do you accept the present environmental conditions in this room?"). In all the surveys, thermal sensation was measured with ASHRAE's 7-point sensation scale with 0 at neutral and +3 at hot and -3 at cold. Thermal preference was measured with Nicol's 5-point scale as shown in Table 2 and Table 3. Thermal acceptability was measured using a binary scale with 0 being acceptable and 1 being unacceptable. The questions for sensation and preferences other environmental parameters were worded similar to the above questions. For ex: "how do you feel the indoor air movement/ humidity/ lighting level and background noise level/ indoor air quality? " and “how do you prefer to feel air movement/ humidity/ lighting level and background noise level?”

Table 2. Scales used to measure thermal sensation, thermal preference and thermal acceptance in different surveys (D: Doha; C: Chennai; H: Hyderabad; T: Tokyo)

| Scale value | | Description of scale | |
|---|---|---|---|
| | ASHRAE 's Thermal sensation (TS) | Nicol's Thermal preference (TP) | Thermal acceptance (TA) |
| 3 | Hot | | |
| 2 | Warm | Much Cooler | Acceptable |
| 1 | Slightly Warm | A Bit Cooler | Unacceptable |
| 0 | Neutral | No Change | |
| -1 | Slightly Cool | A Bit Warmer | |
| -2 | Cool | Much Warmer | |
| -3 | Cold | | |

Table 3. Scales used to measure subjective responses to other environmental variables in different surveys (D: Doha; C: Chennai; H: Hyderabad; T: Tokyo)

| Scale value | Sensation of | | | | | Preference for | | | | Thermal effect on productivity | Air movement satisfaction |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | air movement | humidity | lighting level | back ground noise level | indoor air quality | air movement | humidity | lighting level | noise level | | |
| 3 | Very low | Very humid | Very bright | Very Noisy | Very good | | | | | | |
| 2 | Low | Humid | Bright | Noisy | Good | Much more air movement | Much drier | Much dimmer | Much quieter | Much higher than normal | |
| 1 | Slightly low | Slightly humid | Slightly bright | Slightly noisy | Slightly good | A bit more air movement | A bit drier | A bit dimmer | A bit quieter | Slightly higher than normal | Dissatisfied |
| 0 | Neither high nor low | Neither humid nor dry | Neither bright nor dim | Neither noisy nor quiet | Neither bad nor good | No change | No change | No change | No change | Normal | Satisfied |
| -1 | Slightly high | Slightly dry | Slightly dim | Slightly quiet | Slightly bad | A bit less air movement | A bit more humid | A bit brighter | A bit noisier | Slightly lower than normal | |
| -2 | High | Dry | Dim | Quiet | Bad | Much less air movement | Much more humid | Much brighter | Much noisier | Much lower than normal | |
| -3 | Very high | Very dry | Very dim | Very quiet | Very bad | | | | | | |
| Surveys adopted | D; C; H; T | D; C; H; T | D | D | D; C; H | D; C; H; T | D; C; H; T | D | D | D; C; H; T | D |

### 2.3. Determination of proxy scales for measuring environmental satisfaction

We determined proxy binary scales for environmental satisfaction using the sensation votes of thermal comfort, humidity sensation, lighting sensation, noise level, indoor air quality. We considered the votes in the central three categories as satisfied (coded as 0), the rest as dissatisfied (coded as 1). Those preferring no change in the air movement are coded as satisfied (coded as 0), the rest as dissatisfied (coded as 1). In order to make a wider comparison, we used the ASHRAE Database – II which includes several office buildings in Asia (Ličina, Cheung, Zhang, Dear, & et.al., 2018). From this database, we extracted 11551 sets of data collected from offices contributed by 10 researchers across Asian cities such as: (Seoul, N= 262); Bangkok (N= 1157); Makati (N= 277); Singapore (N= 817); Ahmedabad (N= 1507);

Bangalore (N = 1151); Chennai (N= 878); Delhi (N= 1388); Shimla (N= 1406); Ilam (N= 345); Tokyo (118) Jaipur (596)Jakarta (N= 572); and Harbin (N= 77) for this analysis.

## 3. Results and discussion

### 3.1. Outdoor and indoor environments of the surveyed environments

During the survey period, the outdoor temperature varied widely in Doha (range: 18 – 39 °C, mean: 30.8 °C) and moderately in Chennai (range: 24.5 – 35.5 °C; mean: 28.9 °C), Hyderabad (range: 21.5 – 34.5 °C; mean: 26.7 °C) and Tokyo (20.5 – 30.2 °C; mean: 27.6 °C). Indoor environments varied widely under natural ventilation mode and much less in air-conditioned mode during the survey period in these cities. Descriptive statistics of the outdoor and indoor environments are shown in Table 3. Doha experienced higher absolute humidity and lower indoor temperatures compared to Chennai (also a coastal climate) as shown in Fig. 1 and also the other cities as shown in Table 4. The indoor air movement in Doha was much lower compared to the other three surveyed cities Chennai, Hyderabad and Tokyo. It was reported that the air movement in Chennai, Hyderabad and Tokyo was higher than that of Doha as is also shown in Table 3 (Indraganti, Ooka, & Rijal, 2015).

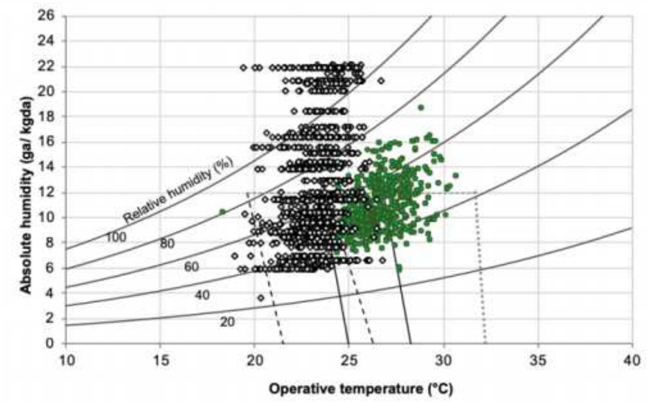


Figure 1. Indoor environmental data of Doha (black diamond) and Chennai-AC (green square) for comparison superimposed over the psychrometric chart.

We estimated the comfort temperature using the Griffiths' method for each thermal comfort vote, taking 0.5 as the Griffith's coefficient. Mean indoor comfort temperature was found to be 24.0 °C in Doha which was lower than that of the AC environments in Chennai (26.9 °C), Hyderabad (25.7 °C) and (27.4 °C). On the contrary, the mean comfort temperature in NV environments in Chennai was (28.6 °C) which was higher than Hyderabad (27.9 °C) and Tokyo (27 °C ).

Table ~~3~~. 4. Descriptive Statistics of outdoor and indoor environmental variables in various cities surveyed ($T_o$ : Outdoor daily mean temperature (°C); $T_i$ = Indoor air temperature (°C); $T_g$ : Indoor globe temperature (°C); RH: Relative humidity (%); AH = Absolute humidity (g/ $kg_{da}$); $V_a$: Air velicoty (m/s); $T_c$ = Comfort temperature (°C); s.d.: Standard deviation; NV: Naturally ventilated; AC: Air conditioned)

| Environmental Variable | Doha | | Chennai | | | | Hyderabad | | | | Tokyo | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | AC (N= 3742) | | NV (N= 132) | | AC (N = 2522) | | NV (N= 1220) | | AC (N= 1788) | | NV (N = 423) | | AC (N= 1979) | |
| | Mean | s.d. | Mean | s.d. | Mean | s.d. | Mean | s.d. | Mean | s.d. | Mean | s.d. | Mean | s.d. |
| $T_o$ | 30.8 | 6.5 | 26.9 | 2.7 | 28.9 | 2.8 | 25.4 | 3.0 | 27.5 | 3.9 | 25.9 | 2.2 | 28.0 | 1.7 |
| $T_i$ | 23.8 | 1.2 | 29.7 | 2.2 | 26.5 | 1.5 | 29.0 | 1.9 | 26.1 | 1.6 | 29.3 | 1.4 | 27.9 | 1.1 |
| $T_g$ | 23.4 | 1.2 | 29.5 | 2.1 | 26.7 | 1.4 | 28.7 | 2.0 | 25.6 | 1.7 | 29.4 | 1.5 | 27.9 | 1.1 |
| RH | 45.4 | 6.9 | 59.7 | 5.5 | 50.1 | 7.5 | 43.1 | 11.1 | 45.6 | 10.8 | 52.6 | 6.4 | 50.9 | 4.4 |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AH | 8.2 | 1.3 | 15.7 | 2.7 | 10.8 | 2.0 | 10.7 | 2.7 | 9.5 | 2.1 | 13.4 | 1.6 | 11.9 | 1.2 |
| $V_a$ | 0.04 | 0.06 | 0.5 | 0.33 | 0.2 | 0.20 | 0.1 | 0.21 | 0.05 | 0.08 | 0.2 | 0.15 | 0.3 | 0.16 |
| $CO_2$ concentration (ppm) | 1337 | 332 | 821 | 622 | 1370 | 460 | 860 | 291 | 962 | 312 | 613 | 167 | 1149 | 413 |
| Noise level (dB) | 57.8 | 6.7 | | | | | | | | | | | | |
| Lighting level (lux) | 361 | 280 | | | | | | | | | | | | |
| $T_c$ | 24.0 | 2.6 | 28.5 | 2.4 | 26.8 | 2.9 | 27.9 | 2.6 | 25.7 | 2.5 | 27.0 | 2.5 | 27.4 | 2.2 |

### 3.2. Gender differences in subjective thermal responses

In Doha, majority of the subjects felt cooler sensations, voting on the cooler side of the sensation scale, more so women. About 19.4% women voted on the cooler side of discomfort as against 12.7% men. We can also note that all the subjects in general voted on the cooler side of the scale in other surveys as well, such as Chennai and Hyderabad, in contrast to Tokyo, as seen in Table 5. This reflects some amount of overcooling in the air-conditioned environments. Table 5 shows another interesting feature with regard to women's discomfort in both cooler and warmer side of the sensation scale in Doha. A significantly higher percentage of women, compared to men, felt both cold and heat discomfort (at 95% CI), as they voted on (-3) cold and (2) hot sensations. We used t-test to test the level of significance. Also, the mean thermal sensation of female subjects was found to be the lowest in Doha compared to the other surveys: Chennai, Hyderabad and Tokyo. Karyono (Karyono, 2000) also observed men expressing warmer sensations than women in Indonesian offices. On the other hand, Fanger (1970) noted no significant gender differences in the mean optimal temperature, given both sexes had the same clo and were equally sedentary in climate chamber experiments with college age subjects.

While the mean thermal sensation hovered around the centre of the sensation scale within a quarter scale point in all the cities, It is important to note that only about 40% subjects felt neutral sensations. It might not appear to have much of an engineering significance in terms of comfort temperature set point (less than 0.25 K). However, the non-neutral and cold discomfort sensations of the female subjects are very clear. A closer look at Table 5 reveals that female subjects most often voted non-neutral in Doha and Chennai. It can also be construed that the indoor conditions were non-optimal for a majority of the female respondents, who more often voted on the negative side of the scale, despite having higher clothing insulation compared to men (except in Tokyo).

Table 5: Gender differences in the frequency distribution of thermal sensation vote (TSV) (voting percentage) in various surveys in AC mode (Values in bold indicate the voting difference between the genders in the survey being statistically significant at 95% confidence interval.)

| | Doha | | Chennai | | Hyderabad | | Tokyo | |
|---|---|---|---|---|---|---|---|---|
| TSV | Male (N = 2558) | Female (N=1184) | Male (N= 1782) | Female (N= 740) | Male (N= 1420) | Female (N=368) | Male (N = 986) | Female (N=993) |
| -3 | **2.9** | **11.6** | 0.9 | 0.8 | 0.3 | 0.8 | 1 | 0.4 |
| -2 | 9.8 | 7.8 | **12** | **18.2** | 8.9 | 12 | 2.9 | 4.4 |
| -1 | **28.7** | **22.6** | 28.8 | 29.5 | 28.7 | 27.4 | 18.5 | 17.7 |
| 0 | 39.7 | 35.6 | **32** | **20.8** | 35.4 | 36.4 | 41.3 | 44.3 |
| 1 | **11.8** | **8.4** | 12.4 | 11.4 | 14.2 | 12.2 | 24 | 23.1 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 2 | **4.7** | **10.9** | 8 | 10.8 | 8.2 | 8.2 | 5.4 | 4.7 |
| 3 | 2.3 | 3.2 | 5.8 | 8.5 | 4.4 | 3 | 6.9 | 5.3 |
| Mean TSV | -0.29 | -0.33 | -0.09 | -0.1 | -0.04 | -0.16 | 0.28 | 0.21 |

Women displayed similar behavior in thermal preference vote as can be seen in Fig 2. In Doha, Chennai and in Hyderabad surveys, the mean thermal preference of female subjects is significantly lower than that of males at 95% CI. Women preferred much warmer environments than men. In Doha, the mean thermal preference for men was at 0.05 (indicating a preference towards cooler environments) while the same for women was -0.09 (indicating a preference towards warmer environments). On the contrary, the other three surveys had both men and women preferring cooler environments albeit at different levels as can be seen in Fig.2.

Thermal acceptability is another subjective measure of the thermal environment. It is measured as a binary variable. ASHRAE recommends 80% acceptability in thermal environments (ASHRAE, 2010). Similar to thermal preference, we found statistically significant gender differences in thermal acceptability in Doha (at 95% CI) in contrast to the other three surveys: Chennai, Hyderabad and Tokyo. In Doha, 84% males found the office environments acceptable on an average as against 78% female subjects accepting the same (Fig .2). Thermal acceptability has several causative factors of which indoor temperature could be one. Lower acceptability among female occupants can be related to the lower temperatures being maintained in Doha and the resulting lower sensation vote on the cooler side of discomfort, compared to the other offices in other cities.

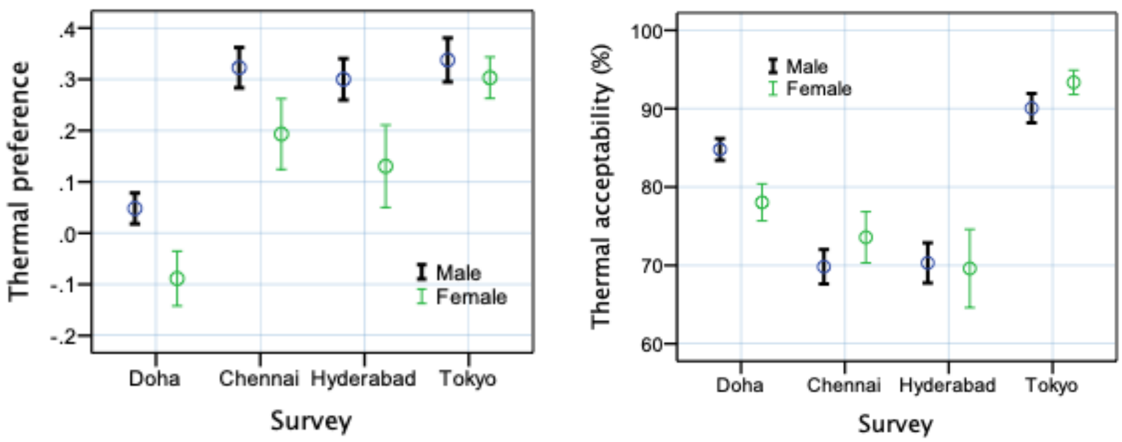


Figure 2: Gender differences in mean thermal preference vote (TP) and thermal acceptability (%) in various surveys in AC mode. Error bars indicate 95% CI around the mean.

Linear regression of TSV with indoor globe temperature in Doha returned significantly different gradients for male and female subjects. These are 0.174 $K^{-1}$ (standard error SE: 0.020, $p<0.001$) and 0.3 $K^{-1}$ (SE: 0.033, $p<0.001$) respectively. Higher slope for female subjects indicates that female subjects are more sensitive to thermal variations than those in the opposite gender. For example, a unit change in sensation vote needed 3.3 K variation indoor temperature in female subjects, while the same change occurred at 5.6 K change in indoor conditions for male occupants. In the other three surveys while there are differences in the thermal sensitivity of males and females, they are not statistically significant. Overall, the linear regression lines of both sexes did not exhibit statistically significant variation. . ~~more~~

~~pronounced as the subjects moved away from the mean thermal conditions experienced in the offices.~~ We looked at the slope of the regression lines during power outages ($AC_{off}$ mode) and noted an interesting feature. While the sensitivity of female respondents more or less remained the same during outages (slope = 0.344 $K^{-1}$, p = 0.004), male respondents were found to be more sensitive than females during outages (slope = 0.504 $K^{-1}$, p<0.001). It could mean that women are more tolerant of temperature excursions the outages caused in air-conditioned environments, while men aren't. This is despite men wearing significantly (at 95% CI) lower clothing insulation (mean = 0.68 clo) than women (mean = 0.79 clo). The mean comfort temperature of women was 26.9 °C (s.d. = 3.2) and that of men was 0.6 K (s.d. = 2.8) lower during outages, although the difference is not significant at 95% CI. Higher sensitivity in men during outages could also be explained by significantly lower ( at 95% CI) mean indoor air temperature men experienced (27.9 °C, s.d. = 2.8) compared to women (mean =28.8 °C, s.d. = 2.7). This underscores the fact that women tolerate warmer temperatures better than men.

### 3.3. Comfort temperature: variations with gender and age group and Body Mass Index

We noted statistically significant differences (at 95% CI) in the mean comfort temperature between men and women in Doha. The mean comfort temperature of male and female occupants was 24.1°C (s.d. = 2.4) and 23.7 °C (s.d. = 3) respectively. Importantly, the mean comfort temperature for both the genders in Doha was around 3 K lower than that of Chennai and Tokyo. When viewed in conjunction with the indoor air speeds in these two surveys (Table 4), the reasons for lower comfort temperature in Doha become clear. Chennai and Tokyo achieved a mean air speed as high as 0.5 – 0.2 m/s, where as Doha experienced near still air conditions (0.04 m/s).

Further, we found slightly and significantly higher comfort temperature for female subjects compared to males in Hyderabad survey (mean = 26.1°C; s.d. = 2.4) in AC mode. The difference was 0.4 K but was statistically significant at 95% CI. In Chennai and Tokyo, the gender differences in comfort temperature are not significant. Overall, (all four cities all modes), the mean comfort temperature for males is 26 °C (N = 8220, s.d. = 2.9) and for females it is 0.2 K higher (N = 3972, s.d. = 3.2), with the difference being statistically significant at 95% CI.

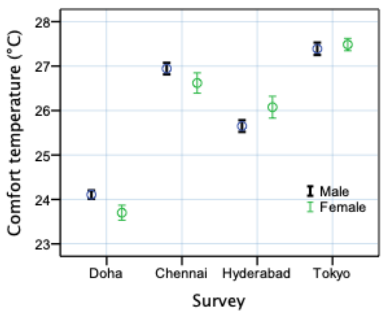


Figure 4: Gender differences in mean comfort temperature in various surveys in AC mode, with Doha and Hyderabad having significant differences between the two genders. Error bars indicate 95% CI around the mean.

#### Effect of age and gender:

We divided the subjects into two age groups, under and over 25 years. Overall, younger age group subjects expressed comfort at 26 °C while older subjects expressed comfort at 0.4 K lower temperature on an average and the difference is statistically significant. On the other hand, the mean comfort temperature of the younger age group males was 26.5 °C while older subjects had 1 K lower comfort temperature and the difference is statistically significant.

Conversely, there are no significant age group differences in comfort temperature in females, overall. In AC offices on the other hand, we noted statistically significant differences in mean comfort temperature of subjects along sex and age grouping as shown in Fig 5.

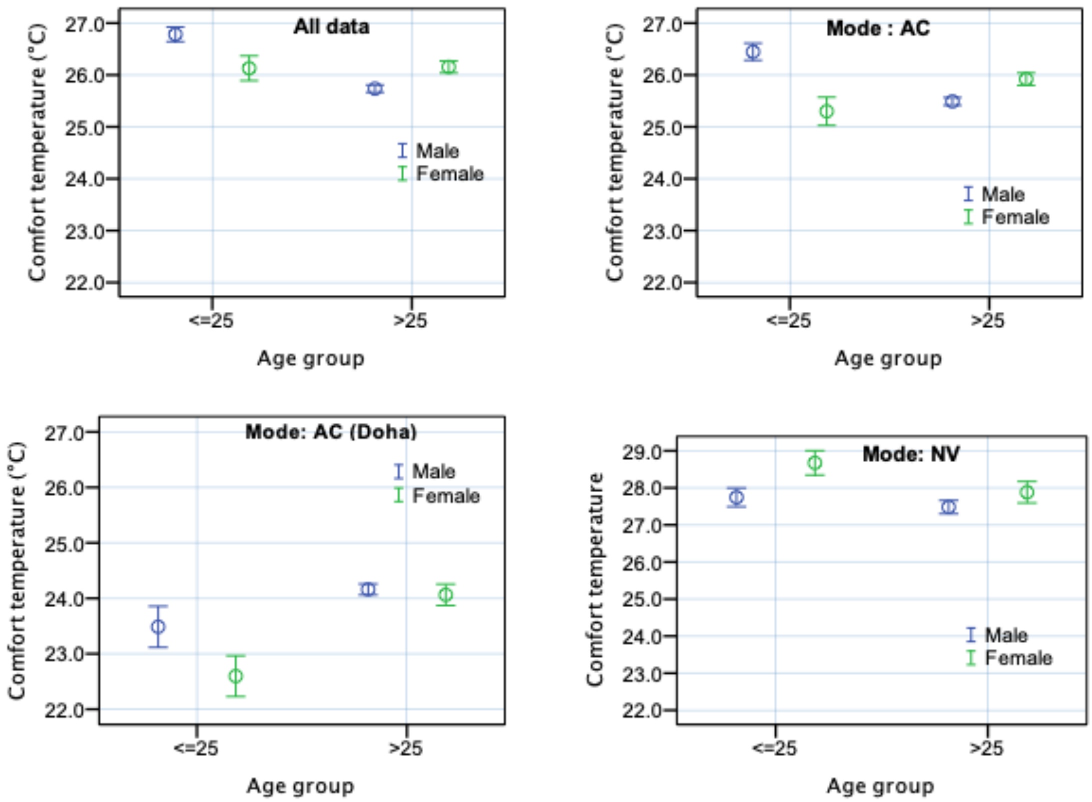


Figure 5: Differences in mean comfort temperature with age group and sex in (a) all surveys and (b) All AC mode (c) Doha data (AC mode). Error bars indicate 95% CI around the mean.

Interestingly in Doha we noted statistically significant differences in comfort temperature of younger and older subjects in both the sexes (Fig. 5). In both the genders younger subjects had lower comfort temperature than their older counterparts (0.9 – 1.5 K lower). This difference is statistically significant at 95% CI. Conversely, an Indian study reported (Indraganti, Ooka, & Rijal, 2015) females under 25 years age to have significantly higher comfort temperatures than males. It could be that millennials and post- millennials being overtly acclimatized to the air-conditioned environments in Doha are finding significantly lower temperatures comfortable than the older generation. This was very evident among female subjects as seen in Fig 5. It could be attributed to the fact that younger age subjects were engaged in activities producing a wider range of metabolic heat than older subjects who were mostly found in sedentary activities, although the differences in the mean met value of the younger and older subjects are not statistically significant in both the genders in Doha. It may be possible that in airconditioned environments, subjects' acclimatization to the narrower thermal regime perhaps had an influence. This finding assumes significance in designing appropriate environments mostly used by younger subjects, such as academic facilities.

Brager and de Dear (2000) demonstrated that people who were exposed to a small range of temperatures (mostly through HVAC systems) developed high expectations for homogeneity and cool temperatures, and were soon critical of the subsequent thermal variations indoors. It could also be argued that most of this reported effect is attributable to the method of analysis they used – a day-survey analysis, which eliminates the day-on-day adaptation, shows only modest differences in sensitivity between AC, mixed mode and NV.

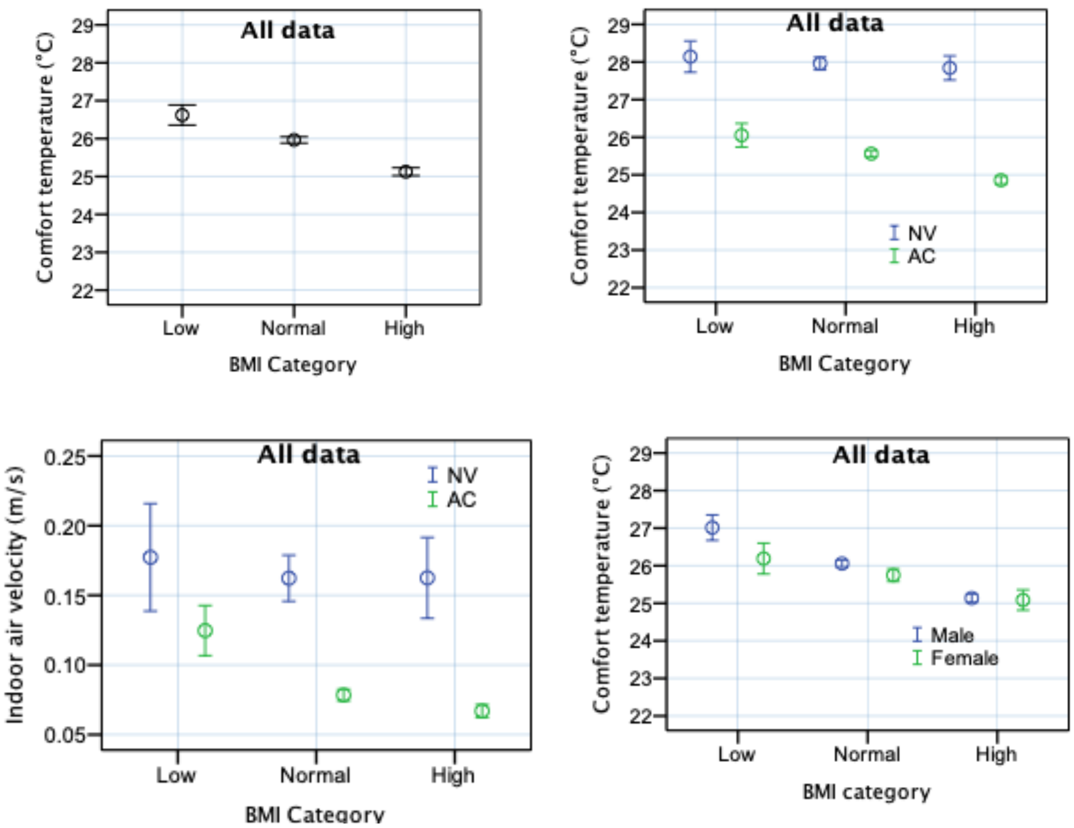


Figure 6: Differences in mean comfort temperature (°C) with BMI category on (a) all data, (b) for different modes (c) mean indoor air velocity experienced by the subjects in various BMI categories in NV and AC modes and (d) for different genders (Error bars indicate 95% CI).

We considered the subject sample under three categories of body mass index (BMI): low (BMI <18 kg/m2), normal (18 kg/m2< BMI < 25 kg/m2), and high (BMI > 25 kg/m2) (WHO, 2004). Overall, the subjects in low BMI category have significantly higher comfort temperature than subjects with normal and high BMI as shown in Fig. 6. It can be explained that subjects with higher BMI have higher metabolic heat production and perhaps could have demanded lower comfort temperature. Similar trend was noticed when the data was split under different modes. The difference in mean comfort temperature with BMI category was statistically significant in AC mode and not in NV mode.

It can be explained that in AC mode, elevated air movement necessary to offset the increased metabolic heat was not available to the high BMI subjects and as a result they must have demanded lower comfort temperature. Evidently, the subjects in higher BMI categories have experienced significantly lower air movement on an average compared to the other two groups as shown in Fig 6. This finding lends support to the argument that higher air speeds are needed to increase the comfort temperature indoors more so when subjects with higher BMI are using space.

Women subjects in normal and high BMI categories in Doha are found to have significantly lower comfort temperature than men in the respective BMI category. The gender difference in comfort temperature for BMI normal and high categories was 0.4 K and 0.6 K respectively. We found no gender difference in low BMI category in Doha survey. No significant gender differences in comfort temperature with respect BMI categories are noted in Chennai and Hyderabad surveys.

### 3.4. Comfort temperature: gender and clothing variations

It is important to note the major differences in clothing insulation of the male and female subjects in the Middle Eastern and Indian environments, which in part explain their variations in comfort temperature. Excepting the Tokyo survey, female subjects had significantly higher clothing insulation. The difference (0.2 clo) is very pronounced in Doha survey than in other surveys. To place in perspective, this is close to the insulation of a light sweater. It is important to note that due to strong cultural influences, women in Middle Eastern offices are required to wear modest clothing which often included head cover scarves, full sleeved shirts and abayas. The differences in mean clothing insulation of subjects wearing non-western outfits such as (thobe, ghutra, abaya, hijab, salwar-kameez etc.) is significantly higher than western outfits. Albeit not as stringent, women in Indian offices too had similar modesty requirements in dressing.

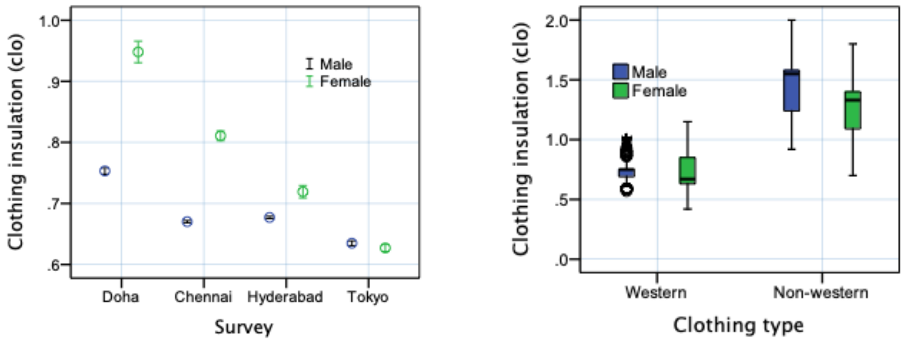


Figure 7: Gender differences in mean clothing insulation (a) various surveys and (b) box plot showing the differences in clothing insulation for Western and non-western ensembles for both the genders in Doha survey. Error bars indicate 95% CI around the mean.

### 3.5. Comparison with Asian offices: gender variations

We estimated the proportions for dissatisfaction in both genders for various proxy environmental satisfaction scales as shown in Fig 8. It can be noted that women are more dissatisfied in all the environmental parameters considered. There are significant differences in thermal comfort satisfaction, noise level satisfaction and lighting level satisfaction between both genders (at 95% CI) as shon in Fig 8.

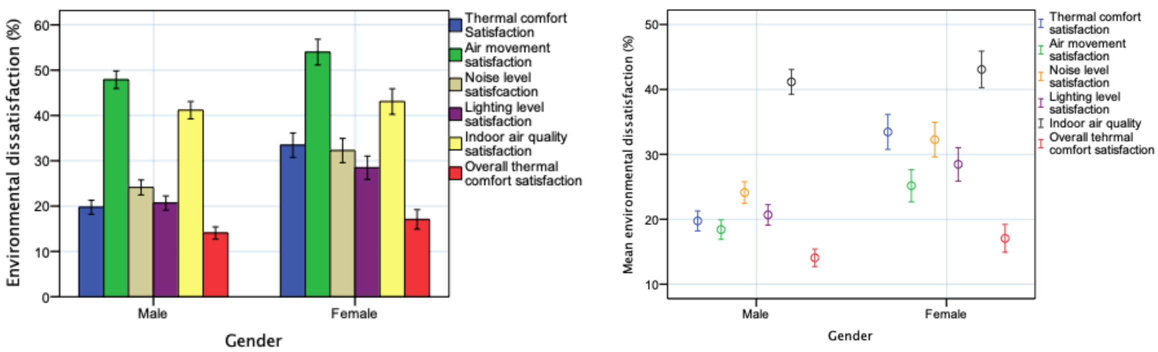


Figure 8: Gender differences in proportion voting on various environmental parameters and mean dissatisfaction for various environmental parameters in Asian offices. Error bars indicate 95% CI around the mean.

We estimated the odds ratio for these satisfaction variables using the binary logistic function in SPSS V22. It was found that female subjects in Asia are 37.3 % ($p<0.001$, N = 22, 343) more likely to be dissatisfied with their thermal comfort sensation with the predictive accuracy being (79%). Similarly, we noted the likelihood of women being dissatisfied with ambient noise level being 49.8% ($p<0.001$, N = 3742) with the predictive accuracy being (73.3%). Much alike women were more likely to be dissatisfied with lighting level too (probability of dissatisfied women: 52.6%, $p<0.001$, N= 3742, prediction accuracy: 76.9%). On the contrary women are less likely (9.2%) to complain about indoor air quality ($p<0.001$). Interestingly Kim et al. also noted similar sensitivities among women subjects for sound privacy, temperature, noise and visual privacy on analysis of a large database collected from offices in USA (Kim, de Dear, Cândido, Zhang, & Arens, 2013).

## 4. Concluding remarks

This paper discussed the effect of age, gender and body constitution on thermal comfort perception and comfort temperature in offices in Doha while comparing the same with similar data from Indian and Japanese offices. We relied on our recent field study data.

In general, more women felt cold and heat discomfort more so in Doha survey. In all the four surveys (Doha, Chennai, Hyderabad and Tokyo) women preferred to have warmer environments more so in Doha. Similarly, thermal acceptability in women is also found to be lower with significant differences being found in Doha. It can be explained that very low indoor temperatures being maintained in Doha, could in part have contributed this higher level of dissatisfaction. Further, we noted female subjects in Doha having significantly higher clothing insulation compared to the rest, owing to stringent dress code and prevalent cultural practices.

Comfort temperature of female subjects in Doha is significantly lower than men and both the genders from other cities studied. Women in younger age groups (<=25 years) and females in normal and high body mass index categories also had significantly lower comfort temperature compared to their male counterparts in Doha.

We estimated the environmental satisfaction using proxy scales generated from subjective environmental sensation measurements in publicly available ASHRAE – II database for comparison for Asian office buildings. It is found that Asian women are more likely to be dissatisfied with thermal comfort sensation, lighting level, noise level and indoor air quality than men.

This study highlights the stark gender differences in comfort perceptions of female subjects in work environments in various Asian offices. Some of these differences although are not of great engineering significance, they call for an attitudinal change in the design of personal environmental controls to be made available for female subjects in order to enhance their satisfaction under various environmental parameters. Only then, our office environments will be inclusive. This is imperative to enhance the dwindling women's labor force participation in Asia.

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# Using CFD to optimizating comfort and energy using different air temperatures and velocities for air conditioning (AC) in Penang State Mosque

**A. Hussin[1, 3], C. H. Lim[1*], E. Salleh[2], Z. Ashhar[1] and S. Mat[1]**

[1] Solar Energy Research Institute, National University of Malaysia, UKM, 43600 Bangi, Selangor, Malaysia.
[2] Kulliyyah of Architecture and Environmental Design, International Islamic University Malaysia, UIAM 50728 Jalan Gombak Kuala Lumpur, Malaysia.
[3] Industrial Training Institute, Manpower Department, Ministry of Human Resources, 13200 Kepala Batas Penang, Malaysia.

* Corresponding author. Tel: +6012-2018451, Email: chinhaw.lim@ukm.edu.my

**Abstract**
In a tropical country like Malaysia, the air-conditioning system is usually the preferred cooling mechanism that is used to provide good indoor thermal comfort in most religious facilities such as mosques. Generally, the worshippers would be able to adapt to a certain range of indoor temperatures. However, improper selection of cooled air supplied by the air conditioning system based on different prayer times and coverage area have led to high energy consumption. In this study, The Penang State mosque was selected as a case study due to its large floor air-conditioned area and high energy consumption. Computational Fluid Dynamics (CFD) was used to model and evaluate the performance of cooled air distributions system inside a mosque. The parameters covered in this study are air temperatures and air velocities supplied by the air-conditioning system. Besides that, the study also included the influence of the indoor thermal comfort on the energy saving for different room temperatures. It was shown that although the air temperature was increased by 6 °C from the baseline, the indoor thermal comfort was able to be maintained at 0.97 of the PMV index. Whilst, by reducing the air velocities from 6m/s to 2m/s, the indoor thermal comfort was able to be maintained at 0.93 of the PMV index. Based on the CFD simulation results and the calculated values of energy saving from the thermal comfort condition, it was observed that the proposed strategy of increasing the air temperature and reducing the air velocity was able to reduce the energy consumption of the air conditioning system while maintaining the indoor thermal comfort range.

**Keywords**: *Air conditioning, Mosque, Air temperature, Air velocity, Comfort, Energy*

## 1. Introduction

Malaysia is located in the equatorial region and has a hot humid and humid tropical climate all year-round. In Penang, the recorded ambient temperature and relative humidity range from 25.2°C to 38.4°C, and 39.6% to 94.3%, respectively. Certain factors such as climate change, increased solar radiation and ambient temperature during the day have affected the thermal comfort of commercial and residential buildings.

Mosque is categorised as a non-residential building. Mosque has a large indoor space, often being visited by Muslim worshippers of various ages and gender. Mosque serves as a place for the Muslim worshippers perform their prayers and also for other communal religious activities. In Malaysia, there are two methods of indoor ventilation to provide indoor thermal comfort, which are either natural ventilation or forced ventilation with the aid fan or air-conditioning system. As mosques serve multi-purposes activities, it very difficult to ensure a comfortable indoor environment just by relying on natural ventilation. Therefore, most mosques use an air-conditioning system to provide indoor thermal comfort.

The air conditioning applications in mosques is an important subject, as it operates at an intermittent time schedule, the indoor thermal environment depends on the characteristics of the supplied air velocity, the temperature distributions, the relative humidity as well as the mean radiant temperature. On the other hand, thermal comfort inside the mosque is a very subjective term as it depends on the worshippers' thermal experience and sensations when they perform their prayers and religious activities (Al-ajmi, 2010). The standard thermal indices with quantitative values that can be used to evaluate the thermal comfort within a space are known as Predicted Mean Vote (PMV) and the Predicted Percentage Dissatisfied (PPD). The PMV and PPD indices have been presented by the International Standard Organization (ISO 7730, 2005). PMV and PPD are commonly used to represent the thermal comfort level in many types of occupied spaces (Castilla et al., 2011; Djongyang et al., 2010).

The indoor environment of a typical air-conditioned building such as mosques must be able to provide indoor thermal comfort to the worshippers, whilst being operated at minimum energy consumption. Previous studies have revealed that air-conditioned mosque management in Malaysia has lack of knowledge to operates their air conditioning system for comfort strategy (Hussin et al., 2015) which has resulted in high building energy index (Hussin et al., 2019). Ultimately, the mosque management must cater for their worshippers with an ideal temperature which balance the thermal comfort and energy consumption within the air conditioning space. The best practices to predicting and assessing the indoor air temperature and thermal comfort performance inside mosque building is by using the Computational fluid dynamics (CFD) method. This prediction tool involves incompressible Navier-Stokes equations which is the main basis of evaluating the airflow in the building space according to the motion of a viscous Newton fluid, which is coupled with advance technology of numerical simulation in computer science (Tian et al., 2018).

Several past scientific researchers that have used the application of CFD models in various indoor environments with considerable success, such as sleeping room environment (Mao et al., 2017), theatre room environment (Popovici, 2017), office room environment (Khatri et al., 2017), classroom environment (Buratti et al., 2017) and public room environment (Li et al., 2009). On the other hand, the CFD method also has been used to evaluate the indoor comfort condition in the mosque building space. Jaafar et al., (2017) conducted a numerical CFD investigation of indoor air related to PMV and PPD indices as well as carbon dioxide percentage. The research specifically focused on the occupants at Al-Masa'a area which is located between Al-Safa and Al-Marwa hills inside Al-Haram mosque located at Makkah, Saudi Arabia. Another research conducted by Mohamed Kamar et al., (2019) by using a CFD method to predict the airflow and temperature distributions inside Al-Jawahir mosque which is located in Johor Bahru Malaysia. The purpose of the research was to examine the effect of installing exhaust fans on the thermal comfort condition inside the Mosque. Both of these studies have successfully provided an overview of the level of thermal comfort contained within the typical space area using the PMV and PPD indices.

The energy management strategies are the most efficient methods that give more savings to building owners. This includes the method of energy conservation by increasing the indoor temperature via adjusting the setpoint temperature (Aghniaey & Lawrence, 2018; Ghahramani et al., 2016) as well as increasing or reducing the air flowrate using variable speed drive application (Saidur et al., 2012; Wang et al., 2014). There are few examples around the world that revealed a wider room temperature range in buildings for comfort. The Australian standard code under the Occupational Health and Safety Act 2004 suggests an indoor thermal environment can range from 20-26 °C, depending on the level of indoor activities (WorkSafe Victoria, 2008). Whilst, the Malaysian Standard (MS 1525, 2014) recommends the best practice for ideal setpoint temperature is between 23 and 27 °C for office application. As the indoor temperature has a direct impact on energy consumption, it is necessary to set the right temperature values at the right place and for the right occupants.

In this study, CFD simulation was undertaken to assess the indoor thermal environment of Penang State Mosque under the energy conservation and energy efficient schemes such as the effect of increasing the supplied air temperature at a constant airflow rate (constant air volume method), and the effect of increasing and reducing the air velocity at a constant supplied air temperature on the overall indoor temperature and airflow distributions (variable-air-volume method). Based on the CFD simulation results, the energy saving from the thermal comfort achievement is calculated and obtained by referring to the indoor ambient temperature that was established.

## 2. Methodology

### 2.1. Experimental case study

The experimental case study was carried out at the Penang State mosque which is located in the northern region of Malaysia. The mosque uses three identical air-cooled chillers with a capacity of 100 RT each, directly connected to five units of air handling unit (AHU) through chilled water piping system. The air ventilation supply for the system is drawn through the ducts and then the cooled air is distributed to the entire mosque volume (36, 774 $m^3$) using jet air diffusers at a constant flow rate of air supply. The air conditioning electrical control panel consists of 3-phase, 415 Voltage and 50 Hz of power supply which has been integrated with an auto timer control system to control the ON/OFF operation. The basic schedule in the daily operation had been set at 3.00 pm (ON) and shutdown (OFF) at 9.30 pm from Sundays to Thursdays and from 10.00 am (ON) until 9.30 pm (OFF) on Fridays.

All the required parameters for determining the thermal comfort was in accordance to ASHRAE Standard (ASHRAE Standard, 2013). The input and validation of the CFD Base Case Model (CFD BSM) was also measured in detail. The indoor climatic conditions such as air temperatures, relative humidity, indoor air velocity, globe temperature, the surface indoor temperature of roof, wall, pole, floor and worshipers body temperature were also acquired. The thermal properties of air, water vapour, building materials, and occupants were referred from Mohamed Kamar et al., (2019). The technical specifications of the instrumentations were already described in Hussin et al., (2018) with an uncertainty of measurement at 10%.

In addition to the thermal comfort requirement under CFD-BSM, the supply air volume from all jet diffusers was set as an input parameter, while the output parameter was set from the return air grille. The other parameters such as roof, wall, inside poles, floor and worshippers were also considered as an inputs under thermal effect. The indoor temperature within the worshipper floor area (2920 $m^2$) was monitored at 1.1m height above floor (Hussin et al., 2015), from the eight positions (DL-1, DL-2, T1, T2, T3, T4, T5, T6). These indoor temperature values were used to validate the simulation results of CFD BSM. Figure 1 shows the mosque geometry indicating the eight positions of indoor temperature measurement during the experimental case study.

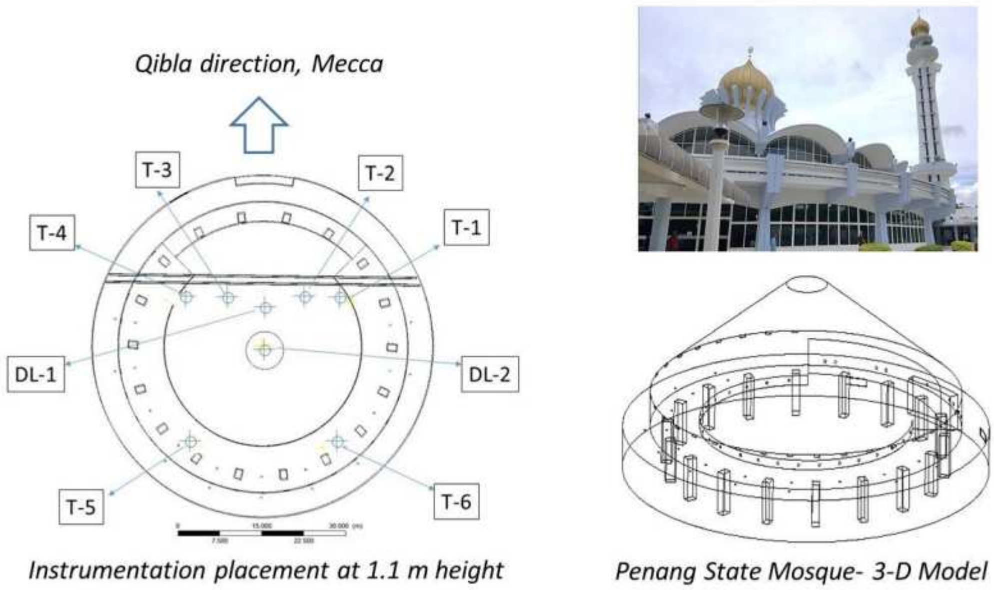



Figure 1. The 3-D geometry model and instrumentation placement

**2.2 CFD modelling setting and configuration**

Three-dimensional CFD simulations of the indoor airflow and thermal comfort of Penang State Mosque were conducted using *Fluent* software (ANSYS 19.2, PA, USA) based on continuity, momentum, and heat transfer equations described by Troppová et al., (2018) and concurrence with the previous work where the energy model and k-ω were used under real case conditions for large volume and complicated geometry of buildings (Li et al., 2009; Noman et al., 2016). The CFD simulations were carried out by using Asus SL390 Laptop with the processor Intel ® Core ™ i7-7700HQ 2.8 GHz (64-bit Windows Pro. 16 GB DDR4-2400 MHz). The CFD simulation was performed in a steady-state condition until all values are stable, and convergence is achieved for all residuals. Since the mosque structure and ventilation operations were symmetric along with the volumetric size, the whole mosque was considered in the computational domain. The details of the boundary conditions and their values are presented in Table 1.

A preliminary grid independence analysis was carried out to determine the suitable mesh size to be used in the CFD BSM. The reference point of DL-2 (Figure 1) was chosen to determine the temperature profile change of each mesh development. The temperature profile was used as an indicators that also concurrence with the previous work of Qiaoyun et al., (2019). For the preliminary simulation, the mesh size for the entire mosque was set up at 0.27 m, and the mesh size for the air supply volume and return grille was set to 0.05 m. The mesh configuration can be seen in Figure 2 (CFD BSM). The mesh size used in this study varies from 0.17 to 2 m. The medium mesh size is used at 6376053 meshes. The total volume of the modelled geometry in this study was 36, 774 $m^3$, which was approximately 3 times bigger than the volume of modelled geometry done by previous work by Mohamed Kamar et al., (2019). The mesh size used in this paper was two times bigger than that was used by Mohamed Kamar et al., (2019).

The preliminary simulation for CFD BSM was implemented by adopting the following assumptions; (i) Mosque building structures such as *mimbar*, domes, minaret towers, entrances door and electrical appliances (such as fans and lamps) were omitted and were not included in the 3-D geometry model. (ii) The 3-D geometry of the congregation was built-in like a long rectangular shape presenting the *saf* position and remains same for the congregation activity. The dimension of the body size is 0.4m x 0.3m. While the height of the worshippers is set at a constant height of 1.65m. This height was chosen as the worshippers are mostly in standing position when they are performing their prayers. The same assumption was used by Noman et al., (2016). One long *saf* approximately consists of about one hundred worshippers, (iii) A large attendance of worshippers such as during Friday's prayer was not included in the CFD simulation study, (iv) Room air was 100 % flowback to AHU units through the return air grille at a constant mass flowrate, (v) Thermal properties of air, building materials, and worshippers remained constant when the air conditioning operations. Input data for return air grille, supply air jet diffuser, surface temperature for ceiling, wall, inner floor, poles and worshippers are indicated in Table 1. The data obtained was the actual data measured during operation of the air conditioning system between 4.30 pm and 5.30 pm, as this period was the peak heat load accumulated with high heat flux effect to the internal thermal environment (Aziz et al., 2018; Catalina et al., 2009), (vi) The number of CFD iterations process was set to 1500 (Mohamed Kamar et al., 2019) whilst convergence achievement guideline is referred from Rong et al., (2016), (vii) Shear Stress Transport (SST) turbulence model had been selected to simulate the airflow induced by the air jet diffusers because of its faster convergence for turbomachinery problem which has been widely used (Pandey et al., 2018).

Table 1. Boundary condition and values for CFD-BSM

| Boundary condition | Domain name/section | Values |
|---|---|---|
| Return airflow | Return grille (RD) | 100 % |
| Supply air temperature | Jet diffusers top- IDT | V=5.5 m/s ; T=19.8 °C |
| | Jet diffusers *imam* - IDi | V=6.2 m/s ; T=18.5 °C |
| | Jet diffusers bottom - IDB | V=6.0 m/s ; T=17.2 °C |
| | Jet diffusers horizontal - IDH | V=6.4 m/s ; T=18.9 °C |
| Surface temperature | Roof | 36 °C |
| | Wall | 32 °C |
| | Pole | 26 °C |
| | Floor | 26 °C |
| Body temperature | | T=30 |
| Metabolic rate | Worshipper | 150 W |
| Heat flux | | 60 $\mathrm{W/m^2}$ |

Notes: air velocity = V, air temperature = T

The following equation is used to estimate the percentage of error (E) between CFD simulated data (CFDSD) and actual measured data (AMD) as proposed by Wang et al., (2019).

$$E = \frac{CFDSD-AMD}{AMD}\ x\ 100\% \quad (1)$$

According to ASHRAE Standard (2013), up to 20% of errors are allowed in the comparative analysis between CFD models and empirical measurement for complex and large-scale 3-D geometry model. The same standard values have been used as benchmarks in the study by Noman et al., (2016).

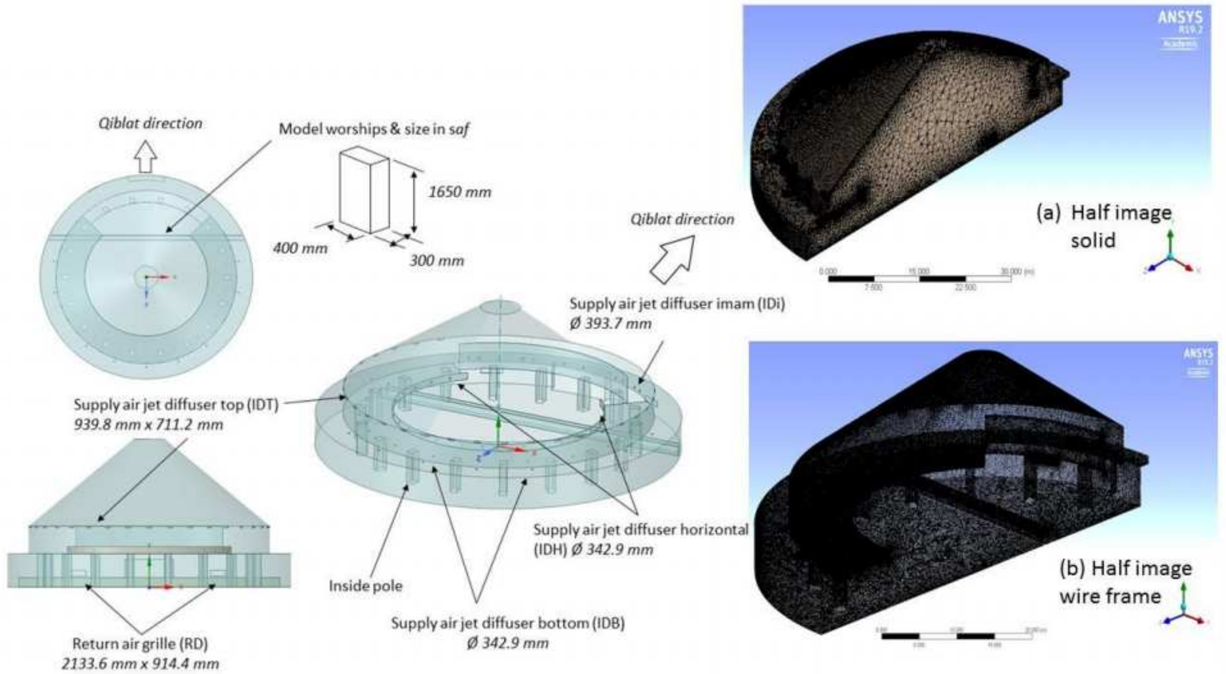



Figure 2. The supply volume air jet diffuser, return air grille, worship model and mesh condition

### 2.3 CFD optimization case study

The Base Case Model (CFD-BSM) was used to simulate the optimization strategy under energy conservation and energy efficient management strategies. The strategies were implemented by adapting the work of previous researchers Zhang et al., (2017) and Youssef et al., (2018);

i) Constant air volume method under energy conservation. Supply air temperature from the base case model (CFD-BSM) was increased from +1 °C to +6 °C at a constant airflow rate.
ii) Variable air volume method energy efficient. Air velocity from base case model (CFD-BSM) was reduced from -1 m/s to -5 m/s at a constant air temperature supply.
iii) Variable air volume method under energy efficient. Air velocity from CFD-BSM was increased from +1 m/s to +5 m/s at a constant air temperature supply.
iv) Other boundary condition is maintained and followed the existing base case model (CFD-BSM) values.

### 2.4 Thermal comfort and energy saving evaluation

The thermal comfort inside an air-conditioned mosque was assessed based on ASHRAE Standard 55 (ASHRAE Standard-55, 2013), where the Predicted Mean Vote (PMV) and Percent of People Dissatisfied (PPD) indexes were investigated. The recommended range of PMV in the ASHRAE Standard-55 is between -0.5 and +0.5 for an indoor space which was calculated from the equation described in International Standard (ISO 7730, 2005). For a building that was operated intermittently such as mosque, Hussin et al., (2015) found that the majority of worshippers accepted the thermal environment condition despite being exposed to the air-conditioning environment intermittently. This was due to the individual's local adaptation behaviour, where the worshippers were conditioned by the higher outdoor temperature which makes the cooler indoor thermal environment to be thermally comfortable. Thus, this study suggesting to adjust the PMV index in between the lower limit (LL) of -1 (slightly cool) and the upper limit (UL) of +1 (Slightly warm) for an air-conditioned space in Penang State mosque. The PMV and PPD indexes were calculated for the experimental measurement and CFD simulation, and the values were presented under individual contour. Several assumptions based on Hussin et al., (2015) were applied such as; the metabolic rate = 1.3 met, the cloth insulation = 0.58 and the energy work balance = 0.

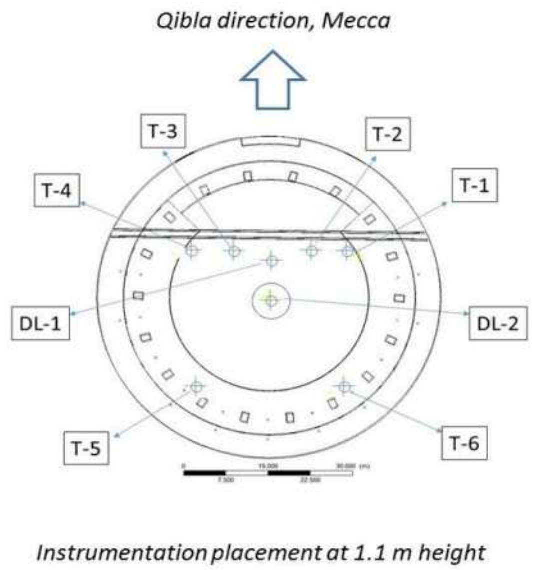
The indoor room temperature obtained from each of the CFD optimization case studies is assumed to be equivalent to the room setpoint temperature. The mean of the obtained room temperature was calculated to determine the percentage of electrical energy consumption (EEC) reduction after increasing the room temperature. As reported by Saidur (2009) and India Bureau of Energy Efficiency (2018), increasing the room temperature setpoint by 1°C can save about 6% of EEC. The EEC saving was obtained by using the following equation;

$$EEC = 6\%/^{\circ}C \times (\text{CFD optimized room temperature} - \text{CFD baseline temperature}) \quad (2)$$

## 3 Results and discussions

### 3.1 Model validation

The results obtained from CFD-BSM simulation was validated against the experimental measurement by calculating the percentage error as detailed in Equation 1. The values used to validate the CFD-BSM simulation results were the indoor air temperature and the air velocity. In Figure 3, the comparison between the mean values and the standard deviations of experimental data and CFD-BSM results for air temperature and air velocity are shown. From the validation procedure, the percentage error was found to be below 10%. It can be seen that the difference between the experimental data and CFD simulation results from the steady-state approach was about +1.55 K and +0.02 m/s for the air temperature and air velocity respectively. The values indicated that the relationships between the actual measurement and simulated values were strong enough (Youssef et al., 2018). The accuracy of the measurement equipment for air temperature and air velocity at ± 0.35% and ±0.3 m/s, the difference in values were considered acceptable which is the same condition indicated by Ning et al., (2016). Once validated, the CFD-BSM simulation model was used to evaluate the indoor thermal condition and the velocity profile within the environment, highlighting the thermal comfort conditions in the Penang State Mosque based on the intermittent occupancy period.




Comparison CFD BSM and actual measured

| Descriptions | CFD-BSM | Actual measured | % error |
|---|---|---|---|
| Air temperature (°C) | | | |
| DL-1 | 22.37 | 23.24± 0.85 | 3.74 |
| DL-2 | 21.99 | 23.45± 0.86 | 6.22 |
| T-1 | 22.33 | 24.55± 0.79 | 9.04 |
| T-2 | 22.26 | 24.43± 0.91 | 8.88 |
| T-3 | 22.50 | 24.30± 0.92 | 7.40 |
| T-4 | 22.33 | 24.26± 0.85 | 7.95 |
| T-5 | 22.87 | 23.80± 1.59 | 3.90 |
| T-6 | 23.41 | 24.46± 1.36 | 3.50 |
| Mean | 22.51 | 24.06± 1.01 | 6.32 |
| Air velocity (m/s) | | | |
| DL-1 | 0.64 | 0.69±0.15 | 7.25 |
| DL-2 | 0.71 | 0.70±0.15 | 1.41 |
| Mean | 0.68 | 0.70±0.3 | 4.33 |

Figure 3. The comparison result between experimental data and CFD-BSM for air temperature and air velocity

Figure 4 shows the top plan view and the vertical cross-sectional view of the simulated temperature distributions and air velocity magnitude in the mosque. The plane view was taken at 1.1 m above the floor. Based on the actual measurement for CFD boundary condition, the Penang State Mosque was studied for an average supply air temperature of 18.6 °C, whilst the average supply air velocity was fixed at 6.0 m/s. Simulation results for baseline model (CFD-BSM) show that the flow pattern inside the praying hall has a medium eddy in the center of the hall, and smaller counter eddies at the corners space which can be clearly seen from the velocity vectors shown in Figure 4. The largest eddy was found near to the supply air and return air outlets which is considered a common scenario as this pattern was also found by other researchers such as Youssef et al., (2018). The velocity profile on both planes were recorded throughout the entire mosque volume space area and the values varied from 0.05 to 1 m/s with an average velocity of 0.68 m/s. Moreover, CFD temperature contour inside the praying hall was between 21.5 °C and 24.5 °C with an average room temperature of 22.5 °C. This result has indicated that the air temperature in the praying hall were under the lower range limit as defined by the ASHRAE standard which is between 22 °C and 26 °C (ASHRAE Standard, 2013). At the 1.1 m height above the floor, temperature contour shows an uneven distributions and the formation of some cold spots at certain areas especially near the center area, as well as at the supply air jet diffusers and return air grille. Additionally, the lower-left corner has a relatively high temperature due to heat released by the worshippers. At this area height, the airflow was dragged out and low because of stack effect from two *safs* forming for congregation activity. In-contrast, temperature contour under cross vertical section view has shown a good uniformity with no cold spots formed. In this case, the big circulation of air velocity supply has given a good mixing process between the supplied cold air and room air due to bigger room volume for cooling purpose.

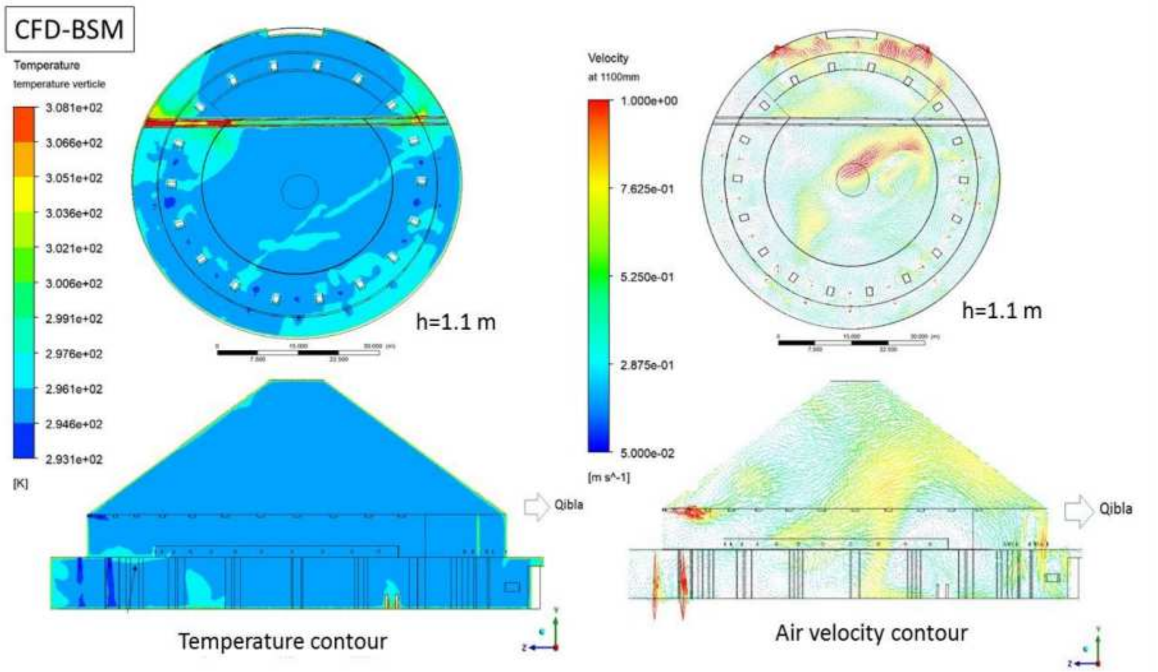


Figure 4. The simulated temperature distribution and air velocity profile

### 3.2 PMV and PPD index

In this research, the mean radiant temperature (MRT) is assumed to be equivalent to the indoor temperature that was obtained by the CFD simulation. This is because the investigated mosque has a large area and space. Building with big volume, large area and space do not have significant difference between MRT and indoor air temperature (Hussin et al., 2018). This is also inline with the indoor climate studies from previous work (Langner et al., 2014; Walikewitz et al., 2015). Therefore, the comparison between the mean values of experimental data and CFD-BSM results for PMV and PPD index from 4.30 pm to 5.30 pm are shown in Table 2. The table shows that the difference between the experimental data and CFD-BSM results for PMV and PPD indexes were 5.97% and 1.25%, respectively. In Figure 5, two profile views of the simulated PMV and PPD index which were shown from the top plane view at a height of 1.1 m from the floor. It was found that the average thermal comfort condition under the PMV index was 0.10 with minimum and maximum values of -0.68 and 0.9, respectively. Whilst, the PPD index has an average value of 14.4% with minimum and maximum values of 5.1% and 27.6% which involved in complex and large-scale 3-D geometry model. The results complied with the ASHRAE standard (ASHRAE Standard-55, 2013) as the percentage error in the comparative analysis between the CFD model and the empirical model was below 20%.

Table 2. Percentage error values of PMV and PPD indexes between experimental and CFD

| Indexes/Location | CFD BSM | Actual measured | % different |
|---|---|---|---|
| (ASHRAE) | (-1 to +1) | | Reference |
| PMV/DL-1 | -0.58 | -0.63 | - |
| PMV/DL-2 | -0.68 | -0.70 | - |
| **Average** | **-0.63** | **-0.67** | **5.97** |
| (ASHRAE) | (20 %) | | Reference |
| PPD/DL-1 | 13.20 | 14.90 | - |
| PPD/DL-2 | 18.12 | 16.90 | - |
| **Average** | **15.70** | **15.90** | **1.25** |

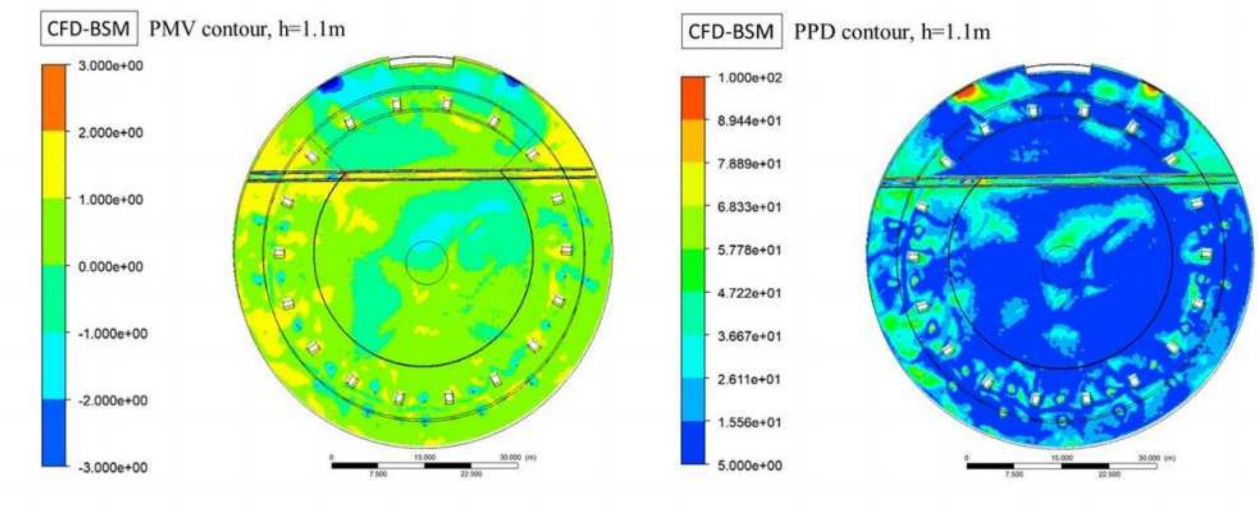



Figure 5. PMV and PPD indexes distributions contour

**3.3 CFD-optimization, thermal comfort, and energy reduction achievement**

Figure 6 shows the temperature profile, PMV index and percentage of energy saving (kWh) obtained from the six optimization cases (n=6) by increasing the supply air temperature from +1°C to +6°C, subjected from the baseline model (CFD-BSM). The result indicates that the room air temperature profile increased similarly in trend with the PMV index and also in line with the increase of supply air temperature. At a constant airflow rate, the PMV index varied from 0.11 to 0.97, where the plot shows a linear curve line from the neutral sense to slightly warm as the supply air temperature was increased. This study has indicated the need to adjust the PMV index in between the lower limit (LL) of -1 and the upper limit (UL) of +1 for an air-conditioned space in the mosque. This has resulted in a reduction of EEC between 6.3% and 31.5%.

Figure 7 shows the temperature profile, PMV index and the percentage of energy saving obtained by changing the air velocity at a constant supply air temperature. A total number of five optimization case studies were undertaken by increasing the supply air velocity from +1 m/s to +5 m/s and a total number of five optimization case studies were undertaken by reducing the supply air velocity from -1 m/s to -5 m/s. The result showed that when the air velocity was reduced from the base case model to V-5, the PMV index profile increased from 0.11 to 2.45, indicating an increment from neutral to slightly hot. This condition was consistent with the increment of room air temperature while the air velocity was reduced (22.5 °C to 28.1 °C). In contrast, the PMV index profiles was reduced linearly from 0.11 to -2.47 (indicating a decrement from neutral to cool) when the air velocity was increased. However, the room air temperature remained the same with no significant difference despite increasing the air velocity. Besides that, there is a significant diffference in terms of thermal comfort performance when the supply air velocity dropped from V-4 to V-5. At V-4 and V-5, the airspeed inside the mosque was drop to 0.05 m/s which is insufficient to provide air movement inside the large-area mosque. This has massively affected the thermal comfort performance of the mosque.

This study has shown that the performance of thermal comfort indexes was still maintained at the optimum values for the supply air velocity between 3 m/s and 8 m/s. Besides that, implementing this energy efficient management strategy by reducing the supply air velocity between V-1 and V-3 from the base case model has reduced EEC between 5.0 %

and 16.1 %. This result only shows the energy reduction from increasing the thermostat setpoint temperature. This EEC reduction from adjusting the motor speed and varying the indoor air ventilation is not included.

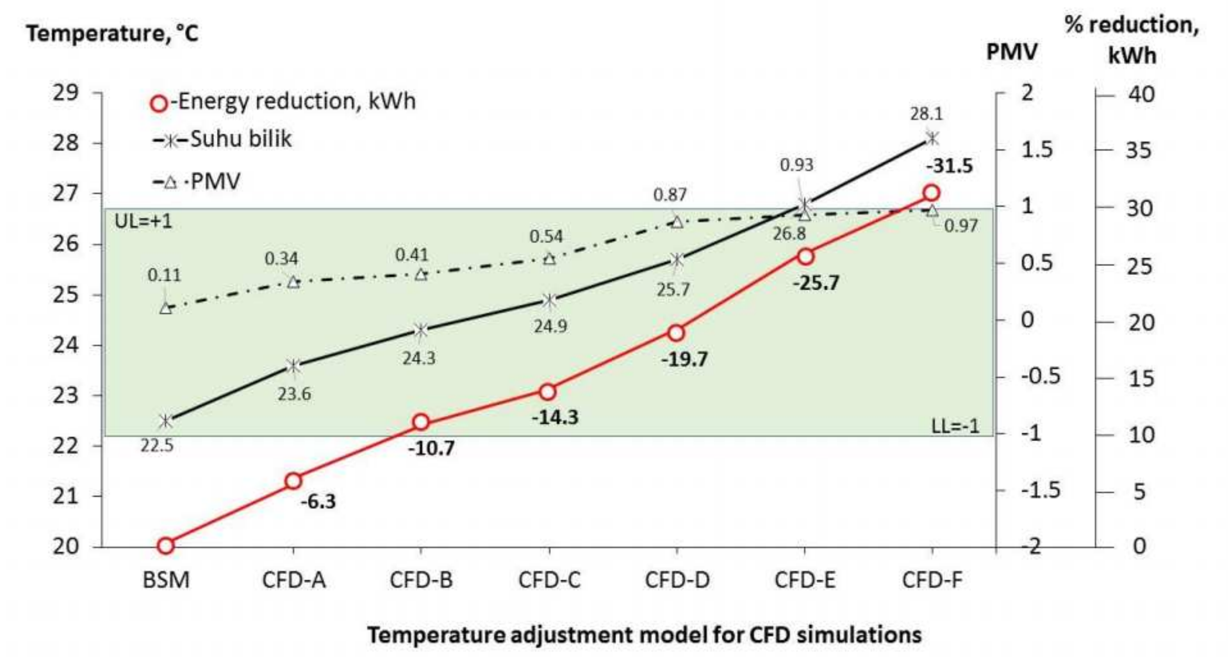



Figure 6. Temperature profile, PMV index, and energy saving in CFD-supply temperature adjustment model

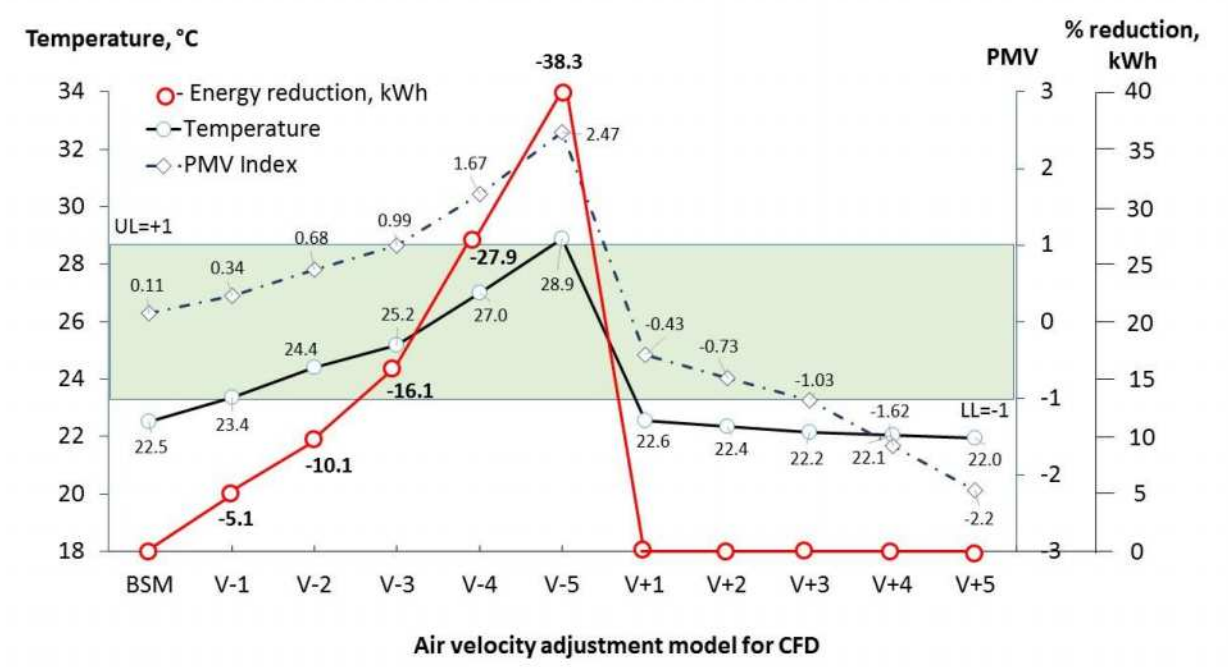



Figure 7. Temperature profile, PMV index, and energy saving in CFD-air velocity adjustment model

## 4.0 Discussions

Energy conservation management which leads to more efficient use of energy without reducing the comfort level is focused on identifying the reason for excessive energy usage and the steps to reduce energy waste. There are many ways to reduce electricity consumption and increase energy efficiency in buildings. In this study, CFD simulations were undertaken to assess the indoor thermal environment of the Penang State Mosque. This study focused on two conventional approaches such as energy conservation management for increasing supply air temperature at a constant airflow rate (constant air volume method), and energy efficient management for increasing and reducing the air velocity at constant supply air temperature (variable-air-volume method). This strategy was successfully simulated and showed a similar trend as the result that was reported by Zhang et al., (2017), where the researchers simulated the thermal conditions provided by the conventional approach at different room air temperatures and airflow rates. Hoyt et al., (2009) investigated the potential energy savings for various thermostat set point temperatures in office buildings, where the effect of increasing the temperature by 1°C resulted in a cooling energy saving of 7–15%, depending on the building operational features and climate zone. Hussin et al., (2015) proposed that an optimum comfort condition should have a PMV comfort index (±1) and a temperature tolerance of 27 °C which was indicated a slightly 1°C higher than Malaysia Standard (MS 1525, 2013). This study found that for a constant air volume method, the optimum strategy was achieved when the supply air temperature was set to T+5, where an indoor temperature of 26.8 °C, a PMV index of 0.93 and energy saving percentage of 25.7% were achieved. On the other hand, for a variable-air-volume, the optimum strategy was achieved when the air velocity was set to V-4, where an indoor air temperature of 25.1 °C, a PMV index of 0.93 (slightly warm), and an energy saving percentage of 15.4% were achieved. This strategy has effectively increases the energy savings of the mosque by optimizing the usage of the air-conditioning system while maintaining the thermal comfort condition at the maximum level. This is one of the factor that Youssef et al., (2018) and Zhang et al., (2017) observed that the optimized indoor temperature served for comfort is satisfied when the indoor thermal environment is faily satisfactory, whereby the occupant was satisfied even though it does not comply to ASHRAE Standards. This condition has then resulted in minimum energy consumption usage to the building owner.

## 4 Conclusions

A 3-D simulation model was implemented to study the thermal distributions and the velocity profiles within the mosque environment in a steady-state condition. The main prayer hall of the Penang State Mosque of Malaysia was chosen as the case study location. An experimental campaign was carried out to measure the parameters necessary to set the input data in the CFD code and to validate the CFD simulation model. Based on the adjustment of PMV comfort index limit ranging from (-1) slightly cool to (+1) slightly warm, the following findings were found:

- For the constant air volume case study, the optimum comfort model at +0.97 PMV index (slightly warm), 28.1 °C indoor temperature and calculated EEC reduction percentage of 31.5 % was obtained when the supply air temperature was set to T+5.
- For the variable-air-volume case study, the optimum comfort model at +0.99 PMV index (slightly warm), 25.2 °C of indoor temperature and calculated EEC reduction percentage of 16.1 % was achieved when the airflow rate was set to V-3.

These operational strategies have given advantage to the Penang State mosque's management, allowed the committee to operate its air-conditioning system at the optimum comfort condition. This allows the mosque to have an optimum room temperature while maintaining the maximum thermal comfort condition and at the same time reducing the energy consumption.

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# Impact of Indoor Environmental Quality Standards on the Simulated Energy Use of Classrooms

**Dolaana Khovalyg[1], Ongun B. Kazanci[2], Ida Gundlach[2], William P. Bahnfleth[3], Jørn Toftum[2], Bjarne W. Olesen[2]**

[1] Thermal Engineering for the Built Environment Lab (TEBEL), École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
[2] International Centre for Indoor Environment and Energy (ICIEE), Department of Civil Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark
[3] Department of Architectural Engineering, Pennsylvania State University, University Park, USA

**Abstract:** The effect of indoor environment parameters specified in national and international standards on simulated energy use of an educational spaces were assessed. Standards considered included those of EN, ISO, ASHRAE and ISHRAE. Eight different climatic locations were considered. Energy use to maintain IEQ parameters according to the highest category, Cat. I, is two times greater for Category II of the same standard, while the difference is only 15% when category changes from II to III and from III to IV. On the other hand, when the category of a particular standard is shifted one level down, requirements for IEQ parameters are relaxed. If parameters are set to comply with Category II instead of the Category I, operative temperature stays within the range specified for Category I 30% less time, while indoor air quality in terms of the $CO_2$ concentration remains within the Category I requirements 60% less. It is less energy expensive to improve IEQ parameters by moving from setpoints of the Category III to Category II than from Category II to Category I.

**Keywords:** IEQ, standards, classrooms, energy use, thermal comfort, air quality

## 1. Introduction

The energy needs of buildings account for 20–40% of the total energy use in developed countries, more than either industry or transportation sectors in the EU and USA (Perez-Lombard L., 2008). Worldwide, the building sector consumed 20% of the total delivered energy in 2016 (U.S. Energy Information, 2016). In addition, buildings contribute significantly to global $CO_2$ emissions, up to 36% in the EU (Directorate-General for Energy, 2017). Generally, design of buildings is guided by a combination of international IEQ standards developed by organizations such as ISO, EN, ASHRAE and national IEQ standards that define the acceptable quality of indoor environment assuring at least the minimum requirements for occupants' well-being and health. Standards categorize IEQ parameters and specify ranges of acceptable values for each category. Specifying a narrow range of acceptable values can result in increased energy demand (for example, as a consequence of high ventilation rates). In the effort to reduce energy use in buildings, it is crucial to focus on maintaining an acceptable quality of the indoor environment and comfort of occupants, and design buildings first to serve the needs of occupants. It is expected that buildings having strict IEQ criteria may consume more energy, which should be quantified through parametric analysis of the relationship between IEQ parameters and actual energy use.

IEQ control in buildings and the resulting energy use are affected by many parameters. Generally, the concentration of carbon dioxide ($CO_2$) as an indicator of ventilation and operative temperature as an indicator of thermal comfort are used to assess the quality of the indoor environment. Adequate air quality and thermal environment are maintained by heating, ventilation, and air-conditioning (HVAC) systems, which are one of the main energy users in buildings. For instance, the energy used by HVAC systems accounted for 11% of the total electricity use in the EU in 2007 (Knight, 2012).

This work compares the energy use of two classrooms designed to meet various IEQ standards using a dynamic building simulation tool. Simulations were performed using the criteria for heating and cooling setpoints, ventilation rates, humidity levels and illuminances for each category in the standards such as EN 15251:2007 (CEN, 2007), ISO 17772-1:2017 (ISO, 2017), ISO/TR 17772-2:2018 (ISO, 2018), EN 16798-1:2019 (CEN, 2019), EN/TR 16798-2:2019 (CEN, 2016), ASHRAE 55-2017 (ASHRAE, 2017), ASHRAE 62.1-2016 (ASHRAE, 2016), and ISHRAE 1001:2016 (ISHRAE, 2016). Some of the criteria were identical across standards, and some of them were not, thus, a unique combination of heating and cooling setpoints, ventilation rates, humidity levels, and illuminances were used. The simulations were performed for eight different locations around the world covering such climates as cold, temperate, arid, and tropical.

The energy use of HVAC depends on multiple parameters such as desired IEQ, climatic zone, building envelope properties, occupancy, and internal heat gains such as appliances and lighting. The energy required for heating, cooling, domestic hot water production, air and water distribution by fans and pumps, and lighting contribute to the total energy needs of each modelled building. To compare the influence of each end-use, energy use of classrooms was categorized and analysed as a total and per category. Overall, the parametric study aimed to correlate energy use and IEQ level based on the requirements of different standards for classrooms.

## 2. Standardized requirements

The energy use and IEQ parameters of the specified building were compared for different categories on international and national standards presented in Table 1. A detailed overview of different standards is provided in a review article (Khovalyg. D., 2020). While some standards contain requirements for all IEQ parameter inputs required by the simulation model (*i.e.* temperature, ventilation rate, relative humidity, and illuminance), other standards contain only the requirements for a specific parameter. For instance, ASHRAE 55 defines only thermal comfort parameters, and ASHRAE 62.1 specifies parameters for ventilation only. Therefore, when ASHRAE standards were considered, values for illuminance were taken from EN 15251.

Table 1: Overview of the IEQ standards

| Standards | Referred in the paper as | Thermal environment | Ventilation rate | Relative humidity | Illumi-nance |
|---|---|---|---|---|---|
| **EN 15251:2007 (CEN, 2007)** | EN 15251 | ✓ | ✓ | ✓ | ✓ |
| **ISO 17772-1:2017** (ISO, 2017), **ISO 17772-2:2018** (ISO, 2018) | ISO 17772 | ✓ | ✓ | ✓ | ✓ |
| **EN 16798-1:2019** (CEN, 2019) **CEN/TR 16798-2:2019** (CEN, 2016) | EN 16798 | | | | |
| **ASHRAE 55-2017** (ASHRAE, 2017) | ASHRAE 55 | ✓ | × | ✓ | × |
| **ASHRAE 62.1-2016** (ASHRAE, 2016) | ASHRAE 62.1 | × | ✓ | ✓ | × |
| **ISHRAE 10001:2016** (ISHRAE, 2016) | ISHRAE 10001 | ✓ | ✓ | ✓ | ✓ |

Specific requirements for the ventilation rates, carbon dioxide concentration increase above the outdoor level, relative humidity, and operative temperature setpoints are listed in **Error! Not a valid bookmark self-reference.**2. As reference setpoints, requirements of EN 15251 Cat II. were used. Requirements for illuminance specified in ISO 17772 and EN 16798 are 500 lux, while EN 15251 and ISHRAE 1001 specify 300 lux for “normal” classrooms for children’s education.

Table 2: Setpoints for IEQ simulations

| Standard | Category | Total ventilation rate[a] [L/s, m$^2$] | $CO_2$ concentr. [ppm][b] | Relative humidity [%] | $T_{op}$ setpoints[c] [°C] |
|---|---|---|---|---|---|
| **EN 15251**[d] | I | 1.0-6.0 | 350 | 30-50 | 21.0 – 25.5 |
| | II | 0.7-4.2 | 500 | 25-60 | 20.0 – 26.0 |
| | III | 0.4-2.4 | 800 | 20-70 | 19.0 – 27.0 |
| **ISO 17772, EN 16798**[e] | I | 1.0-6.0 | 550 | 30-50 | 21.0 – 25.5 |
| | II | 0.7-4.2 | 800 | 25-60 | 20.0 – 26.0 |
| | III | 0.4-2.4 | 1350 | 20-70 | 19.0 – 27.0 |
| | IV | 0.3-2.0 | >1350 | <20, >70 | 17.0 – 28.0 |
| **ASHRAE 55, 62.1**[f] | acceptable | 0.3-1.55 | n/a | < 65 | 19.3 – 26.3[g] |
| **ISHRAE 10001**[h] | A | 7.42 | 350 | 20-70 | 19.0 – 27.0[i] |
| | B | 5.19 | 500 | | |
| | C | 3.25 | 800 | | |

[a] – maximum flow rate is determined for fully occupied room, and the minimum flow rate is defined by the building components emissions only, [b] – concentrations above outdoor level, [c] – minimum for heating (winter season) and maximum for cooling (summer season), [d] – two air volumes have to be delivered before the occupancy, [e] – one air volume have to be delivered before occupancy, [f] – ASHRAE 55 provides setpoints for temperature and ASHRAE 62.1 for ventilation rates, [g] - indoor thermal environment requirements are given as PMV limits, and criteria for the operative temperature were determined from the criteria for PMV, [h] – original requirements are given as maximum $CO_2$ concentration above the ambient level (Cat. A - 350ppm, Cat. B. - 500 ppm, Cat. C – 800 ppm), [i] – if air speed is less than 0.2 m/s.

## 3. Methodology Description

IEQ indicators and energy use of the specified classrooms were compared using the dynamic building performance simulation software *IDA Indoor Climate and Energy* (IDA ICE). The software was validated using the tests specified in ASHRAE 140-2004 (Equa Simulation AB, 2010), EN 15255-2007 and EN 152565-2007 (Equa Simulation Finland Oy, 2010).

### 3.1. Climatic zones

The Köppen-Geiger climate classification (Essenwanger, 2001) was used to select the climate zones for building energy simulations. Since IEQ standards used in this work are normative in Europe, USA, and India, certain locations, the most densely populated ones, representing each region were selected. Climatic zones selected are listed in **Error! Reference source not found.**3. For the simulations in IDA ICE, Test Reference Year (TRY), ASHRAE IWEC 2 and EnergyPlus weather data were used.

Table 3. Climatic zones of the selected locations

| # | City | Country | Climate zone | Abbrev. |
|---|---|---|---|---|
| 1 | Copenhagen | Denmark | Temperate/without dry season/warm summer | Cfb |
| 2 | Tromsø | Norway | Cold/without dry season/cold summer | Dfc |
| 3 | Athens | Greece | Temperate/dry summer/hot summer | Csa |
| 4 | Beijing | China | Cold/dry winter/hot summer | Dwa |
| 5 | Mumbai | India | Tropical/savannah | Aw |
| 6 | New Delhi | India | Temperate/dry winter/hot summer | CWa |
| 7 | Abu Dhabi | UAE | Arid/desert/hot | BWh |
| 8 | Miami | USA | Tropical/Monsoon | Am |

### 3.2. Building construction code

Building envelope characteristics in this study were based on the national Danish Building Regulations from 2015 (DBR1995) without tailoring to the local building codes for locations outside of Denmark. Therefore, the building envelope, which was optimized for the heating-dominated Danish climate, was not optimized for other climatic zones (for instance, cooling dominated climates), as a result, calculated energy usage is expected to be greater compared to actual buildings in some regions. Nonetheless, a uniform building envelope across all climatic zones enables a comparison of the effect of the requirements imposed by different standards, which is the main goal of this work.

### 3.3. The building model

Two classrooms 50 m$^2$ each with a height of 2.5 m were simulated, the overall dimension of the building was 4.0 (w) x 2.5 (h) m. One room faced North and the other one faced South as shown in the plan in Figure 1. The classrooms located in a multi-story building, therefore, the only heat loss or gain was through the façade. All other walls and the floor and ceiling were internal and considered as adiabatic.

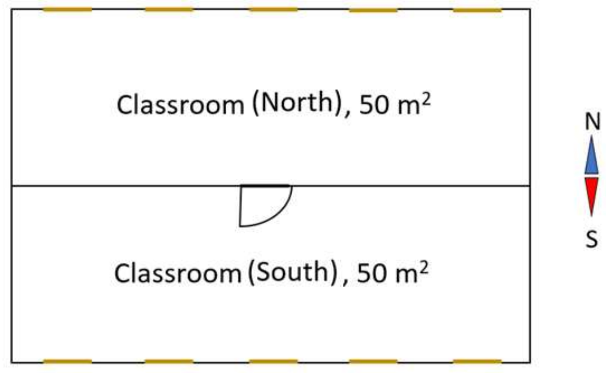


Figure 1. Floor plan of the classrooms

***Wall characteristics***: To define external walls, design thermal transmittance (U-value) and heat losses across external walls of buildings with at least three floors specified by DBR were used. The building code DBR2015 required U=0.19 W/m$^2$K for opaque surfaces. Internal walls consisted of a double layer of gypsum on each side, 3 cm of insulation in the middle, and an air gap on each side of the insulation. Internal slabs between floors consisted of, from top to bottom, 0.5 cm of floor covering, 2 cm of lightweight concrete and 15 cm of concrete. Thermal bridges were set to the values corresponding to the classification “typical” per DBR2015.

***Window characteristics***: The building model had one window per 2.5 m of façade width according to the DBR2015 requirement that the glazing area in non-residential buildings be no more than 10% of the floor area when the light transmittance is at least 75%. This resulted in 5 windows 1.05 m x 1.25 m in each classroom. The requirements for the U-value of windows was 0.6 W/m$^2$K. Shades were integrated with windows and closed at solar heat gains of 100 W/m$^2$. Windows were not operable. As in the case of the opaque envelope, windows were not optimized for a particular climatic zone since the primary goal of this work was to compare the energy use of buildings according to the requirements of different standards.

***Occupancy****:* The occupant density was taken from EN 15251 and EN 16798, and was 2 m$^2$ per person in classrooms. The clothing insulation of the occupants was set to 0.75 ± 0.25 clo. The activity level of the occupants was set to 1.2 met. The schedule of occupancy presented in Figure 2 was taken from EN 16798.

***Internal loads:*** The heat load from appliances for classrooms was set to 8 W/m$^2$ according to EN 16798. For the criteria of illuminance 500 lux, a lighting power density of 12 W/m$^2$ was used. A 3/5 of 12 W/m$^2$ for the illuminance of 300 lux was used. The lighting was assumed to be LED, so the luminous efficacy was set to 60 lm/W (Toepfer, 2017) (DIAL, 2016). The values for daily, weekly, holiday, and total usage time and heat load from appliances were based on EN 16798 recommendations. It was assumed that there were no holidays; therefore, the total usage time was 2868 hours per year. The schedule of daily occupancy of classrooms and the use of appliances and lighting are shown in Figure 2. The operation of equipment and lights was controlled by the occupancy only. Lights had an additional setpoint control – they were switched ON when the illuminance was below the set minimum level and switched OFF when the illuminance was above the set maximum level.

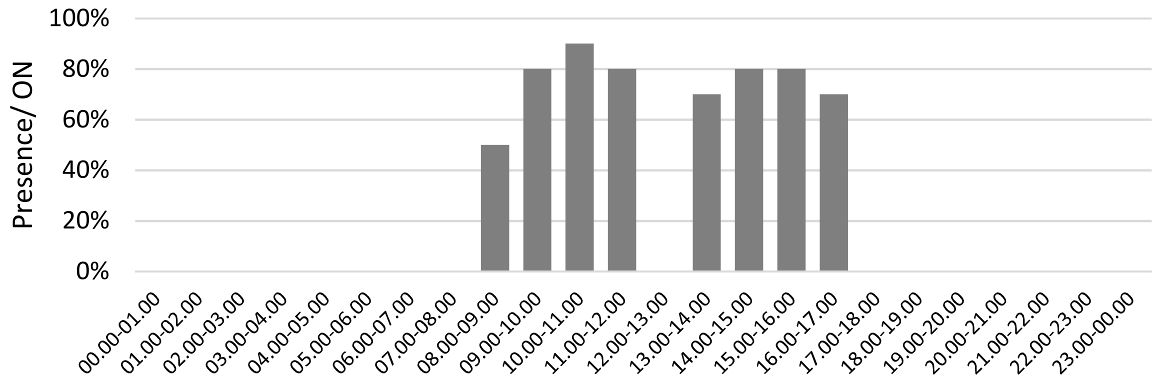


Figure 2. Presence of internal loads (occupants, appliances, lighting) throughout a day (in %)

***Building services:*** The classrooms were mechanically heated, cooled and ventilated. Each room had one terminal unit to compensate for the heat losses or heat gains, no specific type of the unit was assigned. The heaters used PI controllers based on the operative temperature. To define the highest heating power, internal heat gains were set to zero; to define the highest cooling load, 100% of internal gains were considered.

The air handling unit with heat recovery served both rooms. The mechanical ventilation system was balanced, the air was supplied according to the occupancy schedule, and the air was not recirculated or transported from one room to another. The ventilation system included an air filter for the intake air and a filter for the exhaust air, but no other methods of air cleaning were used. Air was supplied at 18°C.

To investigate the need for humidification or dehumidification, simulations were performed without humidification and dehumidification using a standard air handling unit. The setpoints of 60% of maximum RH and 25% of minimum RH were defined based on the requirements for Category II of EN 15251 and EN 16798. Humidification was considered if hours with low humidity operation (below 25%) exceeded hours of AHU operation in high humidity range (over 60%), dehumidification was used in the opposite case. In energy, simulations humidification was used for locations such as Copenhagen, Athens, Beijing and Tromsø, and dehumidification was used for locations such as Mumbai, Abu Dhabi, New Delhi and Miami.

Domestic hot water use was not included in the model. The heat losses from water circulation systems, and heating and cooling supply systems were not considered as well.

## 4. Results and Discussion

The standards ISO 17772, EN 16798, EN 15251, and ASHRAE 55 describe different methods for long term evaluation of the indoor environment, as mentioned by Khovalyg et al. (2020). While ISO 17772, EN 16798, and EN 15251 outline three methods, ASHRAE 55 only one, but all of them allow for long-term evaluation based on the number or percentage of occupied hours when the PMV or the operative temperature is within a specified range. Therefore, this method was chosen to evaluate the indoor environmental parameters across the standards, and all results are based on annual simulations. Thermal environment analysis based on o*perative temperature* was performed only for occupied hours, and it is given as a number of hours within each category of the reference standards. The results for the air quality presented as $CO_2$ concentration were based on the entire year simulations including occupied and non-occupied hours. To investigate how the switch from one category of a certain standard to another category can affect a particular IEQ parameter (operative temperature or $CO_2$ concentration), only one parameter was varied at a time.

Energy use results were evaluated based on annual simulations, and presented as the comparison of four categories of energy use:

- ”Cooling” accounted for the energy use of a chiller and cooling terminal units
- ”Heating” accounted for the energy use of a boiler and heaters
- ”HVAC auxiliary ” accounted for the energy use of fans and circulation pumps
- ”Lighting” accounted for the lights in all office spaces

### 4.1. Effect of climate regulation on energy use

The impact of the location on the energy use of classrooms is shown in Figure 3, where ventilation and indoor temperature were set to the reference values per EN 15251 Cat II. Generally, thermal conditioning (heating and cooling) was the main contribution of differentiating energy use across different climatic zones. Cooling uses a significant amount of energy in hotter regions such as Mumbai, Abu Dhabi, Miami and New Delhi, and its share decreases when the building location shifts north where energy use by heating becomes dominant in relatively cold locations such as Copenhagen, Beijing and Tromsø. Total energy use between two extreme cases, Mumbai and Copenhagen, varied by a factor of 7.6. Generally, the building model placed in Copenhagen had the lowest total energy use due to the mild climate of Denmark resulting in the optimum energy use for heating and cooling. Cooling needs of the buildings located in Copenhagen and Tromsø were the lowest, however, the buildings situated in Tromsø required more heating due to the northmost location.

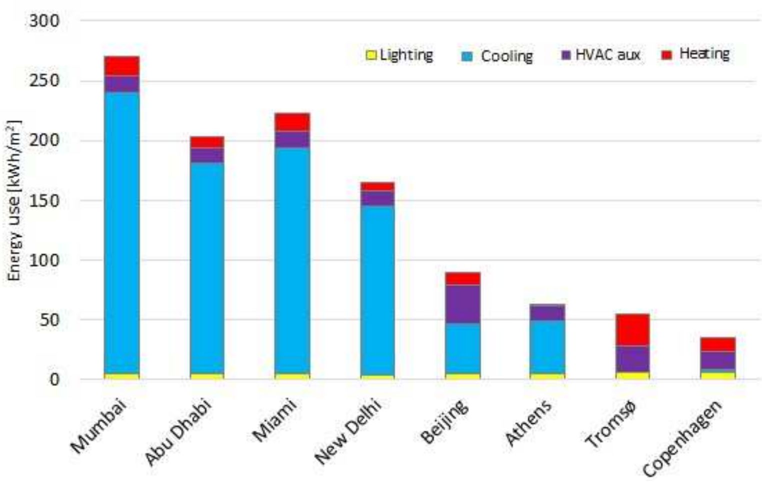


Figure 3. Energy use of the classrooms at reference conditions (EN 15251 Cat II.) situated in different locations

Variation of the energy use in different energy categories across the eight climatic regions considered is illustrated by the box plots in Figure 4. Cooling uses the greatest share of energy (appx. 59%), while “heating” and energy use of auxiliary loads such as fans and pumps (“HVAC aux.”) was, on average, around 20% of total energy use across all climatic locations. For example, “HVAC aux.” on average uses 21%, while “heating” uses 15%. The energy use for “lighting” is 6% which the smallest value compared to other categories of energy use.

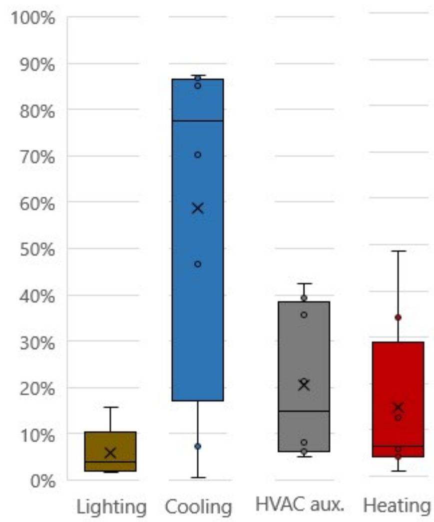


Figure 4. Distribution of energy use across 8 climatic locations

**4.2. Comparison of energy use across standards**

Comparisons of the energy use of the classrooms located in different cities designed according to the requirements of different standards are shown in Figure 5. The plots present energy use (kWh/m$^2$) for each category as well as the total value across eight climatic regions. Two locations, Mumbai and Copenhagen (Figure 6, 7), were selected for detailed illustration of energy use per energy meter since they correspond to the maximum and minimum total energy use.

Generally, the operation of the building designed according to EN 15251 uses the highest amount of energy if the corresponding categories across standards are compared (for instance, Cat. II of EN 15251 *vs.* Cat. II of EN 16798 *vs.* Class B of ISHRAE 10001). If two EN standards are compared, the operational parameters set according to the new EN standard, EN 16798, use slightly less energy if the corresponding categories are compared. For the school building, there were two differences between EN 15251 and EN 16798. The first difference was that the ventilation system was switched ON two hours before occupancy started according to EN 15251, while it was switched ON an hour prior occupancy using EN 16798. The second difference was in illuminance level - the illuminance was 300 lux in the classrooms per EN 15251, while it was 500 lux per EN 16798.

The change in energy use between the categories/classes within the same standard depends on the location of the building. For instance, for classes located in Copenhagen when requirements of the EN 15251 are applied, the total energy reduction is 40% from Cat. I to Cat. II, and 42% from Cat. II to Cat III. If requirements of the EN 16798 were applied, the reduction in energy use from Category I to Category II would have been 40% from Cat. I to II, 29% from Cat. II to III, and 14% from Cat. III to IV.

The difference in energy use between categories, as shown in Figure 7, of the Indian standard ISHRAE 10001 is relatively small. When requirements of ISHRAE 10001 are applied, energy use drops 28% from Class A to B, and 22% from Class B to C. While the requirements for the Class A and B are less energy expensive compared to Cat. I and II of EN standards, requirements for Class C are almost at the same level as Cat. III of EN 16798. The energy use of classroom operated according to ASHRAE standards was almost the same amount as for energy as Cat. III of EN 15251 and EN16798, and between Class B and C of ISHRAE 10001.

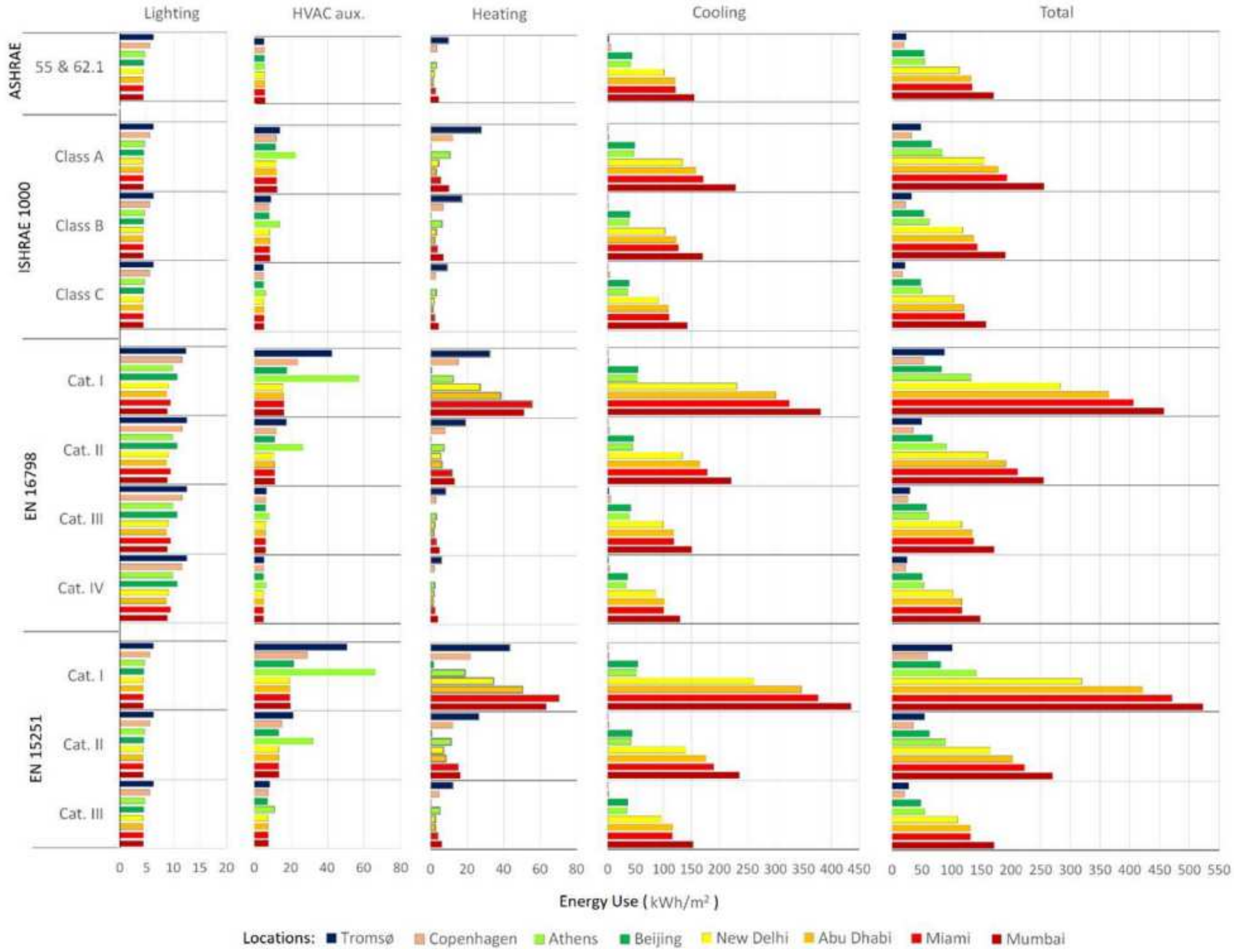


Figure 5. Comparison of the energy use of the school building designed according to various standards

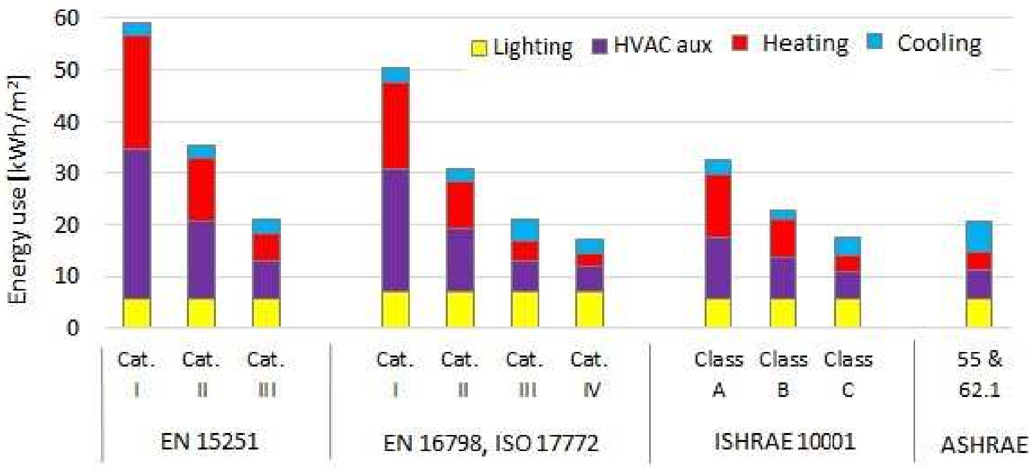


Figure 62. The energy use of modeled classrooms located in Copenhagen

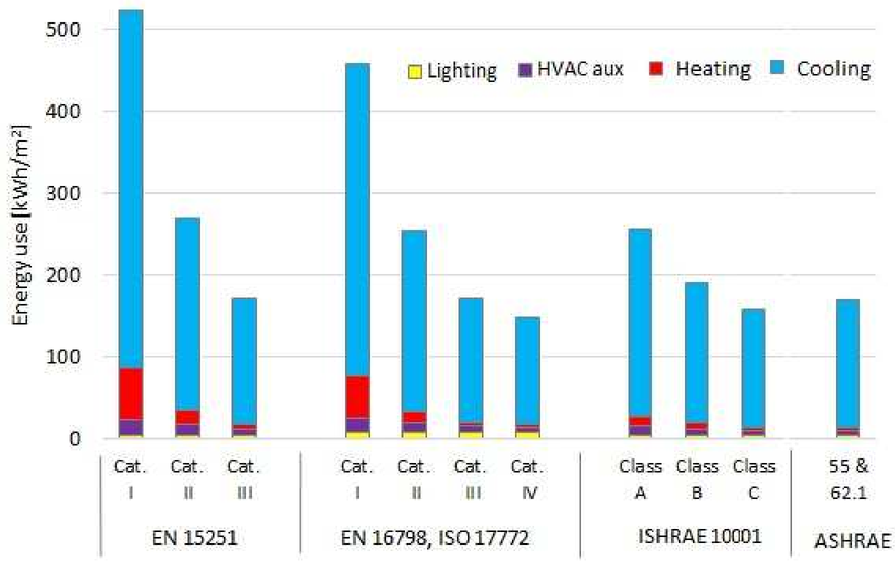


Figure 73. The energy use of modeled classrooms located in Mumbai

### 4.3. Comparison of IEQ parameters: operative temperature

Operative temperature comparison is illustrated in Figure 8 for setpoints corresponding to the different categories of standards EN 16798, ISO 17772, ISHRAE 10001, and ASHRAE 55. The plot shows operative temperature variation between different locations and between different standards both for south and north oriented rooms. Operative temperature ranges set by EN 15251 serve as the reference values. Generally, the south-oriented classrooms tend to be warmer and stay within the range required by a particular category of EN 15251 less of the time. If the building is designed according to Cat. I, it maintains the operative temperature within the narrow range of 21.0-25.5°C for a longer period. With the reduction of the Category, the temperature in the classroom varies in a wider range. For instance, if a building is designed according to Cat. I of EN 16798, 79% of the time temperature is within the range of 21.0-25.5°C (Cat. I, EN 15251) and 21% in the range of 20.0-26.0°C (Cat. II, EN 15251) on an annual basis. The same building designed according to the Cat. III of EN 16798 stays only 23% within the range 21.0-25.5°C (Cat. I, EN 15251), 11% within 20.0-26.0°C (Cat. II, EN 15251), 38% within 19.0-27.0°C (Cat. III, EN 15251), and 23% outside the range of 19.0-27.0°C (outside Cat. III, EN 15251). On average, the building designed according to the requirements of the EN 16798 has tighter control of the operative temperature compared to the buildings designed according to ISHRAE 1000 and ASHRAE requirements.

### 4.4. Comparison of IEQ parameters: $CO_2$ concentration

A comparison of the carbon dioxide concentration results is shown in Figure 9 for the school model designed according to the different categories of the standards EN 16798, ISHRAE 10001, and ASHRAE. As expected, buildings designed according to the highest category of a particular standard have the lowest value of the acceptable level of $CO_2$ concentration and the tightest control, while the buildings that meet the requirements of the lowest category tend to have the highest $CO_2$ concentration most of the time (over 800 ppm above the outdoor level according to EN 15251). As an example, the building model designed according to Category I of EN 16798 maintains indoor environment at the level of 350 ppm rise above ambient most (88%) of the time, while the building designed according to the Category IV of EN 16798 is above the 800 ppm above outdoor limit per Category III of EN 15251 74% of the time. The difference in $CO_2$ levels between the Category I and Category IV according to EN 16798 is drastic, compared to other standards, since EN requires only 550 ppm for Category I

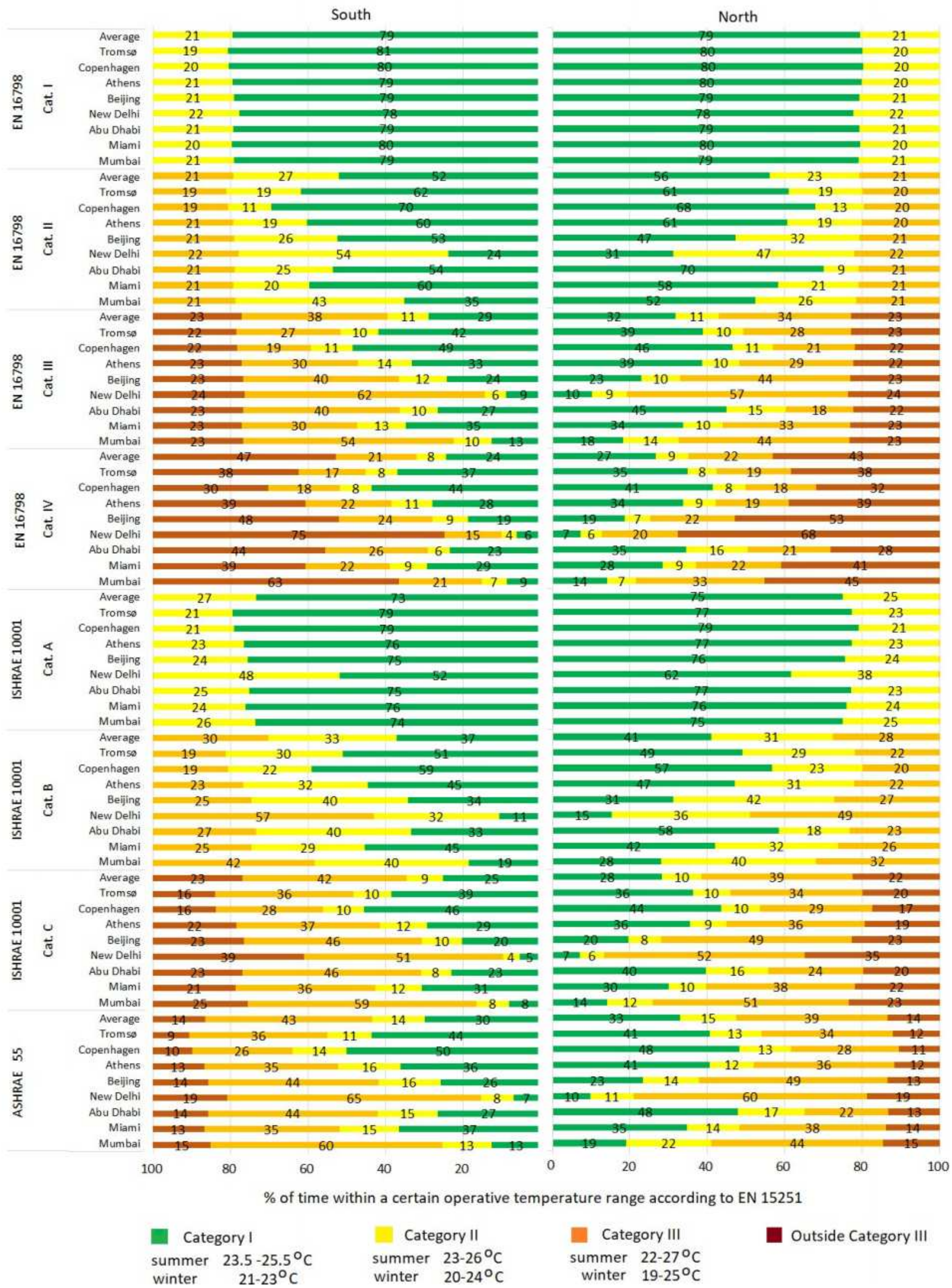


Figure 8. Percentage of the operative temperature within a certain range annually according to the settings of EN 15251 (summer and winter setpoints are indicated in the legend)

and allows over 1350 ppm for the Category IV. The difference between the Categories A and C of ISHRAE 10001 is less pronounced. Air quality delivered according to the ASHRAE is similar to the Category B of ISHRAE 10001. Between different locations of the classrooms, the building model located in Copenhagen tends to have lower $CO_2$ concentration across all categories of the standards, while the building located in Mumbai has the worst air quality.

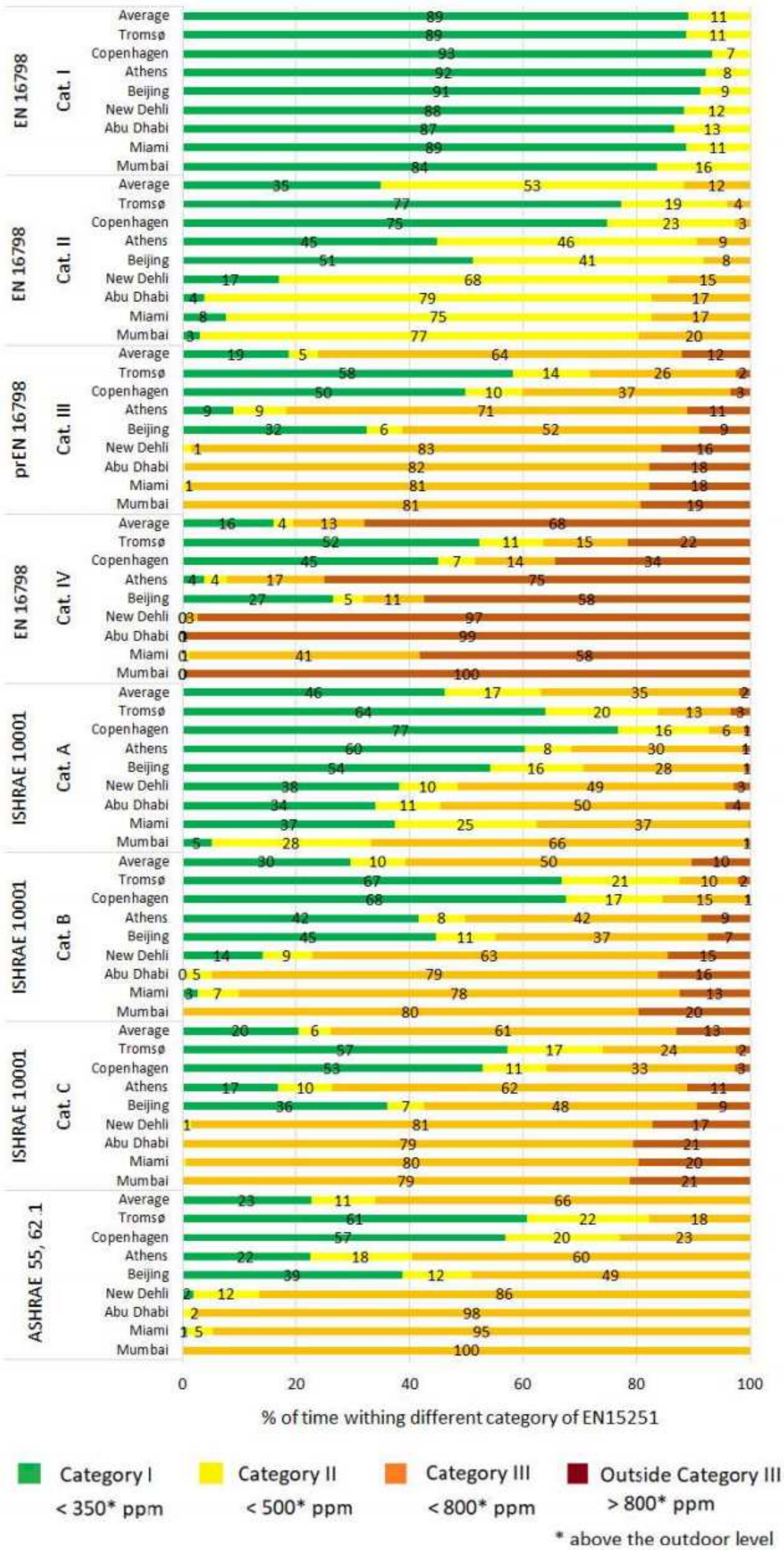


Figure 9. Percentage of the $CO_2$ level within a certain range annually according to the settings of EN 15251 for the classrooms (above outdoor level, the outdoor concentration of $CO_2$ is taken as 400 ppm)

## 5. Summary

The purpose of this work was to compare the energy use, thermal environment and IAQ for the school model with two classrooms using criteria from several standards in order to identify how the criteria from each standard affect energy use and IEQ. A comparison of the results was based on the total energy use for lighting, cooling, heating, and auxiliary equipment such as fans and pumps. The quality of the indoor environment was evaluated based on the operative temperature as an indicator of the thermal environment and $CO_2$ concentration as an indicator of air quality.

The results show that the climate has a significant impact on energy use affecting cooling/heating demand. A building located in warmer climates use significantly more energy to maintain an acceptable indoor environment year-round (for example, in Mumbai and Miami), followed by buildings in cold climates. Temperate climates have the lowest energy use, with the climate of Copenhagen demanding the lowest energy use. The lower energy use in Copenhagen might be influenced by the fact that the building was designed according to Danish building regulations that account for the issues important for the Danish climate.

Generally, energy use decreased with decreasing requirements for indoor environmental quality when criteria from selected IEQ standards were used. The decrease in energy use between adjacent Categories for the school building model was: (i) at least 23.1% when using criteria from EN 15251, (ii) 12.5% with criteria from EN 16798, (iii) 8.9% with criteria from ISHRAE 10001 in most of the cases. The energy use for IEQ set per EN 16798 was lower compared to EN 15251 since the ventilation system was switched ON one hour before the beginning of occupancy and not two hours before. However, the benefit varied depending on climate, with a reduction between 0.3% and 8.8%. The number of degree hours below 21°C and above 25.5°C and the number of hours with $CO_2$ concentration above 750 ppm increased with decreasing requirements to the indoor environmental quality in all categories of EN 15251 and EN 16798 and for seven out of eight locations for ISHRAE 10001.

Overall, the results show that the IEQ parameters significantly affect energy use and that a higher category of IEQ causes a higher energy use. However, for all eight climates, there were one or more categories that provided an acceptable thermal environment and IAQ at moderate energy expense compared to another category. In these cases, it was possible to achieve reduced energy use without reducing the quality of the thermal environment or IAQ. However, it varies from climate to climate, which category results in the lowest energy use, which category results in the best thermal environment, and which category assures the highest IAQ. Therefore, there is no category that always provides both the lowest energy use and the highest IEQ in all simulated cases.

The outcomes of this work inform regarding the relative relationship between different IEQ standards and different categories that could be used by practitioner and educational institutions to evaluate the penalty of not providing the adequate IEQ in educational buildings if only the energy reduction goal is pursuit. The comparison can be improved by accounting for the local building regulations in terms of the building envelope and accounting for the actual outdoor $CO_2$ levels order to have a better comparison of energy use of building in different parts of the world.

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# Methodology of IEQ assessment in energy efficient buildings

**Karel Kabele[1], Zuzana Veverkova[1], Miroslav Urban[1]**

[1] Czech Technical University in Prague, Faculty of Civil Engineering, Department of Indoor Environmental and Building Services Engineering, kabele@fsv.cvut.cz

**Abstract:** Contemporary design, realization and operation of buildings based on cost-effective energy savings has an impact on the quality of the indoor environment. We meet completely new questions about the indoor environment quality in buildings with high energy performance in terms of thermal comfort, air quality, acoustic, light, electromagnetic, ionic microclimate and psychological comfort. The aim of the "Smart Regions Competence Centre" project of the Czech Republic's Technology Agency is, among other, to introduce methodology for expressing the quality of the indoor environment in low-energy buildings. The reason for this project is the fact that clients are currently receiving detailed information only on the energy performance of the building - energy certificate - but they have virtually no information on real or expected quality of the indoor environment in buildings. The methodology is based on a holistic approach to integrate data from smart building control systems, short-term monitoring campaigns, and questionnaire survey among users. In the case of new buildings, the assessment is based on the simulation of the energy performance of buildings. Use of methodology is documented on the results of long-term monitoring of selected IEQ indicators (temperature, CO2, VOC, humidity, noise), energy performance and questionnaires in nZEB building.

**Keywords:** Indoor Environment Quality, Assessment, Methodology, Monitoring of IEQ indicators, Questionnaire survey

## 1. Introduction

Increased attention to energy use in buildings is a trend that has been observed in the construction industry since the 1980s. This trend is accentuated and subsequently suppressed at various times, mainly in connection with changes in energy prices, but it is a long-term, more or less continuous process. The impact of this construction regulation should be primarily on the fulfilment of the primary intent, i.e. the reduction of heat and electricity consumption in buildings, however it will also have implications for other building functions, particularly in the area of indoor environment quality, which is directly related to energy use.

Buildings with low energy performance behave differently from the point of view of indoor environment than traditional buildings. It can be seen from the user´s reactions and objectively proven facts that changes in the quality of the indoor environment are perceived and are an important indicator affecting the utility value of the building.

In buildings designed with the primary emphasis on energy savings it is necessary to increase the control of hygienic and comfort requirements for individual components of the indoor environment, as pressure on energy savings in most cases minimizes the natural interaction of indoor and outdoor environments. Many of the building's functions, those that took place earlier without human intervention, are eliminated in modern buildings with low energy consumption and are replaced by technical systems with high energy efficiency but a negative impact on the indoor environment quality (Kabele et al, 2016).

The building is an interconnected organism, where any change of parameters affecting the energy performance has an impact on the indoor environment quality. Compliance with energy performance requirements must be considered already in the design phase of the building and its technical systems. Omission of context with other building functions often leads to operational problems of buildings. These problems are manifested by unexpected reactions of the building during operation - overheating in winter, problems with regulation of hydronic systems, noise of equipment, poor air quality and air distribution, mould formation, sick building syndrome and others. These problems are most often manifested by user complaints about dissatisfaction with the quality of the environment.

Unlike buildings' energy performance, which is an objective value based on measurable parameters, the perception of the indoor environment is largely subjective and depends on the exposed subject. While for the determination and assessment of energy performance exist sophisticated and well-established tools and methods (energy performance certification, building certification, etc.), for the indoor environment quality, which is more difficult to quantify, the tools and methods are only being developed and there are only emerging first attempts to link energy performance assessment to indoor environment quality assessment in practice.

This methodology does not compete with evaluation tools such as BREEAM, WELL, LEADS etc., which are primarily intended for the comprehensive evaluation of buildings. These instruments assessing IEQ only as a part of the overall assessment and have different weightings (Mattoni et al, 2018).

## 2. Description of IEQ assessment methodology

The aim of this methodology is to create a complex holistic view of the assessed object in terms of individual components of the indoor environment (Bluyssen, 2009) and it is assessment. The content is a methodical description of the process of obtaining and the extent of information, the way of obtaining information and data on the indoor environment quality of buildings, their processing and evaluation with the aim to create relevant information about the indoor environment quality for the investor, owner, user, operator or designer. The output is a set of information expressing whether the assessed object is solved in terms of individual criteria at the level of the current state of knowledge or has the potential to improve the indoor environment quality or there are serious shortcomings in terms of the indoor environment quality. The methodology also aims to assess the building in terms of "Smart Readiness Indicator SRI" according to Annex 1A of Directive 2018/844/EU (2b), which states as one of the criteria "the ability to adapt its operating mode in response to user needs taking due account of user-friendliness, maintaining a healthy indoor environment and the ability to report on energy use" (Verbeke et al, 2018). As the exact definition of SRI has not yet been published by the European Union, this methodology will be updated from the SRI point of view and supplemented after its publication.

The methodology was developed using the results of experiments, analyses and measurements performed and published in 2014-2019 within the framework of the project TE02000077 Intelligent Regions - Information Modelling of Buildings and Settlements, Technology and Infrastructure for Sustainable Development. The methodology is certified by the Ministry of Industry and Trade of the Czech Republic (Kabele et al, 2019).

The methodology does not primarily address the issue of the indoor environment in cases where the indoor environment does not comply with legal regulations and does not replace the hygienic service; on the contrary, it draws attention to problematic cases which must then be dealt with using standard procedures.

The methodology contains four basic parts. The first part summarizes the basic data about the assessed object and the processor and the scope of the evaluated parts of the object is defined, including materials for evaluation (project documentation, local investigation, measurement and regulation records, own measurements, questionnaire survey). Data about the assessed zone with a focus on building-technical solutions and interior, heating, cooling, ventilation, lighting, acoustics and electro-magnetic, -ionic, -static fields and ionizing radiation are processed in the second part. Information about real operation of evaluated object, based on data from measurement, mathematical model and questionnaire survey is processed in the third part. The fourth final part contains an evaluation of the above described state of the building solution in terms of the eight criteria given in Table 1.

Table 1. Criteria for assessment

| | |
|---|---|
| LS | Locality and placed of the object in terms of external environment and social relations |
| STI | Building - construction and technical solution and interior of the evaluated zone (STI) |
| TCW | Thermal comfort for winter period |
| TCS | Thermal comfort for summer period |
| IAQ | Indoor air quality |
| LC | Light comfort |
| AC | Acoustical comfort |
| EC | Electro-magnetic, -ionic,- static fields, ionizing radiation |

Each of the eight criteria contains 3-10 sub-criteria, each of which is evaluated with 0 to 3 points according to the Table 2. The resulting evaluation of each criterion is the average of the non-zero values of the sub-criteria and may thus be in the range of 1 to 3, where 1 means a state corresponding to the current state of knowledge and 3 a critical state requiring immediate correction.

Table 2 Table of points for criteria evaluation

| Points | Meaning |
|---|---|
| 0 | Not evaluated - e.g. lack of data, not relevant for the zone, other reason (the reason must be stated) |
| 1 | No comments - optimal condition, suitable solution |
| 2 | Comments, shortcomings |
| 3 | Serious deficiency - failure to comply with legislation, emergency state, equipment malfunction and, in the case of comments and serious deficiencies, their specification by comment. |

## 3. Case study

The case study of selected zones of a family house shows the use of methodology not only for IEQ evaluation but also for diagnostics and identification of problems related to indoor environment quality in buildings with low energy consumption. Despite the fact that all constructions and technical systems are designed according to valid standards and knowledge of current technology, users observe disturbances in the area of water vapor condensation on the constructions. The aim of this study is also to show the potential for improving the indoor environment quality in the building.

According to the aforementioned methodology, a local survey was carried out, available documentation was studied, measuring equipment for monitoring selected parameters of indoor environment (air temperature, relative humidity, $CO_2$ concentration) was installed and questionnaire for subjective evaluation of the environment quality by users was processed. Based on these data, the individual areas included in the methodology were evaluated, Tab…

### 3.1. Building description

The subject of the case study is a two-storey family house with a glass façade oriented west facing to the garden. There are a living area facing south equipped with a fireplace and connected to a kitchen facing north, room facing south and corridors, on the ground floor, Figure 1. There are three bedrooms, two rooms and living room gallery facing south, two bathrooms and laundry facing north and corridor, on the first floor, Figure 2.

The heat source is the ground-water heat pump, which supplies a circuit of hot water preparation, radiators, underfloor heating and pool heating via an accumulation tank, **Chyba! Nenalezen zdroj odkazů.**. As a supplemental source is used solar thermal system. Cooling of the living rooms of the first floor of the building is ensured by a system of ceiling capillaries connected through the exchanger to the primary circuit of the heat pump.


Figure 1 West view and ground floor of case study building with placing of measure points (4.0, 4.1., 4.2. a 4.3.)


Figure 2 First floor of case study building with placing of measure points (5.0, 5.1., 5.2. a 5.3.)

### 3.2. Questionnaire

To determine how users subjectively perceived environment during the control measurement of selected IEQ parameters, a questionnaire focused on individual components of the indoor environment and their perception by users, was elaborated. The questionnaire was filled in repeatedly by users of the object (4 adults), so their responses reacted to variable values of IEQ parameters. The questionnaire survey was conducted during the period of 22. 11. 2019 - 15. 12. 2019, a total of 51 responses were received. The evaluation of selected questions of the questionnaire in terms of thermal comfort in winter in the selected zone (living space) is shown in the following graphs.

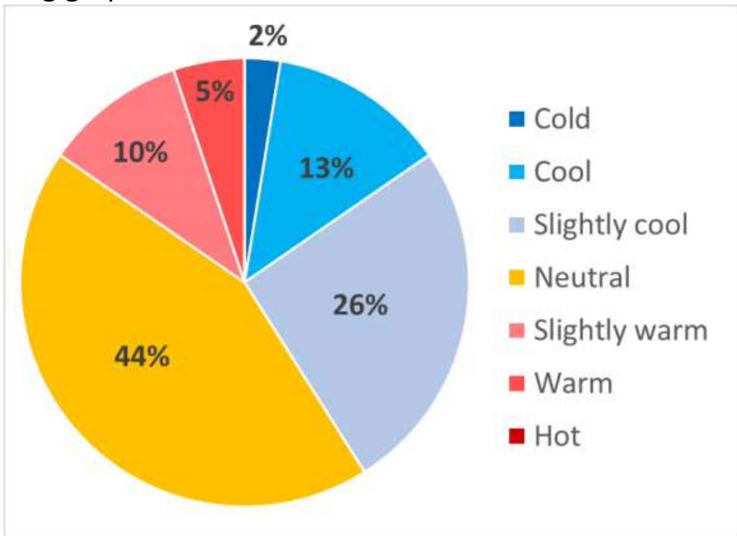



Figure 3 - Perceived temperature - living and dining room

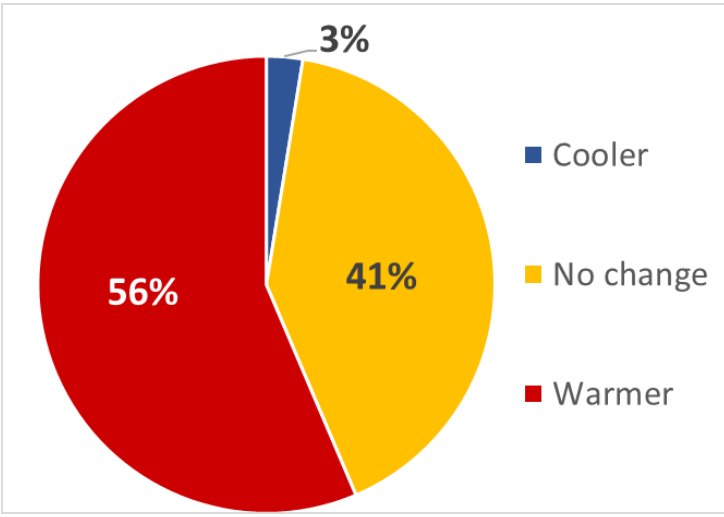



Figure 4 - Indoor environmental status preferences - living and dining room

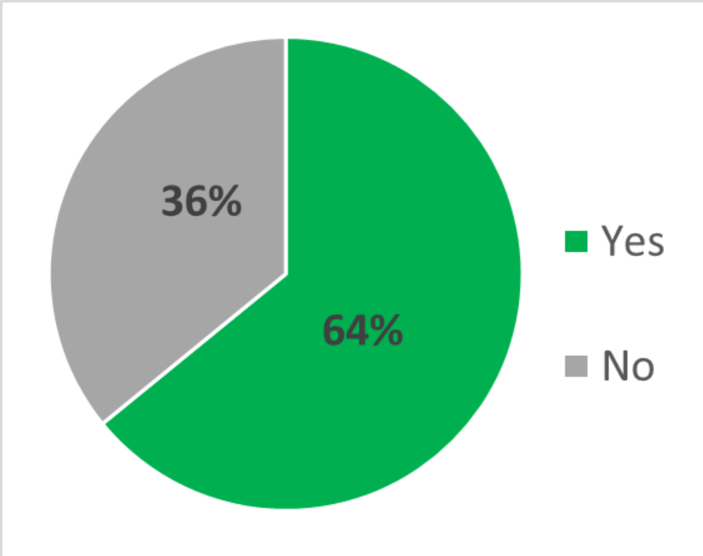



Figure 5 - Satisfaction with indoor temperature - living and dining room

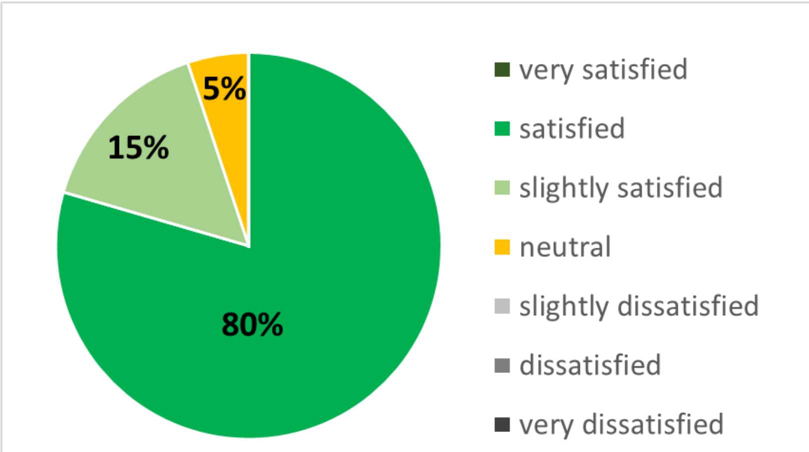



Figure 6 - Overall satisfaction with the indoor environment quality of the living and dining room

### 3.3. Measurement

The second important source of information was measurement of selected IEQ parameters. The Netatmo system, which collects data on air temperature, relative humidity and $CO_2$ concentration, was used for the measurement in a five-minute interval. A total of 8 sensors (4.0, 4.1, 4.2, 4.3, 5.0, 5.1, 5.2, 5.3) have been placed in characteristic locations (near the glass wall, in the middle of the room, in the zone of residence) of selected zones of the building, Figure 1. and Figure 2.

The measurement took place in the period from 22. 11. - 15. 12. 2019. Outdoor air temperature and relative humidity are shown in the graphs in Figure 7. and Figure 8.

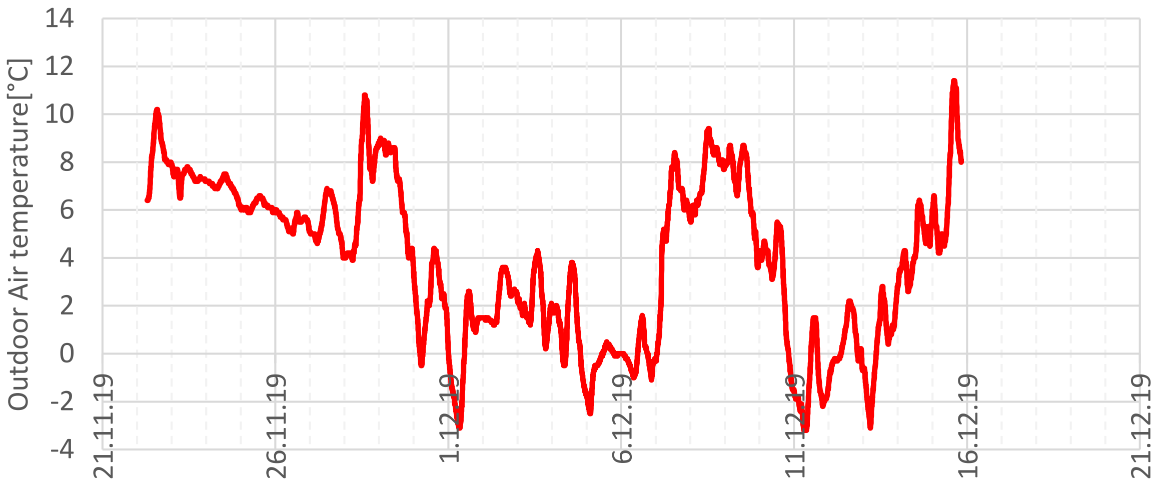



Figure 7 Outdoor Air Temperature during measured period

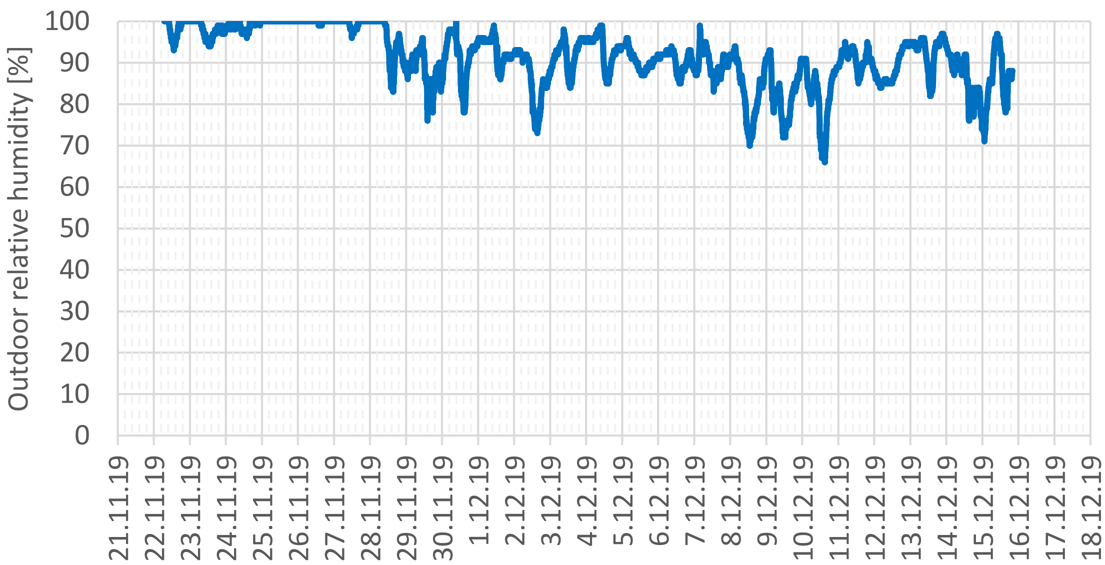



Figure 8. Outdoor Relative humidity during measured period

The data were evaluated using the VISIEQ method developed within the "CTU Methodology". This allows an integrated view of the measured data and allows time identification of problem situations, Figure 9. And Figure 10.

The standard EN 15251, Government Regulation No. 361/2007 Coll. and "CTU Methodology" of IEQ Assessment were used for evaluation of measured data, resp. for limits determination of monitored parameters of the indoor environment.

Figure 9. shows an example of evaluation of sensor 4.1 (living space) by the VISIEQ method, where the air temperature drops during night hours to category -IV is apparent, which means a decrease below 19 ° C, overall in 8.5 % of the monitored period. In 58 % of the monitored period the temperature is in the category -III, i.e. 19 - 20.5 ° C and 33 % of the monitored period in the category -II, i.e. 20.5 – 22 ° C. Relative air humidity and $CO_2$ concentrations were in category I during the whole monitored period, i.e. 40-50 % RH and max. 900 ppm $CO_2$.

## ASSESSMENT OF THE INDOOR ENVIRONMENT QUALITY FROM MEASURED VALUES

| building | room/zone | measured point (marking | measured period | | |
|---|---|---|---|---|---|
| TZB4_Libus_prizemi | Obytný prostor | tzb4.1 | 22.11.2019 | - | 15.12.2019 |

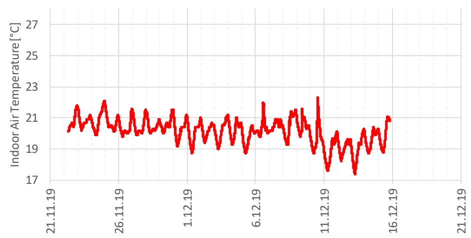
### AIR TEMPERATURE

| | |
|---|---|
| Measuring device (sensor | Netatmo |
| Time step of measuremen | 0:05:04 [hh:mm:ss] |
| Assessed according to: | EN 15251 (2011) |
| | Government Regulation č. 361/2007 Sb. |
| | CTU Methodology of IEQ Assessment |

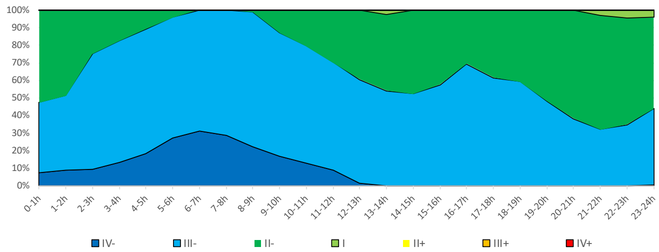
Categories for indoor air temperature assessment: Evaluated

| Categories | IV- | III- | II- | I | II+ | III+ | IV+ | | Day | Hour |
|---|---|---|---|---|---|---|---|---|---|---|
| from [°C] | < 19 | 19 | 20,5 | 22 | 24 | 25,5 | > 27 | from | 1 | 0 |
| to [°C] | | 20,5 | 22 | 24 | 25,5 | 27 | | to | 7 | 23 |

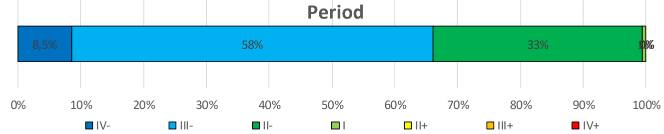
Course of indoor air temperature in the evaluated period:




Hourly Overview of Air Temperature Categories




Air Temeprature Category Contribution over the Measured Period



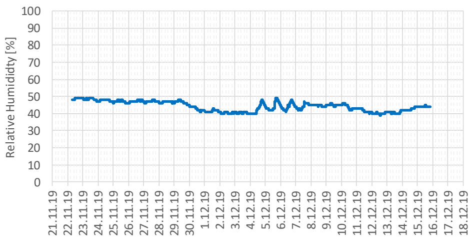

### RELATIVE HUMIDITY

| | |
|---|---|
| Measuring device (sensor | Netatmo |
| Time step of measuremen | 0:05:04 [hh:mm:ss] |
| Assessed according to: | EN 15251 (2011) |
| | Government Regulation č. 361/2007 Sb. |
| | CTU Methodology of IEQ Assessment |

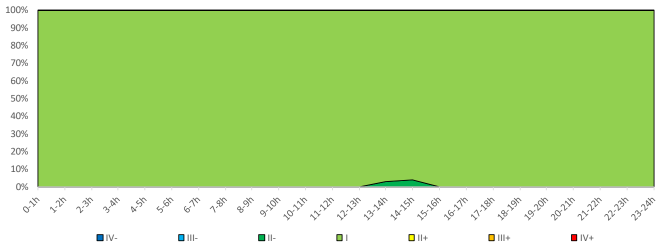
Categories for indoor air temperature assessment: Evaluated

| Categories | IV- | III- | II- | I | II+ | III+ | IV+ | | Day | Hour |
|---|---|---|---|---|---|---|---|---|---|---|
| from [%] | < 35 | 30 | 35 | 40 | 50 | 60 | > 70 | from | 1 | 0 |
| to [%] | | 35 | 40 | 50 | 60 | 70 | | to | 7 | 23 |

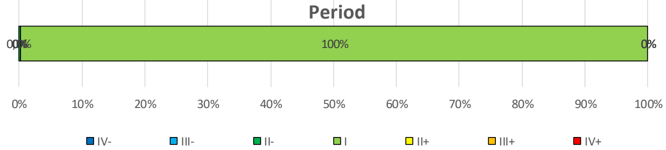
Course of relative humidity in the evaluated period:




Hourly Overview of Relative Humidity Categories




Relative Humidity Category Contribution over the Measured Period



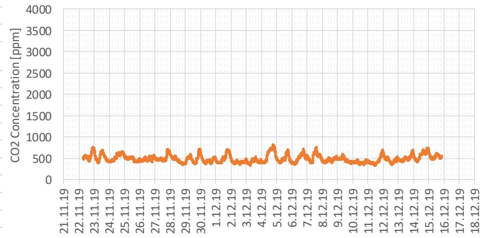

### $CO_2$ CONCENTRATION

| | |
|---|---|
| Measuring device (sensor | Netatmo |
| Time step of measuremen | 0:05:04 [hh:mm:ss] |
| Assessed according to: | EN 15251 (2011) |
| | Government Regulation č. 361/2007 Sb. |
| | CTU Methodology of IEQ Assessment |

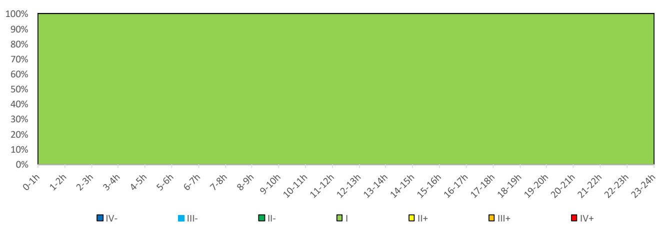
Categories for $CO_2$ concetration assessment: Evaluated

| Categories | I | II | III | IV | | Day | Hour |
|---|---|---|---|---|---|---|---|
| from [ppm] | 0 | 900 | 1200 | > 1500 | from | 1 | 0 |
| to [ppm] | 900 | 1200 | 1500 | | to | 7 | 23 |

Course of CO2 concetration in the evaluated period:




Hourly Overview of $CO_2$ Concentration Categories




$CO_2$ Concentration Category Contribution over the Measured Period

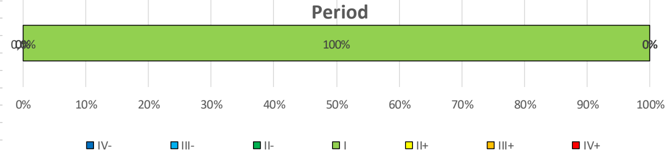



Figure 9. VISIEQ assessment of the IEQ from measured values, Sensor 4.1.

## ASSESSMENT OF THE INDOOR ENVIRONMENT QUALITY FROM MEASURED VALUES

| building | room/zone | measured point (marking) | measured period | | |
|---|---|---|---|---|---|
| TZB5_Libus_patro | Pokoj dětí 1 | TZB5.1 | 22.11.2019 | - | 15.12.2019 |

### AIR TEMPERATURE

Measuring device (sensor): Netatmo
Measuring device (sensor): 0:06:04 [hh:mm:ss]
Time step of measurement: EN 15251 (2011)
Assessed according to: Government Regulation č. 361/2007 Sb.
CTU Methodology of IEQ Assessment

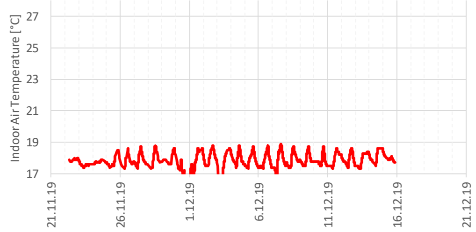
Categories for indoor air temperature assessment:

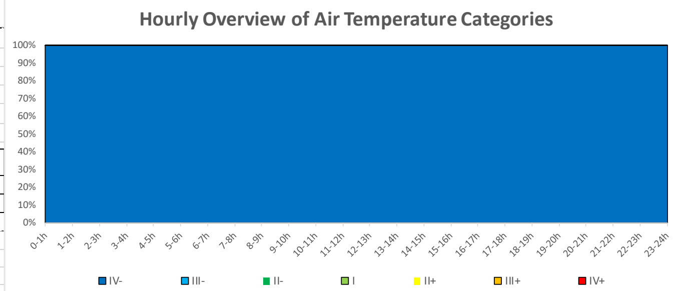
| Categories | IV- | III- | II- | I | II+ | III+ | IV+ |
|---|---|---|---|---|---|---|---|
| from [°C] | < 19 | 19 | 20,5 | 22 | 24 | 25,5 | > 27 |
| to [°C] | | 20,5 | 22 | 24 | 25,5 | 27 | |

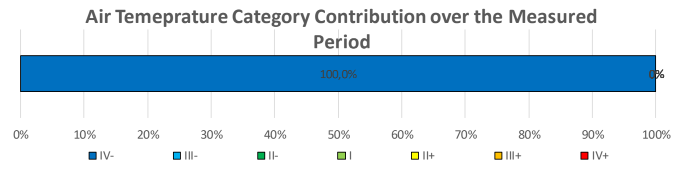
Evaluated

| | Day | Hour |
|---|---|---|
| from | 1 | 0 |
| to | 7 | 23 |

Course of indoor air temperature in the evaluated period:




### RELATIVE HUMIDITY

Measuring device (sensor): Netatmo
Time step of measurement: 0:06:04 [hh:mm:ss]
Assessed according to: EN 15251 (2011)
Government Regulation č. 361/2007 Sb.
CTU Methodology of IEQ Assessment

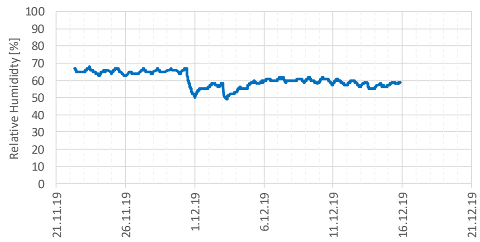
Categories for indoor air temperature assessment:

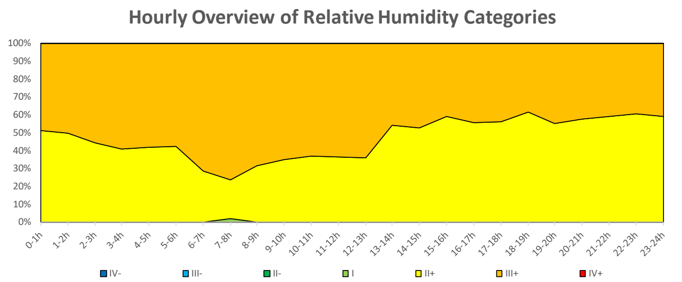
| Categories | IV- | III- | II- | I | II+ | III+ | IV+ |
|---|---|---|---|---|---|---|---|
| from [%] | < 30 | 30 | 35 | 40 | 50 | 60 | > 70 |
| to [%] | | 35 | 40 | 50 | 60 | 70 | |

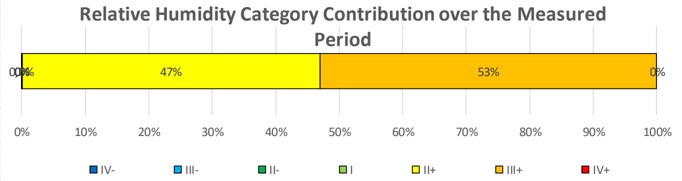
Evaluated

| | Day | Hour |
|---|---|---|
| from | 1 | 0 |
| to | 7 | 23 |

Course of relative humidity in the evaluated period:




### $CO_2$ CONCENTRATION

Measuring device (sensor): Netatmo
Time step of measurement: 0:06:04 [hh:mm:ss]
Assessed according to: EN 15251 (2011)
Government Regulation č. 361/2007 Sb.
CTU Methodology of IEQ Assessment

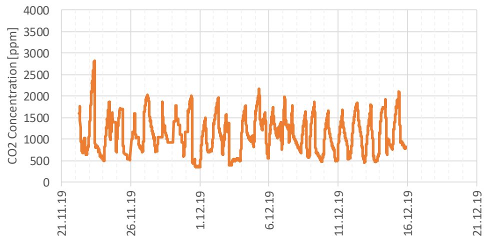
Categories for $CO_2$ concetration assessment:

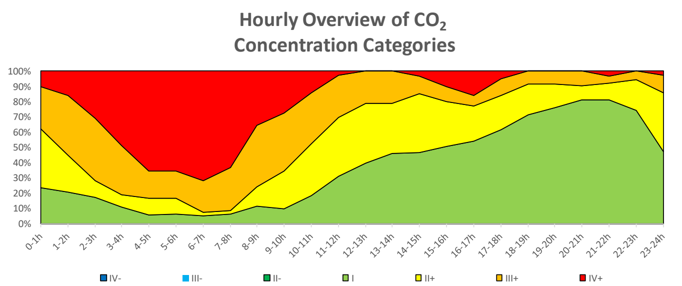
| Categories | I | II | III | IV |
|---|---|---|---|---|
| from [ppm] | 0 | 900 | 1200 | > 1500 |
| to [ppm] | 900 | 1200 | 1500 | |

Evaluated

| | Day | Hour |
|---|---|---|
| from | 1 | 0 |
| to | 7 | 23 |

Course of CO2 concetration in the evaluated period:



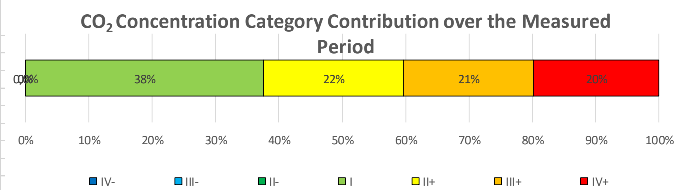




Figure 10. VISIEQ assessment of the IEQ from measured values, Sensor 5.1.

The evaluation of the most critical room is shown in Figure 10. (sensor 5.1, bedroom), where the air temperature is in the category -IV, i.e. less than 19 ° C, during the whole monitored period. Relative air humidity was 47% of the monitored period in category + II, i.e. 50-60 % and 53 % of the monitored period in category + III, i.e. 60-70 %. The $CO_2$ concentration was 38 % of the monitored period in category I, i.e. max. 900 ppm $CO_2$, 22 % in category II, i.e. 900 - 1200 ppm, 21 % in category III, i.e. 1200 - 1500 ppm and 20 % of the monitored period in category IV, i.e. more than 1500 ppm.

### 3.4. Assessment

Based on the all data (the local survey, available documentation, monitoring of selected parameters of indoor environment, questionnaire) an assessment of individual IEQ areas was prepared according to the methodology. The principle of the assessment is to evaluate each area in several criteria. The evaluation result is quantified by the points according to the Table 2.

Table 3 Evaluation of the locality and the placed of an object in terms of external environment and social relations (LS)

| Evaluation of the locality and the placed of an object in terms of external environment and social relations (LS) | | Evaluation 0 - 1 - 2 - 3 |
|---|---|---|
| LS1 | Air quality (pollution) | 1 |
| LS2 | Wind region | 1 |
| LS3 | Noise from the surroundings | 1 |
| LS4 | Orientation to cardinal points | 1 |
| LS5 | Influence of thermal island | 1 |
| LS6 | Psychic perception of surroundings, interpersonal relationships | 1 |
| LS7 | Risk of energy poverty | 2 |
| LS | Average of non-zero values LS1 to LS7 | 1.14 |
| Comment:<br>The building is operated at low interior temperatures | | |

Table 4 Evaluation of building -construction and technical solution and interior of the evaluated zone (STI)

| Evaluation of building -construction and technical solution and interior of the evaluated zone (STI) | | Evaluation 0 - 1 - 2 - 3 |
|---|---|---|
| STI1 | Use of hazardous materials of building structures (asbestos, etc.) | 1 |
| STI2 | Risk of water vapor condensation on structures (thermal bridges) | 3 |
| STI3 | Use of hazardous materials for an equipment (formaldehyde etc.) | 2 |
| STI4 | Use of daylight | 1 |
| STI5 | Active shielding and its control | 2 |
| STI6 | Greenery in the interior | 2 |
| STI7 | Visible defects and disorders (mold, leakage, cracks, poor surfaces, etc.) | 3 |
| **STI8** | **Color space solution** | **1** |

| | | |
|---|---|---|
| **STI9** | **Layout solution, occupancy of the zone** | **1** |
| **STI10** | **Maintenance** | **1** |
| **ST** | **Average of non-zero values ST1 to ST10** | **1.7** |
| Comment:<br>Condensation due to improper operation VOC – carpet, furniture<br>Optimization of blinds operation<br>Greenery - moisture, biofouling<br>Mold due to condensation | | |

Table 5 Evaluation of thermal comfort in winter period (TCW)

| Evaluation of thermal comfort in winter period (TCW) | | Evaluation 0–1–2–3 |
|---|---|---|
| TCW1 | Choice of the heating system | 2 |
| TCW2 | The ability of the heating system to adapt its operating mode in response to the users' needs with due regard to user-friendliness, maintaining a healthy indoor environment - e.g. individual temperature control, user feedback – subjective environmental quality assessment | 2 |
| TCW3 | The ability of the heating system to report energy usage to the user | 2 |
| TCW4 | The ability of the heating system to report the quality of the indoor environment in terms of thermal comfort in winter to the user | 2 |
| TCW5 | Summary of thermal comfort assessment results for winter period from measurement / simulation (e.g. risk of overheating of the zone in winter due to heat gains, under-heating etc.) | 3 |
| TCW6 | Summary of thermal comfort assessment results for winter period from the questionnaire survey (if performed) | 2 |
| TCW | Average of non-zero values TCW1 to TCW6 | 2.16 |
| Comment:<br>Noise of convectors<br>Interface<br>Information difficult to access via mobile application or computer<br>Low interior temperatures<br>36 % dissatisfied responses | | |

Table 6. Evaluation of thermal comfort in winter period (TCW)

| Evaluation of thermal comfort in summer period (TCS) | | Evaluation 0 - 1 - 2 - 3 |
|---|---|---|
| TCS1 | Choice of the heating system | 1 |
| TCS2 | The ability of the heating system to adapt its operating mode in response to the users' needs with due regard to user-friendliness, maintaining a healthy indoor environment - e.g. individual temperature control, user feedback - subjective environmental quality assessment | 2 |

| | | |
|---|---|---|
| TCS3 | The ability of the heating system to report energy usage to the user | 2 |
| TCS4 | The ability of the heating system to report the quality of the indoor environment in terms of thermal comfort in winter to the user | 2 |
| TCS5 | Summary of thermal comfort assessment results for winter period from measurement / simulation (e.g. risk of overheating of the zone in winter due to heat gains, under-heating, etc.) (if performed) | 0 |
| TCS6 | Summary of thermal comfort assessment results for winter period from the questionnaire survey (if performed) | 0 |
| TCS | Average of non-zero values TCS1 to TCS6 | 1.75 |
| Comment:<br>Interface<br>Information difficult to access via mobile application or computer | | |

Table 7 Evaluation of indoor air quality (IAQ)

| Evaluation of indoor air quality (IAQ) | | Evaluation<br>0 - 1 - 2 - 3 |
|---|---|---|
| IAQ1 | Choice of the ventilation system | 2 |
| IAQ2 | The ability of the ventilation system to adapt its operating mode in response to the users' needs with due regard to user-friendliness, maintaining a healthy indoor environment - e.g. user feedback - subjective environmental quality assessment | 1 |
| IAQ3 | The ability of the ventilation system to report energy usage to the user | 3 |
| IAQ4 | The ability of the ventilation system to report the quality of the indoor environment in terms of indoor air quality | 3 |
| IAQ5 | Summary of indoor air quality assessment results from measurement / simulation (if performed) | 3 |
| IAQ6 | Summary of indoor air quality assessment results from the questionnaire survey (if performed) | 1 |
| IAQ | Average of non-zero values IAQ1 to IAQ6 | 2.16 |
| Comment:<br>The system does not provide any information<br>High CO2 concentrations in bedrooms | | |

Table 8 Evaluation of light comfort (LC)

| Evaluation of light comfort (LC) | | Evaluation<br>0 - 1 - 2 - 3 |
|---|---|---|
| LC1 | Choice of the lighting system | 1 |
| LC2 | The ability of the lighting system to adapt its operating mode in response to the users' needs with due regard to user-friendliness, maintaining a healthy indoor environment - e.g. regulation of intensity | 1 |

| | | |
|---|---|---|
| | and spectrum of light sources in the workplace , user feedback - subjective environmental quality assessment | |
| LC3 | The ability of the lighting system to report energy usage to the user | 3 |
| LC4 | The ability of the lighting system to report the quality of the indoor environment in terms of light comfort | 3 |
| LC5 | Summary of light comfort assessment results from measurement / simulation (if performed) | 0 |
| LC6 | Summary of light comfort assessment results from the questionnaire survey (if performed) | 1 |
| LC | Average of non-zero values LC1 to LC6 | 1.8 |
| Comment: | | |

Table 9 Evaluation of acoustic comfort (AC)

| Evaluation of acoustic comfort (AC) | | Evaluation<br>0 - 1 - 2 - 3 |
|---|---|---|
| AC1 | Sources of noise and measures to eliminate them | 1 |
| AC2 | The ability of the system to report the quality of the indoor environment in terms of acoustic comfort | 3 |
| AC3 | Summary of acoustic comfort assessment results from measurement / simulation (if performed) | 1 |
| AC4 | Summary of acoustic comfort assessment results from the questionnaire survey (if performed) | 2 |
| AC | Average of non-zero values AC1 to AC4 | 1.75 |
| Comment:<br>8% dissatisfied responses (fridge, microwave) | | |

Table 10 Evaluation of electro-magnetic, -ionic,- static fields, ionizing radiation (EC)

| Evaluation of electro-magnetic, -ionic,- static fields, ionizing radiation (EC) | | Evaluation<br>0 - 1 - 2 - 3 |
|---|---|---|
| EC1 | Sources of Electro-magnetic, -ionic,- static fields, ionizing radiation and measures to eliminate their negative effects | 1 |
| EC2 | Summary of assessment results from measurement / simulation (if performed) | 0 |
| EC3 | Summary of assessment results from the questionnaire survey (if performed) | 0 |
| EC | Average of non-zero values EC1 to EC3 | 1 |
| Comment: | | |

The summary of indoor environment status evaluation is a well-arranged Table 11, in which the results of the evaluation of individual criteria describing the indoor environment of the assessed zone are presented. The average of non-zero criterion values can range from 1, which indicates no comments, to 3, which indicates a serious problem for the criterion being evaluated. The occurrence of classification '3' in the criterion draws attention to the fact that there is a serious problem in one or more parameters of the criterion.

Table 11 The summary of indoor environment status evaluation

| Zone: Building<br>Evaluation criteria | | Average of non-zero criterion values;<br>N – Not evaluated | Occurrence of classification "3" in criterion<br>Yes/No |
|---|---|---|---|
| LS | Locality and placed of the object in terms of external environment and social relations | 1,14 | No |
| STI | Building - construction and technical solution and interior of the evaluated zone (STI) | 1,7 | Yes 2x |
| TCW | Thermal comfort for winter period | 2,16 | Yes 1x |
| TCS | Thermal comfort for summer period | 1,75 | No |
| IAQ | Indoor air quality | 2,16 | Yes 3x |
| LC | Light comfort | 1,8 | Yes 2x |
| AC | Acoustic comfort | 1,75 | Yes 1x |
| EC | Electro-magnetic, -ionic,- static fields, ionizing radiation | 1 | No |

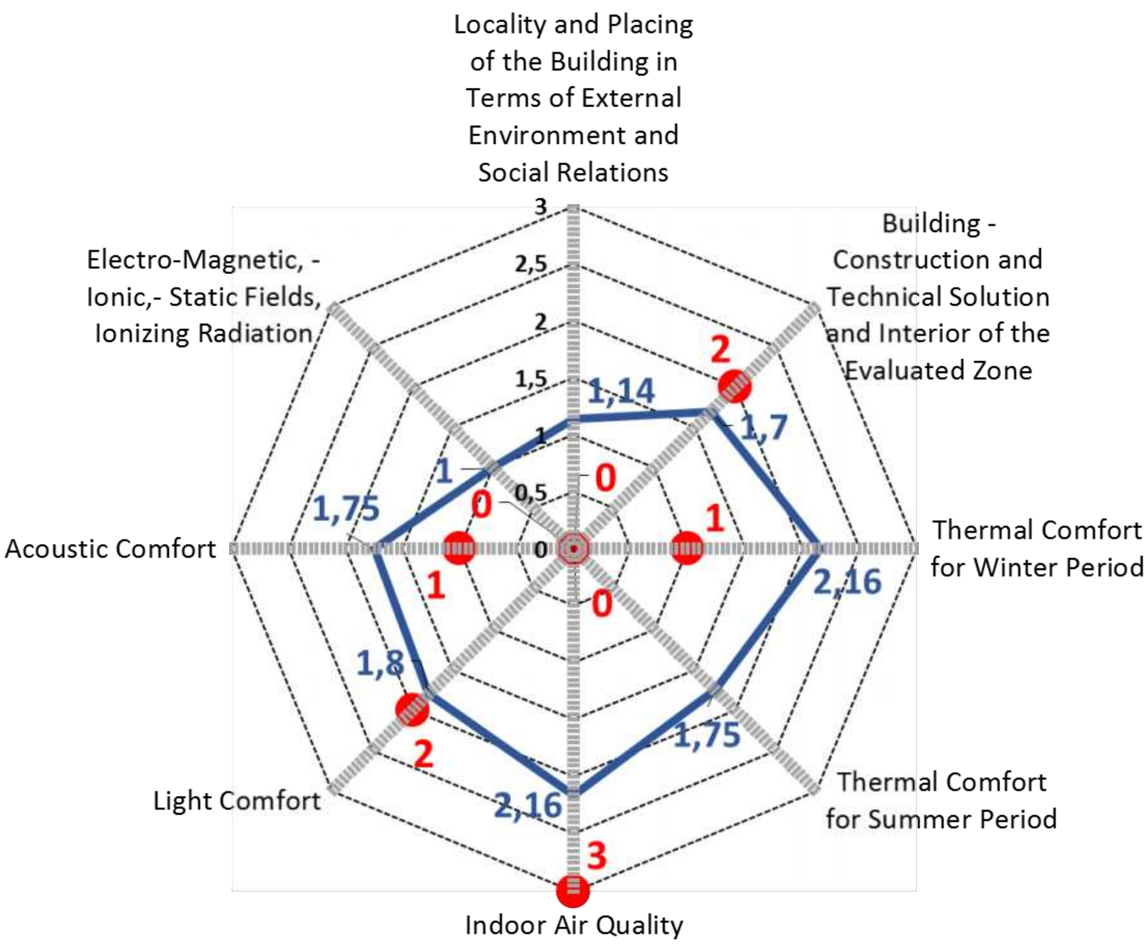



Figure 11 - Summary of indoor environment status evaluation

### 3.5. Results

The results of the assessment point to problems in the areas of winter thermal comfort (TCW), air quality (IAQ), constructions (STI), lighting (LC) and acoustics (AC). The following criteria were assessed as critical:

- STI2 Risk of water vapor condensation on structures (thermal bridges)
- STI7 Visible defects and disorders (mold, leakage, cracks, poor surfaces, etc.)
- TCW5 Summary of thermal comfort assessment results for winter period from measurement / simulation (e.g. risk of overheating of the zone in winter due to heat gains, under-heating, etc.)
- IAQ3 The ability of the ventilation system to report energy usage to the user
- IAQ4 The ability of the ventilation system to report the quality of the indoor environment in terms of indoor air quality
- IAQ5 Summary of indoor air quality assessment results from measurement / simulation (if performed)
- LC3 The ability of the lighting system to report energy usage to the user
- LC4 The ability of the lighting system to report the quality of the indoor environment in terms of light comfort
- AC2 The ability of the system to report the quality of the indoor environment in terms of acoustic comfort

## 4. Conclusion and summary

The certified methodology of the indoor environment quality assessment enables a holistic view of the assessed object (zone) in terms of individual components of the indoor environment. This enables the evaluation of individual criteria with subsequent information whether the object (zone) is solved at the level of the current state of knowledge or whether it has the potential to improve the indoor environment quality, or there are serious shortcomings in terms of the quality of the indoor environment, respectively shortcomings in the sub-criteria of the methodology as described above. This will make it possible to propose specific measures to ensure the quality indoor environment (resp. to eliminate shortcomings) and to implement this subsequently.

The use of the methodology requires a deep knowledge of the assessor in all assessed areas, which can be gained by experience and prior education or completion of the course. Another option is that the evaluation will be processed by a team of reviewers specialized in each area.

The advantage of the proposed methodology is the evaluation method, which is not only intended to classify IEQ in buildings, but primarily to indicate bottlenecks. In addition, a holistic approach helps to identify the causes of the problems and to better find ways possible remedies.

## 5. Acknowledgment

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# Energy savings with dynamic heating profiles in office buildings

**Arnab Chatterjee[1] and Dolaana Khovalyg[1]**

[1] Thermal Engineering for the Built Environment Lab (TEBEL), École Polytechnique Fédérale de Lausanne) EPFL, Switzerland

**Abstract:** One continuing problem of the buildings is that we still live in the same houses, while the outdoors is undergoing tremendous changes. With these external variations, instead of keeping indoor thermal conditions constant, could it be healthier to make it dynamic. It could definitely be more energy efficient. A more dynamic thermal environment that pushes the boundaries of comfort zones may be able to provide occupants with the much-required thermal comfort, along with instances of thermal delight and positive stimulation. Recent studies suggest that exposure to mild cold conditions can lead to the activation of the brown adipose tissues. These brown adipose tissues have been linked to non-shivering thermogenesis, which ultimately helps the body to spend energy. If we let our body spend more energy to maintain thermal balance, it may positively affect health on a population scale. This work is aimed at allowing indoor temperatures to drift more than permitted under current standards. Dynamic heating profiles have been explored, which can substantially reduce energy consumption by the built environment. The energy reduction potential for the open space case study office has been verified in this study using building energy simulations with Open Studio, which show a 35-70% decrease in the heating energy demand indeed.

**Keywords:** Dynamic Indoor Environment, Energy Savings, Temperature step changes, Thermal Comfort

## 1. Introduction

In the current times, the human beings spend most of their lifetime indoor. This indicates that the design of the indoor environment is very important for the well-being of the occupants. Normally the design of the indoor environment in buildings are performed based on the appropriate national and international standards. In these standards, the indoor environment conditions that are acceptable are stipulated and it is generally expected that the new and existing buildings adhere to them very closely.

In the last century, air-conditioning (AC) technology and manufacturing technique were rapidly developed, so that not only public and commercial buildings, but most residential buildings and houses were also equipped with AC installations. Standards for designing indoor thermal environment have been set based on long-term laboratory studies at steady-state indoor conditions. Consequently, the target of AC control has been intended to maintain indoor air parameters constant. With such a control strategy, AC has also caused some negative effects, such as reduced comfort, air pollution, and higher-energy consumption (Zhao, 2007).

Also, it is a known fact that 40% of our society's energy demands stem from buildings (Heller et al, 2015) (Fabi et al, 2015). It is evident that in any move towards a greener future, the buildings sector will have a major contribution. In this aspect, thermal comfort standards have a role to play and at present they are in a transitional period with foreseeable further rapid modifications.

As per well-established thermal comfort theory for mechanically conditioned buildings the temperatures are always held within narrow limits. Extrapolating these standards to low energy buildings, that rely on passive strategies for indoor comfort, does not provide the desired effect. Departing from the focus of near steady state conditions of mechanically conditioned buildings opens up the avenues for reworking the standards towards altered realities of building energy and comfort (Mishra et al, 2016).

Both comfort and discomfort come from dynamic contrast. If the poor thermal environment improves a little, people will feel significantly better. Short-term thermal experience would make some excursion of real thermal sensation. In the condition that started and ended at an air temperature of 20 °C, people feel more comfortable even in the 22 °C environment, instead of the 25 °C condition which is close to the neutral temperature in the steady state. The endurance of people in a cold environment is stronger than in a hot environment. In a research study it was found that people even prefer a little bit lower temperature rather than a neutral temperature (Ji et al, 2017). The evaluations of thermal environment are based on not only the current feelings, but also the feelings accumulated over a past period of time (Ji et al, 2017).

Skin temperature is affected by short-term thermal experience. It will change rapidly when entering a neutral environment with prior cold or hot experience, and after about 15 min or more it will achieve a new balance, that is different from that of subjects who experienced only 26 °C. As the temperature changed from non-neutral to neutral, there are some excursion of thermal sensation. Thermal sensation will amplify with the contrast of temperature before and after. Thermal comfort and thermal acceptance will both improve during this transfer of environment.

The influence of short-term thermal experience on skin temperature and thermal evaluations is asymmetric because of differences in the human body physiological regulatory mechanisms under cold or hot conditions (Ji et al, 2017). The improvement of thermal sensation and comfort is more obvious when getting cold than when getting hot. Skin temperature and heat loss both can be used to predict TSV, and each has advantages. The changes of temperature provide cold or hot stimulation on the human body, which can increase the pleasure of feelings. Comfort results from the elimination of discomfort, suggesting that an unchanging neutral environment may be not the best (Ji et al, 2017).

## 1.1 Dynamic Indoor Environment

Indoor environment conditioning could be achieved by two different concepts: one is to maintain all indoor air parameters almost constant and maintain a neutral thermal sensation (neither warm nor cold); the other is to provide an environment, in which one or some of indoor air parameters could be fluctuating within acceptable ranges and the thermal sensation of human body is not always kept at neutral, but deviating from neutral. Dynamic thermal environments, complete with certain natural features, may be more suitable for the human body. Indeed, thermal environments that are beneficial to the human ability of thermal adaptation should be regarded as the healthiest thermal environments. Beyond the outdoor climate, long-term indoor thermal experience is a crucial factor for physiological adaptation as well (Zhu et al, 2016).

The concept of a one-size-fits-all approach to the provision of thermal comfort for a given population using centralized mechanical systems is not only undesirable but also fundamentally flawed. Diversity in the thermal preferences of building occupants resulting from variations in clothing level, metabolic activity, expectations, physiology, etc. suggest the criteria for evaluating occupants' thermal acceptability in office buildings may need to be recast.

Although extant literature on transient or spatially non-uniform thermal comfort is typically focused on minimization or complete elimination of discomfort, i.e. negative alliesthesia, it has been demonstrated that positive pleasure can be associated with temporal thermal transients; in effect the flipside of the same coin called alliesthesia. What is missing from the research discourse is a discussion of the potential for non-steady-state indoor thermal environments to lift occupant satisfaction rates within thermally neutral indoor climates above the current optimum of about 80%. This is an exciting idea that requires a significant departure from steady-state models of thermal comfort, but the pleasure principle would open up new avenues of design and engineering solutions that excite the thermal sense to overcome thermal boredom in the built environment (Parkinson et al, 2015).

Based on the inference drawn from literature reviews, acceptable temperature steps were proposed as step magnitudes no larger than 3 °C as the performance of the 3 °C steps were better than that of the 6 °C steps in terms of thermal sensation, comfort and acceptability (Zhang et al, 2017). In large step-change condition, more than 45 min was needed for mean skin temperature to achieve steady after down-step and instep skin temperature contributed most to this result (Xiong et al, 2016). Instant change of skin temperature caused by down-step has been found to be remarkably larger than that caused by up-steps (Xiong et al, 2017). The lack of significant physiological changes at a temperature step of 4 °C or less suggests that the thermoregulatory burden in a thermal transient may be adequately controlled when the temperature step does not exceed this level (Chen et al, 2011).

Maximal thermal comfort in the built environment may increase our susceptibility to obesity and related disorders, and in parallel requires high energy use in buildings. Mild cold exposure increases body energy expenditure without shivering and without compromising our precious comfort. Hence, rethinking our indoor climate by allowing ambient temperatures to drift may protect both health and bank account. Letting our body spend more energy to maintain thermal balance may positively affect health on a population scale. Allowing indoor temperatures to drift more than permitted under current standards can substantially reduce energy consumption by the built environment. More frequent cold exposure alone will not save the world but is a serious factor to consider in creating a sustainable environment together with a healthy lifestyle (van Marken Lichtenbelt et al, 2014).

### 1.2 Brown Adipose Tissues (BAT)

Brown adipose tissue (BAT) or brown fat generates heat by burning calories. When it is cold, brown fat's lipid reserves are depleted, and its color gets darker. Brown adipocytes contain many small lipid droplets and a high number of iron-containing mitochondria. It is this high iron content that gives brown fat its dark red to tan color. Most studies focusing on BAT have used a temperature of around 14–16 °C, which is often not appreciated by subjects. Prolonged exposure to a less cold environment maybe a potential solution. New research should not only focus on finding new stimulants for BAT, but also on increasing the potential of BAT in humans. Although increasing energy expenditure can influence the energy balance, potential compensation can occur by increased food intake. This could lead to the attenuation of the beneficial effects of increased energy expenditure on health and metabolism. There are indications that not all of the increase in energy expenditure is compensated (Amir, 1990).

Brown adipose tissue remains an interesting and possibly underestimated target in metabolic health. It still needs further exploration to what extent BAT activation can become a new treatment for obesity and its complications (Moonen, 2019). With respect to thermal (dis)comfort, it was shown that during the experiments involving 10 days of cold acclimation, thermal comfort changes from uncomfortable to just comfortable. This change in comfort was significant and may even increase with longer duration of acclimation. Those experiments used quite low (15 °C) temperatures, but as stated above others (Yoneshiro et al, 2013) have used 17–19 °C with significant effects on energy metabolism approaching realistic indoor temperature conditions. There is some circumstantial evidence from a Dutch newspaper search from 1872 onwards that c.1870 a temperature of 13–15 °C was experienced as being comfortable (Knip, 2016). This links to the conclusion of (Mavrogianni et al, 2011) that in the UK an increase in winter in mean dwelling indoor temperatures of 1.3 °C per decade has occurred between 1978 and 1996.

It is a question if dynamic (drifting) and locally varying temperatures can quite easily be implemented in practice? In fact, there already exist modern buildings that use dynamic temperature drifts and different local indoor climate zones (van Marken Lichtenbelt et al, 2017). In the future, there is a need to undertake monitoring studies under living laboratory and actual daily living conditions, preferably comparing different thermal strategy interventions. This can be accomplished by using living laboratory environments and by studying effects in neighborhoods. The latter can ideally be used for research involving long-term effects on health and wellbeing in combination with other lifestyle interventions (van Marken Lichtenbelt et al, 2017). The table below presents the literature findings on Brown fat adipose tissue activity in human adults.

It is well known that people shiver in response to cold. By shivering, heat production can increase to a level fivefold above the resting metabolic rate (Jansky, 1998). Shivering thermogenesis (ST) therefore is important for short-term protection against hypothermia, but is uncomfortable and impedes coordinated movements. Alternatively, studies in rodents have shown that non-shivering thermogenesis (NST) can replace ST by activating brown adipose tissue (BAT) (Cannon et al, 2004). Although NST had been reported in humans earlier, the relationship to functional BAT in adult humans was not shown until 2009 (van Marken Lichtenbelt et al, 2009) (Virtanen et al, 2009).

In 1961 Davis et al. showed that, paralleling rodent studies, humans are able to increase non-shivering thermo-genesis upon regular cold exposure (Davis, 1961). Recent cold acclimation studies have revealed comparable results and a concomitant increase in BAT activity, with NST being related to BAT activity (Van der Lans et al, 2013) (Yoneshiro et al, 2013). Yoneshiro et al. also found a significant decrease in body fat content following a 6 week (2 h/day at 17 °C) cold acclimation protocol. Interestingly, we observed that shivering and thermal discomfort decreased during a 10-day cold acclimation protocol (6 h exposure to 15 °C /day) (Van der Lans et al, 2013). It is obvious that 15 °C is too low for practical application in the built environment, but we expect that mild cold (e.g., 18–19 °C) will also result in increases in NST and BAT, and with acceptable thermal comfort levels. However, the time needed will be longer and the final level of adaptation will relate to the intensity, duration, and timing of cold exposure.

## 2. Dynamic Heating profiles

This research work is focused on the heating side of the air conditioning system. The priorities are to reduce the energy demand of the building and at the same time provide a healthy and comfortable environment for the occupants. Thus, for this purpose dynamic heating profiles were designed. These flexible setpoints consists of 3 main parts, the step changes, the temperature ranges and the variation profile.

### 2.1 Step Changes

Recent adaptive models recognize that humans tolerate and adapt to different thermal environmental conditions depending on outdoor environmental conditions (Ji et al, 2017). Indeed, in both young adults and the elderly, gradual temperature variations of ±2 °C /h over the range 17–25 °C are accepted without significant discomfort (Ghahramani et al, 2016). During winter, this means that the indoor temperature can be lower, both temporally and spatially, such that occupants are regularly exposed to cool conditions, thereby increasing their energy expenditure (van Marken Lichtenbelt et al, 2014).

In the previous studies, acceptable temperature steps were proposed as step magnitudes no larger than 3 °C as the performance of the 3 °C steps were better than that of the 6 °C steps in terms of thermal sensation, comfort and acceptability. Also, according to research study, the lack of significant physiological changes at a temperature step of 4 °C or less suggests that thermoregulatory burden in a thermal transient may be adequately controlled when the temperature step does not exceed this level.

As seen before, acceptable temperature steps were proposed as step magnitudes no larger than 3 °C as the performance of the 3 °C steps were better than that of the 6 °C steps in terms of thermal sensation, comfort and acceptability. Thus, we designed two different steps of temperature changes namely, Step High (SH) and Step Low (SL). In the Step High profiles, we decide to keep step changes of about 1.5-2 °C while in the Step Low configuration we decided to limit the step changes to 1 °C.

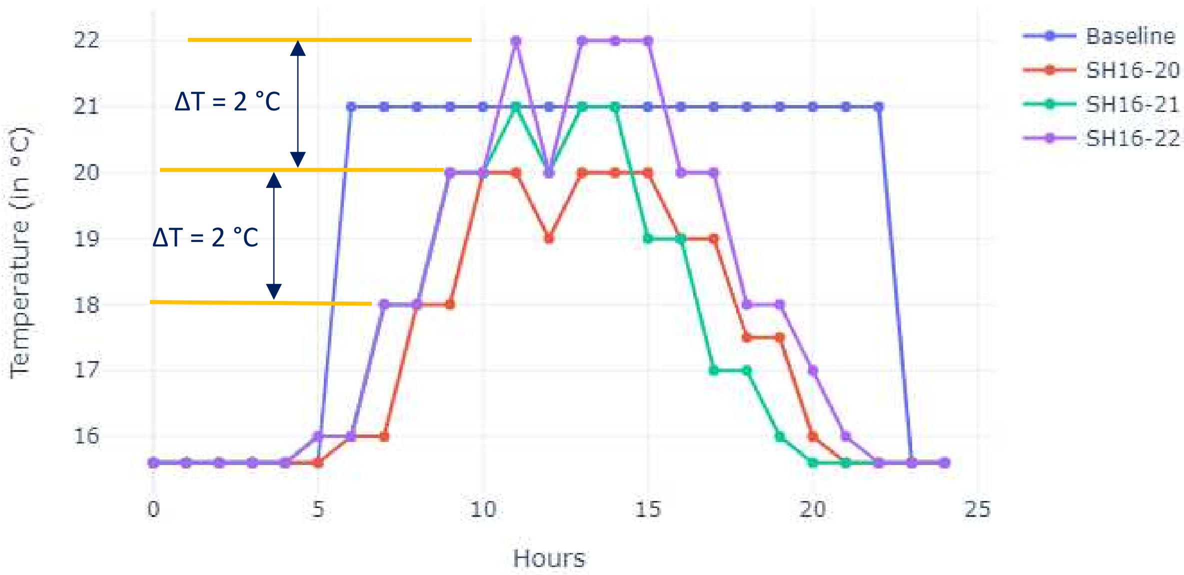



*Figure 1: Design process for the step changes*

## 2.2 Temperature Ranges

Based on our literature review on mild cold exposure and non-shivering thermogenesis, we found that most studies focusing on BAT have used a temperature of around 14–16 °C, which is often not appreciated by subjects but this also the temperature range where there is the maximum possibility of greater BAT formation. A prolonged exposure to a less cold environment, may be a potential solution. Occupants' thermal preference varies according to both indoor temperature and occupied time. They expected to keep indoor temperature in the range between 15.3 °C and 19.4 °C after their thermal sensation reached a steady state.

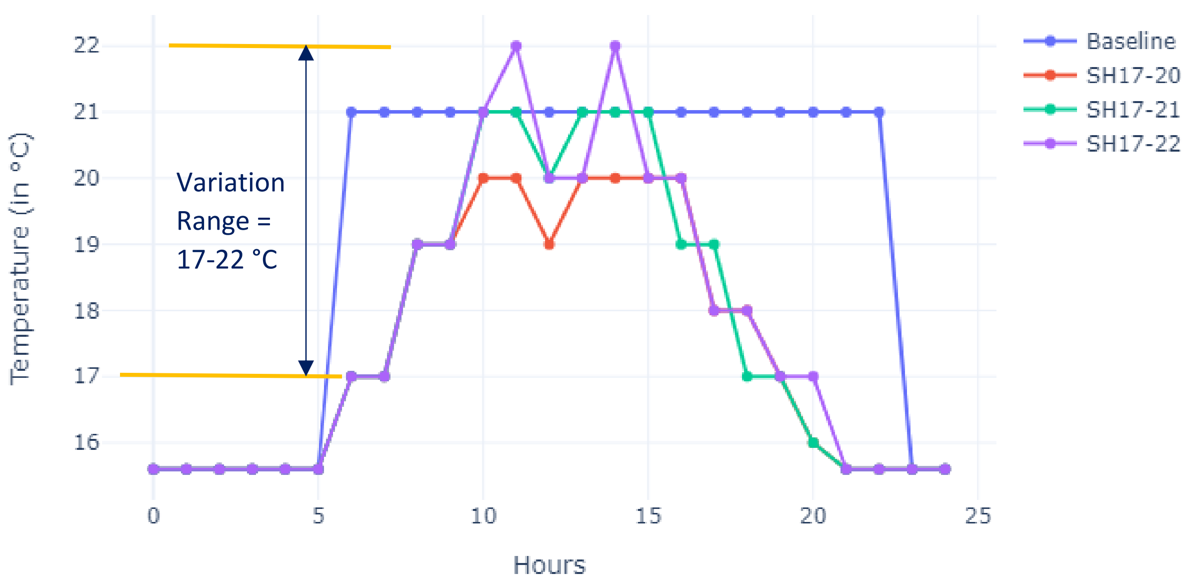


*Figure 2: Design process for the temperature ranges*

In our study, the dry bulb temperature ranges between the lower limit of 16 °C and the higher limit of 22 °C which is quite close to the temperature recommended by the swiss standard SIA 2024-2015. 6 different temperature ranges were defined, (i) 16-20, (ii) 16-21, (iii) 16-22, (iv) 17-20, (v) 17-21, and (vi) 17-22. The idea behind choosing these temperature ranges was to exploit the benefits of the mild cold exposure both in terms of heating energy savings and health benefit of the occupants. And as seen above 15-19 °C is the temperature range where greater BAT formation takes place.

## 2.3 Variation Profile

To design the variation profile, we took inspiration from the variation in the metabolic rate (Rest Energy Expenditure) of the human body. As seen before, the According to the human subject experimental results, the skin temperatures strongly correlated with the thermal sensations at individual level [64]. The graph below shows the variation in the oral body temperature during the day. Here we can see that there is trend that can be observed, the body temperature reaches the maximum value during the midday. Thus, the idea was to reduce the difference between the body temperature and the ambient temperature.

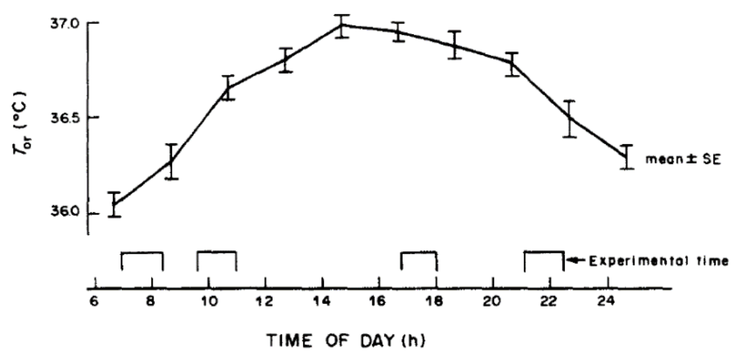



*Figure 3: Variations of human body temperature versus the hour of the day*

Normally, in the morning when the occupancy is low, the temperature setpoints are close to 16-17 °C. And as the occupancy profile increase during the day, there is an upward slope in the heating profile which reaches a maximum of 20-21 °C during the noon. As per the Standard SIA 2024:2015 these are the hours of highest occupancy. And the again as the occupancy decreases there is a downward trend in the heating setpoint values.

During the non-occupancy hours i.e. from 10 pm to 6 am and during the weekends the temperature is maintained at a constant value of 15.6 °C. The figure below illustrates the general trend of the heating profile as discussed in the previous section.

## 2.4 End Result

Thus, summarizing the design process, it consists of 3 main parts, the step changes, the temperature ranges and the variation profile.

I. Two different steps of temperature changes namely, Step High (SH) and Step Low (SL). In the Step High profiles, step changes of about 1.5-2 °C are used while in the Step Low configuration the step changes are limited within 1 °C.

II. Keeping in mind the benefits of mild cold exposure, the temperature ranges were decided to vary between the lower limit of 16-17 °C and the higher limit of 21-22 °C.

III. To design the variation profile inspiration was derived from the circadian rhythm of body temperature and body energy expenditure variations. Occupancy profiles as specified in the standards was another driving force for the following profiles.

At the end of the design process the following dynamic heating profiles were obtained.

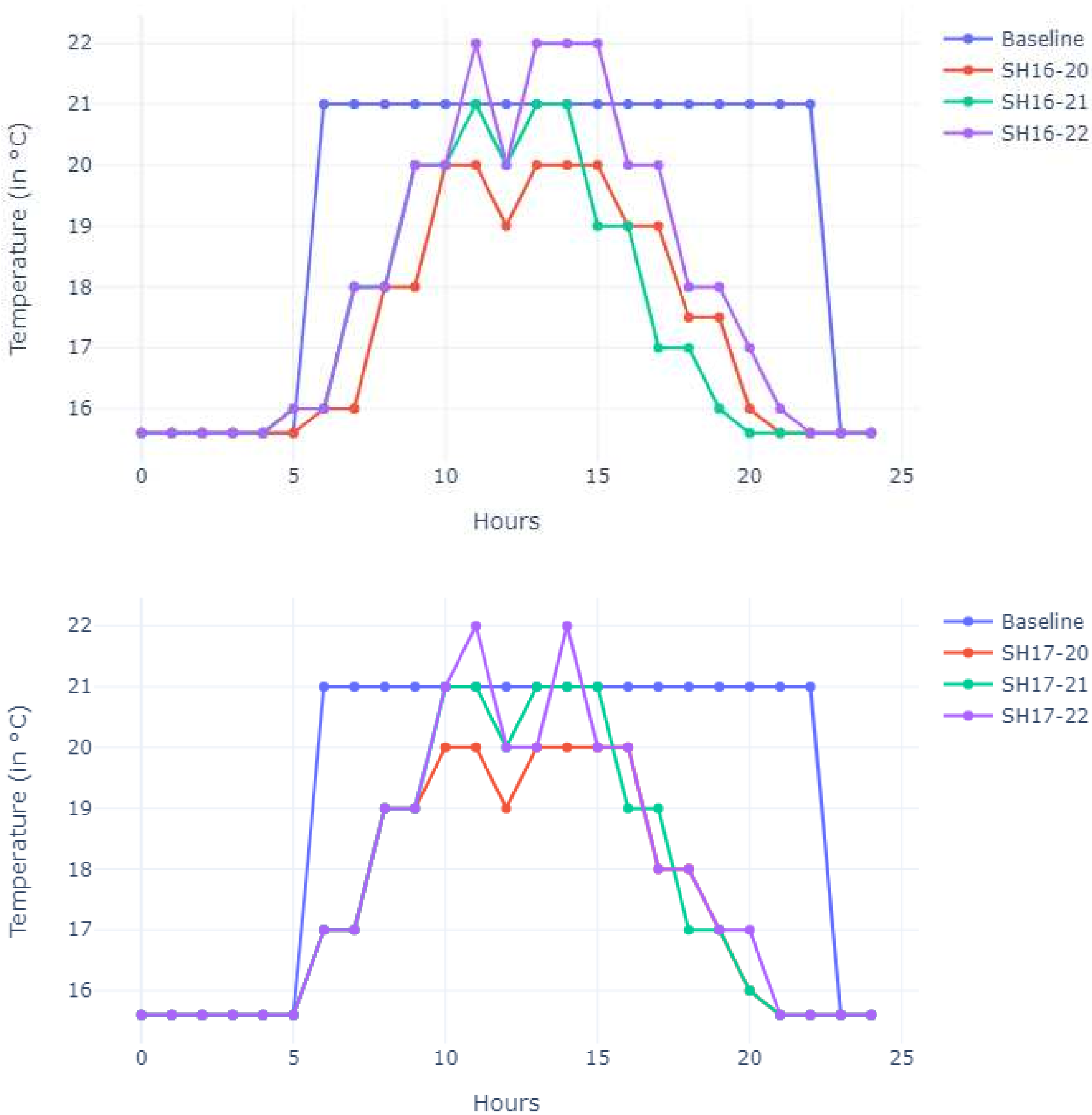
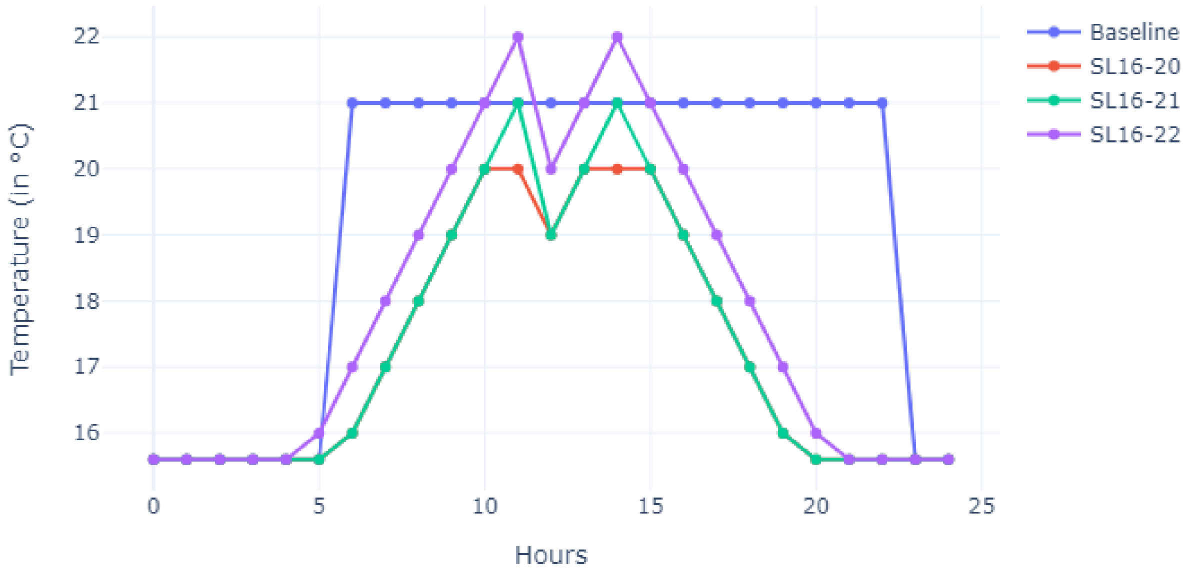



*Figure 4: (a) Step High and, (b) Step Low profiles with minimum temperature of 16 °C*



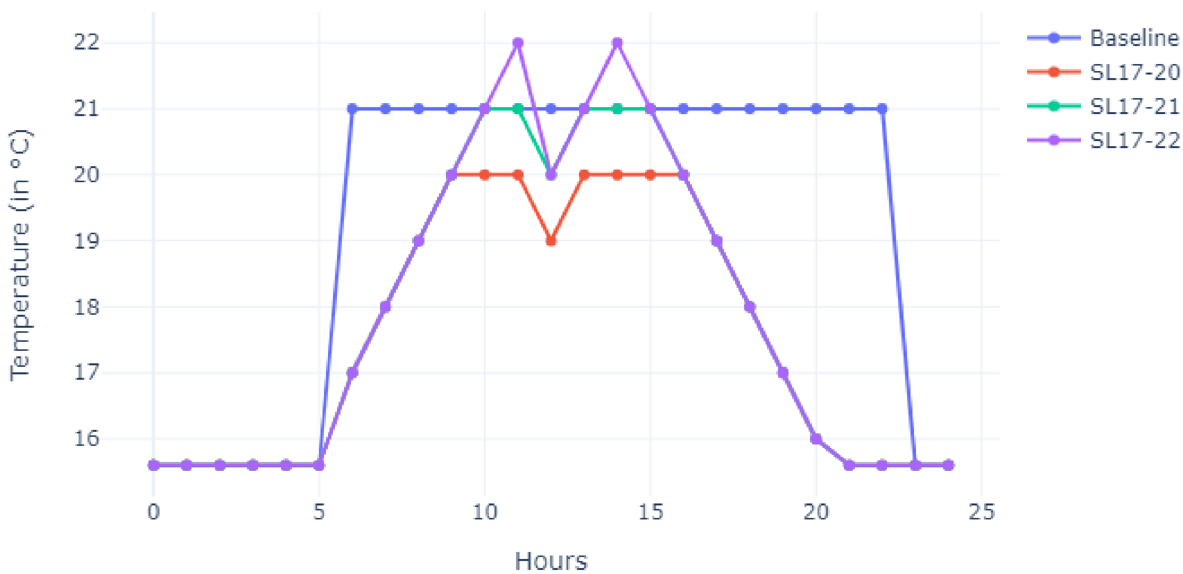




*Figure 5: (a) Step High and, (b) Step Low profiles with minimum temperature of 17 °C*

## 3. Building Energy Simulations

The first step to start the analysis is to measure the building energy needs for the various configurations. For that we decide to model the building using OpenStudio. OpenStudio is a cross-platform (Windows, Mac, and Linux) collection of software tools to support whole building energy modeling using EnergyPlus and advanced daylight analysis using Radiance. OpenStudio is an open source (LGPL) project to facilitate community development, extension, and private sector adoption. OpenStudio includes graphical interfaces along with a Software Development Kit (SDK).

## 3.1 Building Model

As the case study building, one of the buildings at EFPL innovation park was considered. EPFL's innovation area, hosts technology driven companies in an inspiring environment, with access to cutting-edge research, a large network of dynamic entrepreneurs and established companies.

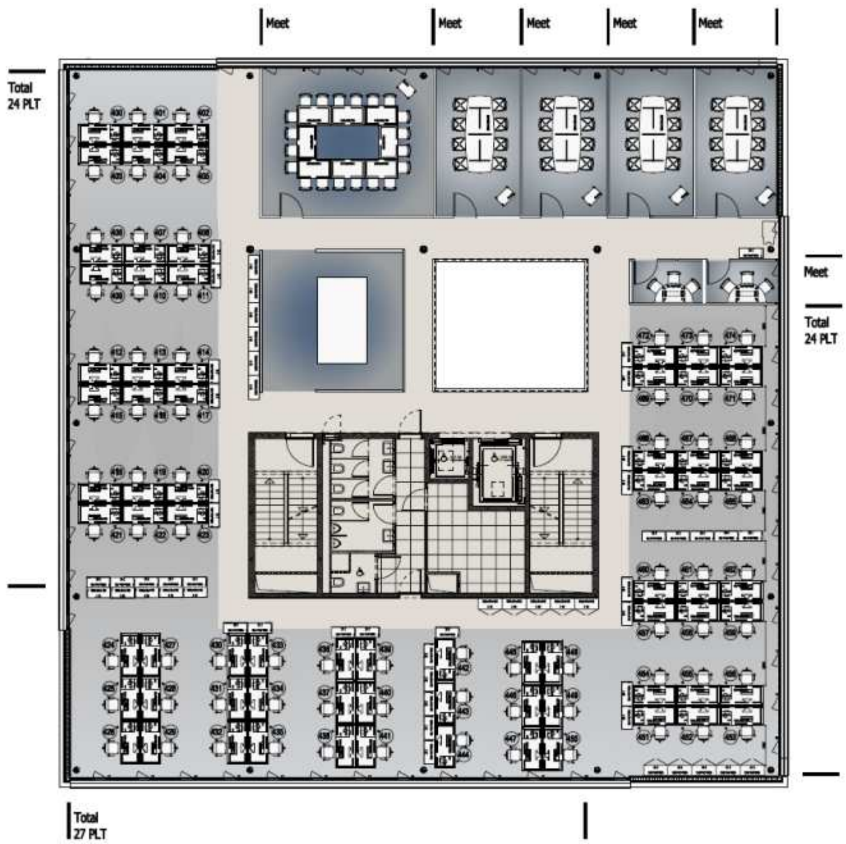



*Figure 6: Building model floor plan*

The above plan was considered as our building model. It was situated in the 4th story which was the highest in the concerned building. The choice of the top story was driven by the fact that there are highest heat losses through the construction elements because of the presence of the roof. The considered story is composed of 5 main room configurations, Open Office, Conference Rooms, Closed Office space, Corridors and Stairs. The choice of the Open office model was driven by the fact that it transforms the spaces into areas of informal meeting and interaction. According to modern management theories, employees are more productive and happier when they can interact freely with each other in a creative, inspiring setting. Thus, it can be expected that most of the future offices can adopt the open office plan. Also, it is a multi-occupant space with variations in occupancy profiles. This presents a greater challenge to be able to regulate the temperature of the indoor environment as compared to closed office.

For our simulation the weather data of Geneva, Switzerland was chosen due to its proximity to the case study building. In the end an additional simulation case with the building in Tampere, Finland was also performed in order to see the variation in the heating energy demand in a colder climate.

### 3.2 Plant Loops

In this section the air loops and the water loops for the different combination of the generation source and emission systems are described. For setting up the simulation cases two different types of generation source systems such as Air Source heat pump (ASHP) and Water source heat pump (WSHP) and two different kind of emission systems which are Cassette system and Radiant System were selected. Only the plant loops of the first system i.e. Air Source Heat Pump with Cassette System has been presented.

In this system the plant loop consists of two parts, the air loop and the water loop. The air loop consists of a cooling coil, heating coil, fan and a schedule manager on the supply side. The schedule manager controls the temperature of the air passing through that loop. During the summer season it is maintained at a constant temperature of 26 °C and for the winter it is maintained at 16 °C. And on the demand side we have the different zones and the fan coils which supply the conditioned air to these zones. Now these fan coils are supplied by the hot water and cold-water loops which conditions the air before it is delivered to the zone. The hot water loop consists of a hot water boiler, pipes, pumps and schedule manager on the supply side. The schedule manager makes sure the hot water is always maintained at 67 °C. And this hot water is then delivered to the coils of the Cassette System which is the zone equipment.

In case of the cold-water loop, it consists of an electric chiller, pipes, pumps and schedule manager on the supply side. The schedule manager makes sure the cold water is always maintained at 6.7 °C. And this cold water is then delivered to the coils of the Cassette System which is the zone equipment. The dynamic heating profiles are assigned to heating setpoint control system of the zone.

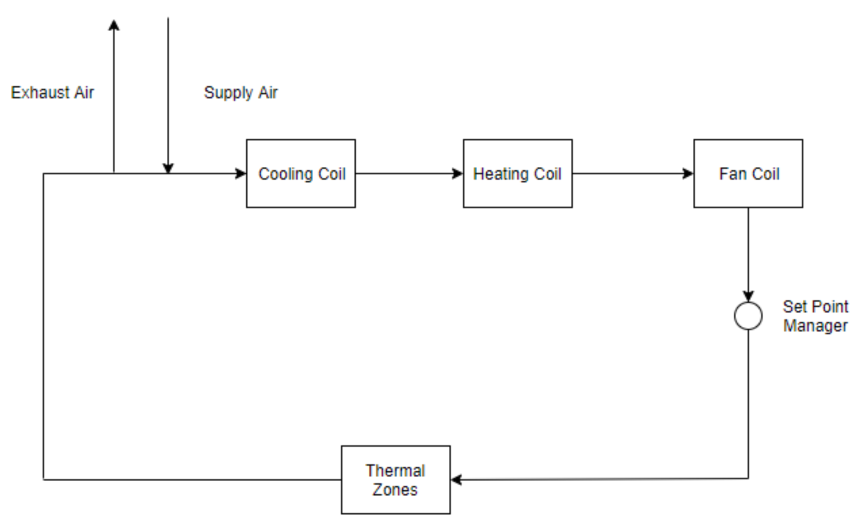



*Figure 7: Representation of the air loop for ASHP*

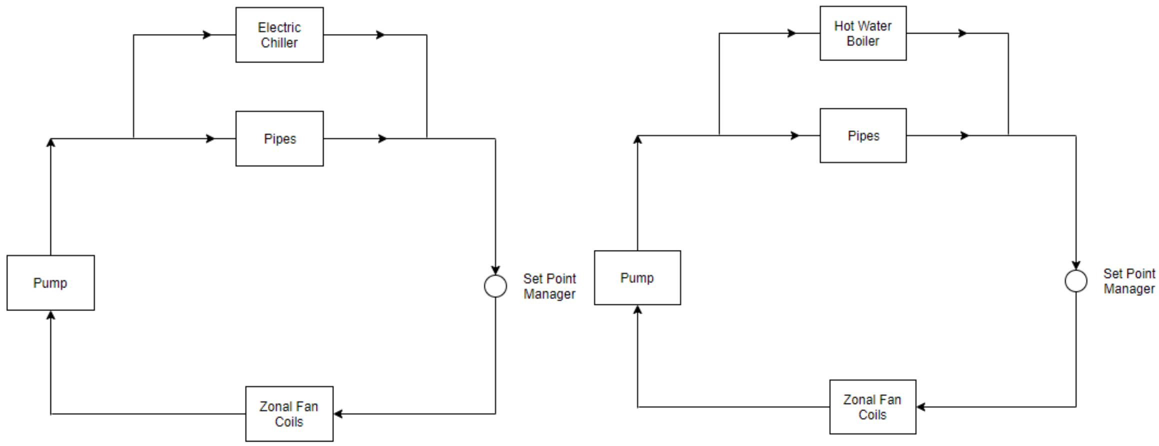



*Figure 8: (a) Cold water and, (b) Hot water loop for the coils of the Cassette System*

## 3.3 Results and Discussion

In this chapter the HVAC system along with the building mode are defined, modelled and dynamically simulated through OpenStudio. The main results for each layout are reported through charts and consequently examined. Firstly, all possible combinations with 13 heating schedules, 2 HVAC generation sources and 2 distribution sources were created. So, in total we had 52 different configurations for simulations.

### 3.3.1 Heating Energy Comparison

The heating energy demand for each of the above configuration has been compared in the following section. Here is presented the annual variation of the heating energy demand between the different configurations.

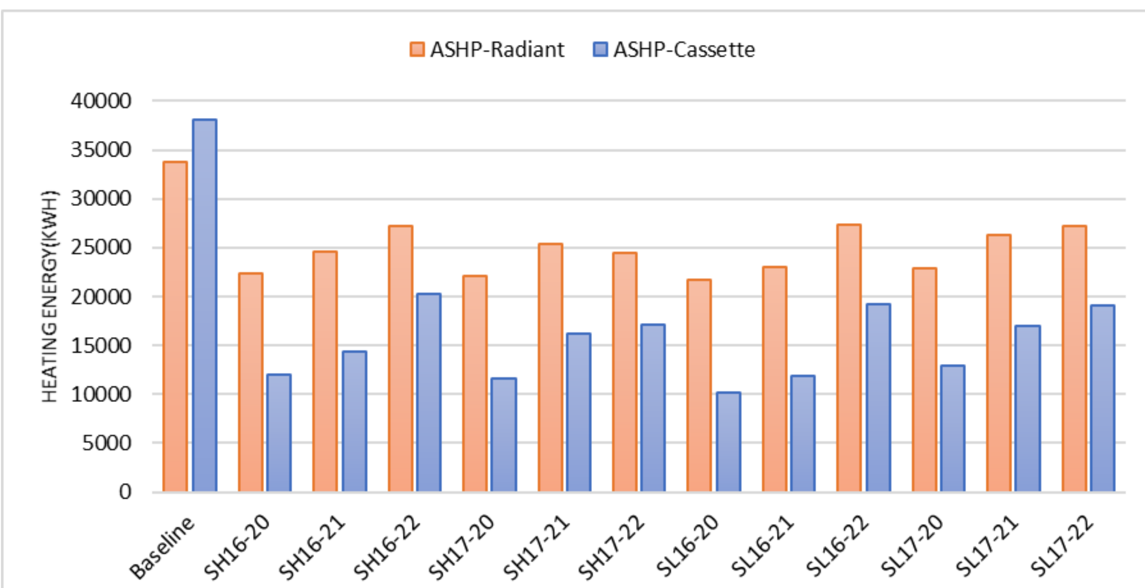



*Figure 9: Annual heating energy consumption for different heating profiles for ASHP System*

In the case of air source heat pump with Cassette system, maximum heating energy consumption of 38095.41 kWh is encountered in the baseline case. And the total energy consumption is 84753.57 kWh. And the minimum heating energy consumption is seen in the case of Step Low 16-20 configuration with a demand of 10174.46 kWh. And the total energy consumption in this case is around 54484.56 kWh. There is approximately 73% and 36% reduction in the heating and total energy consumption between the baseline and the best performing case. In the case of air source heat pump with Radiant system, maximum heating energy consumption of 33780.86 kWh is encountered in the baseline case. And the total energy consumption is 73751.31 kWh. And the minimum heating energy consumption is seen in the case of Step Low 16-20 configuration with a demand of 21706.37 kWh. And the total energy consumption in this case is around 61618.85 kWh. There is approximately 36% and 17% reduction in the heating and total energy consumption between the baseline and the best performing case.

In the case of water source heat pump with Radiant system, maximum heating energy consumption of 31368.33 kWh is encountered in the baseline case. And the total energy consumption is 72641.12 kWh. And the minimum heating energy consumption is seen in the case of Step Low 16-20 configuration with a demand of 15579.93 kWh. And the total energy consumption in this case is around 55864.69 kWh. There is approximately 51% and 23% reduction in the heating and total energy consumption between the baseline and the best performing case. In the case of water source heat pump with Cassette system, maximum heating energy consumption of 35119.12 kWh is encountered in the baseline case. And the total energy consumption is 75329.86 kWh. And the minimum heating energy consumption is seen in the case of Step Low 16-20 configuration with a demand of 23659.42 kWh. And the total energy consumption in this case is around 63874.67 kWh. There is approximately 33% and 16% reduction in the heating and total energy consumption between the baseline and the best performing case.

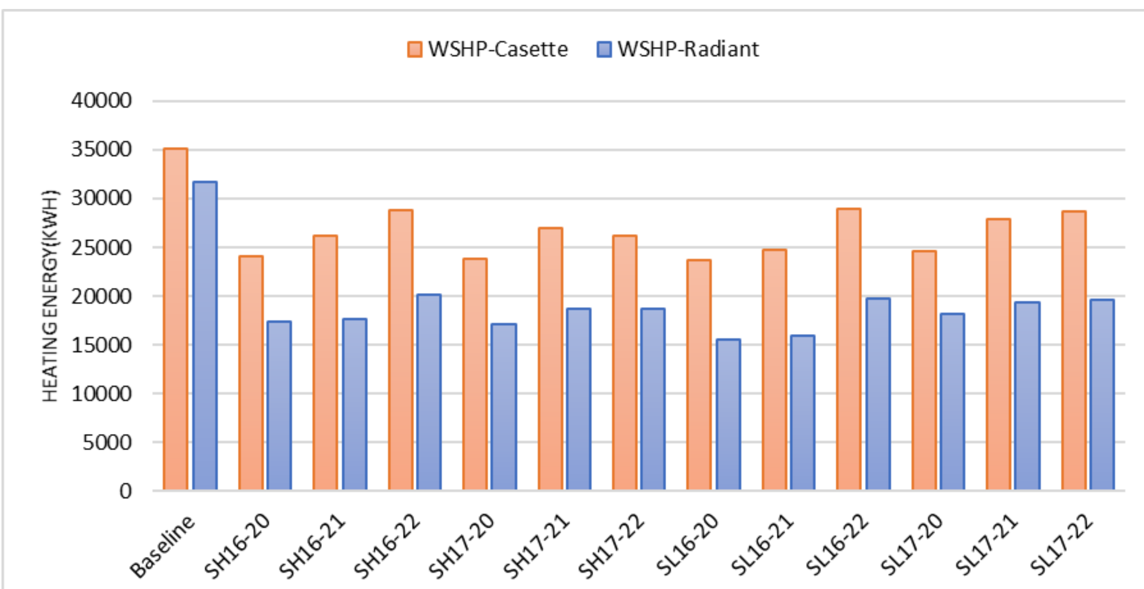



*Figure 10: Annual heating energy consumption for different heating profiles for WSHP System*

### 3.3.2 Temperature Distribution

The following graphs shows the representation of the hourly temperature variation in the Open Office space for the duration of the whole year. In each case the first image represents the temperature distribution in the baseline case and the second image represents the temperature distribution of the best case for that particular HVAC System.

There is a common pattern in the temperature distribution heat map. Normally the winter months are dominated by the presence of blue regions which indicates the temperature less than 19 C. Also, the blue color is darker before 6 am and after 10 pm in the night, which indicates the non-occupant hours and the setpoint is maintained at 15.6 °C. During the occupancy hours the temperatures are in the range of 17-21 °C depending upon the time of the day during the winter season. During the summer season there are the presence of the little red zones indicating temperatures in excess of 26 °C.

In the baseline case it can be seen that during the non-occupancy hours the temperature is constantly under 18 °C while in the occupancy hours it is always maintained at 21 °C (Greenish-blue portions). While in the case of the dynamic profiles, a smoother transition can be observed in the temperature. The first transition which is of the incremental nature is observed during the morning between 6 am and 10 am. After 10 am till 7 pm the temperature fluctuates between 19 and 21 °C. And then in the end there is another transition period where the temperature starts decreasing and reaches to the minimum value of 15.6 °C around 10 pm which is well within the non-occupancy hours. In the next section there is further discussion about the annual temperature distribution in the open office space with respect to the comfort categories.

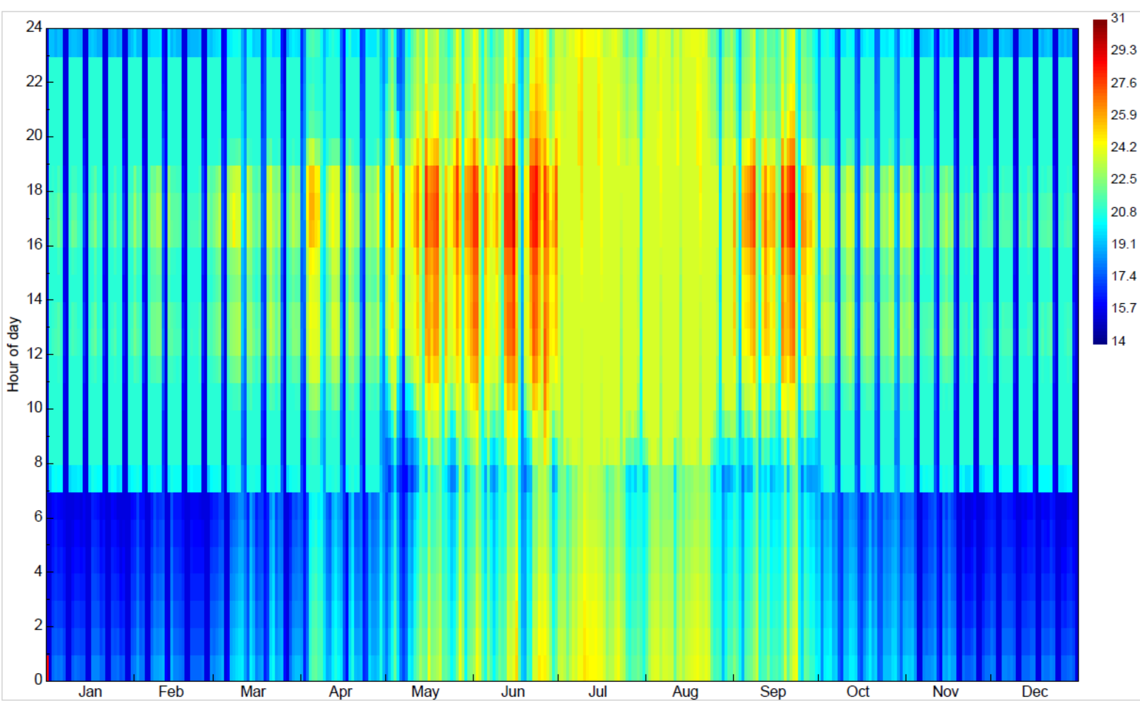


*Figure 11: Heat map of the annual temperature distribution in Open Office for ASHP-Cassette System baseline case*

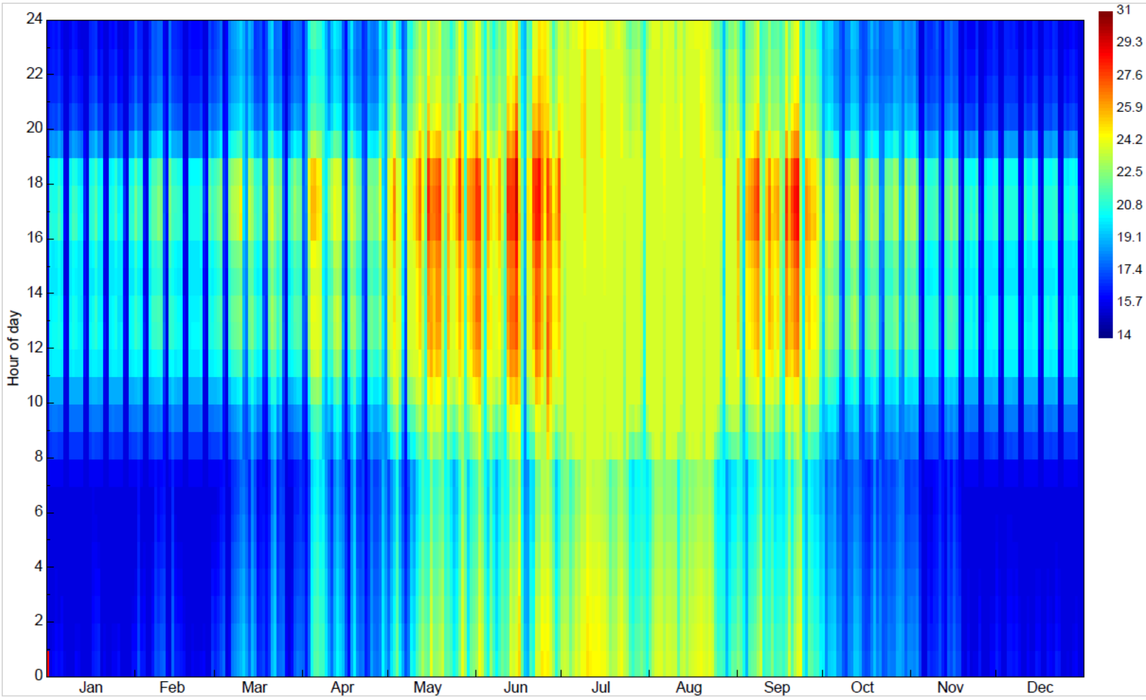



*Figure 12: Heat map of the annual temperature distribution in Open Office for ASHP-Cassette System best case (SH16-20)*

### 3.3.3 Comfort Categories

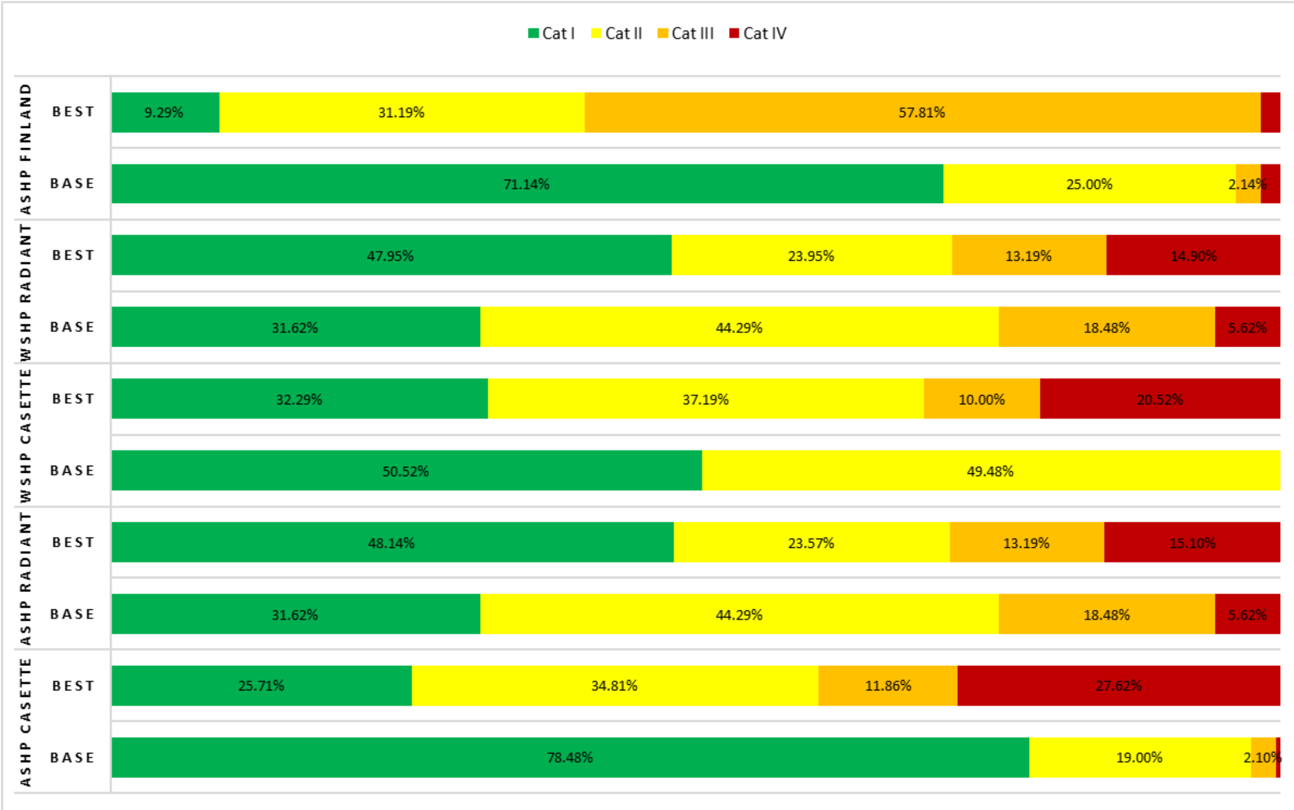



*Figure 13: Representation of the baseline and best cases for all the HVAC Systems based on comfort categories*

For designing any component of the HVAC system, the requirements for the adequate indoor environment should be set according to the international standard ISO 17772-2018. The standard categorizes environmental parameters to “high” or “category I”, “medium” or “Category II”, “moderate” or “category III” and “low” or “category IV”. The definition of each category are as follows,

I. High (Category I) lying in between 21-23 °C should be selected for occupants with special needs (children, elderly, handicapped)
II. Medium (Category II) lying in between 20-24 °C are the normal level used for the design and operation (typically used)
III. Moderate (Category III) lies in between 19-25 °C and can still provide an acceptable environment with some risk of reduced performance of the occupants.
IV. Low (Category IV) lies in the temperature values <19 and >25 °C and should only be used for a short time of the year or in the spaces with a very short time of occupancy.

As can be seen in the representation, the baseline cases in all the systems lie mostly in the Category I condition due to adherence to the strict setpoints. However, if we take a look at the cases with dynamic heating profiles. For example, the SH16-20 in the ASHP-Cassette system which is the global best case with respect to the heating energy consumption. We can see that in this case we have 26% in Category I, 35% in Category II, 12% in Category III and 28% in Category IV. We see that we have higher number of hours when the room conditions lie in the Category IV.

Also taking a look at the results of the ASHP-Radiant System, considering the best case (SL 16-20), the heating energy demand is about 40% more than the best case (SL 16-20) for the ASHP-Cassette System but in case of comfort, the ASHP-Radiant system ensures 23% more number of hours when the air temperature lies in the comfort category I as compared to the ASHP-Cassette system. Also, it is worth mentioning here that the goal of the study is not to compare between the different systems but to show the reduction in the energy consumption of each system without compromising on the comfort conditions.

In this section it was shown that as a result of the dynamic heating profiles we have much higher hours in the category IV. And mostly this happens because the temperature is less than 19 C. As already discussed before, mild cold exposure can provide health benefits to the inhabitants. Thus, in our cases our goal is to expose the occupants to these conditions of cold exposure which according to current standards fall into the Category IV. Now the only thing that requires to be done is that to backup this hypothesis with experimental data. And that experimental part which is very important for this research would be discussed in the next section.

## 4. Conclusions

In our study the different ideas such as dynamic indoor environment, mild cold exposure leading to the activation of brown adipose tissues, circadian rhythm of basal metabolic rate etc. were gathered together to create the dynamic heating profiles. These heating profiles are aimed at three primary goals, i) Energy reduction in the buildings, ii) Provide optimal thermal comfort to the occupants, iii) Long term solution for the treatment of Obesity. Twelve different profiles with varying temperature range and magnitude of step change were designed.

Software simulation study performed in Open Studio has been presented. For the purpose of simulation one of the building from the EPFL's Innovation Park was selected. The building loads (occupancy, lighting, electric equipment), losses (infiltration) and the schedules were setup with respect to SIA 2024-2015. For setting up the simulation cases two different types of generation source systems such as Air Source heat pump (ASHP) and Water source heat pump (WSHP) and two different kind of emission systems which are Cassette system and Radiant System were selected. These selections are based on the fact that these systems are most commonly used in the current office buildings.

As a result of the simulation study it was found that the dynamic heating profiles can reduce the heating energy consumption by 33-73% and the total energy demand by 16-36% as compared to the baseline setup using SIA 2024-2015. In terms of the hours spent in the different comfort categories for the open office space, by transitioning from baseline setpoint to the dynamic heating profile there is an increase in the hours spent in Category IV by 9-27% depending upon the cases.

It is obvious that as a result of the dynamic heating profiles there are much higher hours in the category III and IV. And mostly this happens because the temperature in the zone is less than 19 °C. Thus, these profiles enable the HVAC system to expose the occupants to mild cold conditions without high degree of discomfort. As already discussed before, mild cold exposure can provide health benefits to the inhabitants by the activation of brown adipose tissues. Thus, our goal is to expose the occupants to these conditions of cold exposure which according to current standards fall into the Category IV. The Subsequent steps would be focused on verifying this hypothesis with experimental data.

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# Out with the power outages: Peak load reduction in the developing world

**Sanober Hassan Khattak[1] , Sukumar Natarajan[1] and Woong June Chung[2]**

[1] Centre for Energy and the Design of Environments, University of Bath, Bath, UK, shk44@bath.ac.uk

[2] Faculty of Engineering and Technology, Liverpool John Moore University, Liverpool, UK.

**Abstract:** In developing economies with hot climates, the summer time peak load due to space cooling frequently results in power outages, as the outdated grid is not able to keep up with the demand. In this paper, computer simulation is carried out to develop and analyse a two-pronged strategy for peak load reduction, utilizing a relatively new thermal comfort model, together with variation in building fabric properties. The thermal comfort model is used to dynamically set the cooling setpoint temperature through implementation in MATLAB, with the building is simulated using EnergyPlus V8.8, both linked for co-simulation using the Buildings Control Virtual Test Best (BCVTB).

Compared to the baseline with a typical fixed cooling setpoint of 24°C, the newly developed cooling setpoint control strategy resulted in a reduction of 20% and 41% in the peak load and monthly energy demand respectively. This came at the cost of increasing the average PPD% from 7.2% to 12.6%. This work may be of interest to practitioners wishing to address demand management at the building scale. Moreover, it may be readily extended to analyse a group of buildings towards demand management at a higher level of aggregation.

**Keywords**: Peak load shaving, Demand response, Buildings Energy Efficiency, Space cooling, Dynamic thermal comfort

## 1. Introduction

Over the recent decades, energy use in buildings within the context of global warming and environmental sustainability has attracted much attention from researchers, practitioners and policy makers alike. This sustained focus is because the building sector is responsible for about one-third of the global final energy use, with projections of further increase (Takahashi *et al.*, 2014)

India is a developing economy where the Per Capita energy use is increasing by 3.3% every year (CSO, 2016), and its population is projected to reach 2.3 billion by 2080 (UN, 2016). In summer time, many parts of India experiences extreme temperatures that translates to high peak cooling energy demand within buildings. Coupled with the fact that India, much like other developing countries, has a fragile energy network, results in power outages ranging from 3 to 30 hours per month at peak summer conditions (Prayas Gr., 2016). Such power outages result in unacceptable levels of thermal comfort, leading to many fatalities at peak summer conditions (Chung *et al.*, 2018). For these reasons, addressing this issue of peak energy demand if of significant importance in India and other developing countries with similar climate. To tackle this issue, this paper presents an implementation of a strategy that combines (i) thermal comfort based control of the cooling systems with (ii) variation in the building fabric's thermal mass and thermal resistance. In the following sections, both these concepts are reviewed within the context of developing a peak load reduction strategy at the building level.

## 2. Thermal comfort

Thermal comfort is defined as "that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation" (Turner *et al.*, 2008). To achieve this occupant thermal comfort, the indoor environmental space is conditioned by employing Heating, Ventilation and Air Conditioning (HVAC) systems.

The most commonly used thermal comfort metrics are the Fanger's PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied), developed in 1970 by Ole Fanger, and then adopted into a number of international thermal comfort standards (Carlucci *et al.*, 2018). Concisely referred to as Fanger's PMV/PPD model, it is based on experiments that assume stead state conditions within the indoor building space, and implies that occupants do not really adapt to their thermal environment. While this assumption holds true for tightly conditioned spaces, many studies have shown that occupants do indeed adapt to changing thermal environments, and that the perceived occupant satisfaction is not dictated by as stringent space conditioning as demanded by Fanger's PMV/PPD model (A *et al.*, 1999; Han *et al.*, 2007). These reasons led to the development of the adaptive thermal comfort theory, where human physiology, phycology and behavioural change is believed to induce adaptation in thermal comfort due to temperature fluctuations. The adaptive occupant thermal comfort can be predicted through a simple linear relationship between the indoor operative temperature and outdoor environmental conditions. Figure *1* depicts this relationship as defined by the ANSI/ASHREA 55:2017 thermal comfort standard (Turner *et al.*, 2008). Here, an acceptable thermal comfort band for the indoor operative temperature is defined based on the prevailing mean outdoor air temperature. Similarly, several other global standards have incorporated variations of the adaptive comfort model, as documented by (Carlucci *et al.*, 2018).

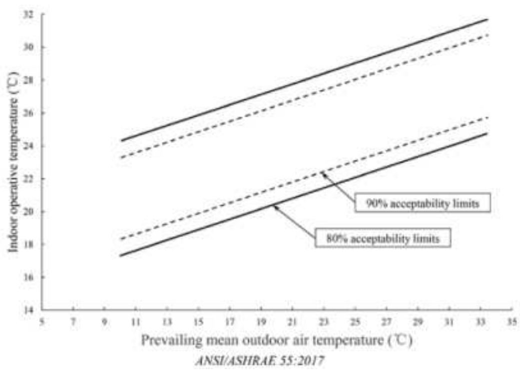


Figure 1 – ANSI/ASHREA 55:2017 adaptive thermal comfort model (Turner et al., 2008)

While the adaptive thermal comfort theory acknowledges people's adaptation to temperature fluctuation, its application is limited to slowly changing environments only (diurnal or seasonal temperature variation). In demand response (DR) strategies, building space conditioning equipment may be periodically turned 'on' and 'off', resulting in short-term cyclical variations. Consequently, Vellei and Le Dréau (2019) argue that neither Fanger's PMV/PPD model, nor the adaptive comfort models are suitable to assess occupant thermal comfort during such cyclical variations.

To address this gap, Vellei and Le Dréau (2019) developed a new model to gauge thermal comfort during short term cyclical variations in temperature, by adding a transient component to the Fanger's PMV based static model, to account for thermal alliesthesia and thermal habituation/adaptation. Alliesthesia has been defined as "the property of a given stimulus to arouse pleasure or displeasure according to the internal state of the subject" (Cabanac, 1979). Within the thermal environment, when a stimulus induces a pleasant perception, it is termed as positive alliesthesia. Similarly, negative alliesthesia is characterised by an unpleasant sensation. The magnitude of alliesthesia corresponds to (i) variation from thermal neutrality (PMV = 0) and (ii) Rate of change of skin temperature. Thermal habituation/adaptation is the phenomenon when sensory perception of humans reduces as they are exposed to repeated thermal exposures. Within the context of temperature fluctuations induced by DR events, exposure to repeated cycles of indoor air temperature variations of similar magnitude and shape would increase thermal habituation/adaptation within the occupants. In Vellei and Le Dréau (2019)'s model, thermal habituation/adaptation is quantified as follows

$$exposure = \sum_{cycle} (PMV - PMV_{min})^2 dt \; [discomfort^2 \; minutes]$$

Where,

$$PMV_{min} = minimum\ PMV\ reached\ at\ each\ cycle;\ or\ zero\ if\ negative$$

Vellei and Le Dréau (2019)'s model is based on Fanger' PMV and defines a new PPD indicator, which is referred to as 'VPPD' in the remainder of this paper, given by the following equation. The constants a,b,c and d are regression coefficients derived from experimental data and quantify the impact of alliesthesia in the thermal comfort model.

$$VPPD = 100.34 + \left\{a * abs\left(\frac{dPMV}{dt}\right) + b * exposure - 96.93\right\} * e^{(-0.03*PMV^4 - 0.23*PMV^2)} + c * abs\left(\frac{dPMV}{dt}\right) + d * exposure$$

$Where,$

$$\left(for\ \frac{dPMV}{dt} < 0\right): a = 10.12h, b = 0.14\ min^{-1}, c = -10.59h, d = -0.14min^{-1}$$

$$\left(for\ \frac{dPMV}{dt} > 0\right): a = -3.34h, b = 1.17\ min^{-1}, c = 4.68h, d = -1.18min^{-1}$$

$$\left(for\ \frac{dPMV}{dt} \simeq 0\right): a = -20.56h, b = 0.65\ min^{-1}, c = 19.16h, d = -0.7min^{-1}$$

A key finding of this model was that humans are sensitive to the rate of cooling, while for heating, it is the absolute value of temperature rather than its differential that mainly impacts alliesthesia. This means that for the range of temperatures expected during DR events, humans are more sensitive to cooling, than to heating. This is justified by the way in which cold and heat perception neurons operate in the human body (Ran, Hoon and Chen, 2016). Consequently, for unsteady indoor environment conditions as in DR events, the acceptable limit of thermal comfort based on the VPPD indicator corresponds to a PMV of up to 1.5, compared to a PMV of 0.85 for the Fanger model. Therefore, the VPPD metric may allow a greater fluctuation in indoor air temperature as compared to Fanger's PPD without compromising thermal comfort. This makes it suitable for use as a control variable for the cooling systems, as the larger permitted temperature fluctuation would promote reduced air conditioning without compromising occupant thermal comfort. Controlling HVAC thermostats based on thermal comfort indicators have been shown to reduce energy demand of buildings. For example, (Saffari *et al.*, 2016) employed Fanger's PMV based temperature setpoint control to evaluate the economic impact of incorporating Phase Change Materials (PCMs) in the building. However, the Fanger's PMV/PPD based approach would not suit HVAC control for a DR strategy with short-term temperature fluctuations, as it is applicable only to steady state or slowly changing systems. Therefore, in such a situation, it is pertinent to use VPPD as a control variable for HVAC thermostat control, the detail of which is presented in Section 5.3.

## 3. Thermal mass

Thermal mass in buildings is the ability of the building mass to absorb and store thermal energy. In heavy weight buildings, the walls and roof may have the ability to store enough energy so as to reduce temperature fluctuations on the inside surface, and shift the peak load to a later time in the day. Therefore, thermal mass based strategies have been employed in several studies as a load shifting strategy (Lee and Medina, 2016; Saffari *et al.*, 2016). Typically, either the thickness or the material, which corresponds to thermal conductivity, in the building envelope is varied or other technologies such as PCMs are utilised to increase the energy storage capacity of the building. For example, Tyagi et. al., (Tyagi *et al.*, 2016) used PCMs to shift peak time cooling energy demand to off peak time. However, Al-Sanea et. al., (Al-sanea and Zedan, 2011) point out that it is not only the thermal mass, but also the thermal resistance that impacts the peak shifting ability of buildings. An insulation material may not have much energy storage capacity, but its high thermal resistance delays the heat transmission to or from the indoor space, thus delaying heat transmission. Therefore, it is important to consider thermal resistance as well as thermal mass when developing a peak load reduction strategy. Based on the reviewed literature, a clear research objective is defined in the section that follows.

## 4. Research objective

From the reviewed literature in the preceding sections, the following observations are made within the context of developing a peak load reduction strategy.

- Fanger's PMV/PPD, and the adaptive thermal comfort models are not well suited to gauge occupant thermal comfort during DR events that impose short-term cyclical temperature variations on the indoor space. Vellei and Le Dréau (2019) developed a thermal comfort model that is designed specifically for assessment of occupant thermal comfort in such conditions. As it includes additional transient terms to that of Fanger's PMV/PPD model to account for thermal alliesthesia and thermal adaptation, it is sensible to develop a VPPD based peak load reduction strategy.

- A key finding of Vellei and Le Dréau (2019)'s model was that humans are more perceptive to cooling than to heating. This is because our coolth receptive neurons respond more to the rate of change in cooling, while our heat receptive neurons respond to the absolute temperature change. Consequently, Vellei and Le Dréau (2019)'s model defines a broader thermal comfort range for the indoor air temperature as compared to Fanger's model. Thus, utilising VPPD as a control variable to establish cooling setpoint temperatures dynamically may result in lowering the average and peak demand.
- Heat transmission to the indoor space may be delayed with increasing thermal mass and thermal resistance of the building fabric. Therefore, including these tactics may lead to lower peak loads.

Based on the above observations from literature, the following research objective is defined for this work,

*"To implement and investigate a peak load reduction strategy that combines (i) VPPD based control of the cooling systems and (ii) Thermal mass and thermal resistance variation in the building fabric."*

## 5. Methodology

### 5.1 Overview

This study employs a simulation-based approach to analyse the peak reduction capability of the newly developed VPPD based approach. The case study building is a residential apartment complex in New Delhi, India (see Section 5.2 for detail on the modelling and validation). The reason for selecting a residential building is that domestic electricity use dominates the buildings energy demand in India. In 2015 -2016, the electricity demand of the residential sector in India was 24% of the total electricity use in the country. Furthermore, it is projected to increase as more households are expected to adopt air conditioning which is a consequence of economic growth (Chunekar and Sreenivas, 2019). Following detail on the case building and its considered variants (Section 5.2), a description of the different cooling setpoint control strategies is presented in Section 5.3, to be applied to the different building variants. The results and analysis are presented for a single controlled zone, which corresponds to a single bedroom within an apartment. Finally, the results are extrapolated to the building level to quantify the impact of the developed peak reduction strategy at the building scale.

### 5.2 Case building and its variants

A typical Indian two bedroom apartment residential building was modelled with EnergyPlus v.8.8 as defined by the Global Building Performance Network, GBPN (Rajan *et al.*, 2014a). It is a two-story building with four apartments on each floor, with a total covered area of 330m$^2$. Figure *2* (left) presents the building's overview while Figure *2* (Right) presents one apartment.

Within each apartment, the drawing room and bedrooms are serviced as separate zones using individual Packaged Terminal Air Conditions (PTAC). The occupancy is set to 0.11 people/m$^2$ corresponding to four people per each 41.25m$^2$ apartment. The weather file used is for middle Delhi (Chung *et al.*, 2018), while the simulation with a time-step of one minute was carried out for May, which has the highest monthly average and peak temperatures. To compare the impact of the different cooling setpoint control strategies, a single bedroom was selected (Figure *2* (Right)). For investigating the impact of building characteristics on thermal comfort, the thermal mass and thermal resistance were adjusted for the typical building based on the work done by Ramesh, Prakash and Shukla (2012).

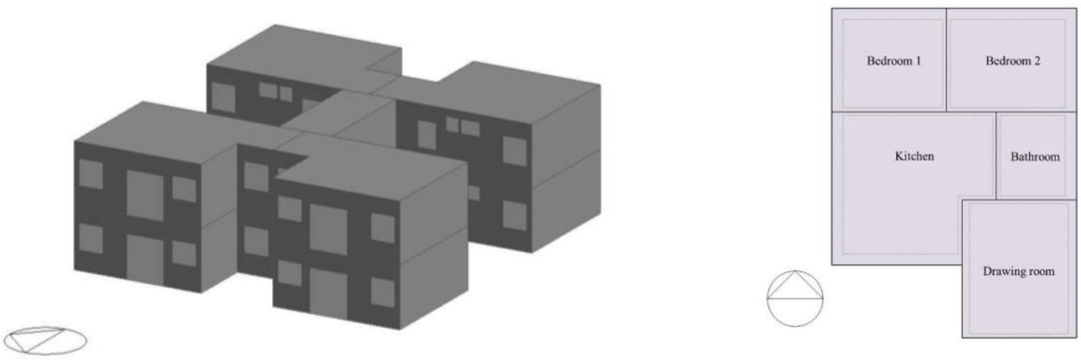


Figure 2 - Building overview (left), Apartment plan view (Right)

To assess the impact of varying thermal resistance within the building envelope, the 'Business as Usual' (BAU) and the 'Energy Conservation Building Code Plus' (ECBC+) building variants defined by the GBPN (Rajan *et al.*, 2014b) have been considered. The BAU parameters are representative of a typical building envelope in India, while the ECBC+ is representative of an energy efficiency envelope, selected in view of economic considerations (Rawal *et al.*, 2012). This leads to the definition of four building variants, with their parameters provided in Table *1*

Table 1 - Building variants considered in this study

| | **Low thermal resistance (BAU)** | **High thermal resistance (ECBC+ )** |
|---|---|---|
| **Light Weight** | Wall thickness = 0.13m<br>U-value wall = 1.72<br>U-value roof = 2.94<br>U-value floor = 2.94<br>U-value Window = 5.8 | Wall thickness = 0.13m<br>U-value wall = 0.35<br>U-value roof = 0.41<br>U-value floor = 0.25<br>U-value Window = 3.3 |
| **Heavy Weight** | Wall thickness = 0.43m<br>U-value wall = 1.72<br>U-value roof = 2.94<br>U-value floor = 2.94<br>U-value Window = 5.8 | Wall thickness = 0.43m<br>U-value wall = 0.35<br>U-value roof = 0.41<br>U-value floor = 0.25<br>U-value Window = 3.3 |

## 5.3 Cooling setpoint control strategies

As the focus of the analysis in on peak load conditions, which is typically mid-afternoon in summertime, natural and mixed mode strategies are expected to lead to uncomfortable conditions. Therefore, only cooling setpoint control strategies suitable for mechanical mode is considered below,

### 5.3.1 Static set point of 24°C

Ghawghawe et al., (2014) analysed static cooling setpoint temperature in relation to the A/C systems COP and thermal comfort for a number of cities in India. They concluded that a static setpoint temperature of 24°C is a typical setpoint which results in comfortable conditions for New Delhi, and is considered here as the baseline cooling setpoint strategy.

### 5.3.2 IMAC (Indian Model for Adaptive Comfort)

This model is based field studies across several cities in India and is valid for buildings operating in AC mode. Based on the field studies, it was found that Fanger's PMV/PPD model or the adaptive comfort models of ASHREA 55 and EN15251 overestimated the occupant discomfort (Manu *et al.*, 2016). As the IMAC model is based on empirical data from the Indian context, it can be employed within India. It is valid within the outdoor running mean temperature range 13°C – 38.5°C and is given by (Angelopoulos *et al.*, 2018),

$$T_{HSP} = 0.28 * \ T_{out} + 14.4$$

$$T_{CSP} = 0.28 * \ T_{out} + 21.4$$

Where, $T_{HSP}$ , $T_{CSP}$ and $T_{out}$ are the heating setpoint, cooling setpoint and outdoor running mean temperature respectively. This model is implemented using the Building Control Virtual Test Bed (BCVTB), to link MATLAB with EnergyPlus V 8.8. At each time step, the free running monthly mean outdoor air temperature was calculated based on which the preceding equation was used to calculate and communicate the cooling thermostat setpoint temperature to EnergyPlus.

### 5.3.3 Static VPPD

In this approach, the cooling setpoint is controlled indirectly through the VPPD metric, by keeping it less than 10%, corresponding to the ASHREA 90% thermal comfort acceptability limit. This was implemented by using the BCVTB, to link MATLAB with EnergyPlus, through the thermal comfort based Fanger's PMV setpoint control available in EnergyPlus. The steps to accomplish this using the BCVTB are as follows,

I. Retrieve Fanger's PMV in MATLAB for the current timestep
II. Implement conditional statements to keep VPPD just under 10% based on Vellei and Le Dréau (2019)'s model as depicted in Figure 3, to generate the setpoint PMV
III. Communicate the Setpoint PMV to EnergyPlus for the next timestep

Figure 3 shows that for a PMV differential of up to 1 vote/hour, Fanger's PPD and VPPD are almost exactly the same. This is because in such conditions, the transient component in the VPPD metric approaches zero. On the warm side of the thermal neutral plane, and where positive alliesthesia is stimulated (indicated by 'P'), Figure 3 shows that the variation between the two models is directly proportional to the rate of change of PMV. For example, in the case where the PMV differential is 6 votes/hour or greater, PPD = 10% corresponds to PMV=1.1 for Vellei and Le Dréau (2019)'s model while the same limit corresponds to PMV=0.4 for

Fanger's model. To implement the static VPPD setpoint control strategy, the following conditions were used, corresponding to step II above.

$$PMV\ setpoint = \begin{cases} \dfrac{dPMV}{dt} < -4 & -0.55 \\ -4 < \dfrac{dPMV}{dt} < -1 & -0.5 \\ 4 < \dfrac{dPMV}{dt} < 1 & 0.5 \\ \dfrac{dPMV}{dt} < 1 & 0.5 \\ 4 < \dfrac{dPMV}{dt} < 1 & 0.85 \\ \dfrac{dPMV}{dt} > 4 & 1.1 \end{cases}$$

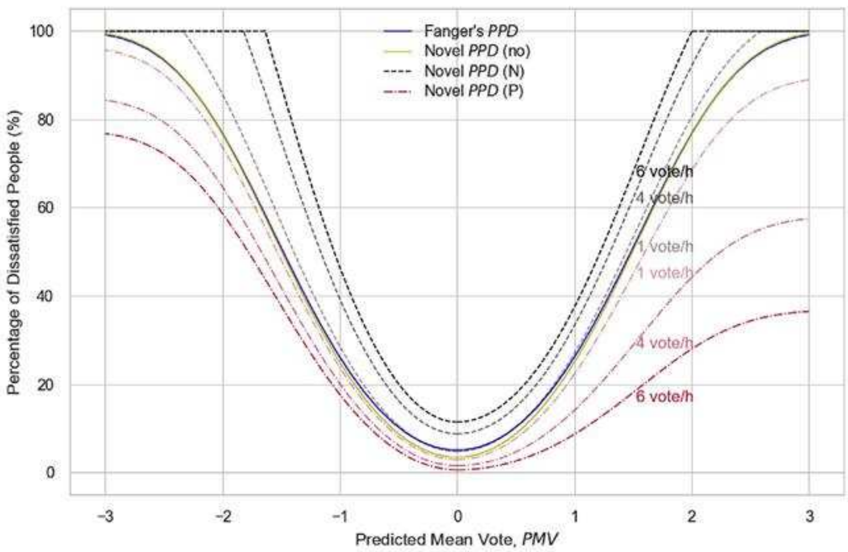


Figure 3 - VPPD% based on the absolute value and rate of change of Fanger's PMV (Vellei and Le Dréau, 2019)

### 5.3.4 Switching VPPD

In this approach, the VPPD percentage is allowed to vary between 5% - 20%, to deliver an average VPPD comparable to the static VPPD approach. This is implemented through co-simulation using the BCVTB platform to link MATLAB and EnergyPlus in the following steps

I. Retrieve Fanger's PMV in MATLAB at the current simulation time step
II. Calculate VPPD base on the equations in Section 2
III. Implement conditional statements to decide AC systems switching on/off
IV. Communicate AC switching to EnergyPlus for the next timestep.

It should be noted that through the use of BCVTB and the steps defined above, a lag of one timestep is introduced, and thus the small simulation timestep of 1min was used uncomfortable conditions. For the same reason, the VPPD thresholds for switching the AC on/off was slightly offset from 5% and 20%. The conditional statement to decide AC switching are provided below,

$$AC\ Switching = \begin{cases} (VPPD > 18) \wedge (PMV > 0) & AC\ on \\ (VPPD \geq 10) \wedge (PMV > 0) \wedge \left(\frac{dVPPD}{dt} \geq 2\right) & AC\ on \\ (VPPD > 18) \wedge (PMV < 0) & AC\ off \\ (VPPD \geq 10) \wedge (PMV < 0) \wedge \left(\frac{dVPPD}{dt} \geq 2\right) & AC\ off \\ (VPPD < 8) & AC\ off \end{cases}$$

The peak load analysis presented in Section 6 is done based on peak load per zone. For this VPPD switching setpoint control strategy, it is assumed that while the AC system is off in one zone, another zone within the building will be serviced. For example, if two additional zones can be serviced before the AC system needs to turn on again, a total of three zones would be serviced in one cycle. Based on this logic, the peak load per zone is calculated as follows,

$$Total\ servicable\ zones = \frac{Total\ cycle\ time}{AC\ on\ time}$$

$$Peak\ loads\ per\ zone = \frac{Zone\ peak\ load}{Total\ servicable\ zones}$$

This essentially assumes that there are different zones within the building that can perfectly coordinate with each other to turn the AC systems On/Off in tandem. Consequently, a higher peak load with a sufficient 'off' period may reduce the peak load per zone in comparison with static VPPD or temperature setpoint strategies.

### 5.4 Comparison scenarios

Corresponding to Table *1*, the four building variants described in Section 5.2 are succinctly abbreviated as follows,

i. BAU LW – The business as usual lightweight building
ii. BAU HW – The business as usual heavyweight building
iii. ECBC+ LW – The ECBC+ lightweight building
iv. ECBC+ HW – The ECBC+ heavyweight building

Within each building variant, the four cooling temperature setpoint strategies are implemented as defined in 5.3, succinctly referred to in the remainder of this paper as follows:

a. Tset = 24 – Fixed cooling setpoint temperature of 24°C
b. IMAC – Dynamic cooling setpoint based on the IMAC model
c. Static VPPD - Dynamic cooling setpoint based on a static VPPD value just below 10%
d. Switching VPPD - Dynamic cooling setpoint based on VPPD ranging between 5% - 20%

Thus, in total, 16 scenarios have been defined. Tset = 24 is the baseline for the cooling setpoint strategies, while the BAU LW is the baseline building variant. Overall, the BAU LW with Tset = 24 is considered the baseline, which also the likely typical scenario in practice.

## 6. Results and Discussion

The analysis presented in this section is for a single zone corresponding to a 6.8m$^2$ bedroom, serviced by a PTAC unit. After the difference in performance for all the scenarios is quantified, the results are then extrapolated to the building level. To demonstrate the difference in operation between the different cooling setpoint control strategies, the indoor air temperature for a single zone over a typical day in May is presented in Figure 4. As the month of May has the highest peak temperatures over the typical reference year, a typical afternoon in May is considered as a representative peak summer afternoon, having a peak temperature over 40°C.

Other than the fixed temperature setpoint of 24°C, the remaining three setpoint control methods result in variable indoor air temperatures. According to the 'VPPD Static' method, the indoor air temperature varies over a small range between 27°C and 28°C. The 'IMAC' based control results in warmer indoor conditions, which varies between 28°C and 32°C in this case. However, it should be noted that the IMAC standard is based on thermal comfort data from field surveys in various Indian cities as opposed to the typical PMV/PPD or adaptive thermal comfort indicators. For the VPPD Switch control strategy, Figure 4 shows that a cyclical pattern develops, which is typical of DR events. Here, the temperature varies between 24°C and 29°C, to keep the VPPD thermal comfort indicator between 5% and 20%. In other words, the AC system is kept 'on' until a VPPD of 5% is reached, which corresponds to approximately 24°C in this example. The AC system is then kept off until the VPPD is just below the specified threshold (20%), corresponding to 29°C approximately in this example afternoon. These observations show that the four setpoint control strategies are behaving as expected, for which the peak load, energy demand and thermal comfort results are presented next.

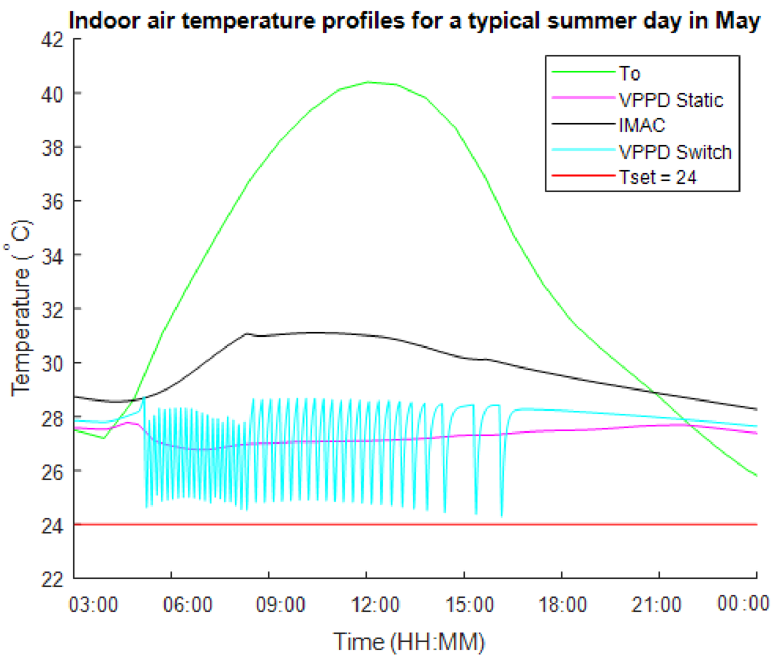


Figure 4 - Indoor air temperature on a peak summer afternoon for the difference setpoint strategies

Figure 5 depicts the daily peak loads in the Month of May for the analysed zone. The results are presented for the four setpoint control methods across the four building variants. First it can be observed that the IMAC and Tset = 24 setpoint control strategies result in the lowest and highest peak load respectively. Viewing this observation relative to the average thermal comfort, it is clear that the fixed 24°C strategy also leads to the highest levels of thermal comfort. Both the VPPD based schemes have comparable levels of average thermal comfort.

While the IMAC standard is not subject to the PMV/PPD thermal comfort model, the high levels of discomfort predicted by the VPPD indicator highlights this large gap between the predictions made through the PMV/PPD models, and observed field data. Considering that the VPPD ranges from 64% - 75%, such a high PPD% indicates that the current PMV/PPD based models are not able to accurately predict thermal comfort in extreme summer conditions, such as those observed in India. It should be noted here that the socioeconomic context is also important, and that this inability of the PMV/PPD model to accurately reflect the occupant’s comfort may be impacted by the living standards that corresponds to a developing economy. Nonetheless, this issue may be investigated in future research to reconcile this difference.

Table 2 - Average thermal comfort across the 16 scenarios

| **Scenario** | **Average Thermal Comfort (VPPD %)** | | | |
|---|---|---|---|---|
| | Tset = 24 | IMAC | VPPD Static | VPPD Switch |
| **BAU LW** | 4.9 | 74.8 | 9 | 11.9 |
| **BAU HW** | 4.2 | 71.6 | 9 | 11.1 |
| **ECBC+ LW** | 7.2 | 63.7 | 9.3 | 12.6 |
| **ECBC+ HW** | 4.8 | 68.5 | 9 | 12.8 |

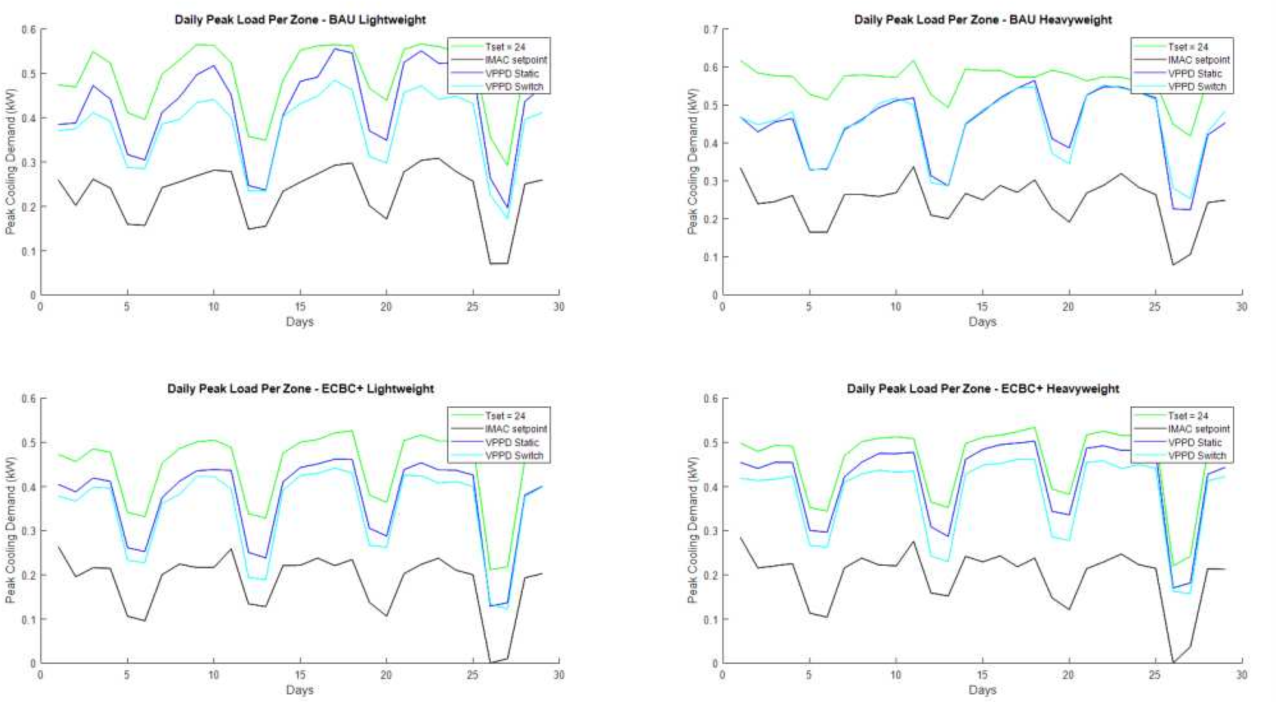


Figure 6 - Peak cooling load comparison for the Month of May

Between the VPPD static and VPPD Switch approaches, except for the BAU HW building variant, the peak load for the VPPD Switch control is observed to be constantly lower. In Figure 7, the average peak loads is compared across all 16 scenarios, showing that the ECBE+ LW building variant leads to the lowest absolute peak load for all setpoint control strategies implemented. The ECBC+ LW corresponds to a high thermal resistance and low thermal mass in the building fabric, suggesting that an increase in thermal mass of the building as implemented through varying wall thickness is not a suitable strategy for peak load shaving. It is possible that the lag in heat transmittance introduced by the heavier building fabric is not large enough to offset the cooling demand to non-peak conditions. For the example afternoon, it can be seen that the high temperatures persist over a number of hours. Thus, for the thermal mass based strategy to be successful, the lag in heat transmittance should be of the same order. Clearly, increasing the thickness of the fireclay brick by 30cm within the external wall likely does not have this effect. However, the increase in thermal resistance has a significant effect on reducing the peak load. Table *3* provides the percentage reduction from the baseline (Tset=24), across the remaining three setpoint control strategies and all building variants. In all cases, the IMAC standard results in a reduction by more than 50%. For the remaining two setpoint control methods, VPPD Switch results in a lower peak load for all scenarios expect BAU HW. Considering that the absolute peak load is lowest for the ECBC+ LW building variant, following the IMAC based control, the VPPD switching method results in the lowest peak load, corresponding to a reduction of 20.5% from the baseline setpoint control.

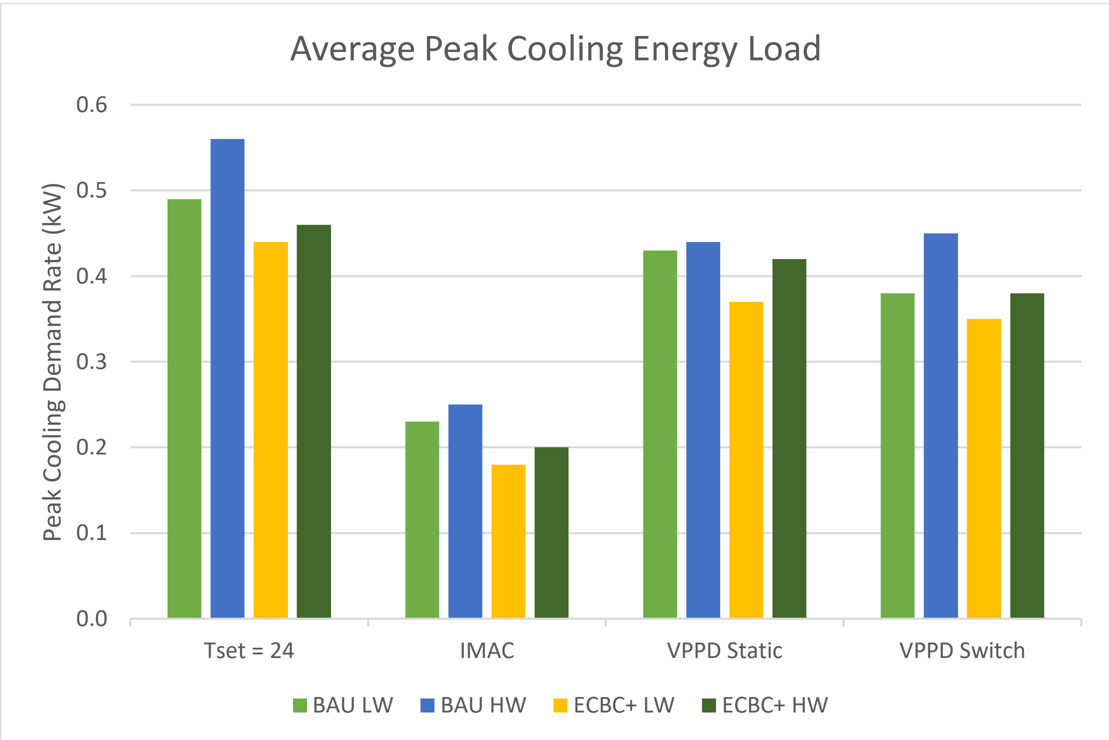


Figure 8 - Average peak load comparison

Table 3 - Reduction in peak load from the baseline

| | Average peak load Reduction from baseline (%) | | |
|---|---|---|---|
| | IMAC | VPPD Static | VPPD Switch |
| **BAU LW** | 53.1 | 12.2 | 22.4 |
| **BAU HW** | 55.4 | 21.4 | 19.6 |
| **ECBC+ LW** | 59.1 | 15.9 | 20.5 |
| **ECBC+ HW** | 56.5 | 8.7 | 17.4 |

Table 4 and Figure 9 provide the energy demand results for the same simulation period over the 16 scenarios. The same trends that were observed for peak loads analysis are also present for the total energy demand. Again, the ECBC+ LW building is the most energy efficient building variant. Here, significant reductions in the monthly energy demand are observed compared to the baseline. The IMAC, VPPD static and VPPD Switch control methods lead to monthly energy demands of 23.1kWh, 109kWh and 102kWh respectively, corresponding to a reduction of 86.7%, 37.1% and 40.6% from the baseline respectively. The analysed zone has a covered area of 6.8m$^2$. Extrapolating to the building level, that has a total covered area of 330m$^2$, implementing the IMAC and VPPD Switch setpoint control methods for the ECBC+ LW building variant in comparison with the BAU LW with Tset=24 baseline, results in a reduction of average daily peak load and total energy demand by 60% and 20% respectively, corresponding to a reduction of 14.6kW and 4.9kW peak load respectively at building scale. Again, it should be noted here that the IMAC standard is not subject to the PMV/PPD metric that indicate highly uncomfortable indoor conditions for the setpoint control method.

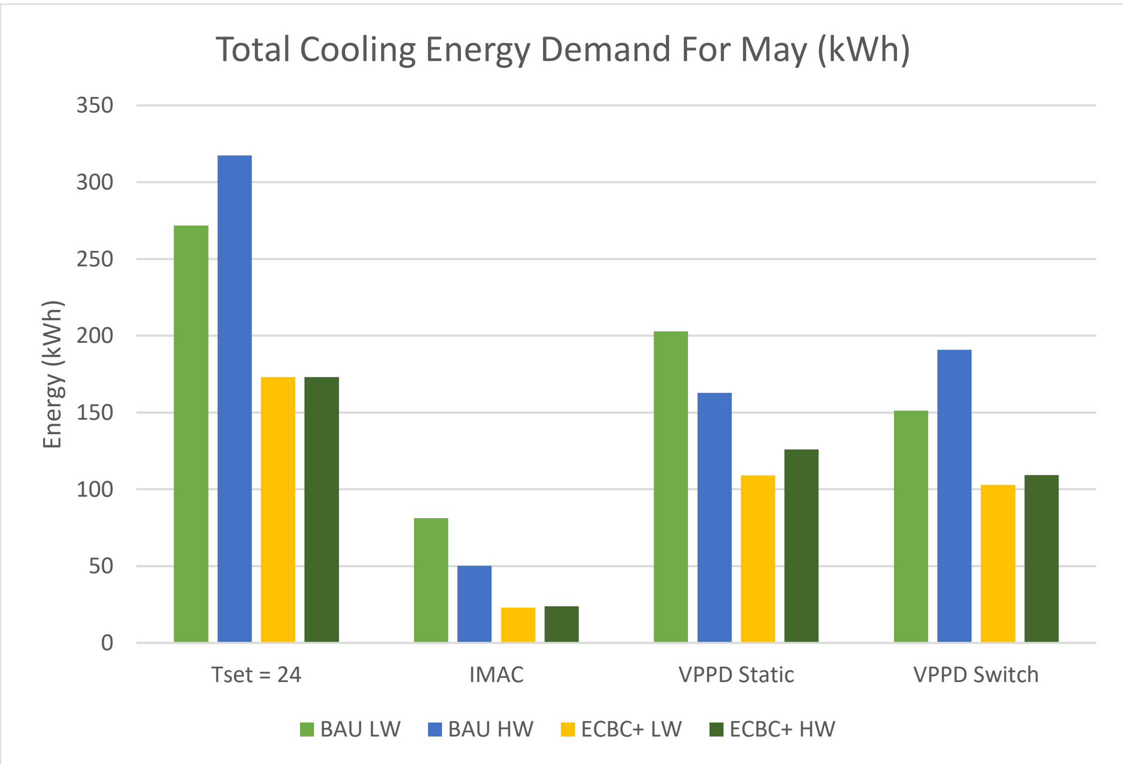


Figure 9 - Total monthly energy demand comparison

Table 4 - Reduction in cooling energy demand from the baseline setpoint control of Tset =24

| | Total cooling demand Reduction from baseline (%) | | |
|---|---|---|---|
| | IMAC | VPPD Static | VPPD Switch |
| **BAU LW** | 70.1 | 25.3 | 44.3 |
| **BAU HW** | 84.2 | 48.7 | 39.9 |
| **ECBC+ LW** | 86.7 | 37.1 | 40.6 |
| **ECBC+ HW** | 86.3 | 27.2 | 36.9 |

In order to further understand the impact of different cooling setpoint control approaches applied, the energy quality aspect is considered here. As the temperature of thermal flows vary, their work potential varies accordingly. The concept of exergy has been widely used to analyse energy flows to account for energy quality in addition to its quantity (Dewulf *et al.*, 2008; Dincer and Rosen, 2012; Khattak, 2016). For a thermal flow of fixed quantity, its work potential and exergy content varies according to variation in the temperature of the thermal flow as well as that of the outdoor environment, given by the equation below.

$$\dot{Ex}_{Thermal\ flows} = \dot{Q}(1 - \frac{T_{out}}{T})$$

Where,

$\dot{Ex}_{Thermal\ flows}$ *is the exergy flow rate of the thermal flow* $\dot{Q}$ *at a temperature* $T$
$T_{out}$ *is the outdoor air temperature*

Consequently, this has led to the development of the 'Low Ex' approach in buildings, that promotes matching of the energy quality in supply and demand (Schmidt and Ala-Juusela, 2004; Khattak *et al.*, 2016). Much work has been done to analyse building systems exergetically (Hepbasli, 2012), as it provides a deeper understanding of the energy required to condition building space. Therefore, the cooling exergy demand for analysed zone, for the most energy efficiency building variant (ECBC+ LW) is calculated using the preceding equation. The cooling exergy demand for the baseline and VPPD Switch scenario are depicted in Figure 10 which shows that the individual peak values of the VPPD Switching method are higher than for the fixed 24°C setpoint. However, the VPPD switching scheme allows intermittent switching 'off' of the AC systems, resulting in cumulative reduced monthly exergy demand. For the fixed 24°C and the VPPD Switch methods, the monthly exergy cooling demand for the simulated period was 13.7kWh and 8.8kWh respectively, a reduction of 35.2% over the baseline. For the same scenario comparison, the VPPD Switch method resulted in a greater energy demand reduction of 40.6% over the baseline. The VPPD switching strategy allows temperature variation from 18°C - 30°C, thus operating at a greater difference from the outdoor environment in comparison with the baseline. This results in a lower quantity but higher quality of energy demand compared to the fixed 24°C setpoint. Additionally, the low absolute values of exergy demand highlight that while the quantity of energy may be substantial, the quality of energy required is low, as it is at little variation from the reference outdoor environment. Therefore, utilising any technology or method that may reduce the consumption of electrical energy (which is pure work) will greatly impact the exergy efficiency. An example would be the use of ground source heat pumps (GSHP) which allow utilizing the lower underground temperature to reduce the load on the AC system's compressor.

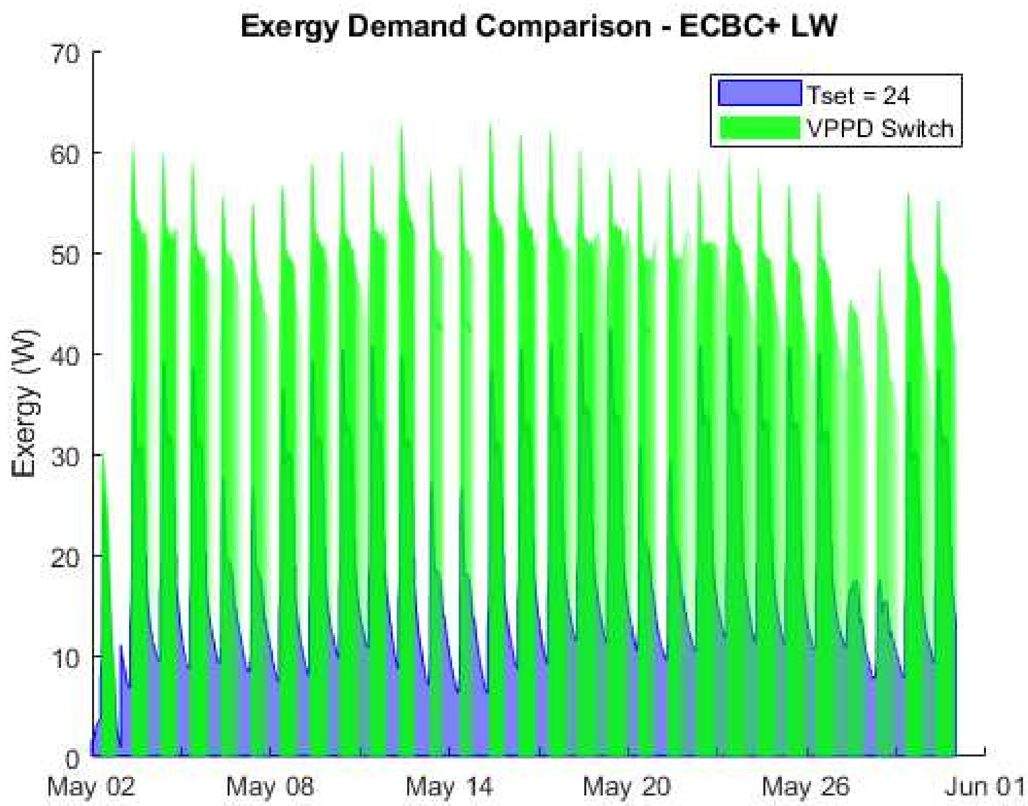


*Figure 10 - Cooling exergy demand comparison*

**7. Conclusions and future work**

In this work, a recently developed thermal comfort indicator was used for the first time as an indirect control variable for dynamically setting the indoor setpoint temperature. The model, developed by Vellei and Le Dréau (2019), is specifically suited for non-steady state indoor environments such as those observed in implementation of demand response events. Specifically, the VPPD% thermal comfort indicator was used to dynamically control the indoor cooling setpoint temperature. Specifically, four setpoint control strategies (Tset-24, IMAC, VPPD Static and VPPD Switch) where used for four building variants to analyse peak load reduction due to variation in the setpoint control strategy, as well as building characteristics. The following conclusions can be derived based on the preceding results analysis and discussion section,

- The IMAC based setpoint control results in the lowest peak load as well as monthly demand, however it is based on data from field observations and is not subject to the typical PMV/PPD or adaptive thermal comfort indicators.
- Based on the VPPD indicator, implementation of the IMAC control results in highly uncomfortable indoor conditions, with average VPPD ranging from 62% - 75%.

Therefore, there is a significant disagreement between thermal comfort prediction using PMV/PPD models and field data.

- For the setpoint control strategies subject to the PMV/PPD thermal comfort metrics, the VPPD switching scheme resulted in the lowest peak energy load as well as monthly energy demand.
- Within building characteristics variation, increasing thermal mass by varying external wall thickness was ineffective in offsetting the peak load. However, increasing thermal resistance reduced the absolute peak load as well as monthly energy demand.
- For the scenarios assessable by PMV/PPD thermal comfort theory, in this case of the typical Indian residential apartment building, the VPPD Switching based scheme results in the lowest energy and exergy demand.

In view of these conclusions, the following directions of future work are identified. First, while the IMAC based setpoint control results in the most energy efficient and reduced peak load option, currently available thermal comfort models predict highly uncomfortable indoor conditions when it is implemented. Therefore, there is a need to develop a thermal comfort model that may alleviate this disparity between prediction of state of the art PMV/PPD based models, and what is observed from field surveys.

Second, Vellei and Le Dréau (2019)'s model includes a transient component that makes it suitable for thermal comfort analysis and prediction in unsteady indoor building conditions, and it is based on the energy balance across the human body. This basis ignores consideration of energy quality, whilst not being able to directly account for material flows such as perspiration or breathing in air of varying humidity. Using exergy, not only the energy quality is accounted for, but material flows can equally well be modelled using the objective thermodynamic indicator (Khattak, Oates and Greenough, 2018; Gonzalez and Cullen, 2019). Consequently, (Shukuya and Hammache, 2002; Shukuya, 2009; Schweiker and Shukuya, 2012) have developed exergy analysis based thermal comfort indicators based on exergy analysis of the human body. The 'minimum exergy consumption rate' is used as a measure for the thermal neutral perception. As such, this approach is based on a more complete analysis of flows across the human body as compared to energy analysis, therefore it may be sensible to implement an exergy based thermal comfort model suitable for un-steady indoor conditions.

Third, the peak load per zone, serviceable by the VPPD switching scheme is based on the assumption that all of the 'off' period of the cycle can be utilised (Section 5.3.4). This could be realised by implementing cooling systems control at the building level. However, the extent to which the 'off' period of the cycle can be utilised within peak load conditions for the Indian context is not known. Therefore, future work can investigate these controls at a single or multiple buildings level.

Finally, the analysis and results presented in this work are based on 16 scenarios, using the BAU and ECBC+ standard building characteristics defined by Rajan *et al.*, (2014b). A more exhaustive analysis over a wider range will allow to develop a deeper understanding on how the building characteristics impact the peak load and energy demand for the VPPD based setpoint control.

**Acknowledgement**
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# When part is too little: cutoff rules' influence on LCA application to whole-building studies

**Vanessa Gomes[1] and Lizzie M Pulgrossi[1]**

[1] Department of Architecture and Construction, University of Campinas, Brazil, vangomes@unicamp.br; lizpulgrossi@yahoo.com.br

**Abstract:** LCA application to whole-building studies (wbLCA) is challenged by the large number of materials, lack of production data and numerous inferences made over the building's long lifespan. Practice calls for modelling simplification, mostly through inventory reduction. Thus, this research investigates how cutoff rules influence wbLCA results of three functionally and conceptually different buildings. Three scenarios were applied: Complete LCA; mass-and-energy contribution-based cutoff, according to the European Standard EN15804:2012 and element-based cutoff, according to LEED v4 rating system (structure and envelope only). Such approach is consistent with the core & shell certification modality. SimaPro 8.5 software supported LC modelling, using Ecoinvent data adapted to the Brazilian context and CML-IA baseline and cumulative energy demand (CED) impact assessment methods. The reference service life was set as 50 years. The *mass-and-energy cutoff rule* preserves more inventory flows, lifecycle mass and impacts than the *element-based approach.* Outcomes variation ranged from 21% (Case C, passive office building) and 47% (Case A, public school building) when shifting from the contribution-based to the element-based approach. The observed patterns suggest category clustering into three groups. LEED wbLCA can be biased by focusing on categories which follow a similar trend, indeed dominated by structure and envelope elements. LEED's cutoff approach is partly consistent with core & shell certification modality and valuable to drive wbLCA into mainstream practice. Given the risk of neglecting an important portion of ecotoxicity, human toxicity and abiotic depletion, which are directly related to building systems and finishings, we recommend that LEED certification *enlarges the product system* to include building services and *broadens scope* to ensure that at least one category in each identified group is assessed. LCA practitioners should proactively include building systems in wbLCA.

Keywords: life cycle assessment; whole-building LCA; cutoff rules; LEED; certification

## 1. Introduction

The construction sector is one of the largest environmental impact generators, due to the consumption of natural and energy resources and large-scale waste generation. In the 1990s, several countries developed their own building environmental rating methods, such as LEED, BREEAM, DGNB and Green Globes.

From a qualitative perspective, these methods have proved to be accessible and applicable, especially over design and construction. Over the last decades, however, authors such as Humbert et al. (2007) have highlighted the discrepancy between the rating results and the actual operational performance of the assessed buildings. Thus, a growing number of studies show the need to merge the approach of the certification systems with that of the life cycle assessment (LCA) technique (Anand and Amor, 2017).

LCA performs a quantitative assessment of the potential environmental impacts caused over the entire life cycle of a given product or process (from the raw material extraction to final disposal), which allows tracing its environmental profile and identifying opportunities for improvement (Todd, 2012).

EN 15978:2011 standard (CEN, 2011) and the EeBguide Project (2012) set procedures for whole-building LCA (wbLCA), which encompass all life cycle stages, from material and components' production to the end of life (Figure 1).

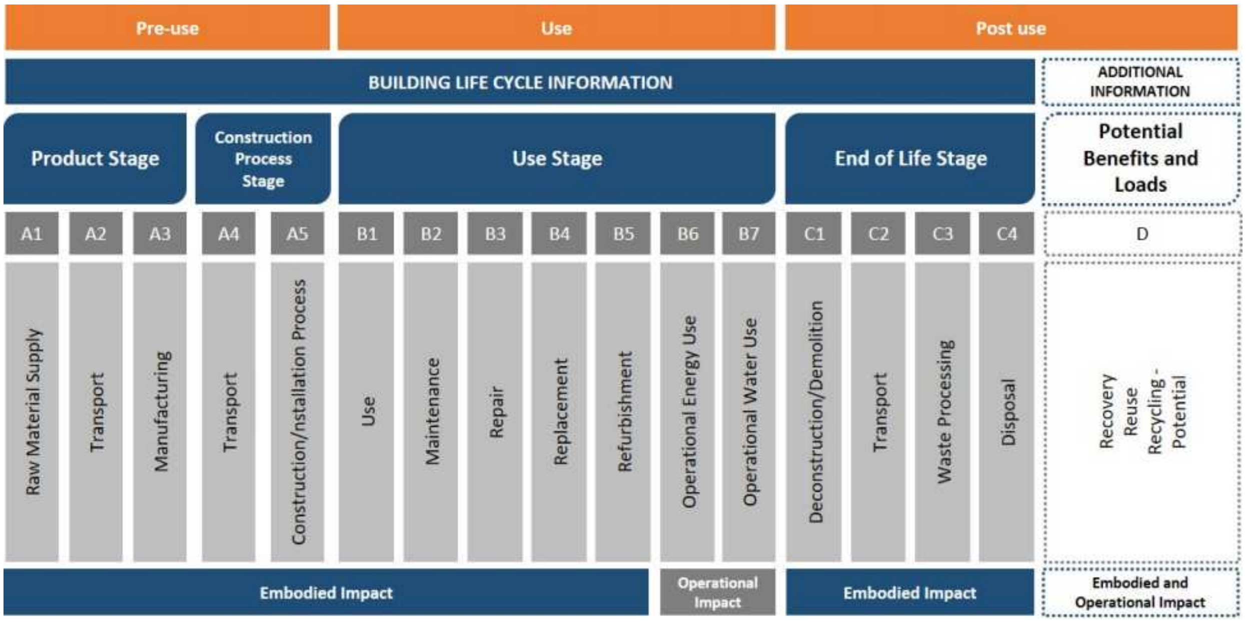

Figure 1. Stages of whole-building life cycle assessment (wbLCA), according with EN 15978:2011 (CEN,2011).

LCA application at whole-building scale becomes a complex task, due to the large number of elements and constructive processes involved, which requires the assembly of a massive data inventory, often unavailable or non-existent, and extensive time and analyst experience to guide the numerous choices made along the way. Such lack of information hinders LCA use in the preliminary design stages (Jusselme et al., 2018). In addition, the long useful life of the building that leads to various assumptions and the adoption of generic data, especially regarding the stage of use of the building.

ISO 14044:2006 and EN 15805:2011 provide guidance on the different strategies for simplify and enable the study, either by limiting the product system - excluding less relevant life cycle stages or reducing the number of inventoried data - through the so-called 'cutoff' rules, provided that they are clearly exposed and in accordance with the assessment objectives (Gomes et al., 2018).

The European standard EN 15804:2012 (CEN, 2012) cutoff criteria admit excluding items which represent less than 1% of the total mass input and renewable and non-renewable energy usage (1% each) of unit processes, as long as the total of neglected input flows per module do not exceed 5% of the total mass or energy (CEN, 2012). However, elements involving material and energy flows known to have the potential to cause significant impacts should not be disregarded, even when within the limit established by the rule.

Another cutoff rule often mentioned in the reviewed literature is the exclusion of components by construction subsystem (Soust-Verdaguer et al., 2016). One example is the LEED certification approach. Starting with its version 4, released in 2013, LEED considers 60 years of reference service life for the building, and encompasses potential impacts in six environmental categories: Global Warming, Ozone Depletion, Acidification, Eutrophication, Photochemical Ozone Formation and Abiotic Depletion - fossil fuels, the first of which is mandatory. Only elements of the building structure and envelope are considered (USGBC, 2013). This cutoff approach is consistent with LEED's main certification audience in most countries: core & shell corporate buildings.

Although the ultimate purpose of applying cutting rules is to enable and disseminate LCA use in whole-building assessments, it is important to understand how these exclusions influence results and support decision-making. Hence, this paper investigates the effects of the described cutoff rules on wbLCA results of three types of buildings in different functional and constructive contexts.

## 2. Metodology

### 2.1. Case studies description

Three types of buildings in different functional and constructive contexts were selected as case studies. Case study A follows the standard design for public schools adopted by the Brazilian federal government, which consists in a single-story building composed by three rectangular blocks around a central circular courtyard. Case study B is a three-story net zero living lab developed by the State University of Campinas to meet - at a minimum - the requirements for LEED BD+C 2009 certification in a cooling-dominated climate (GOMES et al, 2018). Case study C is a six-story office building passively designed for super low energy consumption in a temperate climate. Table 1 offers a concise description of the three case studies.

Table 1. Succinct description of the cases studied

| | A – Standard school building | B – Living laboratory | C – Passive office building |
|---|---|---|---|
| **Case study** |  |  |  |
| **Gross floor area** | 1100 m² | 1005 m² | 3200 m² |
| **Constructive typology** | Reinforced concrete structure and slabs, masonry façades and inside walls, ceramic tile roof | Steel-framed structure and reinforced concrete slabs, green roof and photovoltaic plates, internal partitions in drywall, glass and wood | Structure in thermally enhanced bricks and reinforced concrete slabs, slab roofing, masonry internal walls |
| **Inventory data** | Complete data of building elements and systems (electrical, hydraulic and atmospheric discharge protection) | Complete data of building elements, plus some information about building systems (just HVAC and photovoltaic system) | Complete data of building elements, but no information about building systems |

### 2.2. Modelling aspects

The assessments were performed according to ISO 14040:2006, ISO 14044:2006, EN 15978:2011 (CEN,2011) and EN 15804:2012 (CEN, 2012) and the EeBguide Project (2012). In each case the functional unit was the complete building. Modeling details and system boundaries are presented in Table 2. Modelled processes were preferably extracted from the Ecoinvent database and adapted to the Brazilian context (energy mix, water use and ROW processes). The product system excluded preliminary services and components not permanently incorporated in the building. Operational energy and water (B6 and B7) and end-of-life (EOL) modules C3 and C4 were not addressed, given the study focus on incorporated impacts and lack of consistent EOL data. As the scope of LEED v4 certification includes LCA from cradle to grave, additional information on potential benefits and loads beyond the product system (module D) was disregarded.

Midpoint impact assessment methods (Table 3) were selected, as required by the LEED v4 guidelines for wbLCAs.

Table 2. LCA modelling methodological aspects

| Description | Case studies |
|---|---|
| Objective | Calculate environmental impacts of whole buildings over their life cycle |
| Funcional unit | Whole building |
| Escope / System boundary | Cradle to Grave / Stages: A1-A3; A4-5; B4, C1-2 |
| Geographic boundary | Campinas – São Paulo - Brazil |
| Reference period | 50 years |
| Inventory database | Ecoinvent 3.4 / 3.5 - allocation, cutoff by classification – unit, adapted to Brazilian context |
| LCA Software | SimaPro 8.5 / 9.0 |

Table 3. Impact Categories description

| Impact assessment method | Impact Categories | | Unit |
|---|---|---|---|
| CED v1.11 | Primary Energy, Non-Renewable | PE_NR | MJ |
| | Primary Energy, Renewable | PE_R | MJ |
| CML-IA baseline v3.05 | Global Warming Potential | GWP | kg $CO_2$ eq. |
| | Abiotic Depletion Potential (Fossil Fuels) | ADP_FF | MJ |
| | Ozone Layer Depletion Potential | ODP | kg CFC-11 eq. |
| | Photochemical Oxidation Creation Potential | POCP | kg $C_2H_4$ eq. |
| | Acidification Potential | AP | kg $SO_2$ eq. |
| | Eutrophication Potential | EP | kg $PO_4^{-3}$ eq. |
| | Fresh Water Aquatic Ecotoxicity | FAET | 1,4-DB eq. |
| | Marine Aquatic Ecotoxicity | MAET | 1,4-DB eq. |
| | Terrestrial Ecotoxicity | TET | 1,4-DB eq. |
| | Human Toxicity | HT | 1,4-DB eq. |
| | Abiotic Depletion Potential (Resources) | ADP_R | kg Sb eq. |

The components were distributed into 13 constructive subsystems, as defined by the Brazilian Table of Price Compositions for Budgets (TCPO): Foundations and superstructure; Roofing system; External walls; External windows and doors; External finishes; Internal walls; Internal finishes; Internal doors; Plumbing (water and sewage) system; Electrical and data system; Additional systems (HVAC, photovoltaic system, lightning and fire protection, elevator etc); Construction (A5) and Demolition (C1) equipment.

Material wastage rates in the construction stage can be substantial in current Brazilian practice and were therefore factored in module A5. For the replacement stage (B4), the building (50 years) and components reference service lives were established according with the design life estimation procedure in the Brazilian performance standard NBR 15575:2013 (ABNT, 2013), and a 100%-material replacement rate was adopted in each substitution computed.

### 2.3. Simulated scenarios

The baseline scenario modelled the whole building in the most complete way possible. Scenario 1 applied the *mass-and-energy cutoff rule* defined by CEN EN 15804:2012 and the EeBguide Project (mass-and-energy below 1% of the total building; exclusion should not exceed 5% of the module's mass or energy) to the product stage (A1-3). Scenario 2 adopted the *element cutoff rule* established by LEED v4 (structure and envelope elements only), and included: Foundation and Superstructure, Covering System, External Fences, External Windows and Doors and External Finishing, plus Construction (A5) and Demolition (C1) activities. For each case study, the results obtained across the modelled scenarios for the different impact categories considered were contrasted and parametrically analyzed.

## 3. Results and discussion

### 3.1. Case study A – Standard public school building

This study's baseline life cycle inventory encompassed 40 material production processes. Concrete foundation and superstructure concentrated 75% of the product stage mass, whilst the roofing system responded for 74% of the product stage primary energy, mainly due to the wooden structure (Figure 2). After applying the *mass-and-energy cutoff* rule, Scenario 1 retained 15 material processes that covered 95% of the mass and 97% of the energy relatively to the baseline product stage. Scenario 2 *(element cutoff rule)* also coincidently maintained 15 processes, which however corresponded to 85% of the mass and total energy of the baseline product stage.

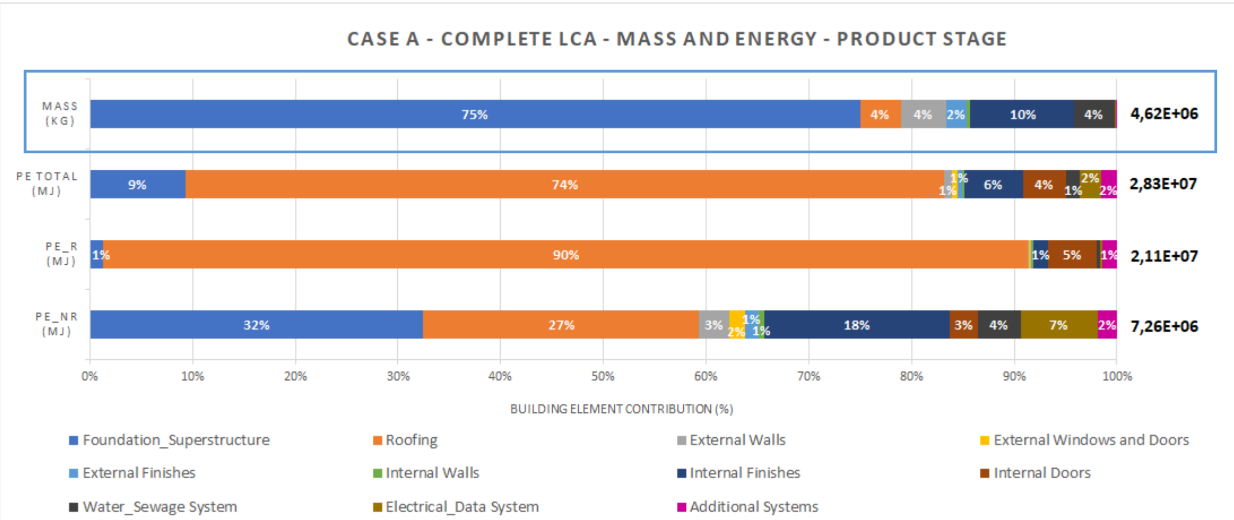


Figure 2. Mass and primary energy results for baseline product stage – Case A.

Baseline LCA results (Figure 3 and Figure 4) revealed dominance of structure and envelope elements (about 50%) for the environmental categories GWP, ADP_FF and ODP, whilst the building systems stood out for eutrophication, ecotoxicity and human toxicity potential (between 57% and 71%). Internal finishing materials were relevant for all categories and particularly contributed to ADP_R (34% of total impact).

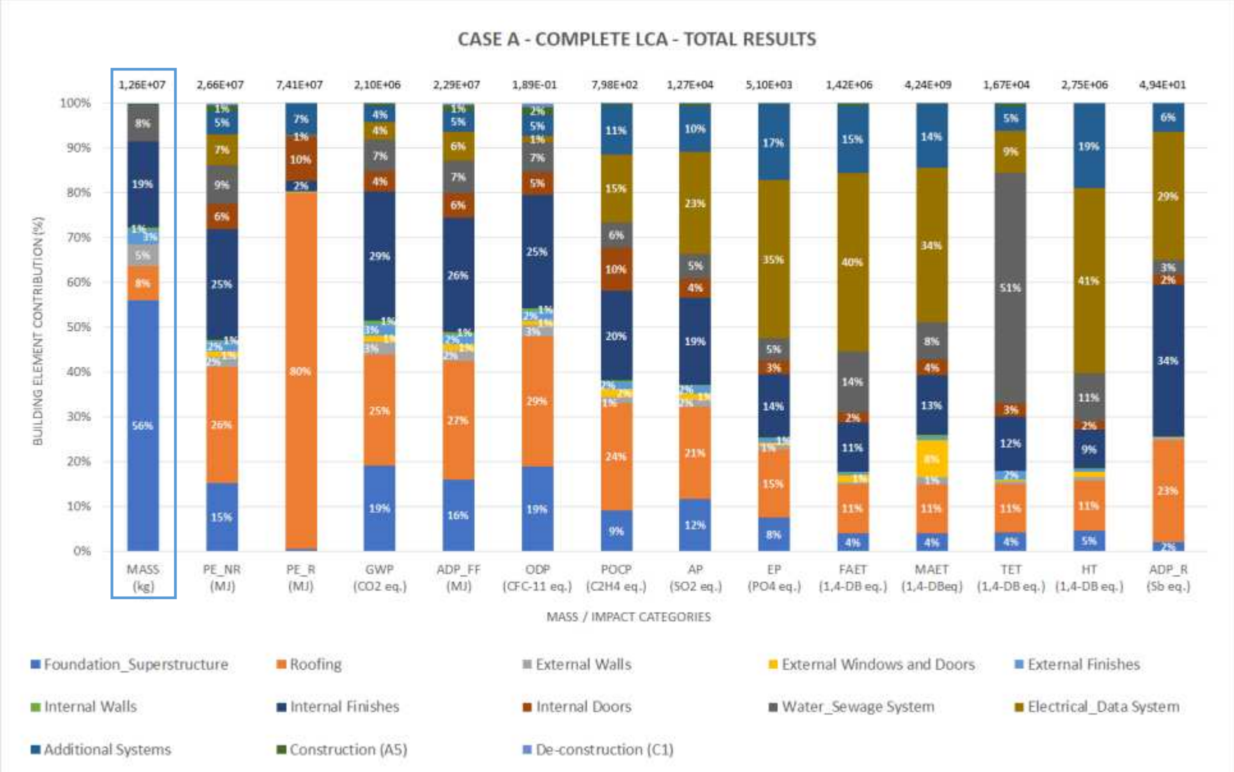


Figure 3. Baseline LCA results per building element – Case study A

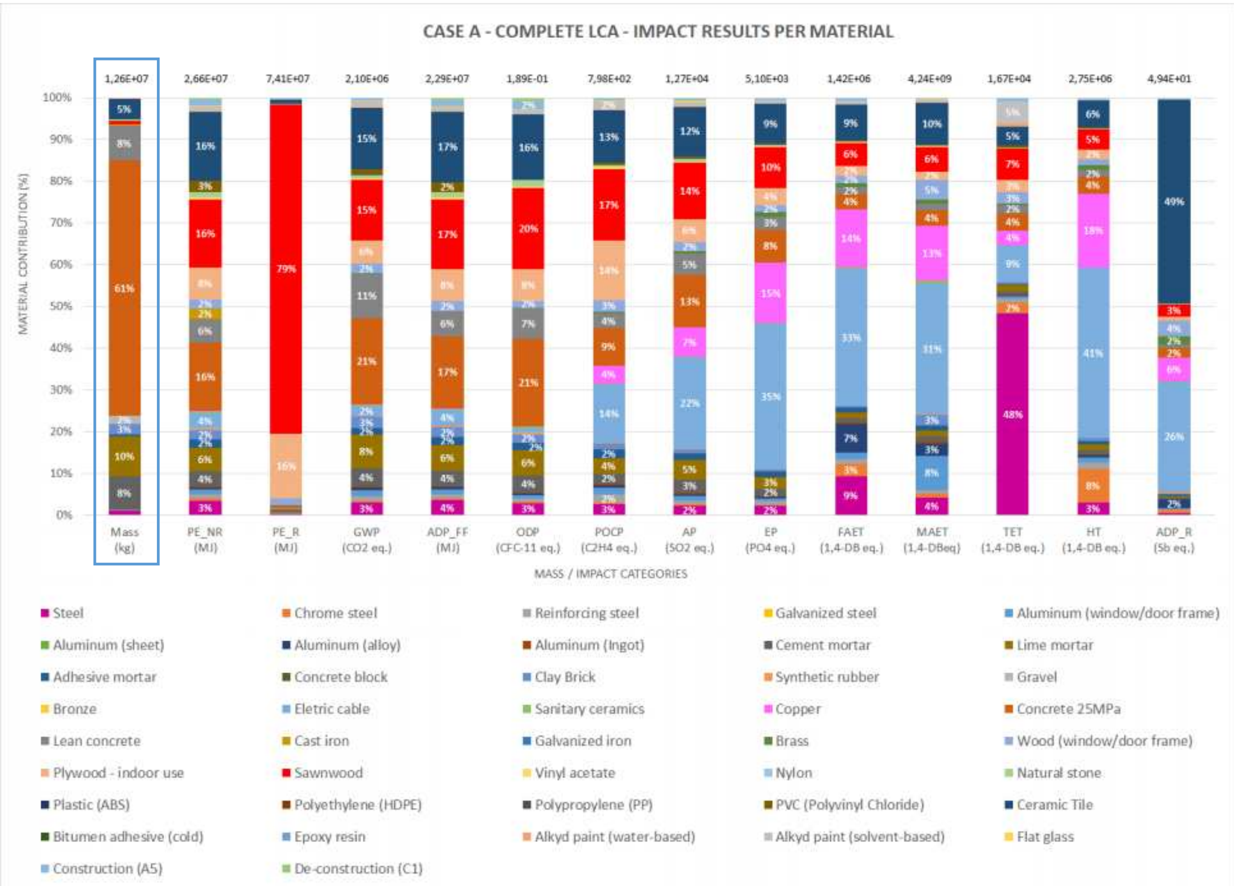


Figure 4. Baseline LCA results per building material – Case study A

Scenario 1 cutoff criteria resulted in at least 80%-coverage of baseline impacts for most categories. Exceptions were HT (68%) and FAET (70%), more sensible to the exclusion of copper components. Contrastingly, Scenario 2 cutoff criteria – which retains only structure and envelope elements and disregards building systems, among others - captures less than 40% of baseline impacts for most categories. Coverage beyond 50% of baseline impacts was found only for GWP, ADP_FF and ODP. For the categories - EP, ADP_R Ecotoxicity and toxicity – more closely influenced by building systems' components – coverage was down to about 20%. A high baseline impact coverage for both scenarios was found only for PE_R, mainly due to the wood computed in the roofing system that was maintained in the modeling (Figure 5).

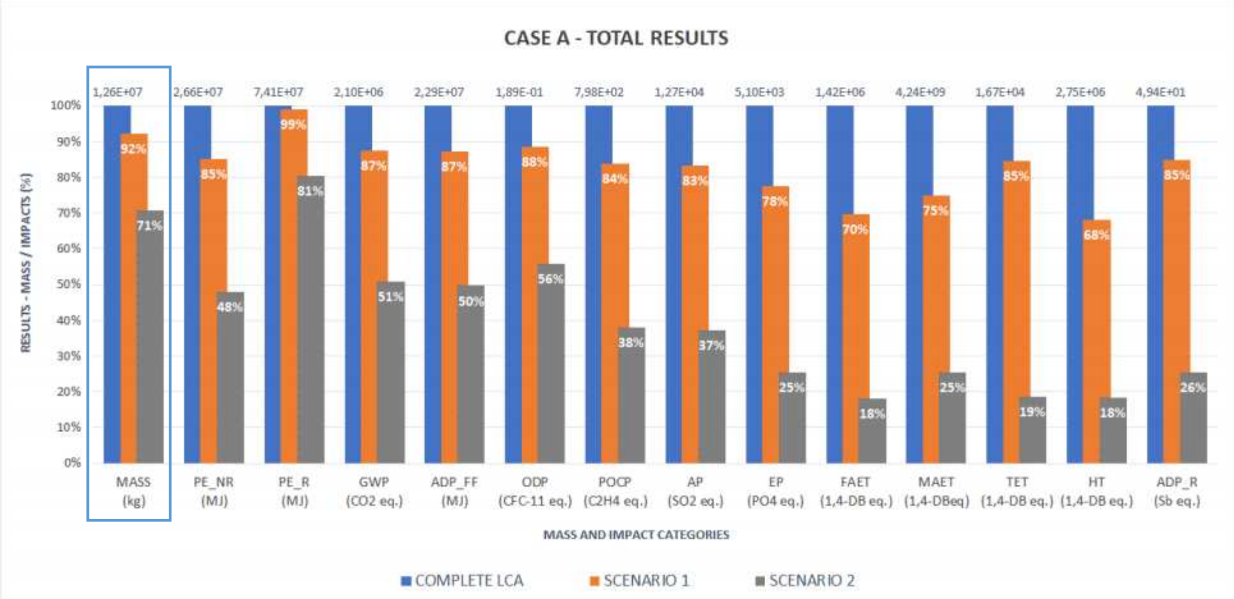

Figure 5. Comparative results for the three modelling scenarios - Case study A

### 3.2. Case study B – ultra low-energy Living Lab

A total of 21 material production processes were inventoried. From those, cutoff Scenario 1 retained 11 processes, which corresponded to 99% of the mass and 98% of the energy of the baseline. Scenario 2 preserved 8 processes that covered about 80% of the mass and 85% of the energy of the baseline product stage.

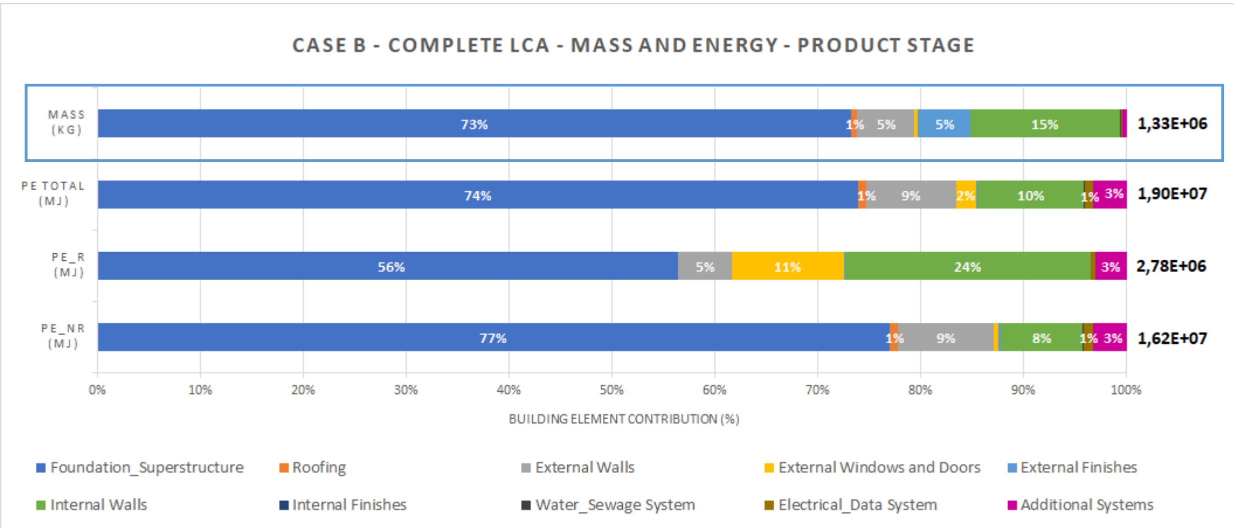

Figure 6. Mass-and-energy results for baseline product stage – Case study B

Foundation and superstructure elements clearly concentrated mass (73%) and energy (74%) in the baseline product stage, mainly due to the reinforcement steel contribution. Envelope, foundation and superstructure elements responded for over 60% of the baseline impacts for all categories but TET (50%) and ADP_R (29%). Internal drywall, glass and wood partitions represented 15% of the mass and 10% of the total energy due to the galvanized steel profiles (Figure 6), whose contributions to environmental impacts ranged between 6% (HT) and 60% (ADP_R) (Figure 7 and Figure 8).

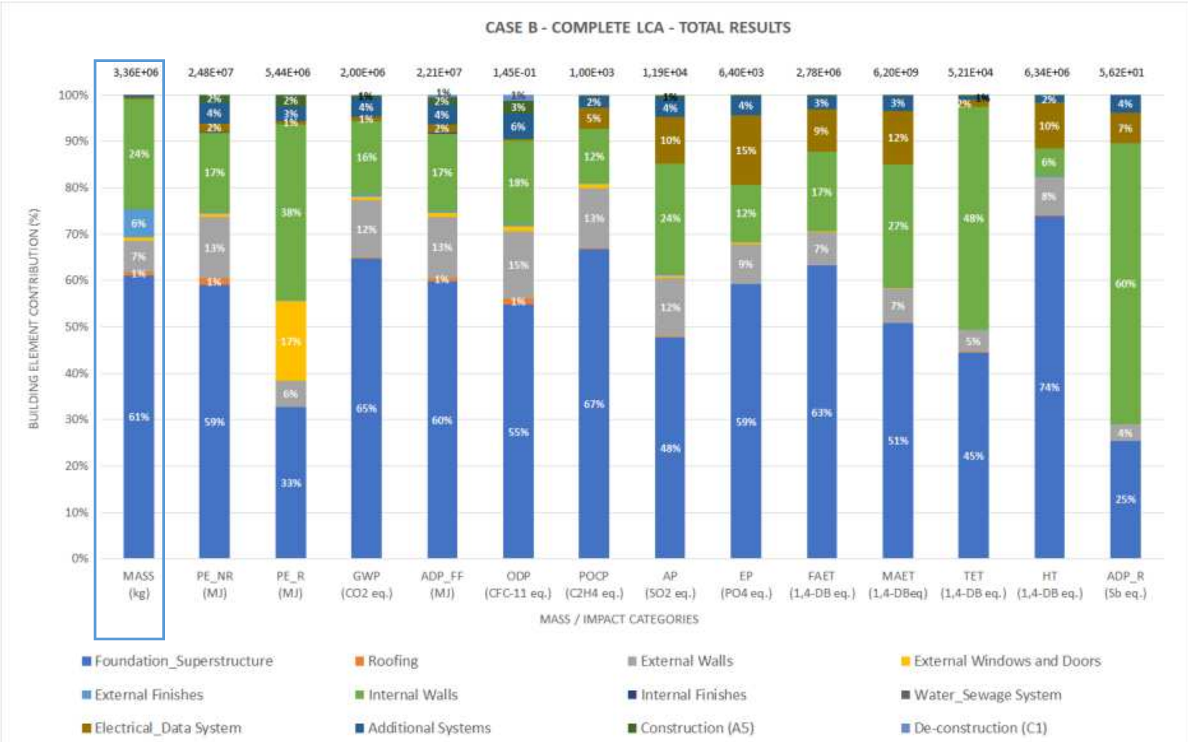


Figure 7. Baseline LCA results per building element – Case study B

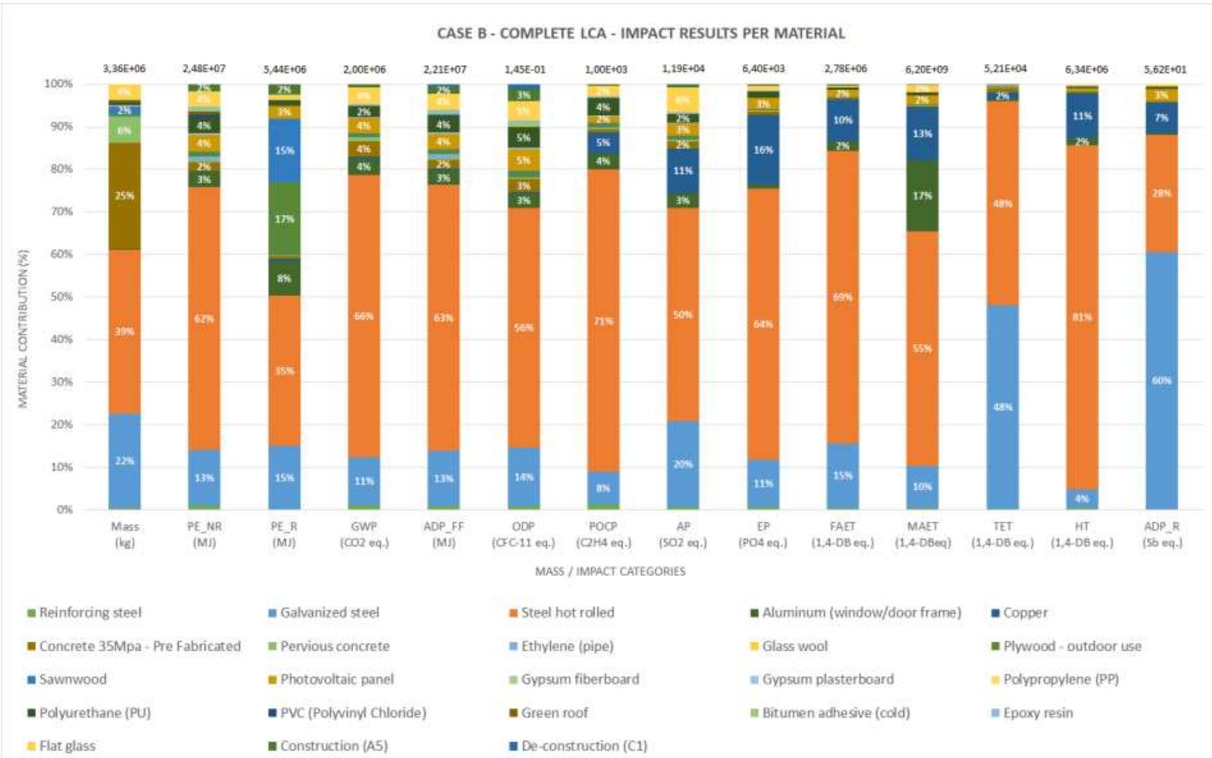


Figure 8. Baseline LCA results per building material – Case study B

Cutoff Scenario 1 maintained 98% of the building life cycle mass and covered over 90% of the baseline impacts for most categories. AP, EP, MAET and HT were more influenced by the exclusion of copper components in the building systems. Still, the results coverage was above 80% of the baseline. For Scenario 2, 69% of the building's life cycle mass was computed (Figure 9. Figure 9). In this case, the results representativeness was below 80% of the baseline for all categories and reached as low as 29% (ADP_R) and 58% (PE_R), as the galvanized steel in the internal partitions and internal wooden components were respectively not accounted for.

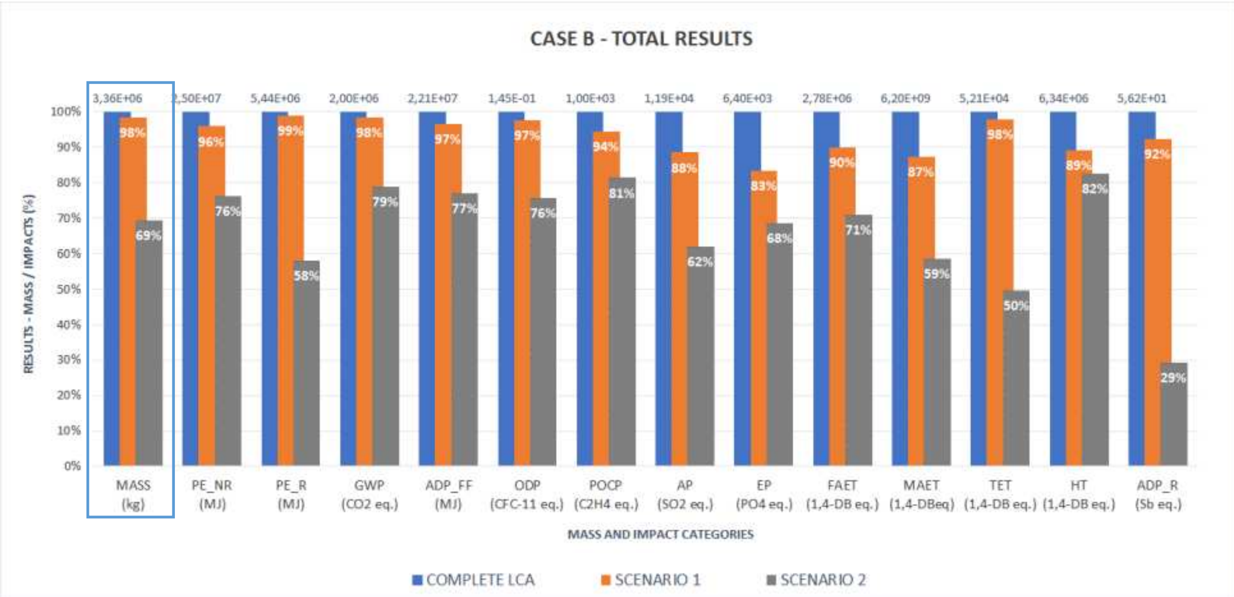


Figure 9. Comparative results for the three modelling scenarios - Case study B

### 3.3. Case study C – passive office building

As in the previously described case studies, the baseline product stage mass was again concentrated (55%) in foundation and superstructure elements due to the concrete usage, but the total energy was instead concentrated in the internal finishes (41% of the total), mainly the wooden floor (Figure 10). A total of 29 inventoried material production processes was inventoried.

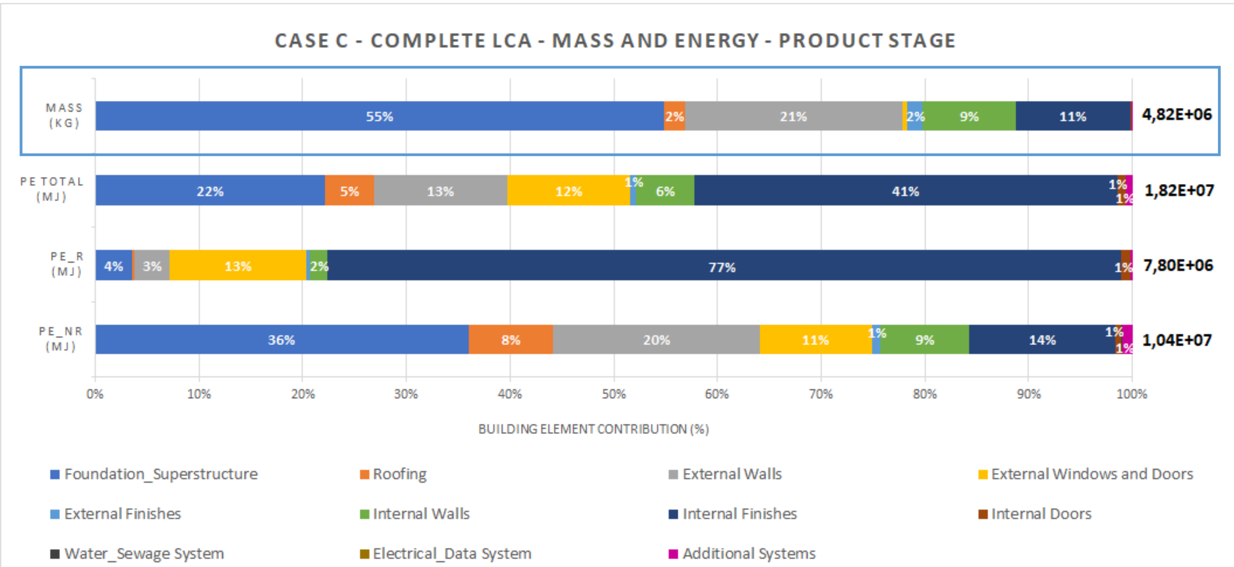


Figure 10. Mass-and-energy results for baseline product stage – Case C

Scenario 1 retained 16 processes and computed 95% of the mass and 96% of the energy of the baseline scenario. Even though Scenario 2 retained 13 processes of the baseline inventory, it corresponded to 80% of the mass and only 52% of the total energy of the baseline product stage for excluding all the internal elements.

The baseline impacts (Figure 11 and Figure 12) once more showed dominance of the structure and envelope elements, which covered more than 60% of the total in all categories but ODP (50% of the results). This case study did not offer information regarding building systems. Internal partitions and finishing totaled between 17% and 33% of the impacts. A remarkable exception refers to PE_R, which reached a 74%-impact coverage due to the wood flooring's contribution. Façades and internal partitions are built in ceramic blocks, which have 29% of the total building mass and responded for 33% of GWP and for 47% of MAET.

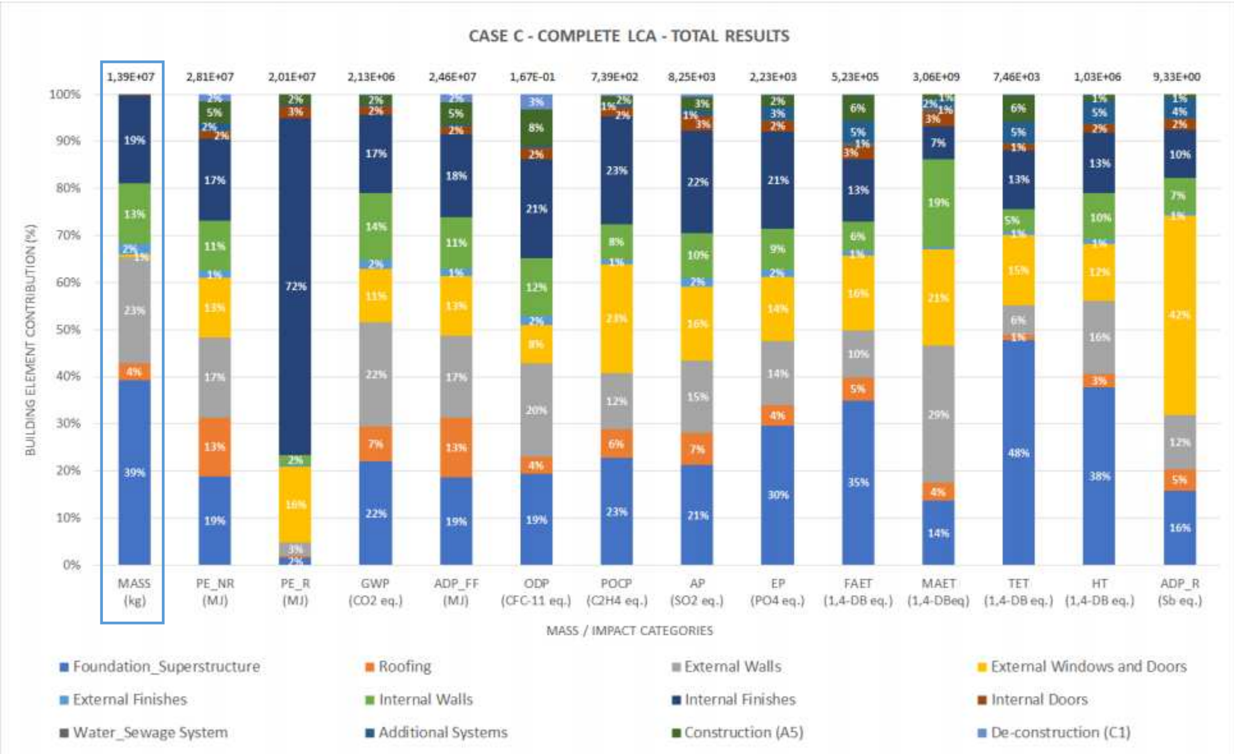

Figure 11. Baseline LCA results per building element – Case study C

When comparing the three scenarios, Scenario 1 covered about 90% of the baseline total mass and scenario results for all impact categories. Conversely, Scenario 2, covered around 70% of the total mass and the impacts in all categories. Only 23% of PE_R impacts were accounted for as the wooden internal finishing components were excluded (Figure 13).

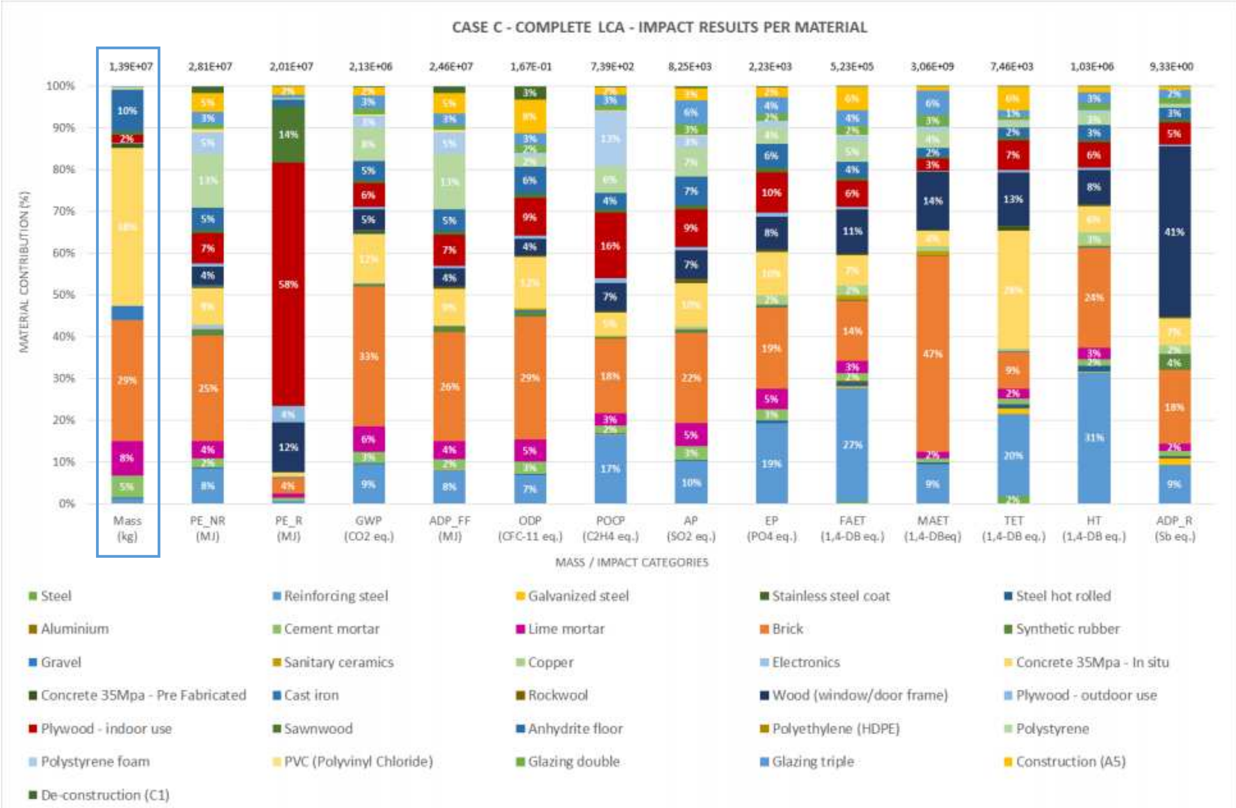

Figure 12. Baseline LCA results per building material – Case study C

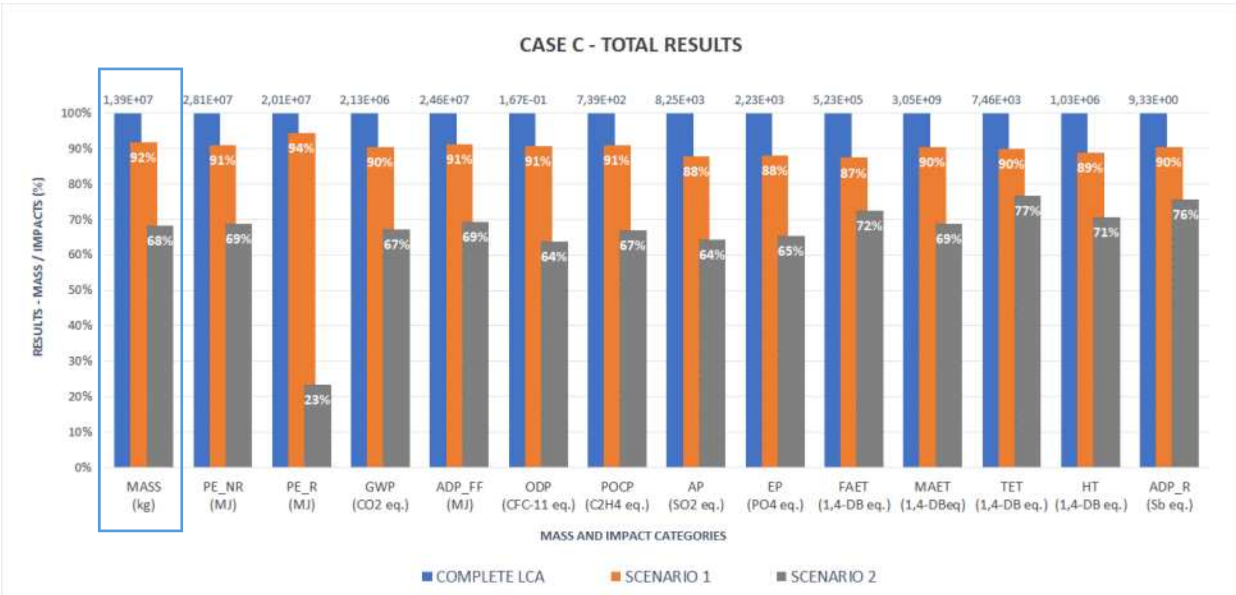

Figure 13. Comparative results for the three modelling scenarios - Case C

## 4. Conclusions

Cutoff rules affect not only the inventory modelling, but also the materials and building elements contributions on the different impact categories. This study investigates the influence of *mass-and-energy contribution-based* and *element-based* cutoff criteria on whole-building LCA results for three case studies.

The mass-and-energy cutoff rule defined in the European standard preserves more inventory flows than the *element-based approach*, as it retains materials in most building elements, including those intensively replaced over the building's life span. For our case studies, the mass-and-energy cutoff covered over 80% of the baseline wbLCA and over 90% of the building life cycle mass. Structure and envelope elements indeed predominated in all cases studied, both in terms of mass and of associated impacts. Still, the LEED v4 *element-based approach* computed only about 70% of the lifecycle mass and between 34% and 69% of the impacts.

Outcomes variation ranged from 21% (Case C, passive office building) and 47% (Case A, public school building) when shifting from the contribution-based to the element-based approach. In case A structure and envelope elements indeed contributed to about 50% of baseline GWP, ADP_FF and ODP. Excluding building systems from the assessment ignored between 57% and 71% of eutrophication, ecotoxicity and human toxicity potentials. Excluding internal finishing materials neglected over one third of ADP_R. The element cutoff criterion removed 25 out of 40 baseline processes, which were concentrated in those building element groups.

Three main patterns were observed, which suggest category clustering into: 1) Global warming, ozone layer depletion, abiotic depletion – fuels, and non-renewable primary energy; 2) photochemical ozone creation, eutrophication and acidification potentials; and 3) abiotic depletion – resources, and human and eco-toxicity. The first group contains the impact categories most recurrently investigated and is typically dominated by structure and envelope elements.

LEED wbLCA can be biased by focusing on categories which follow similar patterns, as only GWP evaluation is mandatory, and the other two categories to be assessed are freely selected within those in groups 1 and 2. Categories in Group 3 are *not* assessed whatsoever despite being the most affected by LEED’s cutoff choice to exclude building systems and interior components (e.g. partitions and ceramic tiles). LEED’s approach is partly consistent with its main audience worldwide - core & shell corporate buildings – and is indeed valuable to drive wbLCA into mainstream practice. However, as projects in this market niche are typically building systems-intensive and undergo numerous churn cycles, the risk of neglecting considerable environmental impacts and mislead decision-making increases

Hence, we recommend that LEED certification *enlarges the product system* to include building services and *broadens scope* to ensure that at least one category in each identified group is assessed. LCA practitioners should proactively include building systems in wbLCA, particularly when handling building systems-intensive cases. In parallel, the use of durable materials in internal elements, reducing replacement impacts should be promoted in design guidelines.

## 5. Acknowledgments

The authors acknowledge the financial support from the Brazilian Coordination for the Improvement of Higher Education Personnel (CAPES, MSc scholarship) and the National Council for Scientific and Technological Development (CNPq), through the research grant # 306048/2018-3.

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# Operational and embodied impact assessment as retrofit decision-making support in a changing climate

**Vanessa Gomes[1], Iris Loche[2]; Marcella R. M. Saade[3], Lizzie M. Pulgrossi[2]; Paula B. Franceschini[2], Ligia L. Rodrigues[2], Rafaela G. Pimenta[2], Leticia O. Neves[2], Doris C. C. K. Kowaltowski[2]**

[1] University of Campinas, School of Civil engineering, Architecture and Urbanism, Brazil, vangomes@unicamp.br;
[2] University of Campinas, School of Civil engineering, Architecture and Urbanism, Brazil
[3] Université de Sherbrooke, Liride laboratory, Canada

**Abstract:** Design decisions that influence a building's environmental performance have typically focused on reducing the operational consumption. Synthetic climate data to account for climate change effects are increasingly used to predict Future building performance. Now or in the future, efficient fixtures and systems can indeed reduce operational energy, but also add embodied impacts that are often overlooked. Joint consideration of operational and embodied impacts to guide retrofit strategies for emission reduction is not yet common practice. Hence, in this paper we investigated the balance between life cycle emissions embodied in envelope retrofit alternatives and those avoided by the energy saved for a reference mixed-mode office space, in a cooling-dominated climate. Two layers of evolutionary-temporal dynamics were considered, by simulating future energy consumption and by modelling emission intensity over time, to ultimately explore how to back feed decision-making towards more resilient design in a changing climate. Window opening effective area, glazing solar heat gain, glazing thermal transmittance, wall absorptance and solar shading devices configurations were varied and simulated in EnergyPlus v.9 to define best cases for each orientation. SimaPro v.8 supported the life cycle emission inventory of Brazilian electricity and building materials usage. Changing climate effects were addressed by simulating synthetic climate files and by dynamic Life Cycle Assessment of the temporal variation in energy consumption, mix and replaced material input. The embodied GWP would equal the operational impacts after about 10-13 years (aluminium) and 4-7 years (galvanized steel) of use, according with the shading device design. The combination of retrofit strategies added comparatively little embodied impacts, whilst enabling operational emissions savings ranging between 57% (S-W) and 64% (N-E and N-W) by 2080. Nevertheless, climate change effects mitigation on the long run would still be limited, as projected annual emissions would more than triple over the same timeframe for all solar orientations. The approach herein illustrated can be generalized not only to retrofit strategies assessment, but also to guide future-proof building design to implement ultra-efficient solutions from the outcome or plan for additional interventions over time.

Keywords: Energy efficiency; Operational-to-embodied impact ratio; Mixed-mode office building; Building simulation; Dynamic life cycle assessment; Future-proof design.

## 1. Introduction

The building sector is responsible for 36% of global energy consumption (International Energy Agency, 2018) and its energy use is likely to increase in the next years (Shams et al., 2012). In Brazil, office buildings were responsible for 15,4% of total energy consumption in 2011 (Lamberts et al. 2014).

Energy is consumed during all the building life cycle, being the operational (80-90%) and the embodied energy (10-20%) the main contributors to the building energy demand (Ramesh et al., 2010). The first one is defined as the annual amount of energy required for use (e.g. heating, cooling, ventilation, lighting) during the life of a building (Giordano et al., 2017), while the second refers to the energy used to extract, process, manufacture and transport building materials and components (Yohanis and Norton, 2002).

Over the past decades, design decisions that influence a building's environmental performance have typically focused on reducing the operational resource consumption. With increased operation efficiency regulations, impacts embodied in building materials manufacturing, construction, renovation and end of life phases became more prominent within the building's life cycle. Such reduced operational energy demand to ensure indoor comfort is typically achieved with efficient fixtures, systems and devices, whose contribution adds more embodied impacts to the equation but is often overlooked.

As the operational energy is assumed to be more significant over the long term (Giordano et al., 2017), the embodied impacts are usually not included in the building energy analysis. However, the former is frequently decreased by increasing the latter (e.g. by adding materials to reduce energy consumption). This trade-off suggests that, in some cases, the search for efficiency may result counterproductive (Copiello, 2017) and should be investigated in detail, from a holistic perspective. That lead us to another problem to solve: even though the average demolition age of buildings has decreased in some places, e.g. Switzerland (Aksözen et al, 2017), service life expectation has consistently increased in others like Japan and Denmark in a pursuit of more sustainable built environments. Indeed, most IEA EBC Annex 72 countries adopt 50 years in their national building assessment methods. In all cases, it is still a very long lifespan, during which use patterns (Collinge et al, 2013), external conditions such as increased temperatures due to climate change (Nik and Kalagasidis, 2013), or in new building regulations to account for them (IPCC, 2007) may change. As retrofit scenarios are often unknown, Vilches et al. (2017) emphasize that buildings should be understood as service providers with different future scenarios that ask for a dynamic understanding.

The lack of understanding of dynamics of material stocks and flows, especially for service units with long life spam such as buildings, became evident in Göswein et al. (2019)'s review the type of dynamics, methods, and tools used in published literature. Also, the modelling approaches used to consider dynamics in the model input parameters and results seem to vary massively from one study to the other.

Müller et al. (2014) reviewed dynamic material flow analysis (MFA) studies for metal stocks and flows and found that it is an extreme simplification to assume that highly sensitive model parameters, such as lifetime distribution parameters, are constant. In the built environment studies, however, material intensity and emission intensity are rarely modelled dynamically (Göswein et al, 2019). Materials input, when considered, focused on spatial-cohort dynamics, that is: composition of a snapshot of one moment in time, e.g. characteristics of groups of buildings constructed in the same period. Emissions inputs were either kept constant or most often considered temporal dynamics. On its turn, output dynamics (impacts) show a more balanced focus distribution into spatial, temporal and a combination of both.

Other bits of complexity are added when dealing with future projections: Operational energy is predicted during the design phase through building simulation. However, typical climate data should not be used to assess the future performance of buildings, since climate changes will affect building energy consumption over time and the electricity mix and emission intensity may also vary temporally.

Future climate data may be created from synthetic data generation tools or by statistical techniques through transformation of historical data (Herrera et al., 2017). Due to the limitations of historical climate data, synthetic climate generators are more prevalent. From the tools for developing spatial and temporal climate files analysed by Yassaghi and Hoque (2019) that produce future weather data – Urban Weather Gen (UWG), AdvancedWEather GENerator (AWE-GEN), Meteonorm, WeatherShift and ClimateChange World Weather Generator (CCWorldWeatherGen) – only the latter was previously used in Brazilian studies.

CCWorldWeatherGen is a global climate change file generator, which uses data from the Third IPCC Report (TRA) of the HadCM3 experimental set (Hadley Centre Coupled Model, v.3) and considers the A2 emissions scenario, the most pessimistic of the four future environmental change scenarios proposed by the IPCC (Jentsch et al., 2013). CCWorldWeatherGen is distributed free of charge and allows the generation of climate change climate files for any part of the world, ready for use in performance simulation programs. The tool is based on Microsoft Excel, transforming the 'current' climate files into Typical Meteorological Year (TMY2) climate files in the EnergyPlus Weather File (EPW) format for the years 2020, 2050 and 2080. The climate data generation is based on the so-called 'morphing' methodology for climate change data transformation, developed by Belcher, Hacker and Powell (2005) (Singapore and Brunei, 2013).

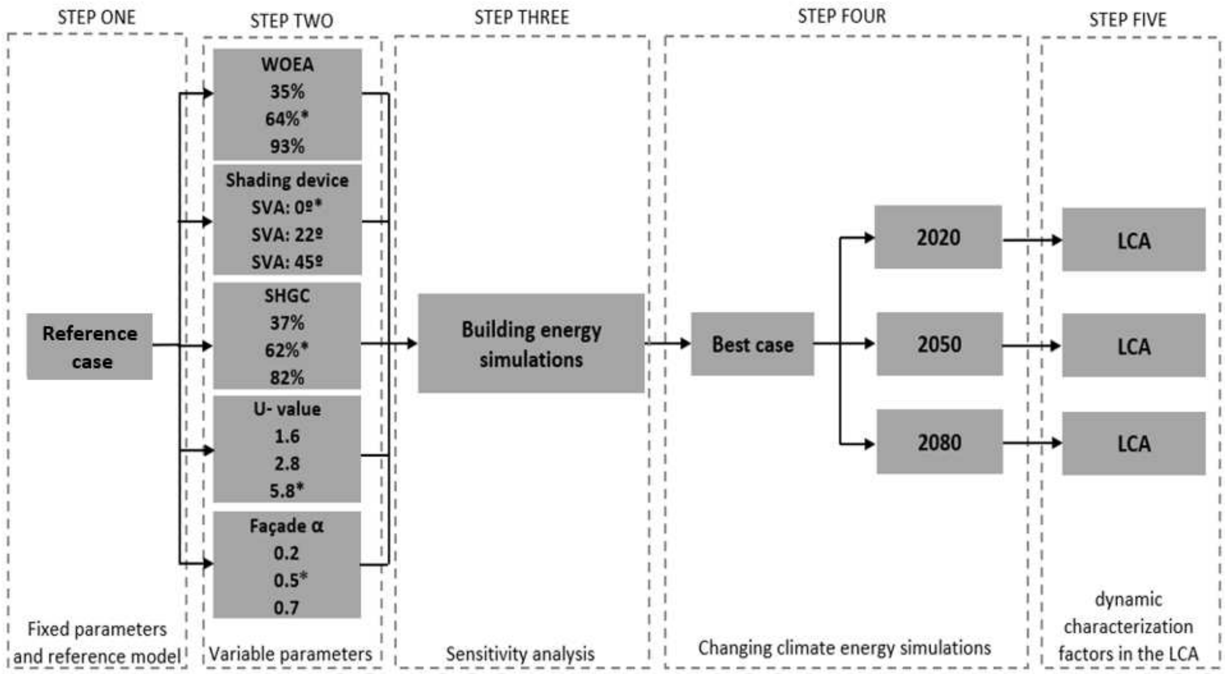
As to the emission intensity variation over time, dynamic life cycle assessment offers theoretical platform to consider time effects in LCA and jointly model temporal variation in impact factors, in building energy consumption and in energy matrix composition. As proposed by Levasseur et al (2010), in a dynamic LCA, the temporal profiles of emissions are considered so that the LCI result for each emission is a function of time rather than a single number. Once a dynamic inventory is calculated, the LCIA characterization model is solved dynamically, i.e. without using steady-state assumptions, to obtain time-dependent characterization factors that depend on the moment when the pollutant is emitted. This approach consists of first computing a dynamic life cycle inventory (LCI), considering the temporal profile of emissions. Then, time-dependent characterization factors are calculated to assess the dynamic LCI in real-time impact scores for any given time horizon and solve the inconsistency between the time frame chosen for the assessment and the time period covered by the LCA results.

Given the described research context, this paper refers to two layers of evolutionary-temporal dynamics, by (i) simulating energy consumption of mixed-mode office space in Brazil under current conditions and the future projections most often considered in climate change studies applied to the built environment (2050 and 2080) and (ii) dynamically modelling emission intensity over time, to ultimately analyse how the operational-to-embodied impacts ratio within the materiality of the devised envelope retrofit alternatives evolves with time and could back feed decision making towards more resilient designs in a changing climate.

## 2. Method

This experimental study is supported by energy simulations and dynamic life cycle assessment (Figure 1). A mixed-mode office space defined as a case study combines the most recurrent features of a 50-building sample drawn from a previously developed database (Pereira, 2019).

The simulations were carried out using EnergyPlus version 9.0 and an Energy Plus weather file (epw) for the city of São Paulo, Brazil, and developed in four main steps: (i) a reference case was defined with fixed parameters, (ii) three values were defined for each of the five variable parameters, (iii) building energy simulations were carried out combining the reference case with the variable parameters, (iv) the best-case (i.e. the best energy performance) was then simulated in three different years (2020, 2050 and 2080) to account for the effects of climate change. Finally, a dynamic life cycle assessment was performed for the period considered.




*Values defined for the reference case

Figure 1. Method Flow Diagram

### 2.1. Step one: Reference case model definition

Geometry and envelope parameters of the reference mixed-mode cellular office room were chosen based on a 50-building sample (Pereira, 2019) drawn from a previously developed database of 153 mixed-mode office buildings located in the city of São Paulo (Neves et al, 2017). Other parameters such as internal loads, occupancy schedule and air-conditioning system were defined based on data from the literature (Table 1).

The reference office space combines natural ventilation and mechanical cooling (mixed-mode system) to reduce energy use. Though our simulations were not calibrated with real-use data, the mixed-mode ventilation system of the reference office room was automated based on ASHRAE 55-2017 adaptive model (ASHRAE, 2017) and implemented through the EMS functionality in EnergyPlus (Figure 2). Such approach was supported by Quesada and Neves (2019), which showed that naturally ventilated periods and air-conditioning setpoints adopted by the ASHRAE's adaptive model were adherent to real users' behaviour in mixed-mode buildings in the city of Sao Paulo.

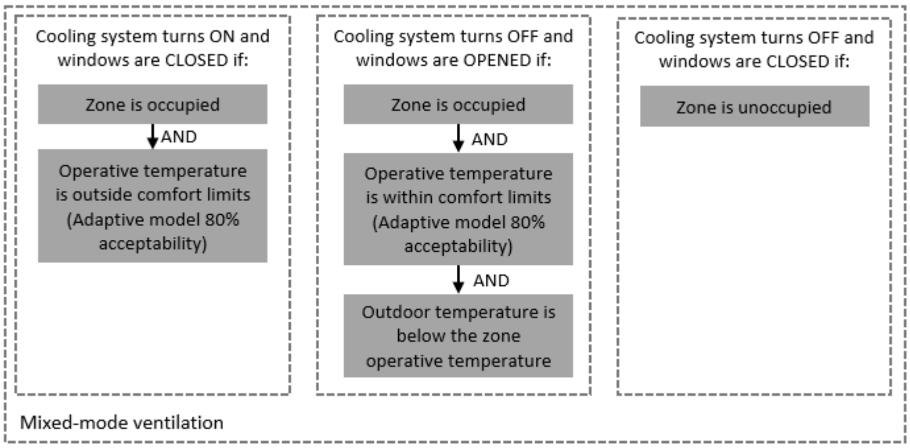



Figure 2. Mixed-mode ventilation system automation based on ASHRAE (2017) adaptive model

Table 1. Reference case parameters

| Parameter | Value | Reference |
| --- | --- | --- |
| **Office room area** | 39.2 $m^2$ (8 mx4.9 m) | Pereira (2019) |
| **Ceiling height** | 2.5 m | |
| **Floor number** | 6th floor (intermediate level of a 12-floor building) | |
| **Natural ventilation strategy** | Cross ventilation (adjacent façades) | |
| **Window-to-wall ratio (WWR)** | 25% | |
| **Window opening effective area (WOEA)** | 64% | |
| **Exterior shading device Vertical shadow angle (VSA)** | $0^o$ (no shading devices) | |
| **Glazing thermal transmittance (U-value)** | 5.8 W/m².K (single pane) | |
| **Glazing Solar Heat Gain Coefficient (SHGC)** | 0.62 (coloured glass) | |
| **Wall absorptance of solar radiation (α)** | 0.5 | |
| **Wall thermal transmittance** | 2.38 W/m².K | Mortar 2 cm + Concrete block 14 cm + Mortar 2 cm (ABNT, 2005) |
| **Wall thermal capacity** | 258.6 kJ/m².K | |
| **Internal loads - equipment** | 10.7 W/m² | Brazilian HVAC standard (ABNT, 2008) |
| **Internal loads - occupancy** | 0.14 person/$m^2$ | |
| **Internal Loads - light** | 9.7 W/m² | Level A of the Brazilian energy efficiency labelling system for commercial buildings (Brasil. Portaria nº 53 and d, 2009) |
| **HVAC system efficiency** | 3.23 W/W | |
| **HVAC system** | Split | Most frequently used in office buildings (ELETROBRÁS, 2008) |
| **Occupancy schedule** | Weekdays from 8am to 6pm (No occupancy or internal loads on weekends) | INMETRO (2018) |

## 2.2. Step two: Variable parameters

Neves et al. (2019) evaluated how building envelope design parameters influence the energy performance in Mixed-Mode Ventilation (MMV) office buildings through simulation-based sensitivity analyses based on three approaches: the OFAT local sensitivity method, the Morris screening method, and the Monte Carlo method. Results showed that the variables window opening effective area (WOEA), exterior shading devices and glazing solar heat gain (SHGC) were the most significant parameters, followed by wall absorptance of solar radiation (α) and glazing thermal transmittance (U-value). The window-to-wall ratio (WWR) and thermal insulation had comparatively little influence. Therefore, in this study five variable parameters were selected, and three values were defined for each parameter, based on data found in the existing literature (Table 2).

Table 2. Variable parameters

| Variable parameters | Values | Reference |
|---|---|---|
| Window Opening Effective Area (WOEA) | 35%,64%*,93% | Stabat et al. (2012) |
| Shading device Vertical shadow angle (VSA) | No*/VSA=22° /VSA=45° | (RTQ-C v.2, PROCEL) |
| Glazing Solar Heat Gain (SHGC) | 37% (solar control), 62%* (coloured glass), 82% (clear glass) | Westphal (2016) |
| Wall absorptance of solar radiation (α) | 0.2 (light colour) ,0.5*(medium colour), 0.7 (dark colour) | NBR 15220-2 (ABNT, 2005) |
| Glazing thermal transmittance (U-value) | 1.6 (low-e glass), 2.8 (double pane), 5.8*(single pane) | Westphal (2016) |

*Values defined for the reference case

### 2.3. Step three: Scenarios and sensitivity analysis

Each value of the five variable parameters previously defined were combined, one factor at a time, to the reference case geometry, generating 11 scenarios. Each scenario was simulated for four solar orientations: external walls with windows located at North-and-East (N-E), North-and-West (N-W), South-and-East (S-E) and South-and-West (S-W) façades, creating a total of 44 energy simulations. A sensitivity analysis was then performed to explore the effect of the variable parameters on annual cooling energy savings for MMV office rooms.

The simulations were carried out using an Energy Plus weather file (epw) for the year of 2020, developed through the free software CCWorldWeatherGenerator v.1.8, to represent current conditions. The reference case geometry and retrofit scenarios were modelled using plugin Euclid for SketchUp that connects the geometry to the software EnergyPlus. To represent the cellular office room located at an intermediate level, the floor and ceiling were set as adiabatic, as well as the walls without windows, considered as internal walls (Figure 3). The Airflow Network (AFN) was used to set up the natural ventilation and to perform calculations for wind pressure coefficient, air flow and internal temperature (ENERGYPLUS, 2016). The operational energy analysis focused on reducing the electricity consumed for cooling the space (kWh/m$^2$year).

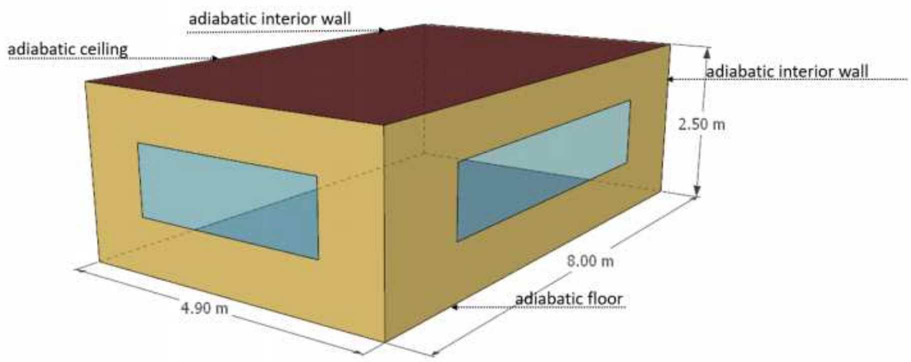



Figure 3: Reference Case Geometry

### 2.4. Step four: Best-case scenario definition and simulation with future weather files

Based on the sensitivity analysis results, the best-case for each solar orientation was defined with the variable parameters values that provided best energy performance. To capture the effects of climate change, the best-case scenario was simulated for three different years, to represent current conditions (2020) and those in future projections (2050, 2080). The future epw weather files were developed through the free software CCWorldWeatherGenerator v.1.8. We used INMET 2018 base climate files developed from the 1981-2010 Brazilian Climate Normal measured at the at the National Institute for Special Research (INPE) weather station in São Paulo (INMET, 2020), and made available in Typical Meteorological Year (TMY) format by LABEEE (2018).

### 2.5. Step five: Dynamic life cycle assessment

Operational electricity GWP was dynamically modelled to obtain LCI results for the most critical GHG gases ($CO_2$, $N_2O$, $CH_4$ and CO) as a function of time. The time-dependent characterization factors were calculated to assess the dynamic LCI in real-time. The emissions corresponding to annual electricity consumption for 2020, 2050 e 2080 were repeated over three time intervals - 2020-2049, 2050-2079 and 2080-2100 - to estimate the operational GWP.

GWP of the bill of materials corresponding to the best-case scenarios for each solar orientation were modelled using static characterization factors, since emissions would happen over one year, but considered future recurrent material inputs for replacements according with NBR 15575 performance standard (ABNT, 2013). Based on expert judgement, service life for aluminum and galvanized steel *brise soleils* in the city of São Paulo were respectively adopted as 50 years and 10 years, and the facades would be repainted every 5 years. Façade glazing service life would equal that of the support building (50 years). Given the practical difficulty to ensure the galvanization thickness in situ, it was considered that - in a realistic assumption - galvanized steel devices should be 100% replaced at the end of every service life cycle.

## 3. Results and Discussion

### 3.1 Building energy simulation

For each studied variable, the light- and dark-colored bars in Figure 4 respectively represent the minimum and the maximum cooling energy consumption values. The reference case is indicated by the purple dashed line.

The reference case model resulted in an annual cooling energy consumption of 27.3 kWh/m$^2$·year for the N-E office room, 25.6 kWh/m$^2$·year for N-W, 15 kWh/m$^2$·year for S-E, and 13.2 kWh/m$^2$·year for the S-W (Figure 4).

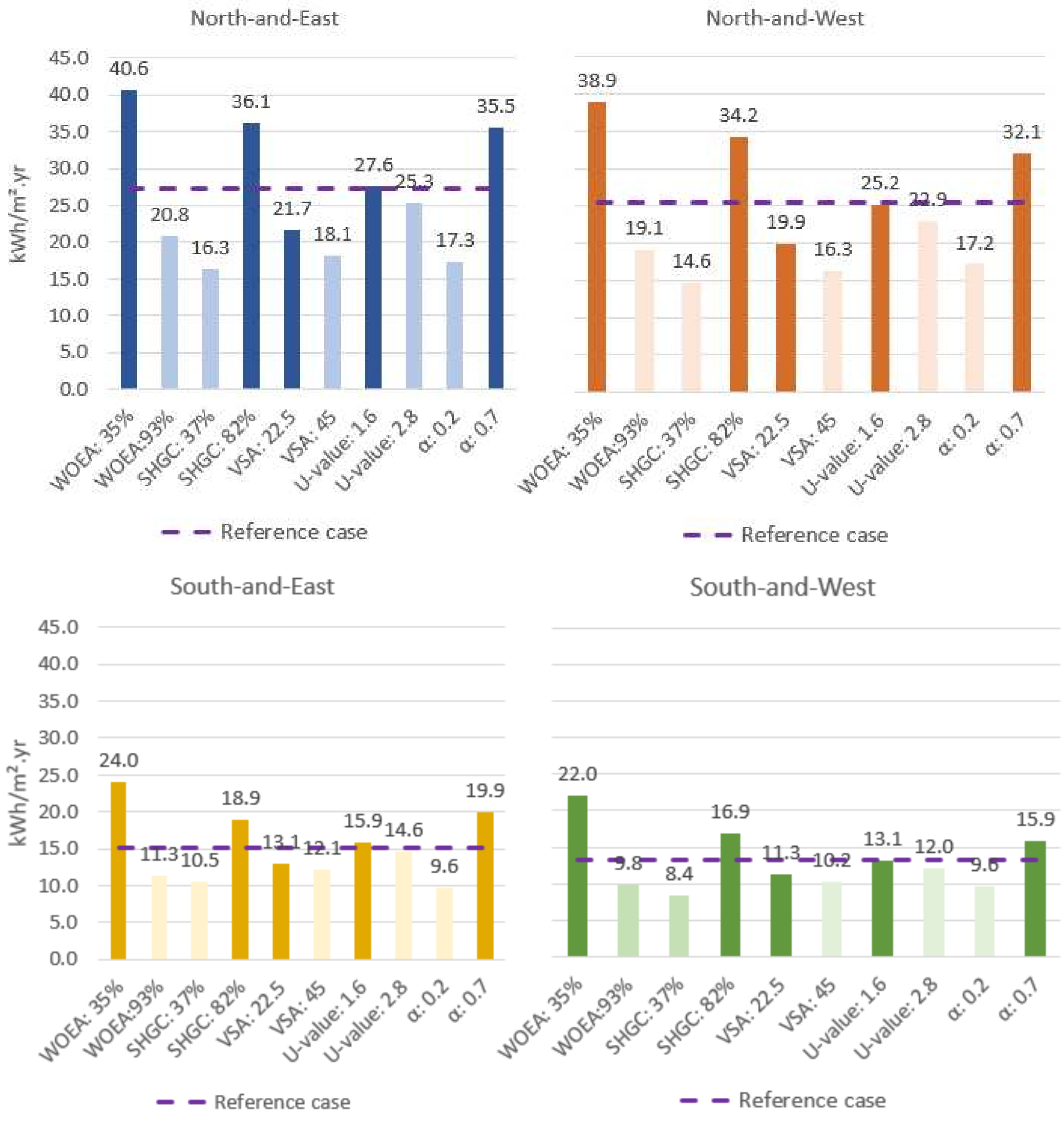



Figure 4: Effects of input variables on the simulated annual cooling energy consumption

The offices with exterior windows located in the N-E and N-W façades showed higher annual cooling demand for all the parameters. Regardless of the solar orientation, Glazing Solar Heat Gain (SHGC), Wall Absorptance of solar radiation (α), External shading device, Window Opening Effective Area (WOEA) and Glazing thermal transmittance (U-value) were, in this order, the most effective parameters to decrease the annual cooling energy consumption.

The best values for each variable simulated, found on the sensitivity analysis (Table 3), were combined with the reference case fixed parameters (Table 1) to create the best-case scenario.

Table 3. Best values for the five variables considered

| Variable | Values |
|---|---|
| Window Opening Effective Area (WOEA) | 93% |
| External shading device<br>Vertical shadow angle (VSA) | VSA= 45° |
| Glazing Solar Heat Gain (SHGC) | 37% (solar control |
| Glazing thermal transmittance (U-value) | 2.8 W/m² (double pane) |
| Wall absorptance of solar radiation (α) | 0.2 (light colour) |

From the variables simulated, the *glazing thermal transmittance (U-value)* had the least effect on the cooling energy consumed, so the best-case scenario was tested with both single (5.8 W/m²) and double (2.8 W/m²) pane glass windows, to analyse the role played by this parameter when combined with the other variables that improved overall energy performance (Figure 5). The best-case with double pane glass windows was always more effective than the reference, particularly for the offices with windows located at N-E and N-W façades (Figure 6).

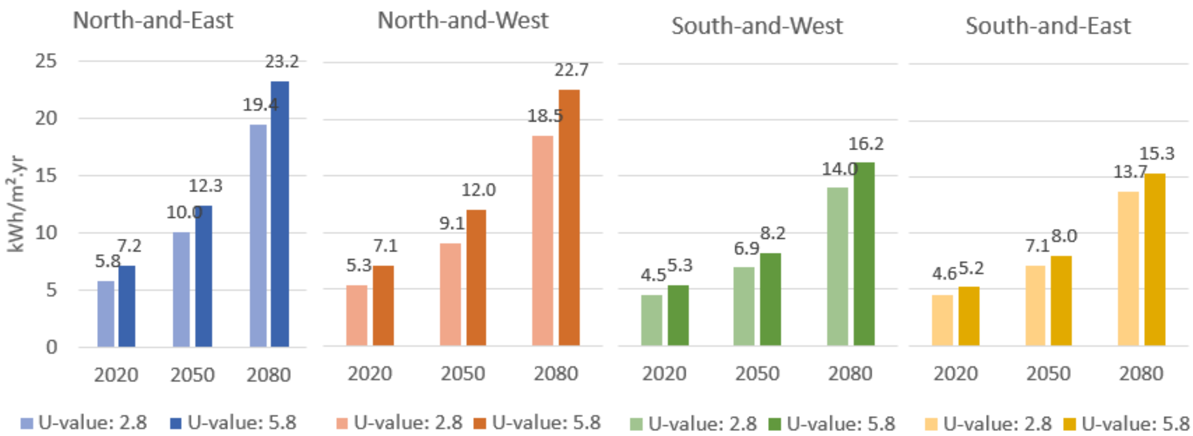



Figure 5: Windows U-value's influence on best-case cooling energy consumption

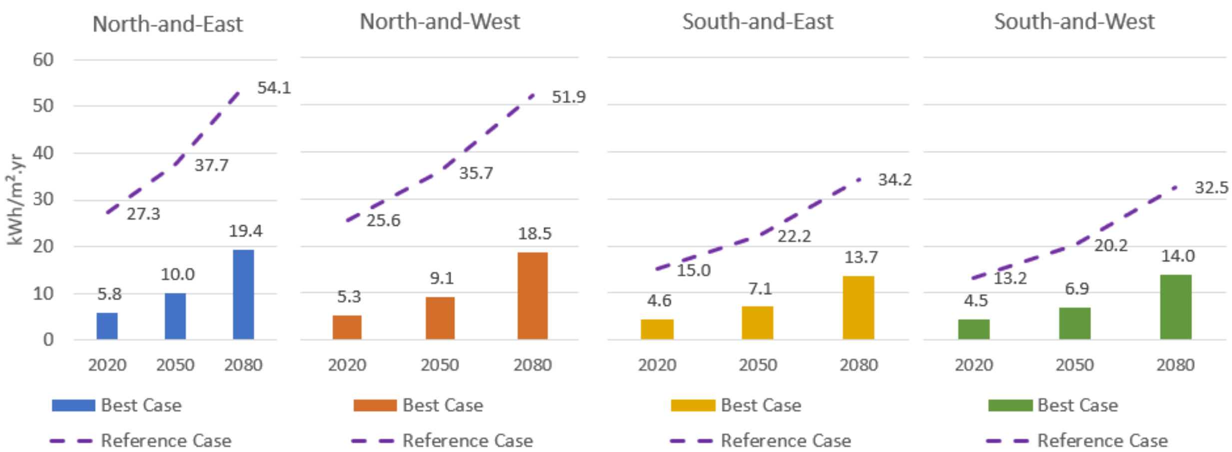



Figure 6: Cooling energy consumption for best-case scenario and reference case (purple dashed line)

Operational electricity – and corresponding emissions - savings between 57% (S-W) and 64% (N-E and N-W) would be achieved by 2080 (Table 4), through the five interventions studied for the reference case (Table 3).

Table 4. Cooling energy savings of the best-case in each orientation relatively to the reference case, for current conditions (2020) and future projections (2050 and 2080)

| **Year** | **Cooling energy savings per solar orientation (kWh/m$^2$year)** | | | |
|---|---|---|---|---|
| | N-E | N-W | S-E | S-W |
| **2020** | 21.4 | 20.2 | 10.5 | 8.7 |
| **2050** | 27.7 | 26.6 | 15.1 | 13.3 |
| **2080** | 34.7 | 33.3 | 20.4 | 18.6 |

## 3.2 Dynamic Life Cycle Assessment (LCA)

Simulated electricity consumption for each solar orientation and corresponding emission inventory are shown in Table 5. Office spaces with S-E and S-W windows followed similar trends and would emit about 20% to 25% less than those with N-W and N-E windows.

With the intensified climate change effects, even though the annual cooling energy savings would grow by about 1.6 times in 2080, relatively to 2020 (Table 4), the projected annual electricity consumption – and respective operational emissions - would at least triple (Table 5).

Table 5. Simulated electricity consumption for the best-case in each solar orientation and corresponding emission inventory

| Simulated electricity consumption | | N-E | N-W | S-E | S-W |
|---|---|---|---|---|---|
| 2020 | kWh/yr | 227.36 | 207.76 | 180.32 | 176.40 |
| 2050 | | 392.00 | 356.72 | 278.32 | 270.48 |
| 2080 | | 760.48 | 725.20 | 537.04 | 548.80 |
| Annualized emitted mass (kg/yr) | | N-E | N-O | S-E | S-W |
| 2020-49 | $CO_2$ | 52.39 | 47.88 | 41.55 | 40.65 |
| | $CH_4$ | 0.31 | 0.28 | 0.25 | 0.24 |
| | $N_2O$ | 0.02 | 0.01 | 0.01 | 0.01 |
| | CO | 0.03 | 0.02 | 0.02 | 0.02 |
| 2050-79 | $CO_2$ | 90.33 | 82.20 | 64.13 | 62.33 |
| | $CH_4$ | 0.53 | 0.49 | 0.38 | 0.37 |
| | $N_2O$ | 0.03 | 0.02 | 0.02 | 0.02 |
| | CO | 0.04 | 0.04 | 0.03 | 0.03 |
| 2080-2099 | $CO_2$ | 175.24 | 167.11 | 123.75 | 126.46 |
| | $CH_4$ | 1.04 | 0.99 | 0.73 | 0.75 |
| | $N_2O$ | 0.05 | 0.05 | 0.04 | 0.04 |
| | CO | 0.08 | 0.08 | 0.06 | 0.06 |

The GWP embodied in the galvanized steel and aluminum *brise soleils* would be respectively 30 kg of $CO_{2eq}$ and 258 kg of $CO_{2eq}$ (Table 6). When glazing (263 kg of $CO_{2eq}$) and painting (15 kg of $CO_{2eq}$) are also computed, the total embodied GWP of best-case with galvanized steel shading devices is about 307 kg of $CO_{2eq}$, less than 60% of the aluminium alternative (536 kg of $CO_{2eq}$).

Table 6. Embodied GWP (in kg $CO_{2eq}$) of individual materials and of the two best-case variations considered

| glazing (8 m$^2$) | aluminum (40,48 kg) | acrylic coating (5,5 kg) | galvanized steel (79,4 kg) | best-case aluminum *brise soleil* | best-case galv. steel *brise soleil* |
|---|---|---|---|---|---|
| 262.64 | 258.36 | 14.51 | 29.79 | 535.52 | 306.95 |

The combination of retrofit strategies added comparatively little embodied impacts (Figure 7), whilst enabling operational emissions savings ranging between 57% (S-W) and 64% (N-E and N-W) by 2080 (Table 4). Yet, climate change effects mitigation on the long run would be limited, as projected annual emissions would more than triple over the same timeframe for all solar orientations (Table 5). The embodied GWP would equal the operational impacts after about 10-13 years (aluminium) and 4-7 years (galvanized steel) of use, according with the shading device design.

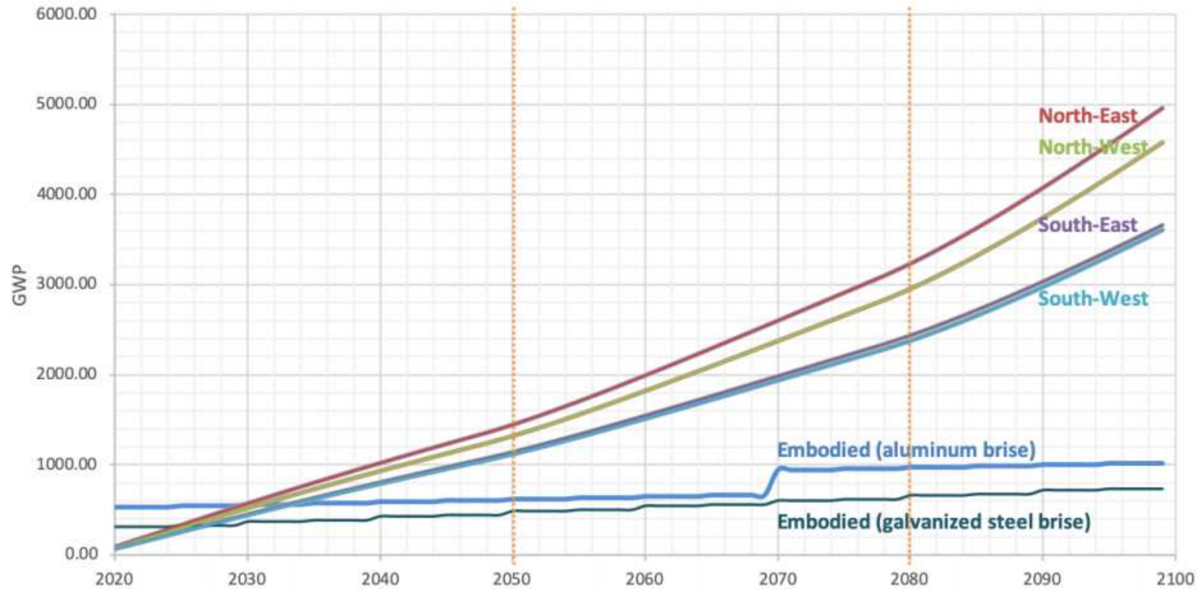



Figure 7: Operational vs. embodied GWP in the shading devices at each solar orientation studied. Continuous lines represent the operational GWP simulated for current conditions (2020) and future projections (2050 and 2080). Embodied impact curves represent initial material input plus increments due to replacement at the end of service life of each element composing the best-case.

## 4. Conclusions

It has become increasingly common to find analyses of future building performance using synthetic climate data, to account for climate change effects. Less common is the joint consideration of embodied impacts to guide current or future retrofit strategies to reduce global warming potential. This paper's contribution adds two layers of evolutionary-temporal dynamics, by (i) simulating future energy consumption of mixed-mode office space and (ii) modelling emission intensity over time, to explore how operational-to-embodied impacts ratio of devised envelope retrofit alternatives could back feed decision-making towards more resilient designs in a changing climate.

Embodied emissions prominence basically depends on manufacture characteristics of the materials used in shading devices, and on their durability, which govern replacement needs over time. In our case study, the cumulative operational impacts would offset the GWP embodied in the best-cases somewhere between 4 and 13 years, according with the material used in the shading devices. Overall, the combination of strategies considered added comparatively little embodied impacts, whilst achieving operational emission savings between 57% (S-W) and 64% (N-E and N-W) would be achieved by 2080.

Nevertheless, operational impacts would be much higher than those embodied in the materials that compose the best-case. Also, with the intensified climate change effects, the annual cooling energy savings achieved by improving the reference case would grow by 1.6 times by 2080, whilst the projected electricity consumption – and respective annual operational emissions - would more than triple.

Since this is a single-case study, results generalisation is challenging. The embodied impacts of our case study reflect a punctual intervention, with limited material mass and specific impacts input basically by designing shading devices for a tropical climate building. Most energy saving solutions for temperate and cold climates rely on important use of insulation materials, which typically have high embodied impacts that are seldom factored in. However, the approach herein illustrated – guidance through joint consideration of embodied and operational impacts from a life cycle, temporally adjusted perspective – can indeed be generalized, not only to retrofit strategies assessment, but also to guide future-proof building design to implement ultra-efficient solutions from the outcome or plan for additional interventions over time.

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# Visual Thermal Landscaping: a Novel Method in Personalising Thermal Comfort

**Sally Shahzad[1], Santiago Arias-Franco[1], Hom B Rijal[2]**

[1] Sheffield School of Architecture, Arts Tower, University of Sheffield, Sheffield, S10 2TN, UK, s.shahzad@sheffield.ac.uk
[2] Tokyo City University, Department of Restoration Ecology and Built Environment, Yokohama, 224-8551, Japan

**Abstract:**
Do the occupants adapt to a predictable thermal environment, which is always the same? In this work, Visual Thermal Landscaping (VTL) model was applied, which is a novel method in analysing thermal comfort through a human centric approach in regard to individual differences and spatial context. This is a qualitative architectural analysis method, in which data is mapped on the building layout. It allows intuitive interpretation of collected data through field studies of thermal comfort according to the meaning, individual information (e.g. comfort survey), connections between individuals, their environment and other individuals within the context. Simulation and statistical analysis were also applied on the field data. The simulation accurately predicted the temperature and energy use in the building. The PMV and the statistical analysis suggested that a slight change in the temperature will improve thermal comfort conditions. However, the VTL model revealed the complexity of satisfying everyone with a predictable uniform and steady indoor temperature, due to individual differences and the dynamic aspect of thermal comfort. This study suggests the application of personalised thermal comfort systems to enhance user comfort and satisfaction.

**Keywords:** Visual Thermal Landscaping, thermal comfort, personalised, individual differences, method

## 1. Introduction

Do the occupants adapt to a predictable thermal environment, which is always the same? This work investigated user comfort regarding a uniform and steady thermal environment in a fully air conditioned office building in Stockholm, Sweden. It also examined the application of a novel Visual Thermal Landscaping in assessing thermal comfort. This is a qualitative visual analysis method using colour coding for a personalised analysis of thermal comfort according to the spatial context and meaning.

Air conditioned buildings aim to provide a steady thermal environment. Energy is used to regulate the indoor temperature of such buildings. Many studies examine thermal comfort under steady state conditions, such as Blythe (2008), Schellen et al. (2010) and Dai et al. (2017). For uniform and steady thermal environments, PMV model is widely used (Zhang and Zhao, 2008). The ASHRAE Standard 55 (2004) aims to satisfy 80% to 90% of the occupants through the application of the standard comfort zone. Many studies focus on the optimum temperature, such as the work of van Hoof and Hensen (2006), Cui et al. (2013), and Jiang et al. (2018). However, research shows that no particular temperature is acceptable to all (Humphreys, 1972, Baker and Standeven, 1995, Nicol, 1995, Humphreys, 1996, Baker and Standeven, 1997, Humphreys, 1995, Shahzad, 2014). Humphreys and Nancock (2007) state that 'people differ in the room temperatures they desire'. Meir et al. (2009) explain that the ASHRAE has a contradiction in presenting the comfort zone and defining thermal comfort.

The latter is a state of mind and satisfaction, but ASHRAE leaves this open to interpretation (ASHRAE, 2009). However, the comfort zone is very precise with clear boundaries. He suggests that comfort is not so 'clear cut'. Individual differences in perceiving the thermal environment have been recognised (Anderson, 2012, Shahzad et al., 2019). However, this is not reflected in the main stream of thermal comfort research, such as modelling thermal comfort and human behaviour (Schweiker et al., 2016). Some studies recognise individual differences related to age, gender, and body mass, as discussed in a review by Wang et al., (2018), rather than simply differences between individuals. This work examines individual differences in perceiving and preferring the thermal environment within the spatial context using a novel Visual Thermal Landscaping model. It investigates how different individuals respond to a uniform and steady thermal environment throughout the day.

## 2. Methodologies

Statistical analysis is the most common method in assessing thermal comfort (Shahzad, 2014). Although very useful, human interpretation of the current statistical analysis is not easy. Also, individual differences in perceiving the thermal environment are acknowledged, but overlooked. Visual Thermal Landscaping was developed (Shahzad, 2014) through architectural analysis techniques using colour coding. The VTL model allows an intuitive interpretation of collected data through field studies of thermal comfort according to the meaning, individual information (e.g. comfort survey), connections between individuals, their environment and other individuals within the context. In this work, the application of the VTL model is compared against PMV and statistical analysis.

Field studies of thermal comfort were applied in this work in an office building in Stockholm, Sweden in the summer of 2012. The building was a fully air conditioned sealed box with no openable windows. The only means of thermal control was the use of internal blinds to avoid direct solar gain. Environmental measurements were applied both constantly using tinytag data loggers and at the workstation level, while a thermal comfort survey was recorded by the participant. Because of the qualitative analysis, a relatively small sample size was preferable in this work. Forty one datasets were collected from eighteen occupants with a good balance of age and gender. All respondents were asked to respond to the survey three times a day, including morning (09.00am to 12.00pm), noon (12.00pm to 14.00pm) and afternoon (14.00pm to 17.00pm). Based on the availability, not every respondent could fill in the survey three times a day. Mainly sedentary activities were observed. A mixture of summer clothing (0.5 clo) and warmer clothing (up to 0.7 clo) was observed. Occupants only wore trousers and no skirts or a dresses were observed. The follow up interviews revealed that several ladies considered the office uncomfortably cool; hence, not suited to wear a skirt. Two female occupants mentioned the need for extra clothing layers in the office during the summer, because of the indoor cool conditions. They both explained that upon exiting the office, they remove the extra layers. As all occupants were wearing trousers in this study, only the thickness and sleeves of the shirt as well as additional scarf and warm clothing layers have been considered for clothing.

Visual Thermal Landscaping was the key analysis method and the focus of this study. Shahzad (2014) introduced and explained this visual analysis method. It provides a platform for a qualitative analysis of thermal comfort data per respondent according to meaning, spatial context and in relation to other occupants (Shahzad et al., 2019). This method was developed through architectural knowledge and expertise. A colour coding system was applied to reflect the thermal comfort survey data on the plan of the building (as demonstrated in Figure 1) according to the respondent’s workstation and situation in the office. Further information was reflected on the plan regarding the architectural, spatial, contextual, and work related information. For example, the workstation arrangements, neighbouring occupants, teams, windows, blinds, open plan, personal offices, and other information were reflected as part of the VTL model, as illustrated in Figure 18.

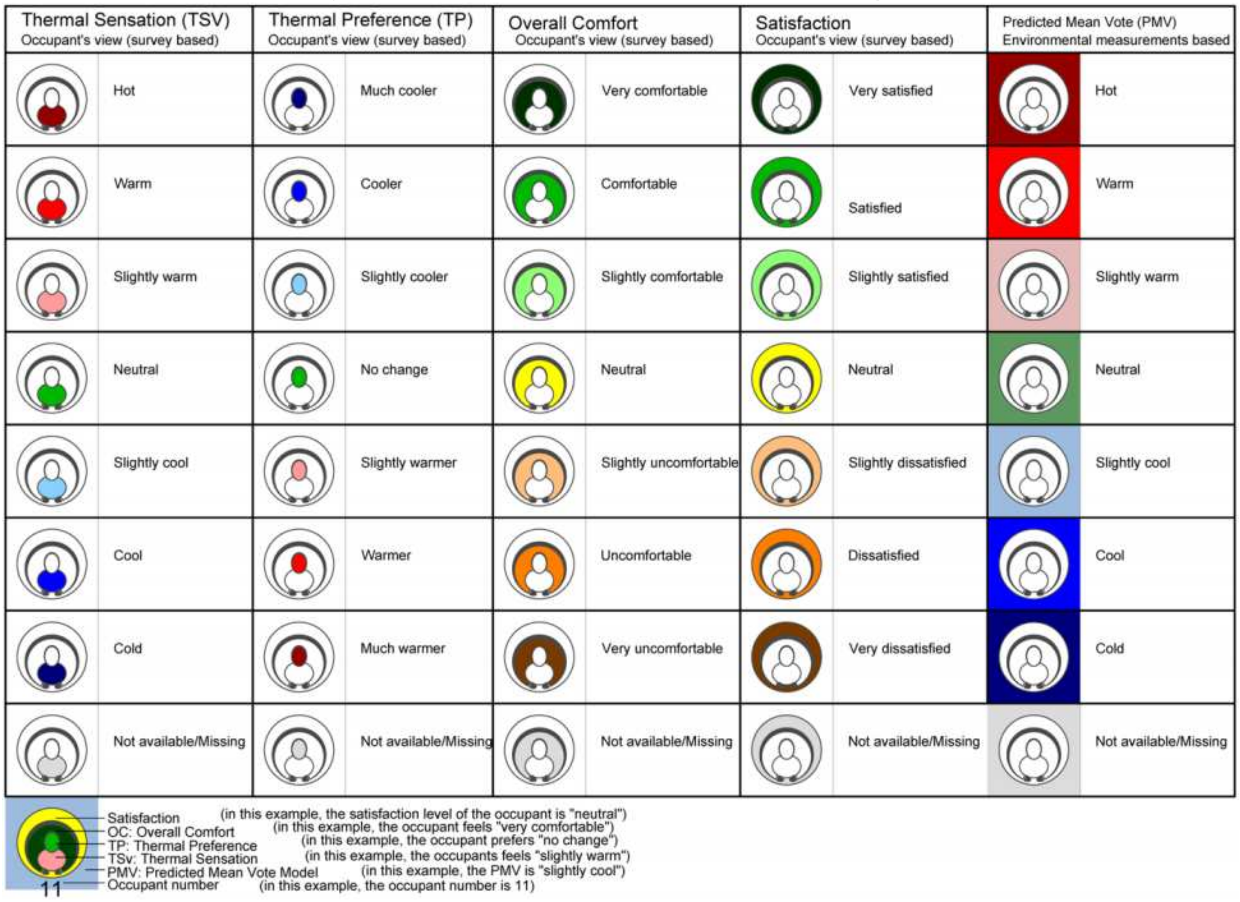


Figure 1. The legend to read the colour coding of the VTL model (Shahzad et al., 2019)

In order to analyse the data using VTL, interpretation and qualitative analysis is required, as demonstrated in Shahzad et al. (2019). The VTL method allows drawing fresh and unexpected conclusions. Hence, in order to get the most out of this method, a more flexible approach is required. Thus, grounded theory was applied as the main methodology in this study. In this approach, instead of starting the research with a pre-judged hypothesis (Glaser and Strauss, 1967), rather several hypotheses exist (Groat and Wang, 2002) and the researcher allows the theory to emerge from the data and analysis (Groat and Wang, 2002, Hunter and John, 2008). It relates to real life conditions and people (Star, 2007), which is suited to the field studies of thermal comfort. This approach leaves the door open for unexpected results, which is arguably a valuable contribution.

## 3. Analysis

In this section, the building performance is assessed using the actual recorded data as well as simulation analysis. Also, the common statistical analysis of thermal comfort is applied on the surveyed data to assess occupants’ response. Finally, Visual Thermal Landscaping is applied on the data and a detailed interpretation is discussed. The contrast between the three analysis methods will be further examined in the discussion section.

### 3.1. Simulation and Thermal Analysis

The thermal measurements of the building were compared to a simulation of the thermal environment. Figure 2 demonstrates the recordings of the indoor temperature and humidity ranges at the workstation levels around the office. This is based on forty one data sets and it demonstrates the thermal conditions across the office. Relative humidity changes between 30% and 45%. The indoor temperature ranges are quite narrow, mainly between 22.5°C and 23.5°C. This shows a steady thermal environment in the building, which in agreement with an air conditioned sealed building. The PMV analysis indicates a slightly cool thermal environment (i.e. PMV = -0.92 and PPD = 23%). This suggests that a slight increase in the temperature (e.g. 1.5°C to 2°C) is more likely to result in higher levels of thermal comfort.

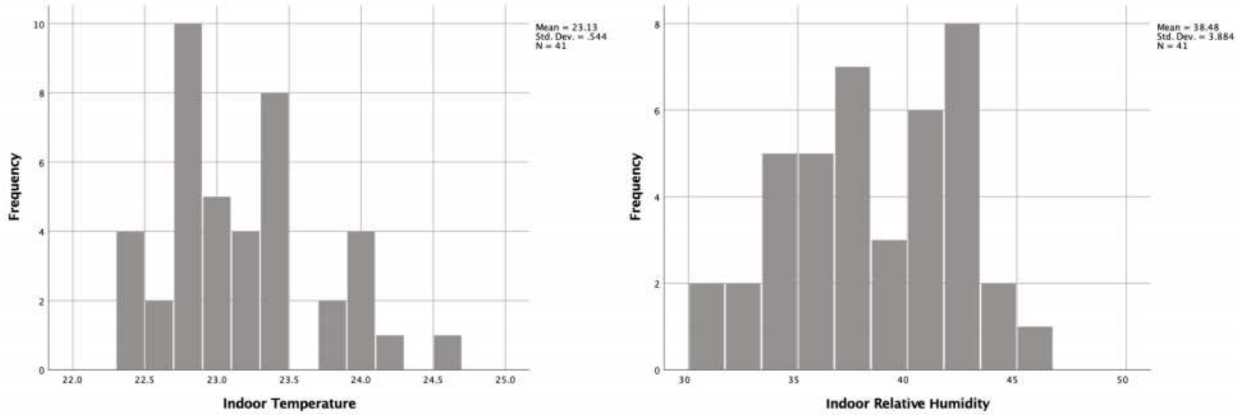


Figure 2. The frequency of indoor temperature and relative humidity recordings

Figure 3 demonstrates the indoor and outdoor temperatures, based on the constant recording using data loggers, which were installed in a specific place in the office. The recording was applied during three working days with five minutes intervals. Overall, 3977 datasets were recorded. The outdoor measuring equipment were in place since early morning, while the indoor measurements started in the afternoon of the first day, due to access issues. As it is demonstrated in Figure 3, the outdoor temperature changes between 15°C and 35°C during these three days with an average temperature of 22.98°C. However, the indoor thermal environment is quite steady throughout the three days with an average temperature of 23.13°C. This is expected, as the building is an air conditioned sealed box.

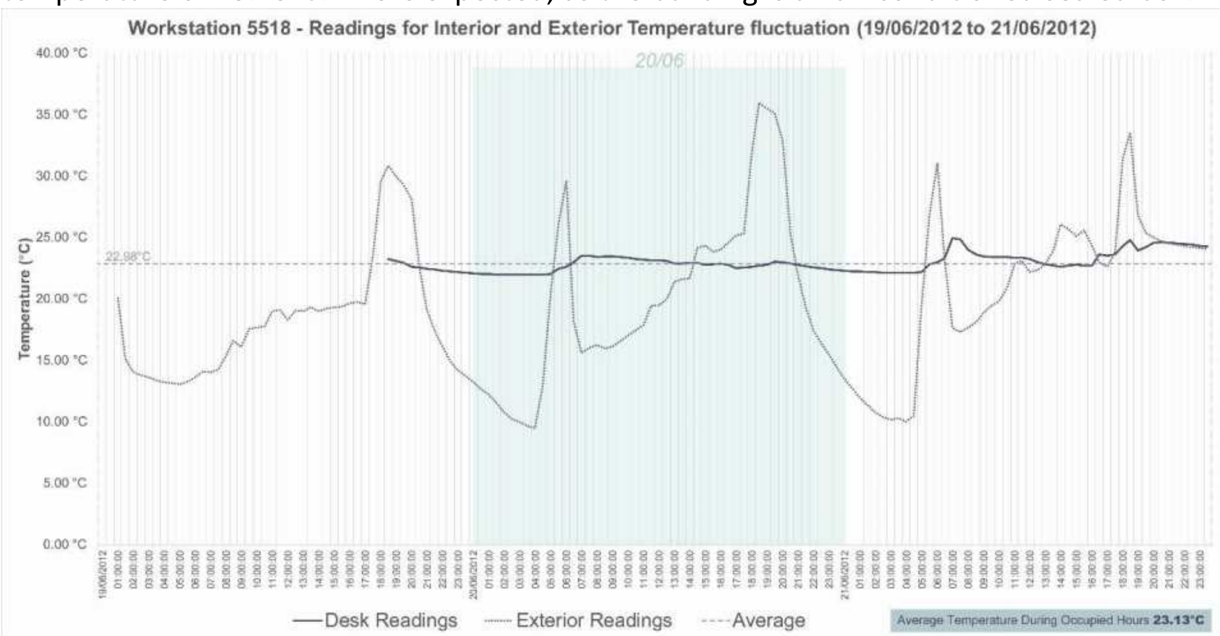


Figure 3. Actual readings of the external and internal temperatures during a three-day period

Thermal simulation was applied, using IES dynamic thermal, as demonstrated in figures Figure 4. Based on the simulation, the outdoor temperatures is expected to change between 11 $^{o}$C and 22 $^{o}$C, while the indoor thermal environment is kept steady during the occupied hours with an average temperature of 22.69 $^{o}$C.

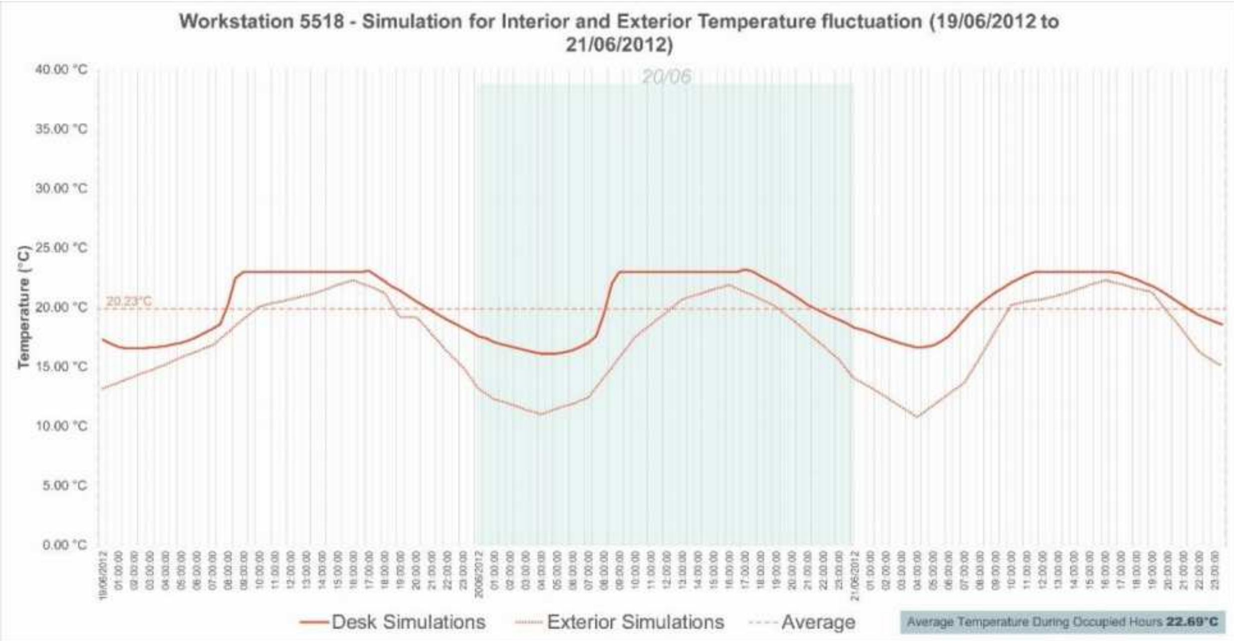


Figure 4. Simulation of the external and internal temperatures during a three-day period

The results of the thermal simulation were compared against the actual thermal readings inside and outside the building. Figure 5 demonstrates the comparison of the outdoor temperature readings and simulation. There is a good correlation between the two; however, the simulation line is much more smooth and it does not show sudden local changes in temperature. The simulated and readings of the minimum temperatures are quite similar; however, the maximum temperatures are significantly different.

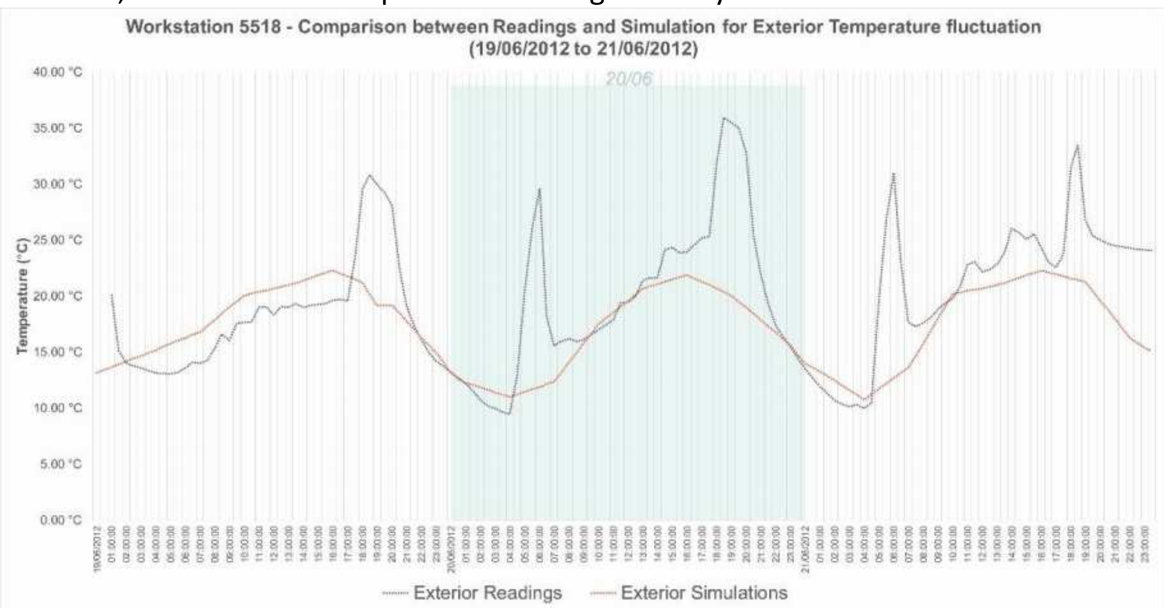


Figure 5. Comparison of simulation and actual recording of the external temperature during a three-day period

Figure 6 illustrates the comparison of indoor simulation and readings. During the occupied hours, there is a good correlation between the two. The simulation also predicts a steady thermal environment in the building with very similar temperature setting with an average temperature of 22.69 $^{o}$C, while the actual average temperature was measured, as

23.13 °C. The difference between the two is during the out of hours periods, in which the simulation considered the air conditioning to be off, due to energy saving matters. However, the air conditioning is kept on during the night hours, as decided by the facilities manager. Hardly any occupant stays at work after 19.00pm.

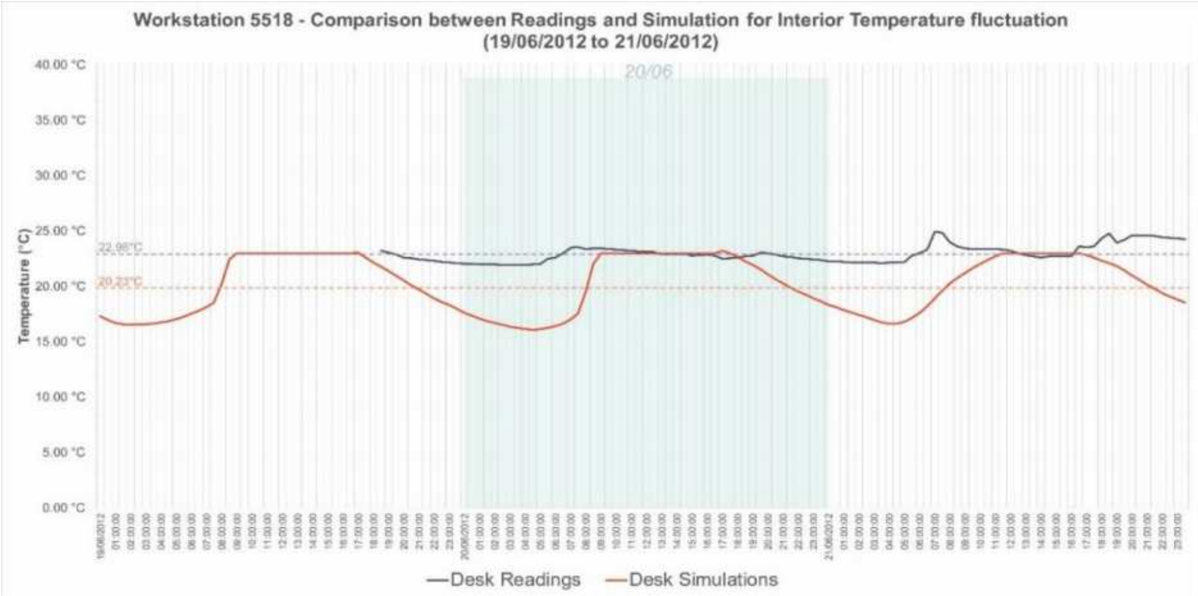


Figure 6. Comparison of simulation and actual recording of the indoor temperature during a three-day period

Figure 7 demonstrates the comparison of the indoor and outdoor simulation and reading during the three days.

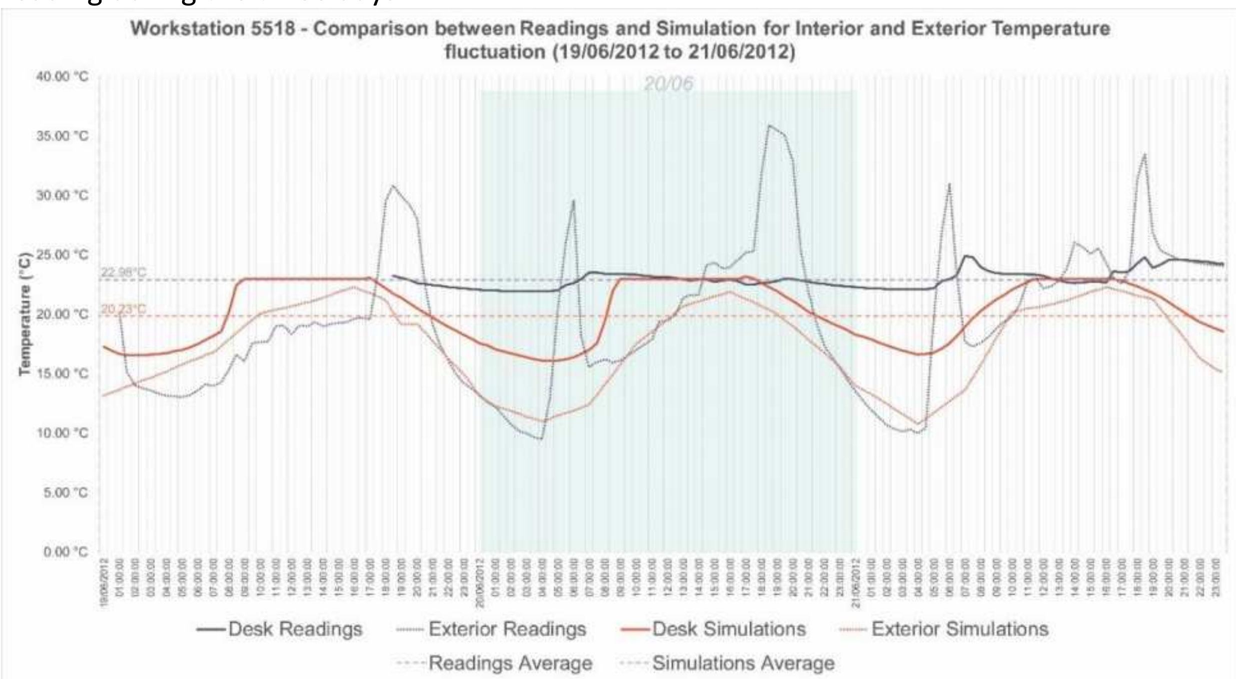


Figure 7. Comparison of simulation and actual recording of the external and internal temperatures during a three-day period

Figure 8 shows the indoor and outdoor simulation and readings during one day and in more detail. The consistency of the indoor temperature during the occupied hours is quite visible. During the unoccupied hours, the difference between the simulation and readings of the indoor temperature can measure up to 6 °C, which can be significant regarding the energy use.

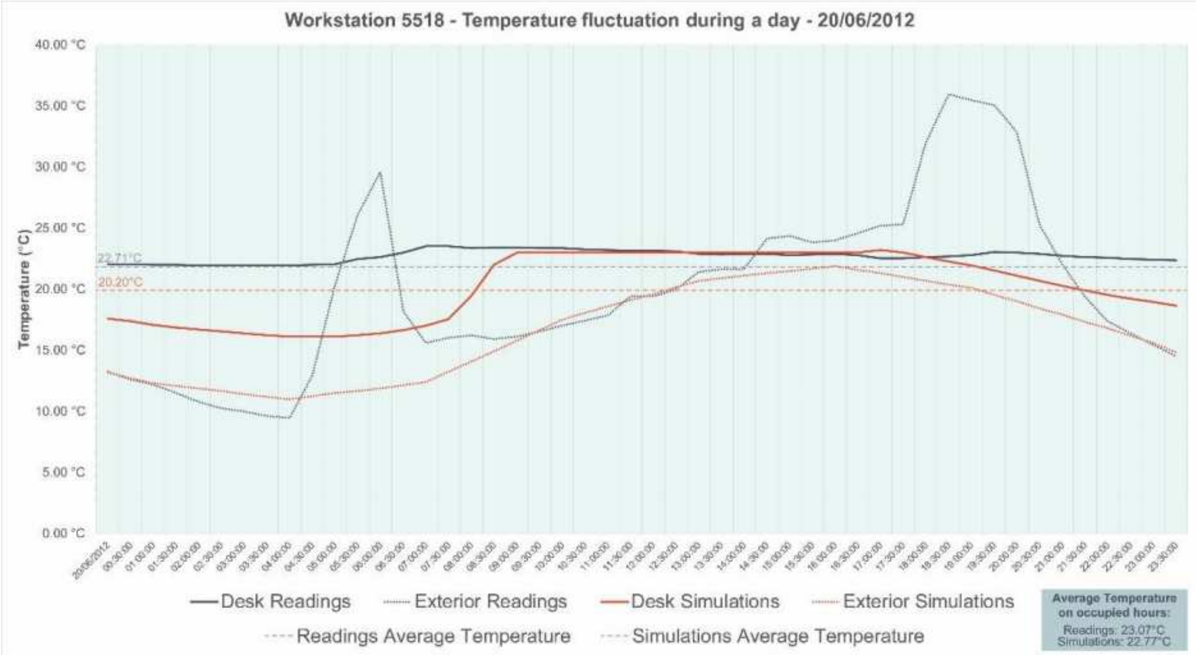


Figure 8. Comparison of simulation and actual recording of the external and internal temperatures in a day

Figure 9 shows the comparison of the outdoor relative humidity between the simulation and readings, which is up to 30% difference.

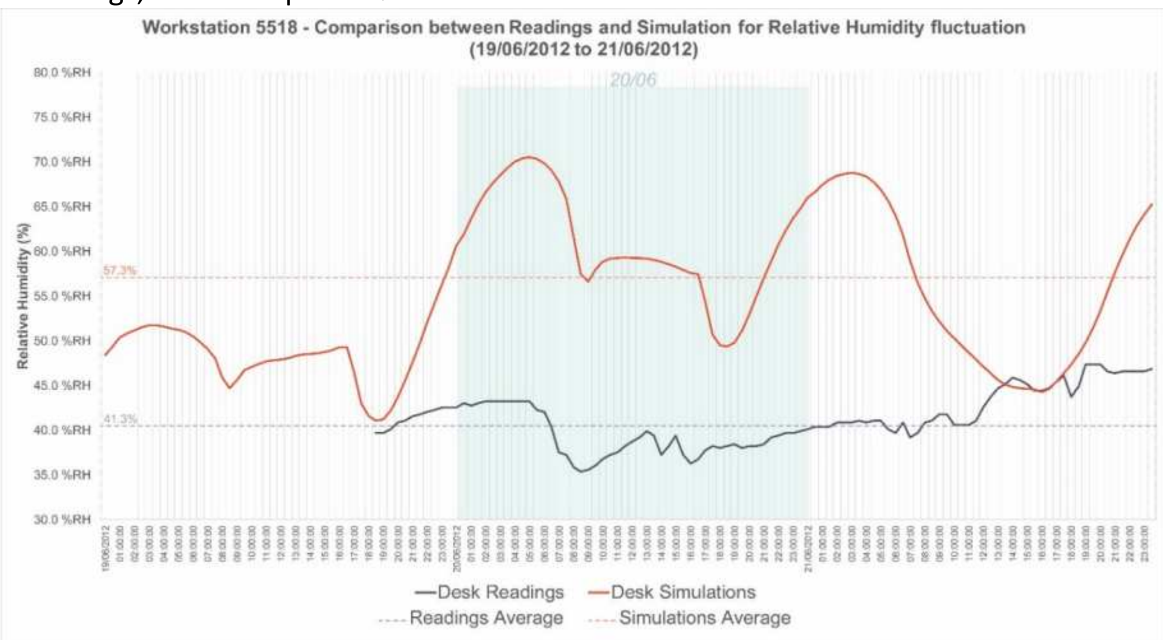


Figure 9. Comparison of simulation and actual recording of indoor relative humidity during a three-day period

Figure 10 shows the difference in indoor relative humidity between the simulation and readings, which is significantly different, up to 27%.

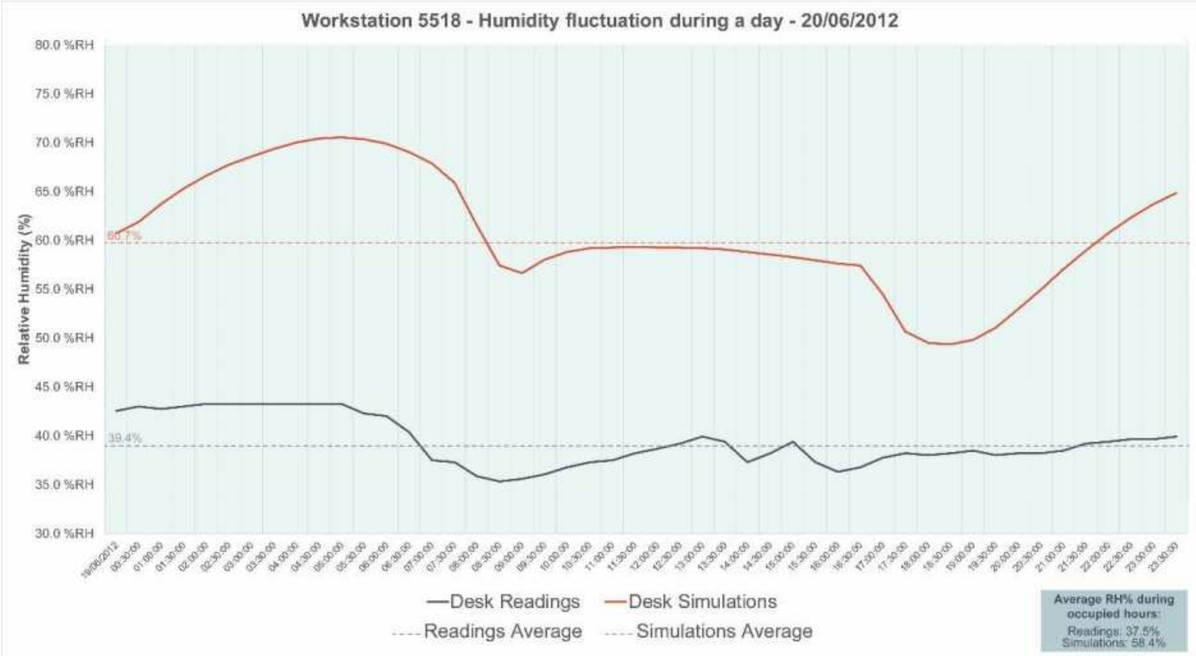


Figure 10. Comparison of simulation and actual recording of indoor relative humidity in a day

Overall, both the simulation and the actual recordings of the thermal environment indicate a uniform and steady thermal environment across the office and during the three day period. This suggests that the building had a good thermal control, and thus, a good thermal performance within a small range. The PMV analysis suggested that the thermal environment falls towards slightly cool and a slight increase in the temperature (e.g. 1.5$^{o}$C to 2$^{o}$C) is more likely to result in higher thermal comfort levels.

### 3.2. Thermal Responses

In this section, thermal responses of the occupants, including thermal sensation, thermal preference, overall comfort and satisfaction are analysed. The frequency of thermal sensation, thermal preference, overall comfort and satisfaction is analysed in Figure 11. Majority of the occupants feel slightly cool and neutral, while they prefer slightly warmer and neutral. This is in line with the PMV analysis, as mentioned above. There is a relatively good degree of comfort level, while satisfaction level varies and in many cases, it appears quite poor.

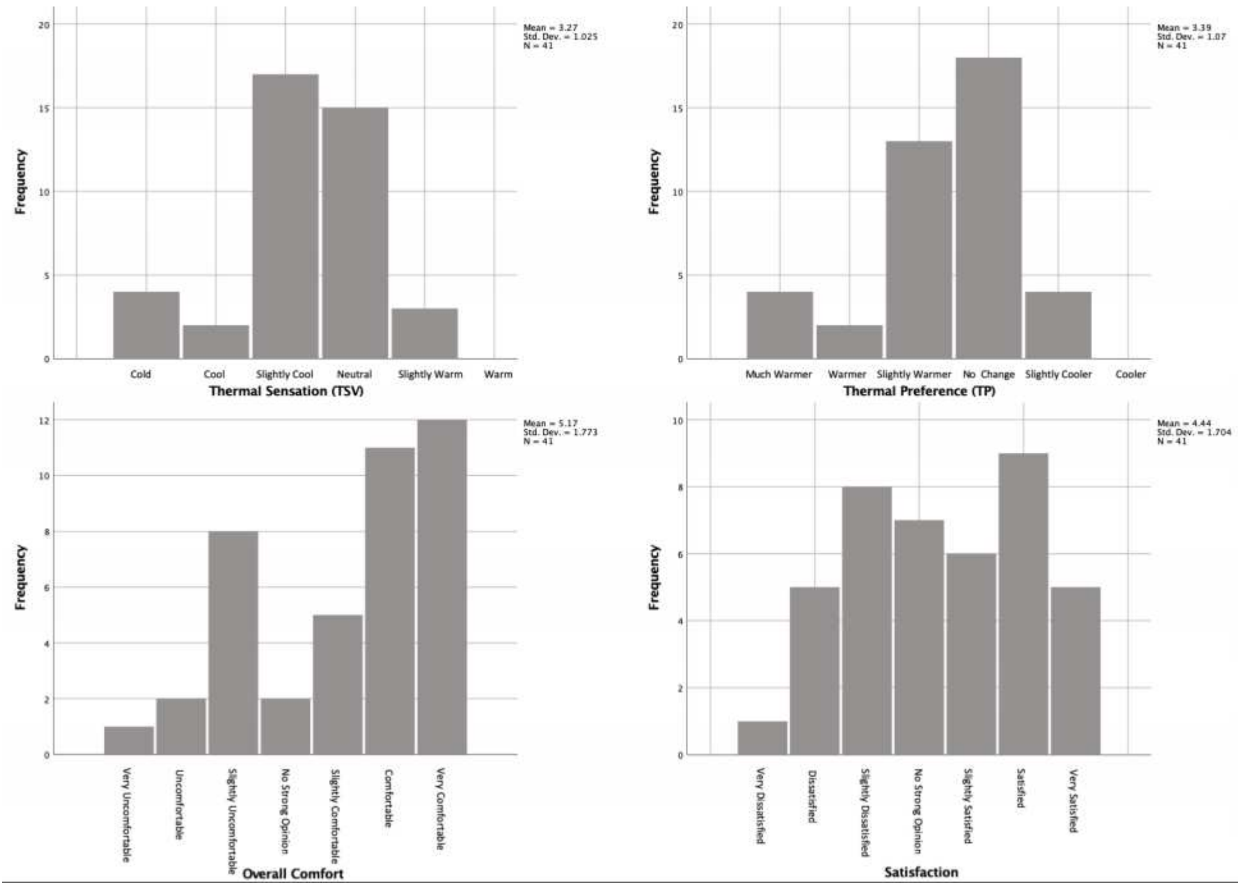


Figure 11. The frequency of TSV, TP, OC, and satisfaction responses

The relationship between thermal sensation, thermal preference, overall comfort, and satisfaction is examined in Figure 12. The regression analysis of thermal sensation and thermal preference shows that when respondents feel neutral, they prefer no change, as it is usually expected. It also shows that occupants, who feel cool, rather than preferring warmer temperature, they prefer somewhere between slightly warmer and warmer. Thus, when feeling cool, they don’t prefer the same degree of change in the temperature, rather slightly less intense change (i.e. half a scale). The same condition applies to respondents, who feel slightly warm. They also don’t prefer the same degree of change in the temperature, rather slightly less change (i.e. somewhere between no change and slightly cooler). This suggests that respondents can tolerate slightly warm or cool conditions, as they don’t prefer much change in the temperature.

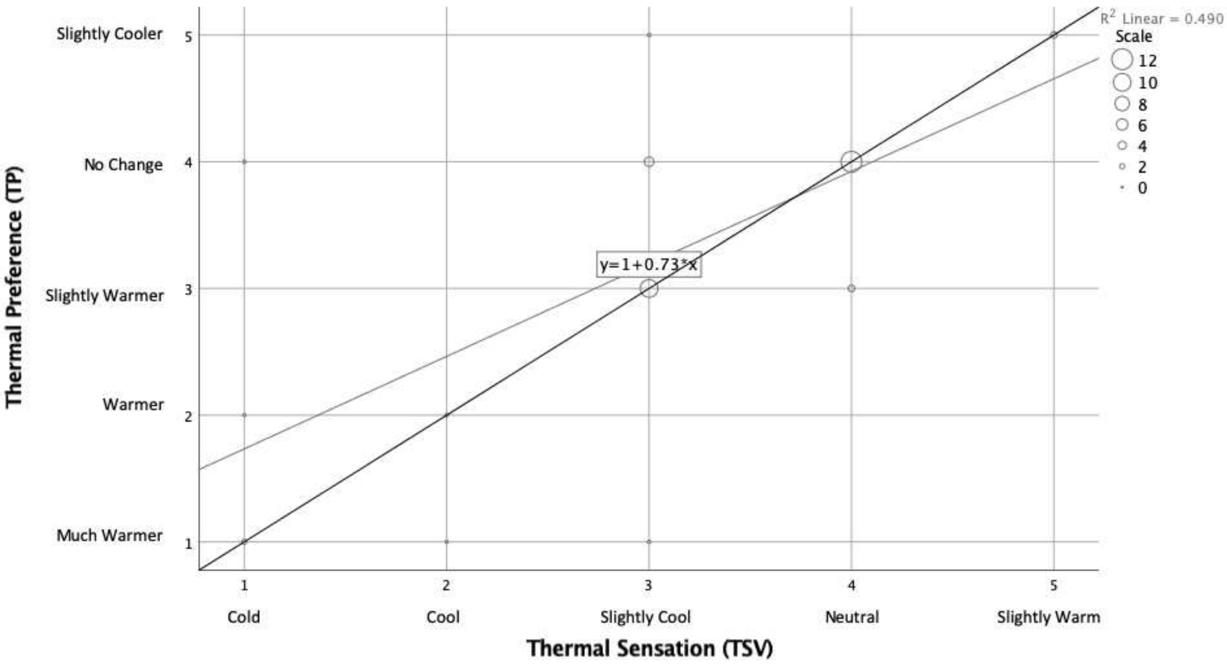


Figure 12. The relationship between thermal sensation and thermal preference

Figure 13 demonstrates the relationship between thermal sensation and overall comfort. It shows that, when the occupants feel neutral (i.e. TSV = 4), overall comfort is at the maximum. This suggests that majority of the occupants are comfortable, when feeling neutral. This is in agreement with the findings of Fanger (1970), McCartney and Nicol (2002), (Liu et al., 2012, Cigler et al., 2012, van Marken and Kingma (2013), Schellen et al. (2013), Indraganti et al. (2013).

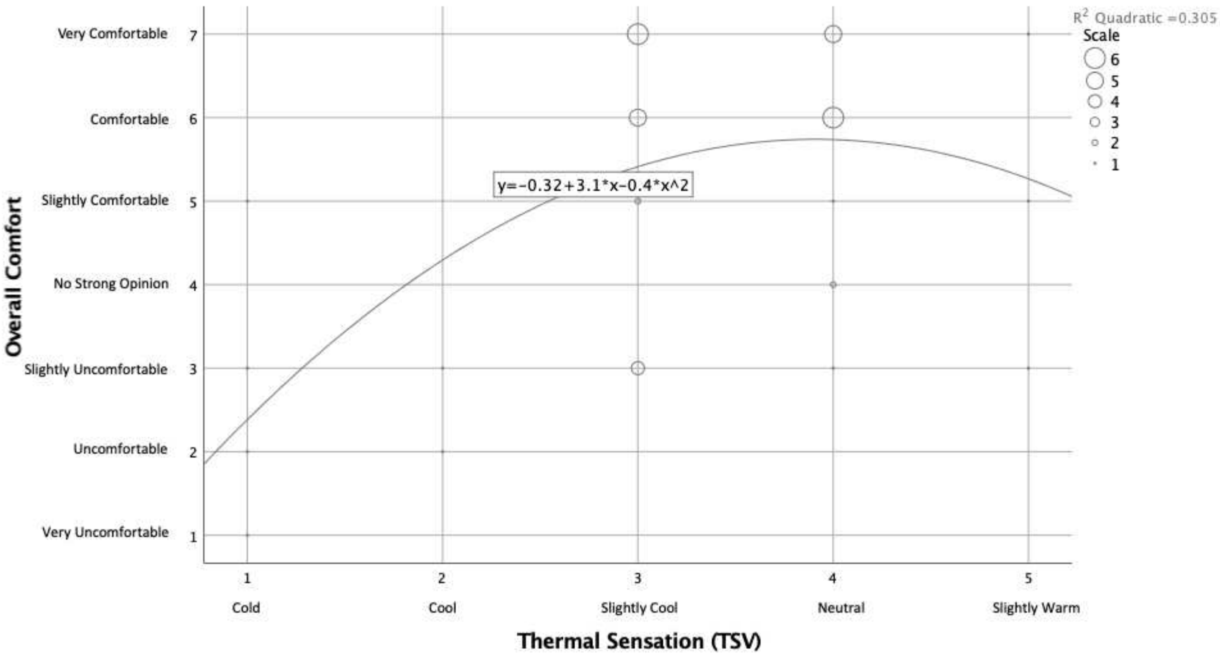


Figure 13. The relationship between overall comfort and thermal sensation

Figure 14 demonstrates the relationship between overall comfort and thermal preference of the occupants. This is quite similar to Figure 13, as the preference on no change has the maximum overall comfort level. This suggests that majority of the occupants prefer no change in the temperature to feel comfortable.

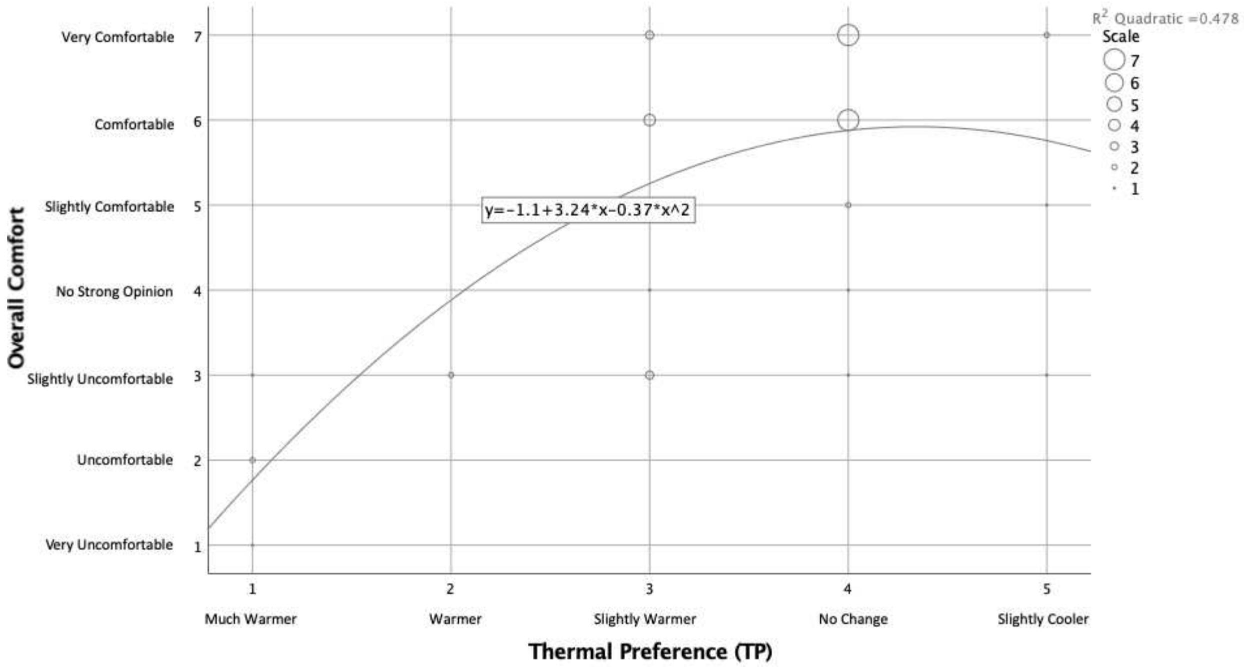


Figure 14. The relationship between thermal preference and overall comfort

Figure 15 illustrates the regression analysis between overall comfort and satisfaction. It shows a good correlation, as the higher the comfort level, the higher the satisfaction level and vice versa.

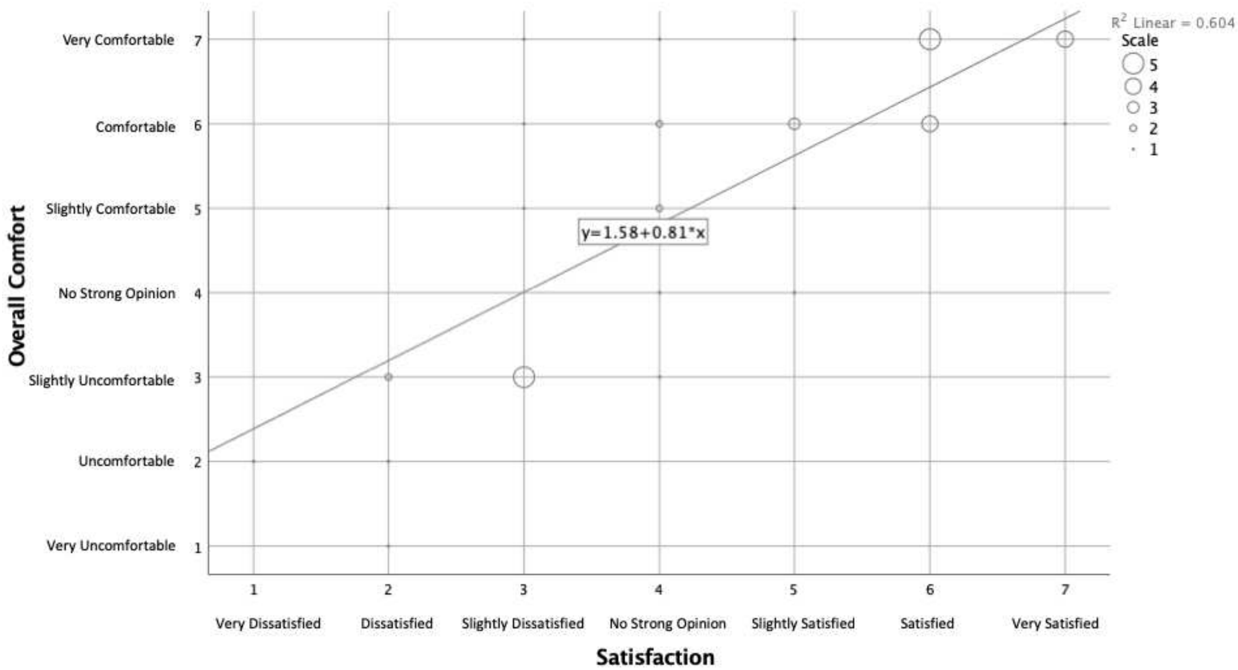


Figure 15. The relationship between overall comfort and satisfaction

Figure 16 shows the relationship between indoor temperature with thermal sensation, thermal preference, overall comfort and satisfaction. The temperature range is very small, mainly between 22 °C and 24 °C. There is a great similarity between all four graphs, as within a small range of temperature occupants responded quite differently. For example, the mean is quite close in all scales of thermal sensation. The same applies to thermal preference, overall comfort and satisfaction.

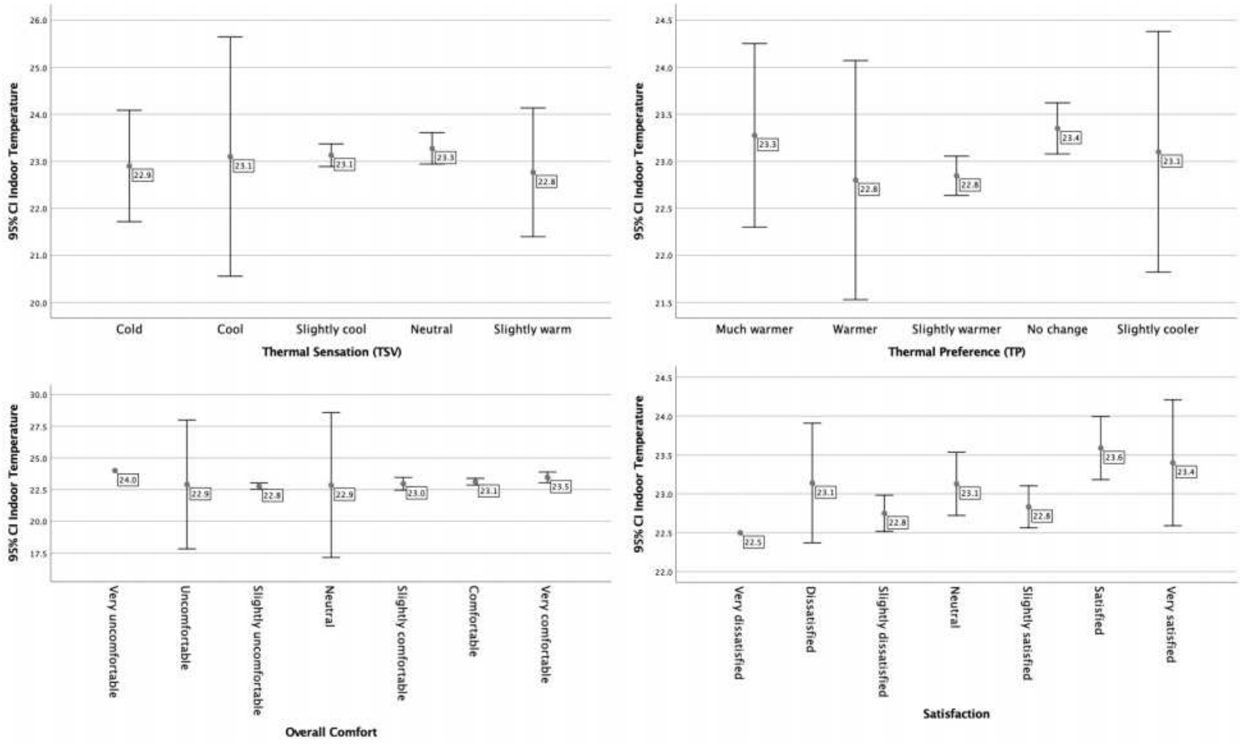


Figure 16. The relationship between the indoor temperature with TSV, TP, OC, and satisfaction

Figure 17 demonstrates the regression analysis of the indoor temperature with thermal sensation, thermal preference, overall comfort and satisfaction. All graphs show quite scattered responses and the slope of the regression lines are not significant. Thus, suggesting that the relationship between indoor temperature with all four variables is not that significant; thus, difficult to draw conclusions.

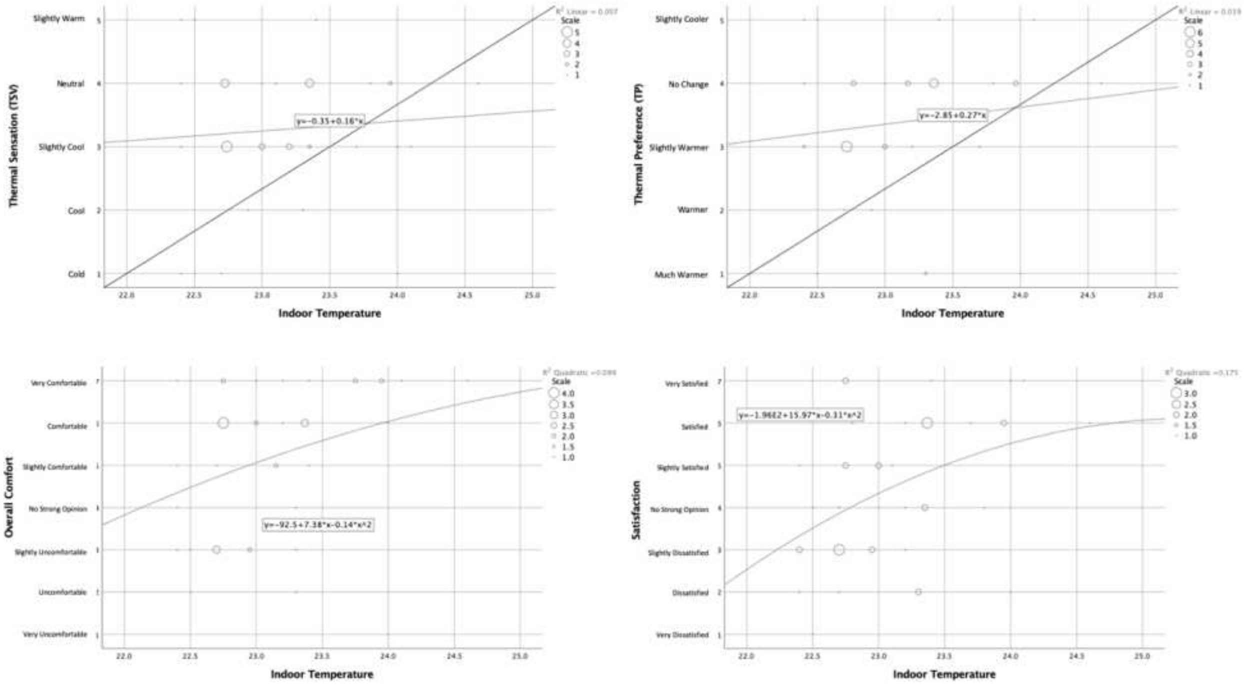


Figure 17. The relationship between the indoor temperature with TSV and TP

Overall, majority of the occupants feel neutral (i.e. TSV = 4), prefer no change (i.e. TP = 4) and they have a relatively high comfort level. There is a good relationship between the four variables, including TSV, TP, OC, and satisfaction. Occupants' thermal responses are significantly varied, specifically considering the narrow range of the thermal environment (i.e.

about 2 °C). It is difficult to draw conclusions on the relationship between indoor temperature and the four variables.

### 3.3. Visual Thermal Landscaping

In this section, VTL model is applied, as illustrated in Figure 18. Accordingly, a detailed interpretation is discussed regarding each respondent in connection with other respondents, spatial context, teams, and the respondent's other responses.

Respondents S02 and S03 feel cool and prefer warmer conditions at noon and in the afternoon. However, the degree of their sensation and preference is different. S02 is wearing a jumper all day, while S03 is wearing a long sleeve shirt all day. S02 feels cold and prefers warmer at noon, which is reflected in his slightly uncomfortable and dissatisfaction. Although, S03 shares similar comfort and satisfaction levels; he feels slightly cool and prefers much warmer. This suggests that although S03 does not feel that cold, but the level of change he prefers is much higher than S02, who feels cold. In the afternoon, both S02 and S03 feel cool; however, again the level change preferred by S03 is higher (much warmer for S03, as compared to warmer for S02). Feeling cooler than at noon is reflected in S03's drop in comfort (i.e. uncomfortable) and satisfaction levels (i.e. dissatisfied). Although the thermal sensation of S02 and S03 changes throughout the day, their thermal preference does not change.

Occupants S09 and S10 go through very different thermal experiences throughout the day. In the morning and afternoon, S09 feels neutral, prefers no change and he is comfortable wearing a long sleeve shirt. At noon, although the room temperature hasn't changed, S09 feels slightly warm and prefers slightly cooler conditions. Also, there is a drop in his comfort level to slightly uncomfortable. In contrast, S10 is wearing a jumper and still he feels cold and prefers much warmer conditions throughout the day. This is reflected in his overall comfort and satisfaction level, which are poor (i.e. very uncomfortable and dissatisfied in the morning, while uncomfortable and very dissatisfied at noon).

Participants S11, S12 and S13 want totally different things both in the morning and at noon. Although they all feel slightly cool or cold in the morning; S11 prefers slightly warmer, while S12 and S13 are both happy to feel cold and slightly cool, as they prefer no changes in the thermal environment. At noon, they all have different sensations (slightly cool, neutral and slightly warm) and different preferences (slightly warm, slightly cool and no change). Surprisingly, the overall comfort and satisfaction level of S12, who feels neutral and doesn't prefer any change, is quite lower than the other two, who don't feel neutral and prefer a slight change in the temperature. Only in the afternoon, both S11 and S12 feel slightly cool and prefer slightly warmer. However, their overall comfort and satisfaction levels reveal a different level of comfort. S12 is slightly uncomfortable and slightly dissatisfied, while S11 feels very comfortable and slightly satisfied. S13 also feels slightly cool; however, he prefers no change and he is comfortable with the thermal environment. Overall, S11 has been very consistent in his thermal sensation (slightly cool), thermal preference (slightly warmer), overall comfort (comfortable or very comfortable), and satisfaction level (slightly satisfied). He consistently feels slightly cool and prefers a slightly warmer condition; thus his thermal decision is neutral. S13 consistently shows a tendency for slightly cool temperatures, as in the morning and afternoon he feels slightly cool and prefers no change in temperature. At noon, he feels slightly warm and he prefers slightly cooler.


Figure 18. Visual Thermal Landscaping of the case study building in Stockholm

Respondents S14, S15 and S16 want totally different temperatures throughout the day. Although in the morning, S14 and S15 both feel slightly cool; they have opposite preferences. S14 prefers slightly cooler while S15 prefers slightly warmer. S14 is very satisfied and very comfortable, while S15 is slightly dissatisfied and slightly comfortable. Also, S14 is wearing a long sleeve shirt, while S15 is wearing a jumper in July. These suggest that S15 faces more difficulties regarding the room temperature, while S14 although prefers a slightly cooler conditions, he is very comfortable and satisfied with it. Meanwhile, S16 considers the thermal environment as neutral, prefers no change and feels satisfied and very comfortable. Like S14, he is also wearing a long sleeve shirt. This suggests that in the morning, both S14 and S16 are fine with the thermal environment, while S15 is unhappy. At noon, similar situation continues, the only major difference is that S14 prefers no change, while feeling slightly cool. Overall, S15 and S16 have been consistent in their thermal sensation, thermal preference, overall comfort, and satisfaction. S14 has been consistent in thermal sensation, overall comfort and satisfaction; however, his thermal preference changes from slightly cooler in the morning to no change at noon.

### 3.4. Energy

The energy consumption of the building was assessed using both simulation and the data received from the facilities manager of the building. Figure 19 demonstrates the simulated energy consumption using IES software.

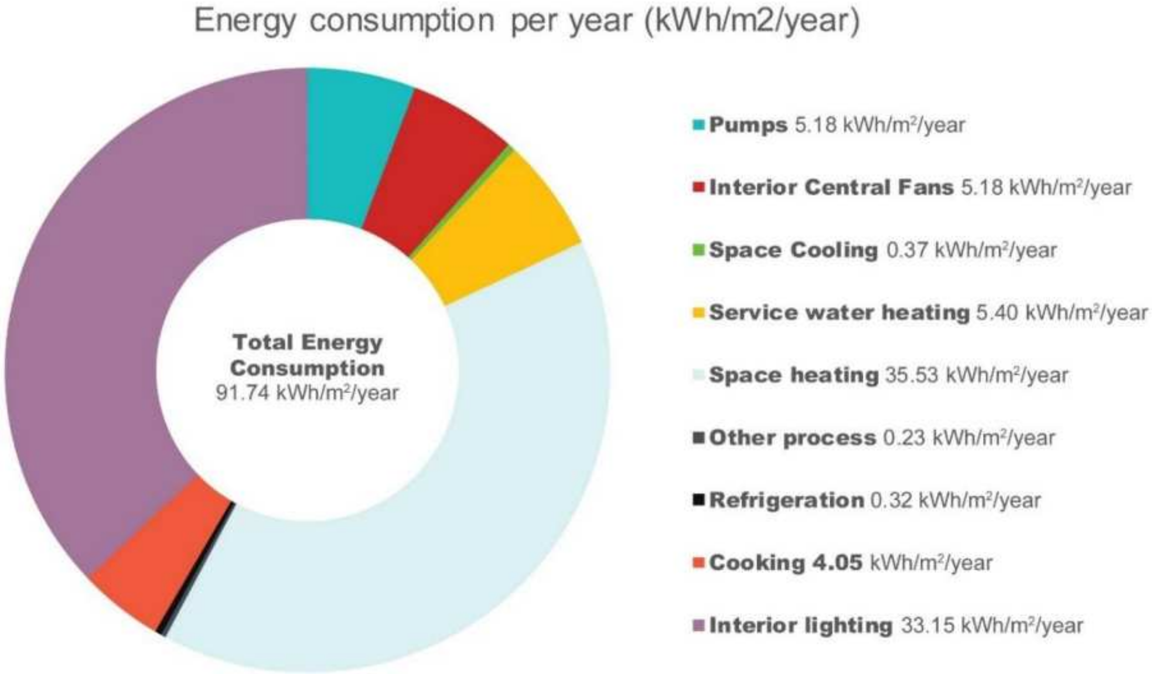


Figure 19. Energy use and breakdown per year, using IES-VE simulation

The simulation indicates 91.74 kWh/m2/year, while the actual energy use was recorded, as 98.60 kWh/m2/year. The two figures are quite close, as demonstrated in Figure 20.

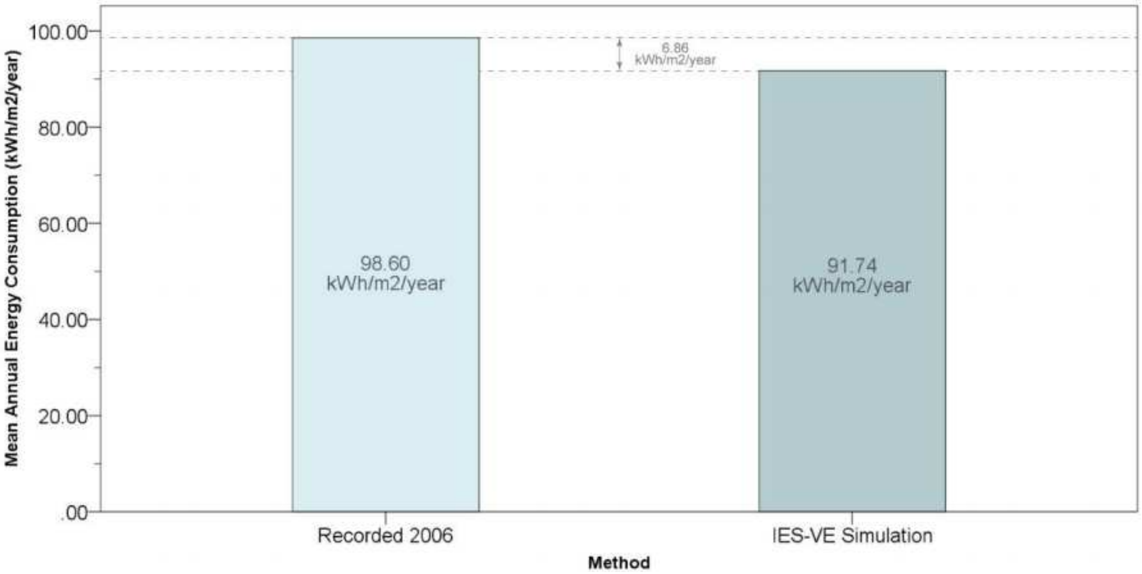


Figure 20. Comparison between simulation and actual data regarding the energy use of the building

## 4. Discussion

The thermal comfort condition of the occupants fully air conditioned sealed office with no openable windows was investigated in this work. A field study of thermal comfort was applied through a grounded theory approach. The collected data was analysed through simulation, statistical analysis and a qualitative analysis using the Visual Thermal Landscaping model. The results of the simulation were compared against the actual thermal performance of the building, based on the environmental measurements during three days on site. The building performance analysis indicated that the thermal environment in the building is uniform and steady within a narrow band (i.e. mainly between 22.5°C and 23.5°C). This shows a good thermal control and thermal performance of the building, which is consistent with the expectation of a fully air conditioned sealed box. The results of the temperature analysis through simulation were very close to the actual data, except that during the unoccupied hours the simulation considered the air conditioning to be off, due to energy saving purposes. However, in the actual building, air conditioning was left on over night, although no occupants were reported to stay in the building. Also, the simulation did not predict the sudden changes of the outdoor temperature. However, except the sudden changes, the rest of the outdoor temperature analysis was quite similar. The humidity analysis was significantly different (i.e. up to 30% different). Also, the sudden changes of the humidity were not detected through the simulation. There was a good similarity between the simulation and actual data regarding the energy performance of the building. Knowing that simulation is the main tool used for improving the thermal performance of a building. The results of this work suggest that when it comes to a fully air conditioned sealed workplace, the simulation can be quite accurately predicting the thermal environment.

The PMV analysis suggested that the building is expected to be on the slightly cool side, while increasing the temperature by 2°C improves the thermal comfort of the occupants to the neutral point. This is in line with the statistical analysis, which showed that 41% of the respondents felt slightly cool and 32% of the occupants preferred slightly warmer conditions. The statistical analysis observed that within the narrow band of indoor temperature, quite a variety of thermal sensation, thermal preference, overall comfort, and satisfaction levels. No significant relationship was found between the indoor temperature and the thermal preference, overall comfort, and satisfaction of the occupants. Respondents with a thermal sensation of slightly cool or warm preferred less degree of change in the temperature, suggesting a higher degree of tolerance than expected. Overall comfort and satisfaction were correlated. The highest overall comfort level was detected, when the occupants had a neutral thermal sensation or a no change thermal preference.

The VTL model showed that individuals had quite a different perception of the thermal environment, some quite opposite perceptions (e.g. cool, slightly warm and neutral). Also, the degree of change they preferred was quite different from one another, even for the individuals with similar perception of the thermal environment. Knowing that it was a uniform and steady thermal environment, the observed individual differences in perceiving, preferring and experiencing the thermal environment quite distinctly becomes more significant. Some of these individuals seat quite closely together and still they sense and prefer very different thermal conditions. This is quite visible at S09, S10, S11, S12, and S13 workstations. 51% of the respondents prefer either no change or slightly cooler thermal environment. This means that by increasing the temperature up to 2$^{o}$C, as suggested by the PMV analysis, 51% of the occupants are more likely to feel uncomfortable. This suggests that a uniform thermal environment cannot satisfy all these individuals.

56% of the respondents felt and preferred different thermal environment throughout the day, knowing the thermal environment has been steady. Not only that individuals were observed, as quite different in their perception and preference, but also individual's perception and preference changed throughout the day. This shows the dynamic aspect of thermal comfort. Thirteen occupants feel neutral and two of them prefer slightly warmer conditions. Sixteen respondents prefer no change, while six of them feel other than neutral (e.g. variations from cold to slightly warm). This suggests that changing the temperature for these respondents is likely to result in their discomfort, although their thermal sensation has been other than neural. 94% of the occupants did not change their clothing layer throughout the day. 88% of these respondents either had a sensation other than neutral or preferred a change in the thermal environment at least at some point in the day. Changing clothing layers was not practiced to restore the comfort level. For example, S13 is wearing a jumper at noon, while feeling slightly warm and preferring a slightly cooler conditions. According to the follow up interviews, women in the office did not wear skirts or dresses in the summer in the office, as they found the indoor temperature uncomfortably cool. They also explained that they had to wear extra layers in the office, whilst upon exiting the workplace, they removed those layers.

## 5. Conclusion

This work examined user satisfaction of a steady and uniform thermal environment. A key part of the analysis was done through the application of a novel Visual Thermal Landscaping method in assessing thermal comfort. This is a qualitative visual method, which is useful for a personalised analysis of thermal comfort according to spatial context and meaning.

Overall, the air conditioned sealed office building provided a uniform and a steady thermal environment, indicating a good degree of thermal control and performance. simulation revealed to be able to accurately predict the indoor thermal environment and energy use of this building. The PMV analysis suggested a slightly cool thermal environment and that by increasing the temperature up to 2oC, a high level of user comfort can be achieved. The results of the statistical analysis was in line with the PMV analysis, showing that 32% of the occupants preferred slightly warmer conditions. The temperature was not significantly related to the thermal sensation and thermal preference of the occupants. It suggested a higher tolerance level, as the degree of preferred change was lower than the scale of thermal sensation. The VTL model highlighted the individual differences in perceiving and preferring the thermal environment. It revealed the complexity of thermal comfort within the spatial context of an open plan office and the difficulty of satisfying all with an individual indoor "optimum temperature". It also showed the dynamic aspect of thermal comfort, as the individuals changed their perception and preference throughout the day, although the indoor temperature was quite steady. Studies suggest to provide a variety of thermal environments within the office, so that individuals can select their workstation. This study finds difficulties with this idea, as individuals may not have the liberty to choose their workstation. Their choice is limited to either the availability of a workstation or the need to sit close to their team to encourage teamwork and knowledge transfer purposes. The latter as was the case in this study. Also, the dynamic aspect of thermal comfort suggests that even if the individual finds a specific thermal condition comfortable, they are likely to change their mind throughout the day. This study suggests the application of personalised thermal comfort systems to enhance user comfort and satisfaction.

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# Effects of light and ambient temperature on visual and thermal appraisals

**Maaike Kompier[1], Karin Smolders[1] and Yvonne de Kort[1]**

[1] Human Technology Interaction Group, Faculty of Industrial Engineering and Innovation Sciences, Eindhoven University of Technology, the Netherlands
Correspondence email: m.e.kompier@tue.nl

**Abstract:** More than one third of a buildings' energy consumption is designated for heating and cooling. Therefore, allowing more variations in the indoor temperature provides an energy saving potential. Additionally, these variations are expected to have beneficial health effects on the building occupants. To compensate for potential discomfort amongst them due to these temperature variations, LED lighting may be used as light could influence thermal responses via cortical and sub-cortical brain regions.
Two laboratory studies were performed to examine how different light conditions can influence both visual and thermal appraisals. Temperature was manipulated between these studies: the first was in a thermoneutral environment (21 °C) whereas the latter was performed in a mild cold environment (17 °C). In contrast, light was manipulated within the studies. Participants came to the laboratory on multiple days, during which they were exposed to different light conditions in terms of both correlated colour temperature and intensity. Participants evaluated their visual and thermal experiences repeatedly throughout the session.
We can conclude that visual and thermal comfort are closely related. These findings could be applied in office environments to save energy by controlling the temperature less strictly and compensating potential thermal discomfort with visually comfortable light settings.

**Keywords:** Cross-modal effects, thermal appraisals, visual appraisals, temperature, light

## 1. Introduction

More than one third of the global energy consumption in the 21st century is taken up by buildings (*Energy Efficiency: Buildings*, no date). Space heating and cooling have been indicated by the International Energy Agency (IEA) to offer the most potential for energy savings in buildings. Less use of heating and cooling systems, however, is likely to lead to an indoor environment with a variable temperature instead of a constant one. Previous studies have shown that these variations can be beneficial for energy metabolism and human health (van Marken Lichtenbelt et al., 2017). However, due to this variation, office workers might experience thermal discomfort, especially before acclimatization (Hanssen et al., 2016). Changes in light intensity (Kim and Tokura, 2007) and/or correlated colour temperature (CCT; Candas and Dufour, 2005) may help relieve this short-term discomfort, and additionally, light has the potential to benefit health and productivity. This points to the relevance of studying interactions between climate and light in indoor settings.

Mogensen and English (1926) were the first to refer to a widespread belief of apparent or psychological warmth of colours. Over the years, this belief has been formulated as the hue-heat hypothesis, which associates blue(ish) colours and light to the experience of coolness, whereas red(dish) colour and light are related to the experience of warmth. Scientific evidence for this hypothesis is, however, mixed (e.g. Winzen, Albers and Marggraf-Micheel, 2014; Huebner et al., 2016; Ziat et al., 2016; Chinazzo et al., 2018; te Kulve, Schlangen and van Marken Lichtenbelt, 2018). Another cross-modal psychological association through which light is thought to influence thermal appraisals is the association of bright light with the sun, and therefore an environment may feel warmer in bright light compared to dim light (Xu and Labroo, 2014).

Visual-thermal interactions were investigated in terms of subjective evaluations in a correlational field study by Chinazzo et al. (2018). No statistically significant correlation between light intensity and thermal sensation was reported. However, when splitting the data in three slightly different temperature levels, they did find a small correlation between illuminance and thermal sensation suggesting that, in a relatively cool environment in summer, people do experience a higher thermal sensation when they are in bright light compared to dim light, in line with the cross-modal association described above. Remarkably, the thermal satisfaction in cool and neutral environments did not covary with illuminance. Only in a relatively warm environment the thermal satisfaction was significantly higher in illuminances above 300 lux compared to illuminances below 300 lux. The authors tentatively attributed these findings to thermal expectations induced by the illuminance level (Chinazzo et al., 2018), but as the study was purely correlational, this theory remains to be tested.

Te Kulve et al. (2018) studied similar interactions of light and temperature in a controlled laboratory environment, which could give more insight in explanatory mechanisms. They found an effect of light on thermal experience in a cool environment. A higher CCT of the light was associated with more self-assessed shivering compared to a lower CCT, which is in line with the hue-heat hypothesis. However, thermal sensation and comfort were not affected by the CCT of the light. Brightness of the light did not change the thermal perception of the environment either. In the warm and neutral thermal environments, no statistically significant effects of light - CCT or light intensity - on thermal perception were reported (te Kulve et al., 2018).

Apart from these cross-modal psychological associations that originate largely in cortical brain areas, the subcortical brain region is involved in both visual and thermal comfort evaluations. Correlational analyses by te Kulve et al. (2018) showed that the change in visual comfort was related to a change in thermal comfort in both the cool and the warm environment, which might be explained by these shared origin in the subcortical brain region. This finding further builds evidence for a relationship between light and thermal perception, while suggesting an alternative mechanism tying perception of visual and thermal comfort together. However, still the evidence is limited and any causality in this relationship of visual and thermal comfort is unknown. These findings imply that in uncomfortable thermal environments, the lighting can potentially be used to change visual comfort, and thereby also thermal comfort.

The Chinazzo et al. (2018) and te Kulve et al. (2018) studies report merely modest effects, on only a selection of the variables, and solely in non-neutral thermal environments. The findings of these studies hint towards interesting applications of the interaction between light and temperature perception, however, more research on the interrelationships between these factors is required before it can be employed in real office environments. The current study continues the line of research on cross-modal effects of light on temperature perception. The main research question is:

*What is the effect of light on thermal perception?*

Based on prior research on the hue-heat hypothesis (Candas and Dufour, 2005) and the association with sunlight (Xu and Labroo, 2014), it is hypothesized that both warm and bright light increase the thermal sensation.

The following research questions were formulated to further investigate the dependencies of the effect of light on thermal perception.

*To what extent is this effect of light intensity and CCT moderated by the ambient temperature?*

Based on the work by Chinazzo et al. (2018) and te Kulve et al. (2018), we expect that the effects are more pronounced in the mild cold environment compared to a neutral environment.

*How do thermal and visual comfort relate?*

The relationship between visual and thermal comfort as described in the work by te Kulve et al. (2018) predicts that in case of an increase in visual comfort, thermal comfort might also increase. Therefore, we expect a positive relationship between visual comfort and thermal comfort.

## 2. Method

Two laboratory studies were performed to examine how different light conditions can influence both visual and thermal appraisals. In both studies, participants were exposed to different light conditions and transitions in randomized order, two of which (warm, dim and cool, bright light) were shared between both studies. Ambient temperature was manipulated between these studies: the first was in a thermoneutral environment (Study 1; 21 °C) whereas the latter was performed in a mild cold environment (Study 2; 17 °C). The dependent variables included appraisals, mood, alertness, physiological arousal and thermoregulation. In this Windsor contribution, we investigate the shared within-subjects light manipulation in combination with the between temperature manipulation, and assess how these factors influence visual and thermal appraisals. Currently, the manuscript of Study 1 is under review, whereas the manuscript of Study 2 is being drafted.

### 2.1 Participants

In both studies, only healthy participants were recruited via the J.F. Schouten School for User-System Interaction Research database. The following inclusion criteria applied: no extreme chronotypes (only people in the range of 3.8 < Midsleep < 6.6 on the Munich Chronotype Questionnaire (Roenneberg, Wirz-Justice and Merrow, 2003), based on Zavada et al. (2005)), people using no medication other than the contraceptive pill, and no people who had travelled intercontinentally over the past three months. Participants were screened for this with an online questionnaire prior to the study. In total, we had 61 participants in the studies: 38 participants in Study 1, 23 in Study 2 (Table 1). The studies were approved by the Institutional Ethical Review Board. All participants gave their written informed consent and received monetary compensation for participation.

Table 1. Participants Characteristics

| | Cold (n=23) | Neutral (n=38) | Overall (n=61) |
|---|---|---|---|
| **Gender** | | | |
| Female | 13 (56.5%) | 19 (50.0%) | 32 (52.5%) |
| Male | 10 (43.5%) | 19 (50.0%) | 29 (47.5%) |
| **Age (in years)** | | | |
| Mean (SD) | 23 (± 2.0) | 24 (± 2.9) | 23 (± 2.6) |
| Range | 18 to 26 | 20 to 31 | 18 to 31 |
| **Length (in meters)** | | | |
| Mean (SD) | 1.7 (± 0.13) | 1.8 (± 0.098) | 1.7 (± 0.11) |
| Range | 1.4 to 2.0 | 1.6 to 2.1 | 1.4 to 2.1 |
| **Weight (in kg)** | | | |
| Mean (SD) | 64 (± 11) | 69 (± 11) | 67 (± 11) |
| Range | 47 to 88 | 48 to 95 | 47 to 95 |
| **BMI** | | | |
| Mean (SD) | 22 (± 2.6) | 22 (± 2.5) | 22 (± 2.5) |
| Range | 18 to 27 | 18 to 30 | 18 to 30 |

## 2.2 Setting

Both experiments were conducted in a climate chamber of 3.6x5.4x2.7m3 (WxLxH). Using a partitioning wall, this room was split to create two work spaces in the room. The reflectances of the various surfaces in the room were measured using a Minolta Luminance Meter LS-100. The walls of the climate chamber were off-white with a reflectance of 80.9%, whereas the white partitioning wall separating the two working areas had a reflectance of 91.8%. The grey floor had a reflectance of 27.7%, and the desk was light grey with a reflectance of 49.0%.

## 2.3 Stimuli

In Study 1, the indoor climate was kept constant at a neutral temperature of 21 °C, whereas in Study 2 the indoor climate was set to a mild cold temperature of 17 °C (Table 2). During the sessions, participants wore a standardized clothing set with an estimated clothing value of .7 clo, including insulation of the chair.

Table 2. Environmental Characteristics (averaged per session)

| | Neutral (n=153) | Cold (n=92) |
|---|---|---|
| **Air Velocity (m/s)** | | |
| Mean (SD) | 0.032 (± 0.016) | 0.019 (± 0.0045) |
| Min | 0.011 | 0.010 |
| Max | 0.080 | 0.033 |
| Missing | 0 (0%) | 17 (18.5%) |
| **Relative Humidity (%)** | | |
| Mean (SD) | 48 (± 2.9) | 67 (± 7.4) |
| Min | 42 | 46 |
| Max | 54 | 75 |
| Missing | 0 (0%) | 17 (18.5%) |
| **Air Temperature (°C)** | | |
| Mean (SD) | 20 (± 0.62) | 18 (± 0.14) |
| Min | 20 | 18 |
| Max | 22 | 18 |
| Missing | 0 (0%) | 17 (18.5%) |
| **Black Bulb Temperature (°C)** | | |
| Mean (SD) | 20 (± 0.62) | 18 (± 0.15) |
| Min | 19 | 17 |
| Max | 21 | 18 |
| Missing | 0 (0%) | 17 (18.5%) |

Two light settings were created using two sets of four ceiling-mounted luminaires (PowerBalance Tunable Whites; RC464B LED80S/TWH PSD W60L60), which were installed above each desk. The two lighting conditions purposefully differed substantially in both visual experience and melanopic activation. The warm, dim light condition had a CCT of 2708 K and 97 lux, and the cool, bright condition had a CCT of 5854 K and 1021 lux on the eye. Table 3 shows the α-opic equivalent daylight (D65) illuminances of the two light conditions. In Figure 1 the spectral power distribution of the light conditions is shown.

Table 3. Light Characteristics of the two conditions

| | Warm, dim light (lux) | Cool, bright light (lux) |
|---|---|---|
| ***S-cone-opic*** ($E^{D65}_{v,sc}$) | 26 | 901 |
| ***M-cone-opic*** ($E^{D65}_{v,mc}$) | 75 | 982 |
| ***L-cone-opic*** ($E^{D65}_{v,lc}$) | 99 | 1010 |
| ***Rhodopic*** ($E^{D65}_{v,r}$) | 46 | 891 |
| ***Melanopic*** ($E^{D65}_{v,mel}$) | 37 | 855 |

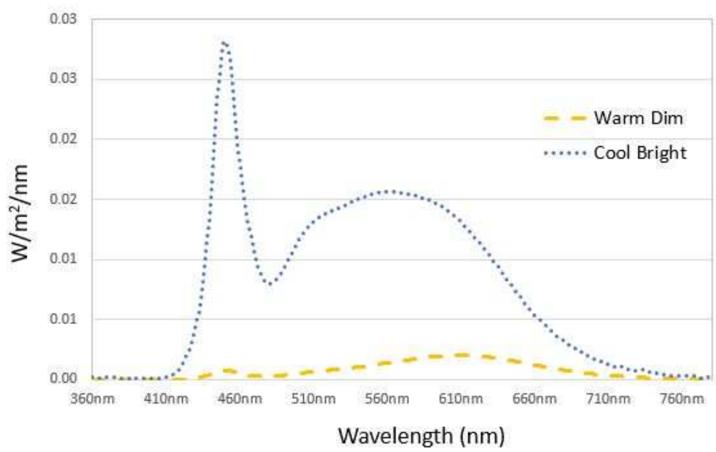


Figure 1. Spectral power distributions of the light conditions

## 2.4 Procedure

In both studies, participants attended four experimental sessions of 90 minutes each, at least one day apart. For the current analyses, only two of the lighting conditions were included (i.e., only the two conditions that were identical between both studies). The protocol of the two studies was highly similar, except for an additional cognitive task in Study 2.

At arrival, participants were guided to their desk in the climate chamber. In baseline lighting (warm, dim light), participants first completed an initial questionnaire, applied the sensors for the physiological measurements and practiced the task(s). After thirty minutes of adaptation to the environment, the measurements started. Physiological measures were taken continuously for an hour, whereas the questionnaire and task were completed every fifteen minutes (four times in total). Methods and results of the physiological measurements, task and non-comfort related self-reports are reported elsewhere. The first measurement block was a baseline measurement, after which the experimental phase of the study started, in either warm, dim or in cool, bright light. In this phase, participants completed three repeated measurement blocks, each fifteen minutes in duration, which were identical to the baseline measurement. Figure 2 shows a schematic representation of this procedure for one session.

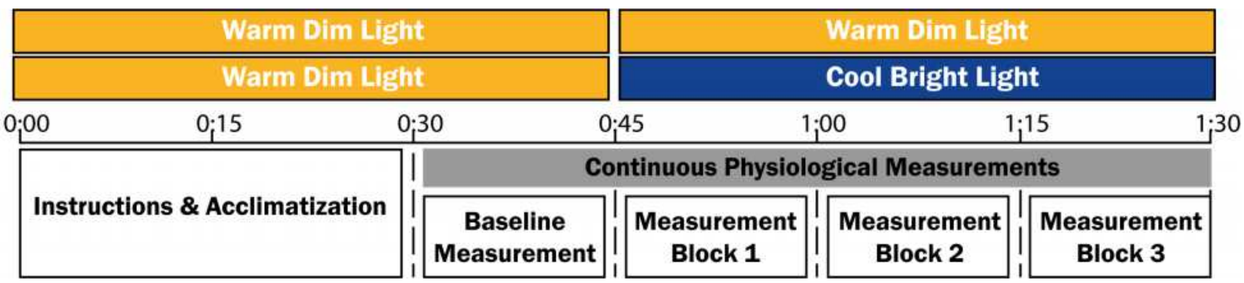


Figure 2. The timing of the light conditions in the procedural overview of one experimental session

## 2.5 Measurements

Thermal appraisals were evaluated using three items based on the ASHRAE standard 55 (ASHRAE, 2004). A discrete seven-point scale was used for thermal sensation (Sensation$_T$: from Cold (-3) to Hot (3)), a binary scale for the evaluation of thermal acceptance (Acceptance$_T$: Acceptable/Unacceptable), and one scale split in two 3-point parts for thermal comfort (Comfort$_T$): from Very Uncomfortable (-2) to Just Uncomfortable (0) and from Just Comfortable (1) to Very Comfortable (3)).

Visual appraisals were probed using five items that were aligned with the thermal comfort items. In the visual appraisals, a distinction was made for the perceived intensity and the perceived colour of the light. Therefore, the visual sensation of the lighting intensity ($Sensation_{VI}$) and experienced colour of the light ($Sensation_{VC}$) were evaluated separately using seven-point discrete scales ($Sensation_{VI}$: from Dim (-3) to Bright (3) and $Sensation_{VC}$: from Very Warm (-3) to Very Cool (3)). Again, a binary scale was used for visual acceptance of the lighting ($Acceptance_V$: Acceptable/Unacceptable). Visual comfort was evaluated using the same scales as for $Comfort_T$, although separately for the intensity and colour of the light. However, as they correlated highly and had a Cronbach's α of .86, they were averaged into one visual comfort measure: $Comfort_V$.

**2.6 Statistical Analysis**

After outlier and normality checks, analyses were done using mixed linear models with Participant and Session nested within Participant as Random Intercepts on the combined dataset of Study 1 and Study 2. The effect of Light Condition on sensation regarding the intensity and CCT of the light was tested separately to examine whether the manipulation had been visible. In this model, Light Condition was the only fixed effect that was included.

Additionally, mixed linear models with Participant and Session nested within Participant as Random Intercepts were run for $Sensation_T$ and $Comfort_T$. In these models, Light Condition, Thermal Condition and the interaction between Light Condition and Thermal Condition were included as fixed effects to predict thermal perception. For post-hoc comparisons, Tukey's corrections were applied. Due to the skewed distribution of $Acceptance_T$, this variable was only visually inspected.

Last, to explore parallels in light-induced variations in visual comfort and thermal comfort as well as the relation between visual and thermal comfort, two multilevel models were run. Both included Participant and Session nested within Participant as Random Intercepts. The effect of Light Condition, Thermal Condition and the interaction between Light Condition and Thermal Condition (fixed effects) on $Comfort_V$ (DV) was tested, as well as the relation between $Comfort_V$ and $Comfort_T$.

All statistical analyses were performed using RStudio Version 1.1.463.

**3. Results**

**3.1 Manipulation Check**

Significant main effects of Light Condition on $Sensation_{VI}$ and $Sensation_{VC}$ were found in the expected direction. Participants perceived the warm, dim condition as significantly less bright ( EMM= -0.5 ± SE = 0.1) compared to the cool, bright light (EMM = 1.6 ± SE = 0.1; $t(1,59) = 18.4$; $p<.001$). The sensation of the colour of the light in the warm, dim condition was warmer (EMM =0 .5 ± SE = 0.1) compared to the cool, bright light (EMM = -1.5 ± SE = 0.1; $t(1,118) = -12.8$; $p<.001$).

**3.2 Main effect of light on thermal perception and interaction of light and temperature**

$Sensation_T$ was significantly affected by the Thermal Condition only (Figure 3; t(1,103) = 2.6, p = 0.01). Thermal sensation was lower (EMM = -1.0 ± SE = 0.1) in the cold environment compared to the neutral environment (EMM = -0.6 ± SE = 0.1). There was no significant main effect of Light Condition (t(1,59) = 1.5, p=0.14) and no interaction effect between Light Condition and Thermal Condition (t(1,59) = -1.5, p=0.14).

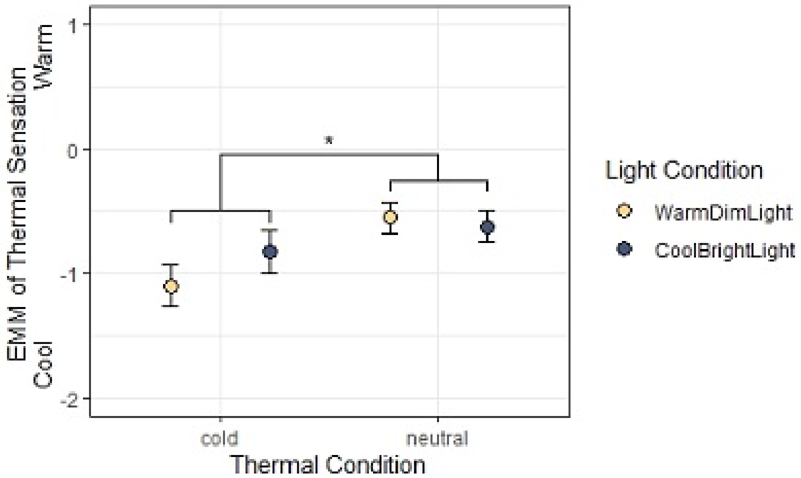


Figure 3. Main effect of temperature on thermal sensation. The error bars show the standard errors around the estimated marginal means of thermal sensation. *: p<0.05

$Acceptance_T$ was only visually inspected due to the skewed distribution. Overall, only 7.1% of the total occasions (n=365) were voted as unacceptable. In the warm, dim light in the cold environment, least participants evaluated the thermal environment as acceptable (78.3%). In the other conditions, thermal acceptance was always well above 90%.

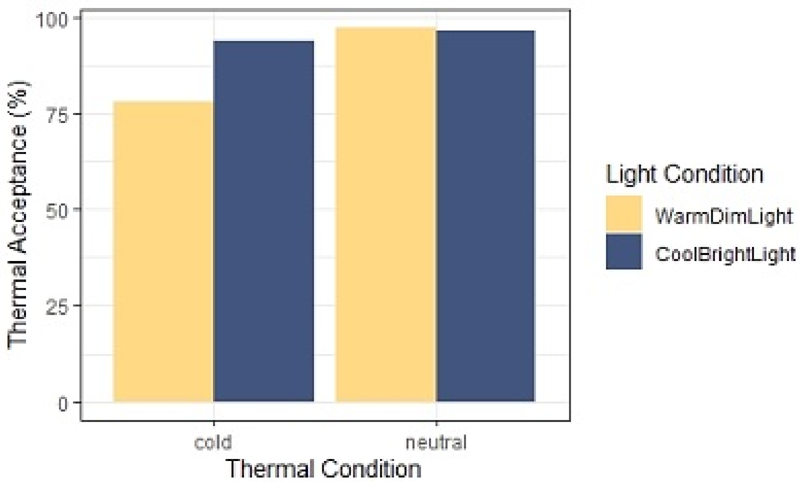


Figure 4. Percentages of the thermal acceptance votes

The temperature significantly affected Comfort$_T$ (t(1,107) = 3.4, p < .001). In the neutral environment, the average thermal comfort vote was 1.3 (EMM ± SE = 0.1), whereas – in line with the expectations – in the cold environment this was lower (EMM = 0.8 ± SE = 0.1). The effect of Light Condition and the interaction between the Light Condition and Thermal condition showed no statistically significant effects, but suggested non-significant trends with t(1,59) = 1.8 with p = 0.07 and t(1,59) = -1.7 with p = 0.09, respectively. Post-hoc comparisons with Tukey's correction only demonstrated a significant effect of temperature in the warm, dim light condition (Figure 5; t(1,106) = -3.4, p = 0.01). In the cold environment with warm, dim lighting, thermal comfort votes were 0.6 (EMM ± SE = 0.2), whereas in the neutral environment the average thermal comfort vote in warm, dim light was 1.4 (EMM ± SE = 0.1). In the cool, bright light, there were no significant differences between the two Thermal Conditions (t(1,107) = -1.4, p = 0.50). There were also no significant differences in thermal comfort between the two lighting conditions in the neutral (t(1,59) = 0.5, p = 0.97) or the relatively cold environment (t(1,59) = -1.8, p = 0.26).

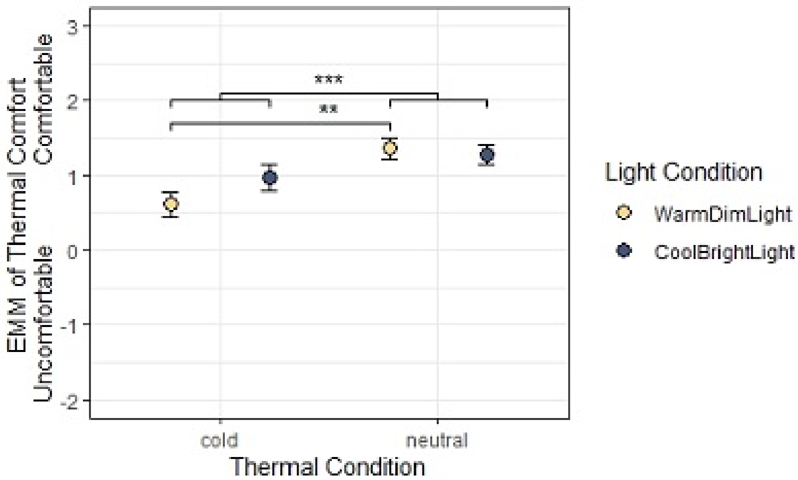


Figure 5. Interaction effect of light and temperature on thermal comfort. The error bars show the standard errors around the estimated marginal means of thermal comfort. **: p <0 .01, ***:

### 3.3 Exploring interrelationships between thermal and visual comfort

The effect of Thermal Condition and the interaction between the Light Condition and Thermal condition showed no statistically significant effects on Comfort$_V$ (t(1,118) = 1.1 with p = 0.28 and t(1,59) = -1.0 with p = 0.34, respectively). The main effect of Light Condition on Comfort$_V$ showed a non-significant trend (Figure 6: t(1,59) = -1.7, p = 0.09). Post-hoc comparisons with Tukey's correction demonstrated that in the neutral thermal environment, participants evaluated the warm, dim light as more visually comfortable (EMM = 1.4 ± SE = 0.1) compared to the cool, bright light (EMM = 0.8 ± SE = 0.1). In the cold environment no such difference between the light conditions was significant (t(1,59) = 1.7, p = 0.32). In both the warm, dim light condition (t(1,117) = -1.1, p = 0.70) and the cool, bright light condition (t(1,117) = 0.2, p = 1.00) there were no differences in Comfort$_V$ between the two Thermal Conditions.

The relationship between $Comfort_V$ and $Comfort_T$ was significant ($p < 0.001$): a higher visual comfort vote was related to a higher thermal comfort vote ($\beta = 0.2 \pm SE = 0.1$).

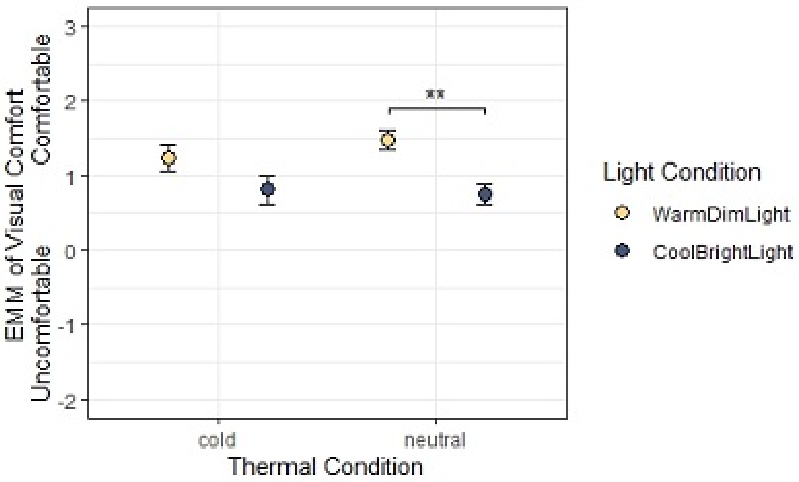


Figure 6. Effect of light and thermal condition on visual comfort. The error bars show the standard errors around the estimated marginal means of visual comfort. **: p <0.01

**4. Discussion**

In order to explore how light and temperature can be used to realize energy savings in buildings, we studied cross-modal effects of light and temperature. Additionally, interrelationships between visual and thermal perception were examined. In two separate studies, the effects of various light conditions on visual and thermal appraisals were tested. The first study was performed in a neutral environment and the second in a mild cold environment. In this Windsor contribution, the results of these studies were merged to examine the combined effects of light and temperature on visual and thermal appraisals.

Thermal comfort and sensation both were largely dependent on the ambient temperature. Participants perceived the cold environment as colder and more uncomfortable compared to the neutral environment. Similarly, the visual comfort and sensation were mainly influenced by the light conditions. In general, the warm, dim lighting was evaluated as warmer and dimmer compared to the cool, bright lighting. In addition to those findings, the current study demonstrated a significant relationship between visual and thermal comfort. The positive but small β-estimate indicates that when visual comfort increases, thermal comfort increases slightly as well. These findings are in line with the results found by te Kulve et al. (2018) who performed a similar analysis on several studies. In these studies, temperature was manipulated within participants, whereas light was manipulated both within and between the participants. Any potential directionality or causality in this relationship is difficult to demonstrate. A potential explanation of the relationship might be the central regulation of comfort in the insula of the brain (Frackowiak, 2004). The insula processes the influence of peripheral cues and translates these to consciously experienced emotional states. This physical proximity of the two concepts in processing in the brain may result in the relationship as was found in the current study. Discomfort concerning either the visual or the thermal environment may therefore lead to perceived discomfort of the other modality. This central regulation of comfort might also result in the inability of human beings to specify correctly and completely where the general feeling of discomfort that they experience originates from, which could lead to an overlap in thermal and visual comfort responses.

In addition to the relationship between thermal and visual comfort, some cross-modal effects emerged. The effect of light on visual comfort was only visible in the neutral, relatively comfortable, condition. In the cold environment, the effect of the light conditions on visual comfort was attenuated. Furthermore, thermal comfort only differed between the two ambient temperatures in warm, dim light. However, this difference in thermal comfort due to different ambient temperatures was not present in cool, bright light. As suggested by Chinazzo et al. (2018), this might be explained by the thermal expectation of the occupant, which influences the occupants' comfort. They suggested that the quantity of light could potentially affect people's thermal comfort. In the current study, not the quantity, but the colour of the light might have induced a thermal expectation of a certain type of environment. In the cool, bright light condition, participants may have had the expectation of a cool environment. When this expectation was met by the mild cold ambient temperature, participants thermal comfort changed.

Interestingly, in the current study no effects of intensity and CCT interventions on thermal sensation were found. The psychological association of bright light with sun light and therefore warmth (Xu and Labroo, 2014) was not confirmed by this study. This might be explained by the employed conditions. In this study, we contrasted warm, dim light with cool, bright light which both do not evoke the psychological association with sunlight and therefore warmth. Additionally, the current study could not provide evidence for the existence of the hue-heat hypothesis (Candas and Dufour, 2005). Variations in CCT of light might not be strong enough to influence participants' belief of the temperature. Possibly, only saturated colours are able to actually evoke differences in thermal sensation (Winzen, Albers and Marggraf-Micheel, 2014; Ziat et al., 2016). Additionally, the intensity and correlated temperature effects may have cancelled each other out based on the combination of the association between bright light and warmth and the hue-heat hypothesis.

The main finding of the current study is the significant relationship between visual and thermal comfort, which would plead for a holistic approach when studying any comfort related question. Whenever one aspect in the environment leads to discomfort, this is likely to influence the comfort experience of any other aspect. Using less heating and/or cooling in an office building to save energy should therefore be applied vary carefully as this may render thermal discomfort and thereby influence the general comfort experience.

This study also had some limitations that need to be taken into account when interpreting the results. Both studies were conducted in the rather clinical setting of a climate chamber without daylight access. If comfort is a holistic experience, it may well be that participants' comfort was greatly influenced by this setting. Field studies could be done to test whether there is a relationship between thermal and visual comfort in real life. Additionally, the temperature manipulation turned out to be smaller than expected due to the temperature of the outdoor air that was used to heat, cool and ventilate the room. In Study 1 in winter, it was hard to heat the room up to the target temperature of 21 °C, whereas in summer the climate chamber could not be cooled down to 17 °C. Despite the relatively small difference in ambient temperature, the seasonal thermal adaptation is expected to have increased the perceived ambient temperature as, generally, people prefer slightly higher temperatures when it is warmer outside compared to when it is colder outside (Hoof, 2010). Additionally, the temperature manipulation coincided with seasonality, which may have influence the results based on the study by Chinazzo et al. (2018).

Future research could specifically focus on determining any potential causality in the relationship between thermal and visual comfort. Additionally, thermal effects of light intensity and correlated colour temperature should be disentangled in order to confirm which psychological association, the hue-heat hypothesis or the association of bright light with warmth, is causing these cross-modal effects. Finally, in the current study warm, dim lighting was used as a baseline light condition, which resulted in a transition before the cool, bright light condition, in contrast to no transition in the warm, dim light condition. Future studies could examine whether such a transition can lead to changed sensation independently of the light condition that is being transitioned to.

From this study, we can conclude that visual and thermal comfort are closely related. However, whether thermal comfort can be influenced by light, or visual comfort by ambient temperature, is a complicated question. There could be multiple mechanisms at play, such as the hue-heat hypothesis or an association of bright light with warmth. The interrelationships between visual and thermal comfort are expected to be caused by the central regulation of comfort in the brain mainly. These findings could be applied in office environments to save energy by controlling the temperature less strictly and compensating potential discomfort with visually comfortable light settings.

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# Indoor Daylight Supply – a must have for all climates

**Renate Hammer[1] and Peter Holzer[2]**

[1] Institute of Building Research & Innovation, AT, renate.hammer@building-research.at
[2] IPJ Ingenieurbüro P. Jung, Konzepte für innovative Gebäude, AT,holzer@jung-ingenieure.at

**Abstract:** Post-industrial urban lifestyles lead to a dominant share of a lifetime spent indoors. The physiological need for a daylight supply is not any longer covered that received during outdoor activities. Thus, there is a rising need to deliberately design indoor environments for sufficient daylight quality. This is proven to be valid for all climates of the world, not at least the hottest and generally most extreme ones. Within Europe, a milestone was acheived by the approval of the new European Standard EN 17037 "Daylight of buildings" by end of 2018. It is the first Europe-wide standard to deal exclusively with the design for, and provision of, daylight. EN 17037 formulates minimum levels of indoor daylight qualities as regards (1) illuminance levels, (2) visual contact to the surrounding, (3) direct sunlight in rooms and (4) prevention of daylight glare. The most relevant, scientifically evidenced facts on the health related aspects of daylight supply are included and discussed in the context of the new standard EN 17037, demonstrating the comprehensiveness of the consideration of the non-visual aspects of daylight design in the Standard.

**Keywords:** daylight, illuminance, direct light, glare, non-visual perception

## 1. Problem and Relevance

There are a multitude of complementary relationships that arise in the interplay between man-made structures and light. By taking appropriate measures in the design process, the intensity and nature of these complementary relationships may be influenced.

Utilization of daylight as a resource for thermal building optimization, when regarded in light of larger societal goals, is particularly environmentally significant for its near-avoidance of greenhouse gas emissions. Thermal building optimization leads to a quantitative and qualitative reduction of available interior daylight due to several factors. These include a preference for compact building forms, an increase in building component dimensions through use of highly efficient insulation materials, the specific positioning of windows in relation to site-specific sun path, and the use of highly effective, functional glazing. Simultaneously, the general rise in room comfort and the availability of high-performance artificial lighting have led to current living conditions, in which post-industrial populations spend approximately 90% of their lives indoors, and in turn, are exposed to a reduced supply of daylight. (Jantunen et al.; 1998)

Thus the issue must be raised of what impacts this indoor living, especially in thermally optimized building, may have on human photobiology. And more over if the minimum levels of indoor daylight qualities required within the EN 17037 of 2018 focusing on the needs of human visual comfort do meet the needs of human photobiology in this conflict of aims.

## 2. Hypothesis

There is a causal relationship between the evidence of epidemic occurrences of solar radiation deficiency disorders, extended periods of time spent indoors behind glazing in general, and that spent in thermally optimized buildings in particular. The minimum levels of indoor daylight qualities required within the EN 17037 can mitigate but not solve this problem.

## 3. Methodology

### 3.1. Quantitative and qualitative physiological response of indoor solar radiation in

In order to investigate the quantitative and qualitative physiological response of the daylight spectrum that reaches the room, a potential study was conducted. First the reference conditions were described by determining key evaluation times, then the measured surfaces were ideally positioned and a concrete geographic location was defined.

Subsequently the radiation intensity of terrestrial solar radiation under the defined reference conditions was calculated as a result of the computer-generated radiation path through the atmosphere and its subsequent trajectory through the selected functional glazing. (Gueymard et al., 2004) (ISO 15469, 2004)

Finally, the photobiological response potentials resulting from further refraction of the radiation behind the glazing were calculated using selected response curves. Special attention was given to pre-vitamin D3 photosynthesis, erythema formation, melatonin suppression, and light sensitivity in photopic vision conditions. The resulting response potentials were compared with the borderline and threshold values, and effective doses compared with values from existing studies in medical literature. The light triggered activation of cytochrome c oxidase responsible for energy production within human cells can only be mentioned thus binding threshold values are still missing. (Karu, 2010)

### 3.2. Comparison with standard recommendations of EN 17037

As EN 17037:2018 - Daylight in buildings should be applied to all spaces with daylight openings that may be regularly occupied by people for extended periods the qualities defined within cover a relevant span of the time humans spend indoors. Thus the recommendations given in the document for exposure to sunlight, adequate subjective impression of lightness, for providing an adequate view out and to limit glare are investigated in detail to point out their efficacy in human health and comfort to create context with the demands resulting chapter 3.1.

Spectral transmission at the reference times displays characteristic, significantly heterogeneous courses with respect to the four selected glazing types: double-glazed insulated glass, triple-glazed insulated glass, double-glazed solar protection glass, and uncoated single-glazed glass.

It is clearly shown that every investigated pane is virtually impermeable for the UV radiation spectrum that is necessary for the process of photosynthesis of pre-vitamin D3. (CIE 174, 2006) Moreover, the attained erythema dose falls drastically. Both the threat of erythema formation as well as the chances of skin adaptation are remote.

In the visible light spectrum, however, the selected glazings are so transparent that the photophysiological-relevant threshold values are significantly exceeded for all presently known non-visual indirect effects of melatonin suppression. (DIN SPEC 5031-100, 2015) Nonetheless the reduced radiation intensity is often readily perceptible, leading to increased use of artificial lighting as daylight compensation.

Photobiological effects are also identified in the infrared spectrum. Due to the lack of response curves, however, response potentials cannot be determined.

## 4. Results

Spectral transmission at the reference times displays characteristic, significantly heterogeneous courses with respect to the four selected glazing types: double-glazed insulated glass, triple-glazed insulated glass, double-glazed solar protection glass, and uncoated single-glazed glass.

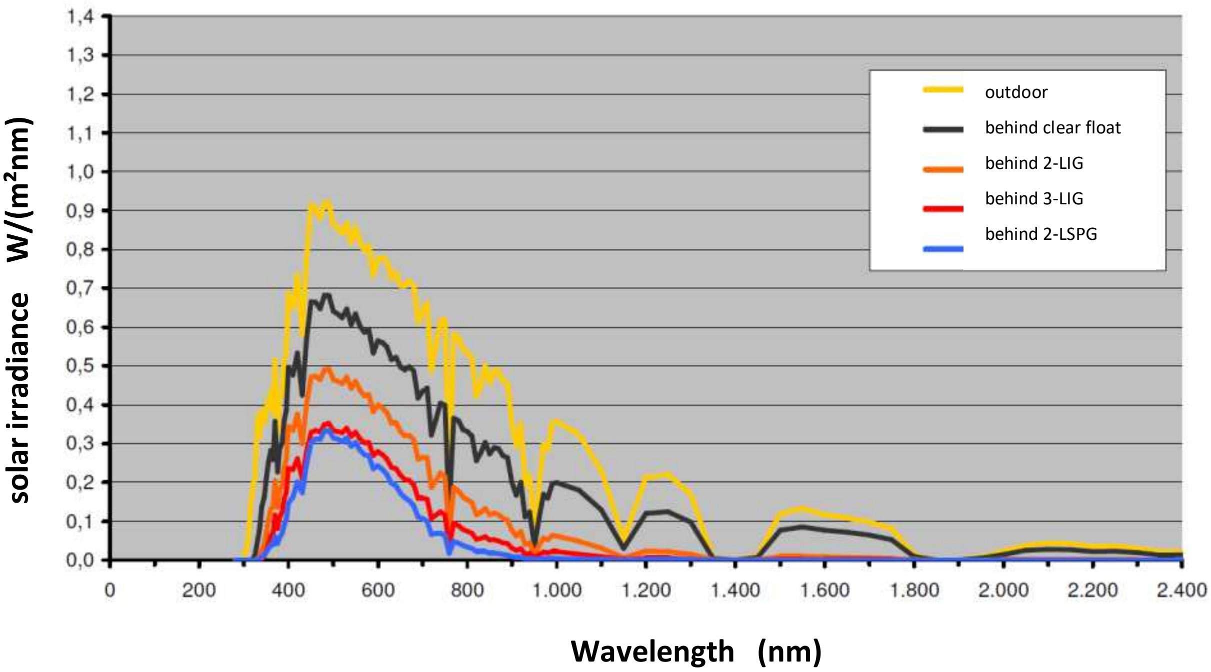


Figure 1. Spectral distribution: solar irradiance, June 15th , 12:00 am, Vienna.

It is clearly shown that every investigated pane is virtually impermeable for the UV radiation spectrum that is necessary for the process of photosynthesis of pre-vitamin D3. Moreover the attained erythema dose falls drastically. Both the threat of erythema formation as well as the chances of skin adaptation are remote.

In the visible light spectrum, however, the selected glazings are so transparent that the photophysiological-relevant threshold values are significantly exceeded for all presently known non-visual indirect effects of melatonin suppression. Nonetheless the reduced radiation intensity within room depth is often readily perceptible, leading to increased use of artificial lighting as daylight compensation. (Plischke, 2016)

As defined daylight is the visible part of global solar radiation it could be expected that the recommendations of EN 17037 should only cover aspects of visual comfort. (Schierz, 2016) But the target values set lets one assume that non-visual effects of the melanopic system have been taken into consideration. (Lucas et al., 2014)

Photobiological effects are also identified in the infrared spectrum. Due to the lack of response curves, however, response potentials cannot be determined. But referring to the recommendation of the EN 17037 that the glazing material of the view opening should provide a view that is perceived to be clear, undistorted and neutrally coloured the need to provide radiation of the red and near infrared spectrum can be justified. This is a crucial argument in avoiding the use intensely tinted solar protection glazing.

## 5. Recommendations

This paper provides scientifically based, decision-facilitating principles for the utilization of daylight supply, at a specific site for context-oriented building planning.

Daylight falls in the building interior only after having been quantitatively and qualitatively compromised by high-tech functional glazings. Thus, it is our recommendation to increase daylight supply in general and that of direct sunlight in particular. From this perspective, consideration of the spatial geometry of direct solar radiation when designing building volumes, shells and floor plans becomes absolutely essential.

Every building that is intended to house the extended use of indoor spaces by its occupants should be connected with the outdoor space in such a manner that regular, sufficient consumption of unfiltered daylight is assured. One should explicitly consider the building's functions in dealing with the requirements of living, working, care-giving, supervising, instructing and similar activities within buildings.

Exploitation of thermal energy through the utilization of passive solar design approaches and technologies in buildings, as well as promoting the most extensive use of availabile daylight possible, requires proportionately large windows as collecting surfaces. In order to avoid resulting superfluous thermal gains in the warm season, one must provide for uncompromising, effective, functionally independent, user-specific shading systems for the interior rooms coupled with ventilation options.

We strongly recommend ensuring natural night-time darkness in the interior, especially in sleeping areas, or in cases of artificial exterior light, taking appropriate planning measures to create such conditions.

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# Ethnic differences in preferred air flow temperature

**Yifen Qiu[1,2], Simon Hodder[1], & George Havenith[1],**

[1] Environmental Ergonomics Research Centre, School of Design and Creative Arts, Loughborough University, LE11 3TU, UK;
[2] School of Aeronautical Science and Engineering, Beihang University, Beijing 100191, China

**Abstract:** Ethnic differences in thermoregulatory responses in exposure to heat and cold have been described but evidence for differences in comfort thermal sensation is limited. Comparisons of thermal perception responses to different climates between different ethnicities are complicated by the use of thermal sensation and comfort scales in different languages.
Therefore, in the present study a different approach was chosen, i.e. rather than exposing individuals to fixed conditions and asking for a rating, the individuals were instructed to adjust the climate to their personal preference. It is hypothesised that this will lead to a sensation rating of neutral, and of thermal comfort in all individuals.
Groups of Chinese and British male individuals were recruited for the study, which was approved by the local research ethics committee. Participants wore identical clothing and were seated in front of an airflow generating device which allowed individual temperature control of the airflow aimed at the participant. In the setup, participants were exposed to approximately 600 wm$^{-2}$ of solar radiation. For the first 30 minutes, no airflow apart from the chamber airflow at 25°C was present. Then, the cooling system was activated and participants controlled the airflow temperature for the next 15/20 minutes.
In the first 30 minutes thermal ratings increased due to the radiation exposure to ‘warm’ and ‘slightly uncomfortable’ with a preference to ‘being cooler’. Once the adjustment was allowed, sensations quickly changed to ‘neutral’, ‘comfortable’ and ‘no change’. The selected temperature of the cooling airflow was on average around 5 to 7 degrees higher in the Asian groups compared to the British..
It is concluded that relevant differences in preferred comfort temperature in this simulation exist, with British groups requiring a more powerful cooling to attain comfort in the conditions tested.

**Keywords:** Thermal comfort, Thermal Preference, Ethnicity.

## 1. Introduction

Standards for the determination of thermal comfort (ASHRAE standard 55, ISO 7730) are used worldwide for all individuals irrespective of their ethnicity, nationality or country of origin. ASHRAE Standard 55 (ASHRAE 2013) recognises that there is a thermal comfort difference in winter and summer months within the same country, but it does not consider thermal preference differences of individuals from different ethnicities. More recently comfort standards have been extended with the addition of the ‘adaptive model’ which suggests that comfort temperatures in naturally ventilated buildings vary for different climatic regions. Whether such differences are related to short and long term adaptation of individuals to the local climate or are actual ethnic differences is so far unclear.

Many studies investigating ethnicities have been undertaken in their typical geographical location, thus potentially confounding ethnicity with adaptation. It is known that acclimatisation influences a person’s physiology. Particularly in the heat, their ability to produce sweat is increased following repeated exposure to the environment. Whether thermal sensitivity or preference is altered by this process is unclear.

An additional confounding factor in most studies investigating ethnic variation in thermal comfort is that of the language in which the subjective scales are presented. Predominately, most comfort studies use the standardised scales of thermal sensation, comfort and thermal preference (ISO 10551) and for comparisons of ethnicities these are translated into the respective languages. However, the wording for these scales, e.g. 'warm' or 'hot' in different languages may have different meanings/connotations in different regions/cultures (Tochihara et al. 2012). This complicates comparisons of subjective responses of different ethnic groups to the same condition. An alternative, is to allow people to control and select their preferred comfort temperature for the environment, (Fanger et al. 1977).
This experimental protocol allows the quantification of the participants actual comfort temperature.

The present study aimed to determine preferred comfort temperatures for Chinese and British males in a non-uniform thermal environment with the addition of solar radiation.

## 2. Method

### 2.1. Participants

Thirty-one Chinese and twenty British physically healthy male participants volunteered in this study. Participants provided written, informed consent before participating in this study, which was approved by the Loughborough University Human Ethics Committee. All Chinese participants had been living in the UK for a minimum of 2 months.

Participants wore a standardised clothing ensemble of white cotton/polyester (65/35%) long sleeve shirt, beige cotton/polyester (65/35%) trousers in the appropriate size, and their own under garments and shoes giving an estimated intrinsic insulation 0.11 m2 °C W-1 (0.7 Clo).

### 2.2. Test facility

The study was undertaken in a climate chamber in the Environmental Ergonomics Research Centre at Loughborough University. The ambient air temperature was set at 25°C, relative humidity 50% and an air velocity of $0.2ms^{-1}$. In addition, two simulated solar radiation lamps (Thorn OQI 1000), provided a radiant heat load on the participants torso and upper legs of around $620Wm^{-2}$.

A Personal Climate System (PCS) enabled the participant to control the temperature of an airflow directed towards their upper legs and upper body. The PCS gave a range of temperatures at the outlets between approximately 12 and 39 °C. The PCS temperature was controlled by the participant using an analogue dial, with markers indicated the direction colder and warmer. There was a fixed air flow through the system, which exited through a set of 8 air vents (80mm diameter) on the upper front face of the PCS.

Participants sat in front of the PCS on a height adjustable chair. The experimental set up and chair height was arranged to maintain the same solar radiation load and air flow at the participant's upper body.

### 2.3. Physical and physiological measurements

A series of objective physiological measures were taken on each participant. Prior to testing, participants weight (Mettler Toledo, UK ±5 grams), height (Leicester Height Measure) and body fat percentage based on 7-point skinfold measurement (BI-Harpenden Skinfold Callipers) were measured.

**2.4. Subjective measurements**

Subjective assessment of thermal sensation (TS), thermal comfort (TC) and thermal preference (TP) were explained to the subject. The scales were based on those defined in ISO 10551 and included additional Chinese translation of the descriptors.

The participants' ratings of thermal sensation, thermal comfort and thermal preference were taken every 5 minutes throughout the duration of the experiment.

**2.5. Experimental procedure**

Participants arrived at the laboratory approximately 30 minutes prior to the experiment. They were taken to a thermal-neutral (21 °C, 40-60% rh) preparation room. They completed medical consent forms and were briefed on both the withdrawal criteria and the experimental procedure. This included information regarding the PCS control guide, timetable of PCS adjustment and the subjective scales of thermal sensation (TS), thermal comfort (TC) and thermal preference (TP) were explained.

The participant was then taken into the climatic chamber and sat in the chair and gave their initial subjective ratings, and these were subsequently taken at 5-minute intervals for the rest of the experimental session.

At 30 minutes the PCS' airflow to the participant was activated and the participant was allowed to use the Personal Climate System adjustments. They were instructed to adjust the air temperature to maintain their thermal comfort. At the end of 5 minutes the participant had to stop adjusting the air temperature. From then on, participants were given 30 seconds in every 2 minutes to make fine adjustments to the air temperature of the PCS. Participants were instructed to select a temperature that would provide them with long term comfort. The periods of non-adjustment were used to encourage participants to select a longer-term comfort temperature and avoid a multitude of excessive adjustments. The period of adjustment lasted for 20 minutes, upon which the experiment ended. Total duration of the experimental exposure was 50 minutes.

**2.6. Statistics**

Test results were analysed (SPSS statistics, IBM, Version 23) for equality of variance (Levene's Test) and subsequently for ethnicity using an ANOVA, focussing on the results at the end of the personal control period. Subjective scores were compared using a non-parametric test, i.e. a Mann-Whitney U test for independent samples.

## 3. Results

The environmental conditions were similar for both groups of participants, Table 1.

Table 1, Group characteristics and test results. Coloured cells indicate significant difference (p<0.05) between Chinese and Western European.

| Variable | nation of participant | N | Mean | Std. Deviation |
|---|---|---|---|---|
| Height (m) | Chinese | 31 | 177.9 | 6.2 |
| | British | 20 | 181.9 | 7 |
| Mass (kg) | Chinese | 31 | 69.05 | 8.17 |
| | British | 20 | 80.38 | 12.1 |
| surface area ($m^2$) | Chinese | 31 | 1.86 | 0.13 |
| | British | 20 | 2.01 | 0.16 |
| Age (years) | Chinese | 31 | 23.2 | 1.7 |
| | British | 20 | 21.6 | 1.9 |
| Body fat (%) | Chinese | 31 | 9.9 | 3.6 |
| | British | 20 | 7.3 | 2.6 |
| Solar radiation ($W/m^2$) | Chinese | 31 | 620 | 24 |
| | British | 20 | 621 | 15 |
| Shaded air temperature (°C) | Chinese | 31 | 25.1 | 0.2 |
| | British | 20 | 24.9 | 0.1 |
| Humidity of the chamber (%) | Chinese | 31 | 48 | 0.7 |
| | British | 20 | 48.2 | 0.6 |
| Thermal Sensation score | Chinese | 31 | -0.02 | 0.61 |
| | British | 20 | -0.1 | 0.72 |
| Thermal discomfort score | Chinese | 31 | -0.23 | 0.5 |
| | British | 20 | 0 | 0 |
| Thermal preference score | Chinese | 31 | -0.03 | 0.41 |
| | British | 20 | -0.05 | 0.22 |
| Air flow temperature Leaving vents (°C) | Chinese | 31 | 22.2 | 4.8 |
| | British | 20 | 16.7 | 3.3 |
| Air flow temperature in front of subject (°C) | Chinese | 31 | 26.6 | 1.9 |
| | British | 20 | 24.5 | 1.4 |
| | British | 20 | 34.3 | 0.6 |

### 3.1. Scores of Thermal Sensation (TS), Thermal Comfort (TC) and Thermal Preference (TP)

In Figure 1, during the first 5 min of experiment in the chamber, TS increased rapidly with exposure to the solar radiation, after which it levelled off until the personal cooling was activated at 30min. TC and TP changed rapidly during the first 5min of heating, followed by a slow but steady increase in discomfort and an increase in thermal preference to 'cooler' until cooling was started. All scores show that the target of getting participants warm and uncomfortable, and needing cooling to compensate for the heating in the chamber during the first 30 min was achieved. While there seemed to be a trend that Chinese felt warmer in the heating period, their thermal preference was less ‘cool’ than the British at that time, suggesting that they preferred a warmer environment. After 30min, when cooling air started to flow to the front of participants and participants were able to adjust the air flow temperature, scores changed rapidly and were all close to 0 (‘neutral’, ‘comfortable’ and ‘no change’) after the first 5 min adjusting, showing that the system allowed the participants sufficient control to achieve their personal comfort level and that the participants understood the control option. Scores of the two groups remained close to 0 during the last 15min air flow temperature adjusting period, with score differences between the two groups being very small and not significant for all but the discomfort score which was 0.23 higher in Chinese (P=0.04).

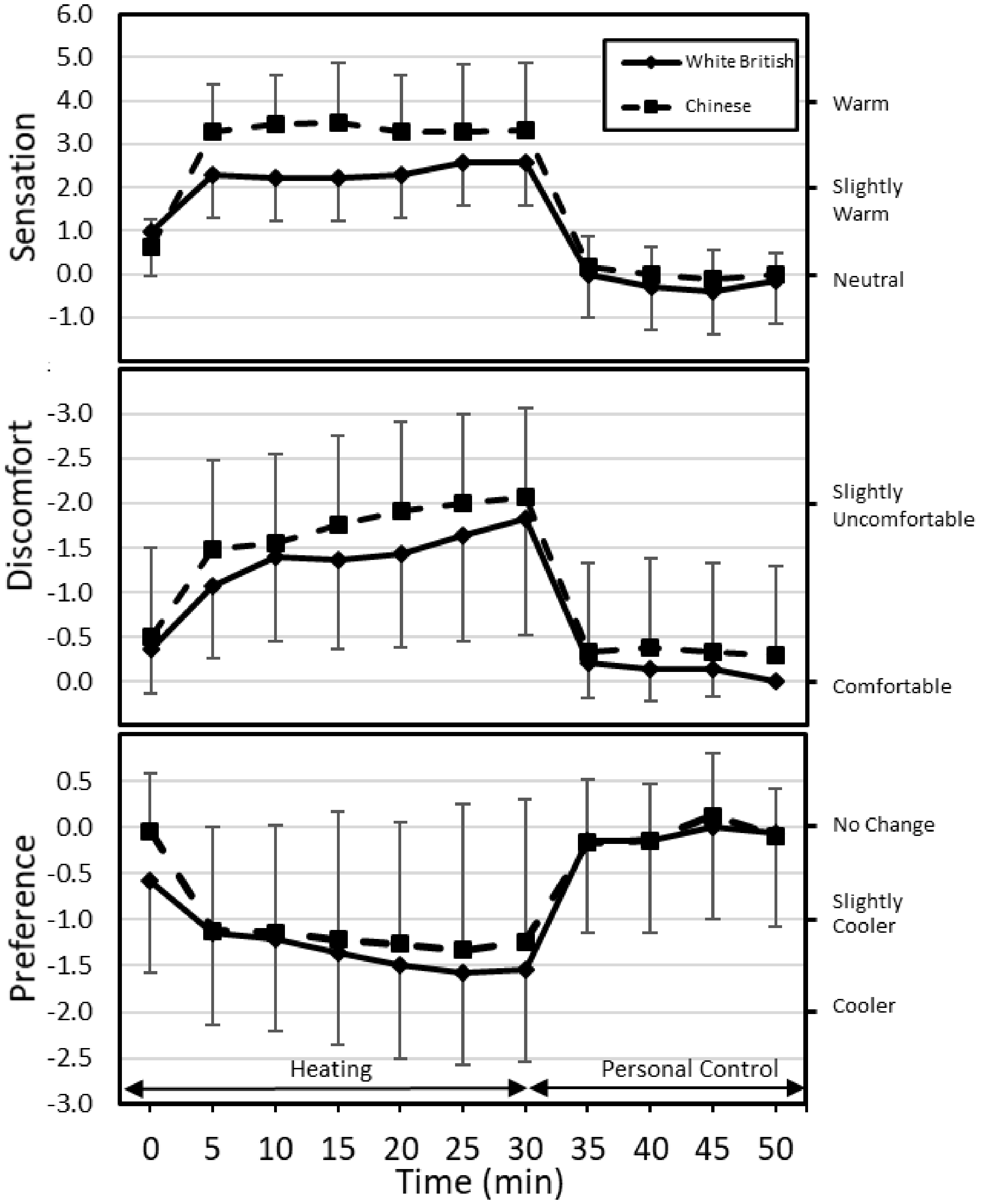


Figure 1, Rating of thermal environment for Thermal Sensation, Thermal Comfort and for Thermal Preference

## 4. Discussion

The aim of the experimental design was to compare two groups of different ethnic background, Chinese and Western-European, for their thermal preference, and thermal comfort in a personal climate adjustment design, allowing the participants to achieve their optimal thermal comfort and thus avoiding any language issues in interpretation of discomfort or sensation scales.

The main outcome of the study is that for all the Chinese group selected substantially (4.7-5.8°C) and significantly warmer outlet temperatures of the PCS, leading to significantly warmer (1.6°C - 2.2°C) temperatures in the microclimate air next to the skin in the areas targeted by the PCS.

Chinese participants also tended to feel warmer in the warming phase (moderate temperature and solar radiation, but no control), though this did not lead to a stronger preference for wanting to be cooler than for the Europeans. These observations are relevant to the development and design of personalised climate systems as well as to analysis of thermal comfort in buildings.

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# Feasibility of using personal fans for increasing thermal comfort in mixed-mode shared work spaces in Brazil: a field study

**Maíra André[1], Renata De Vecchi[1] and Roberto Lamberts[1]**

[1] Laboratory of Energy Efficiency in Buildings, Department of Civil Engineering, Federal University of Santa Catarina, Brazil.
*Corresponding author: maira.andre@gmail.com

**Abstract:** Recent studies on thermal comfort have shown that personal conditioning systems can increase percentage of users in thermal comfort in shared spaces while reducing energy consumption. Although underused in Brazil, personal fans have great potential in this context. Therefore, the main objective of this research is to evaluate the feasibility of using desk fans in shared office spaces to increase thermal comfort during Subtropical hot season. A field survey was performed in two open offices applying questionnaires and, simultaneously, environmental conditions measurement during two periods: one with regular use of HVAC and operable windows and other with availability of individual desk fans. Despite the expected increase in thermal comfort, thermal acceptability and neutral sensation, there was no statistically significant difference between the mean votes of users in the period with and without desk fans. Nevertheless, the main impact of desk fans availability was on the possibility of increasing local air velocity and adjustment according to the great variability of preferences verified among users. Nevertheless, it was verified that the noise produced by the equipment was a barrier to increasing air movement, therefore, equipment design is important for assuring maximum potential achievement of user-centric control with personal conditioning systems.

**Keywords:** Thermal comfort, Desk fan, Personal conditioning system, Field survey, Open office

## 1. Introduction

Recent studies on thermal comfort have shown that personal conditioning systems (PCS) can increase users' thermal comfort and allow energy consumption reduction (Zhang et al., 2015; Brager et al., 2015; Schiavon et al., 2010). This is due to the possibility of personal adjustment of local environmental conditions, increasing users' control over the microclimate of their workstation and satisfying their individual preferences (Melikov, 2016). The thermal comfort generated by adjusting the workstation allows the environment temperature to be set at a wider temperature range (Melikov, 2016; Brager et al., 2015; Veselý and Zeiler, 2014). So, the air conditioning energy consumption decreases with no prejudice to users' thermal comfort. Depending on local climate, the extension of set point temperature can achieve 30 to 70% energy savings (Hoyt et al., 2015).

In Brazil, where a hot and humid climate prevails, the increment of air speed is an effective strategy to produce thermal comfort with less energy consumption for most of the year. High acceptability and preference for more air movement is verified among occupants of naturally ventilated and mixed mode operation buildings in Brazil (Lamberts et al., 2013; Candido et al., 2010; De Vecchi et al., 2017). Therefore, studies indicate a great potential of using ceiling fans in class rooms and offices to increase users thermal satisfaction during warm periods or climate locations (Candido et al., 2010; De Vecchi et al., 2017).

However, ceiling fans generally enhance the whole environment air speed not allowing an individual control like provided by desk fans. Moreover, due to the greater distance from user, ceiling fans demand more power than a desk fan for reaching the same air velocity close to the occupant, resulting in a higher energy consumption (Schiavon and Melikov, 2009). Despite being widespread in the market, the presence of desk fans in Brazilian offices is not so common. Most of the studies about desk fans impact on thermal comfort are conducted in climatic chambers (Zhang et al., 2015; M. He et al., 2017; He et al., 2018), which may indicate a different thermal acceptability and perception from those verified in the field (Zhang et al., 2010). Despite the high acceptability temperature identified with the use of desk fans in offices that reaches 30 °C (Zhang et al., 2015; Y. He et al., 2017; M. He et al., 2017), when users have control or can express their opinion, they prefer to activate the air conditioning at lower temperatures (He et al., 2018; Shetty et al., 2019). Hence, the goal of this study is to identify office occupants' willingness to use desk fans and the actual capacity of these equipment to increase thermal comfort during the warm period.

## 2. Method

In order to assess the impact of desk fan usage on users' thermal comfort, a field study was carried out in two shared open offices. Questionnaires were applied simultaneously with indoor environment thermal variables measurement. Both offices had operable windows and air-conditioner units (splits), which allow users to alternate between natural ventilation and air conditioning. Throughout the study period, users were able to freely control the environment systems and adapt their condition, like modifying their clothing. Researchers assessed users' thermal perception by providing them with individual desk fans and comparing two different periods, one with equipment available and another with no equipment available.

### 2.1. The selected offices

This study was conducted at two shared work spaces (A and B) in Florianópolis, a southern city of Brazil, located at latitude 28° South and longitude 48.5° West. Florianópolis' climate is characterized as subtropical with hot summer (Peel et al., 2007), reaching mean maximum temperatures of 34 °C, and mean relative humidity of 85%. However, there is high thermal daily and monthly fluctuation allowing the mean minimum to reach 15 °C during the hot season (INMET, 2018). The Field survey was carried out in summer, from January 23$^{th}$ to February 6$^{th}$ in office A and from February 28$^{th}$ to March 16$^{th}$ in office B.

Both offices are located on the Campus of Federal University of Santa Catarina. Office A is a work space occupied by undergraduate and graduate students with 88 m², while office B has 102 m² and is occupied by engineers responsible for the campus buildings' maintenance. Thirteen occupants participated on the study in each office; their disposal in the room layout is indicated in grey in Figure 1. The split machines are indicated in light blue, and the one in green in office A was not working. Each office occupant had a personal computer. In office B, all natural ventilation openings are composed by sliding windows, while office A has top hung windows in northeast façade and sliding windows in southwest façade.

**Office A** **Office B**

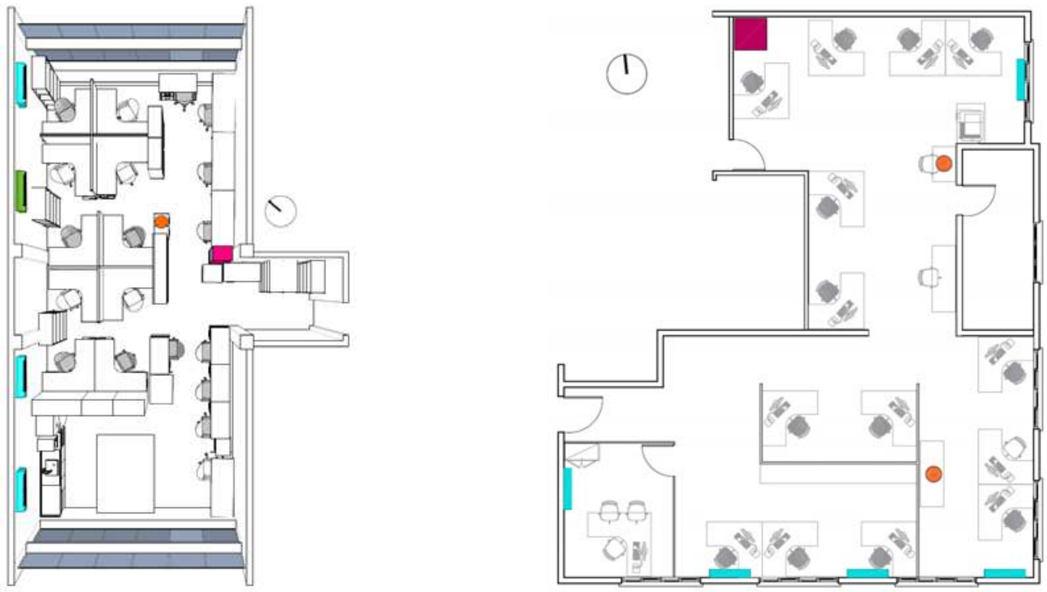


Figure 1. Offices A and B layout: surveyed occupants in grey; Split equipment in blue (one not working in green); server cabinet in maroon; microclimatic station in orange.

Considering the differences between offices, subjects' profile is slightly different, as shown in Table 1. In office A, gender proportion is more even than in office B; and younger people prevail in both cases. These characteristics are also reflected in body mass index (BMI), calculated by the WHO recommended equation (WHO, n.d.). The index indicates normal weight prevails in occupants of office A, while in office B there are more people that are overweight; one of them is classified as obese (BMI ≥ 30.0). The dress code in office B is also a bit more formal than in office A, and thus, clothing insulation was 0.10 higher, but still similar in both offices, as well as the metabolic rate.

Table 1. Subjects' anthropometric characteristics and personal variables during the study

| **Office** | **A** | | **B** | |
|---|---|---|---|---|
| **Gender** | 54% Male / 46% Female | | 83% Male / 17% Female | |
| **Age** | 77%<br>15%<br>8% | 20-30 years<br>31-40 years<br>41-50 years | 50%<br>17%<br>25% | 20-30 years<br>31-40 years<br>41-50 years |
| **BMI** | Mean 21.9 ± 2.1 | | Mean 26.1 ± 4.3 | |
| **Clo** | Mean 0.47 ± 0.11 | | Mean 0.57 ± 0.08 | |
| **Met** | Mean 1.08 ± 0.15 | | Mean 1.04 ± 0.14 | |

### 2.2. Measurement protocol and instrument

Orange dots in Figure 1 show the position of microclimatic stations used in the field study. As shown in Figure 2a, a hotwire anemometer was also used additionally for instant and localized measurements (close to users). The microclimatic stations registered indoor parameters such as air temperature, air velocity, relative humidity and globe temperature. Office B was monitored with two stations due to the environment non-uniformity; thus, a single point would not represent accurately the office conditions.

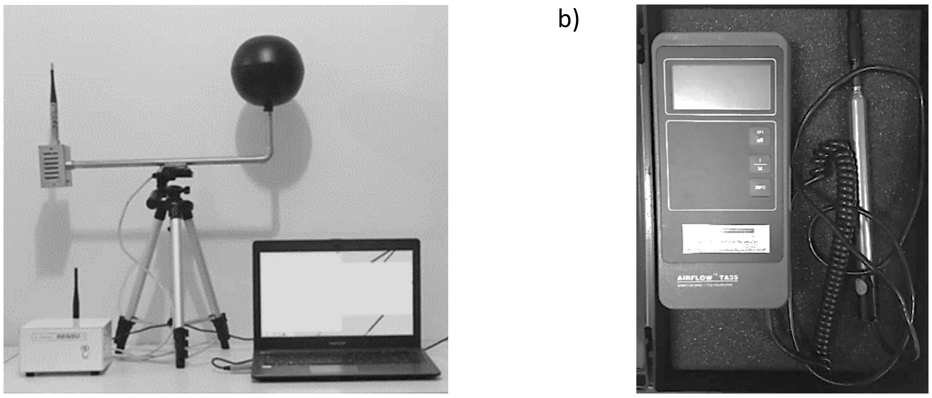
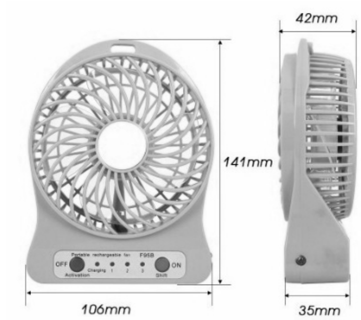



Figure 2. Measurement instruments: a) Microclimate station; and b) hot wire thermo anemometer.

The indoor environmental conditions were collected throughout the day (from 9am to 6pm), while the handheld thermo anemometer was used in the specific moments when occupants were answering the applied questionnaire to measure the air speed at different body spots. After a 20 minutes interval from the survey beginning (to account for acclimatization and metabolic rate stabilization), users were asked to fulfil an online questionnaire sent to their smartphones or email. The campaign was carried out in two stages: 1) one week with regular use of existing on-site systems (HVAC and operable windows); and, 2) one week and a half with provision of individual desk fans. The period with fans was a little bit longer to account for users' adaptation due to the presence of the new equipment. On the last day, another questionnaire was applied to identify users' perceptions of fan effect and to evaluate their experience. The mean outdoor environmental conditions were obtained through the nearest meteorological station data.

The supplied USB desk fan is a rechargeable equipment with a lithium battery, 10 cm diameter, and 3 activation levels as indicated in Table 2.

Table 2. Desk fans manufacturer information

| | **Manufacturer information** | |
|---|---|---|
|   | **Electrical Power (W)** | 4.5 |
| | **Electric current (A)** | 0.5-1 |
| | **Electric tension (V)** | 5~9 |
| | **Number of fan blades** | 4 |
| | **Activation levels** | 3 |

The main questionnaire included an initial section with users' anthropometric data (age, gender, height and weight) applied once. Other personal information such as activity and clothing insulation were requested twice a day once in the morning and once in the afternoon , as well as the second part of the questionnaire. The second part aimed to assess thermal perception including four questions about thermal perception, two questions about air movement, one on air quality acceptance and another one about local thermal discomfort. Table 3 shows the thermal dimensions and the answering scales. The local discomfort question asked users to indicate the type and body part where the local discomfort was felt.

Table 3. Second questionnaire section about thermal perception – thermal dimensions and scales

| | | |
|---|---|---|
| **Thermal acceptability** | Binary scale: Acceptable; Unacceptable | |
| **Thermal sensation** | 7-value scale: from +3 (hot) to -3 (cold) | |
| **Thermal comfort** | 4-value scale: +2 (very comfortable); +1 (just comfortable); -1 (just uncomfortable); -2 (very uncomfortable) | |
| **Thermal preference** | 3-value scale: +1 (hotter); 0 (no change); -1 (colder) | |
| **Air quality acceptability** | Binary scale: Acceptable; Unacceptable | |
| **Air movement acceptability** | Binary scale: Acceptable; Unacceptable | |
| **Air movement preference** | 3-value scale: +1 (more); 0 (no change); -1 (less) | |
| **Local thermal discomfort: type and relative affected body part(s)** | 3 types: warmth discomfort; cold discomfort; draft discomfort | 5 body parts: Head; torso; back; arms; hands; legs |

A third part was only answered during the period when occupants had desk fans to indicate their status (on/off), activation level, targeted body parts (face, neck, torso, arms, hands, none). The last question of the section was asked when the fan was on: "what is your eye sensation now compared to when the fan was off?" with three possible answers: "drier"; "the same, I feel no change", "less dry". A last part of the questionnaire was applied once after the whole survey was complete to evaluate fan usage. Here, users were asked to indicate their driving motivations to use or not the fan and to rate their accordance in a 5-value scale, from total agreement to total disagreement.

The collected data was organized in spreadsheets so the users' votes could be correlated to environmental conditions and compared to each other. To do so, the average environmental condition of each user at the answering moment and the corresponding operating temperature according to ASHRAE were calculated. The ambient systems operation was also registered (air conditioning or natural ventilation). The main questionnaire resulted in 383 answers, while the final part – answered just once by each person – resulted in 26 responses. Statistical analyses were performed to compare the results of periods with and without fans available, by applying the Welch's t-test. Chi-square test was also applied to evaluate the independency between variables, as well as determination coefficient for their linear correlation. All statistical analyses considered a 90% confidence interval.

## 3. Results

### 3.1. Environmental conditions during the study

Results from indoor environment measurement are presented in Table 4, separated by office and fan availability period. The t-test indicated significant differences between operative temperature (TO), relative humidity (RH) and air velocity (Vel) between offices A and B.

Table 4. Indoor environmental conditions per period

| | TO (°C) | | | | RH (%) | | | | Vel (m/s) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Office** | **A** | | **B** | | **A** | | **B** | | **A** | | **B** | |
| **Desk fan** | w/o | w/ | w/o | w/ | w/o | w/ | w/o | w/ | w/o | w/ | w/o | w/ |
| **Maximum** | 28.1 | 29.1 | 27.5 | 27.7 | 69 | 76 | 77 | 86 | 0.27 | 1.32 | 0.34 | 1.50 |
| **Mean** | 26.6 | 27.2 | 24.8 | 25.6 | 57 | 58 | 61 | 59 | 0.12 | 0.23 | 0.11 | 0.22 |
| **SD** | 0.86 | 1.02 | 1.02 | 0.9 | 8 | 9 | 8 | 7 | 0.05 | 0.27 | 0.07 | 0.25 |
| **Median** | 26.5 | 27.3 | 24.5 | 25.6 | 60 | 60 | 58 | 59 | 0.10 | 0.14 | 0.10 | 0.10 |
| **Minimum** | 25.4 | 25.4 | 23.3 | 23.5 | 45 | 43 | 50 | 45 | 0.04 | 0.00 | 0.03 | 0.00 |

Moreover, significant difference in indoor TO and Vel was identified between the periods with (w/) and without (w/o) desk fans available in each office. The difference in air speed was expected due to the effect of fan activation on air movement. However, no significant difference was expected in operative temperatures, since the surveys were performed in consecutive days.

It was also verified a dependence pattern in the outdoor air temperature (Text) to office identification (office A or B) and fan availability (w/ or w/o) by the chi-square test. In Figure 3, it can be observed that outdoor air temperature was similar in both analysis periods in office A, while a significant difference is found in office B.

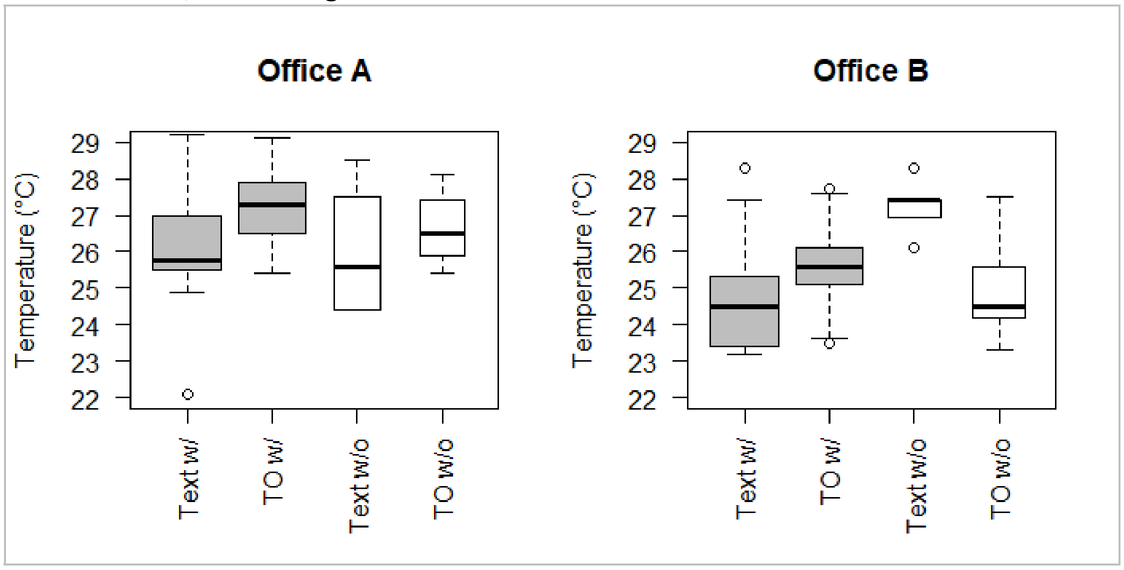



Figure 3. Indoor operative temperature (TO) and Outdoor temperature (Text) in each analysis period by office

In addition, indoor operative temperature in office A remains higher than outdoor in both periods while in office B, during the period without fans, the median indoor operative temperature was lower than the outdoor, which relates to the air conditioning (AC) use. Figure 4 shows the frequency of day periods (mornings and afternoons) in which the AC was on. Thus, the highest frequency of use was observed on office B during the period without fans (B w/o), coinciding with higher outdoor air temperature.

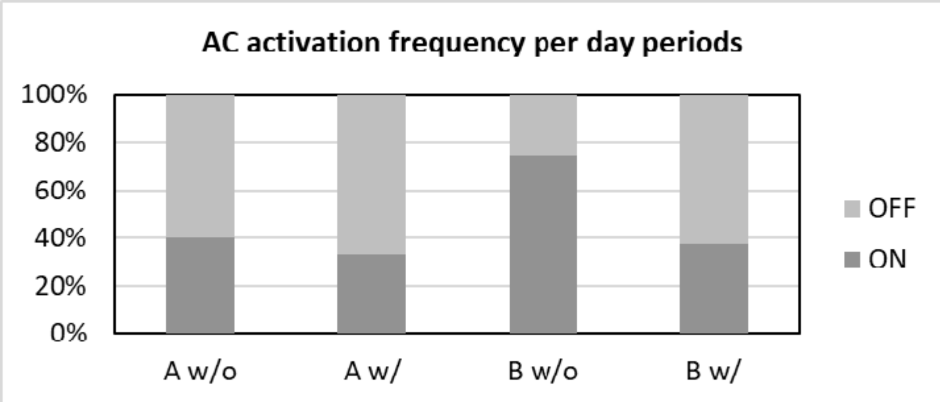


Figure 4. Air conditioning (AC) activation frequency per day period (morning and afternoon)

The use of air conditioning was lower in office A, and a slight difference is verified between the frequency of use during the period with and without fan availability. In office A, the operative temperature at which users turned the air conditioning on was higher, 28.0-30.0 °C, while in office B it was 25.6-27.7 °C. These differences do not support the assumption that the fan availability allowed the reduction of AC usage. However, air conditioning activation has an important impact on desk fan activation. As can be seen in Figure 5, the occurrence of fan activation was higher when air conditioning (AC) was off, suggesting that the space was running in natural ventilation (NV) mode.

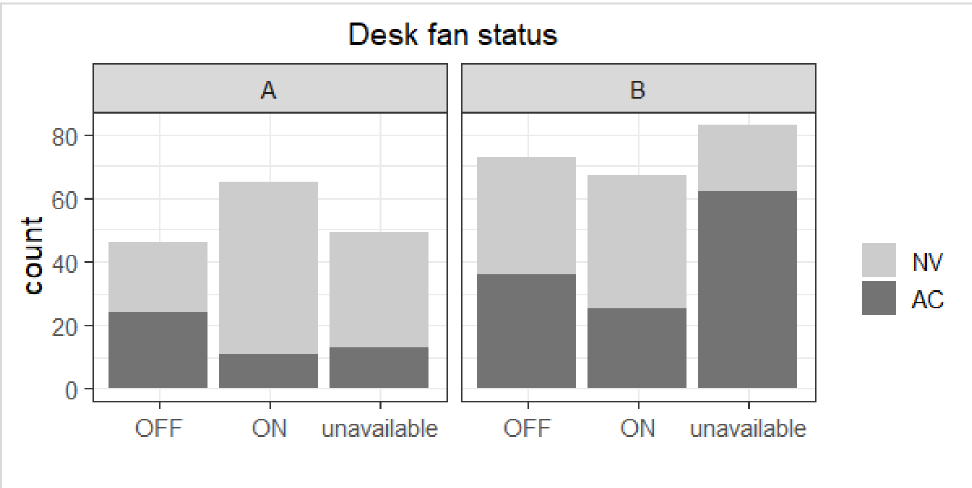


Figure 5. Desk fan use *versus* conditioning mode: Natural Ventilation (NV) or Air conditioning (AC) per office

### 3.2. Thermal perception

To analyse the impact of fan availability on users' thermal comfort, a comparison of thermal perception votes between study periods is presented. In office A, 166 responses were collected against 223 in office B.

Thermal conditions were indicated as acceptable in 99% of the votes, showing no difference between the period with or without fan availability. Also, there were no responses indicating "very uncomfortable" conditions. Thermal comfort votes, as shown in Figure 6, indicate a small change on "Very comfortable" votes and proportional decrement in "just uncomfortable" votes considering the periods when desk fans were available (w/).

The statistical comparison between mean thermal comfort votes indicated no significant differences, since “just comfortable” votes prevailed in both periods.

Figure 6 also indicates a higher percentage of users from office B presenting uncomfortable votes, however the difference between offices was not significant either.

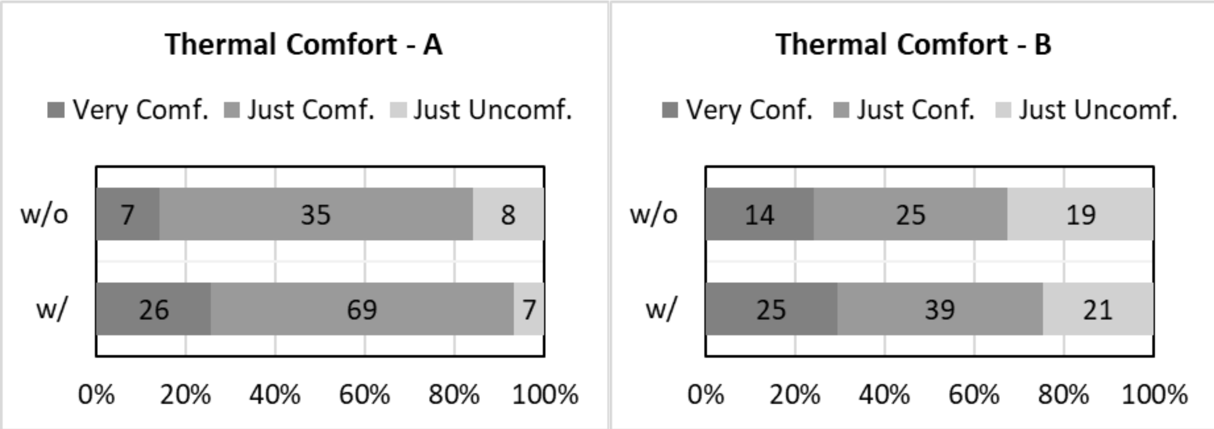



Figure 6. Thermal Comfort votes per period and office

In the case of thermal sensation, two unexpected results were identified in Figure 7. In office B, there was 8% reduction in “slightly cool” sensation with desk fans availability, and the onset of warm sensation in office A, representing 4.5% of the votes. These circumstances are supposed to relate to the air conditioning activation, which in the case of office B, was more frequent in the period without fans and may have caused a reduction in thermal sensation. In office A, in the same period, the AC was less activated and the average temperature was higher (see Figure 3), which may have caused warmth discomfort to some users.

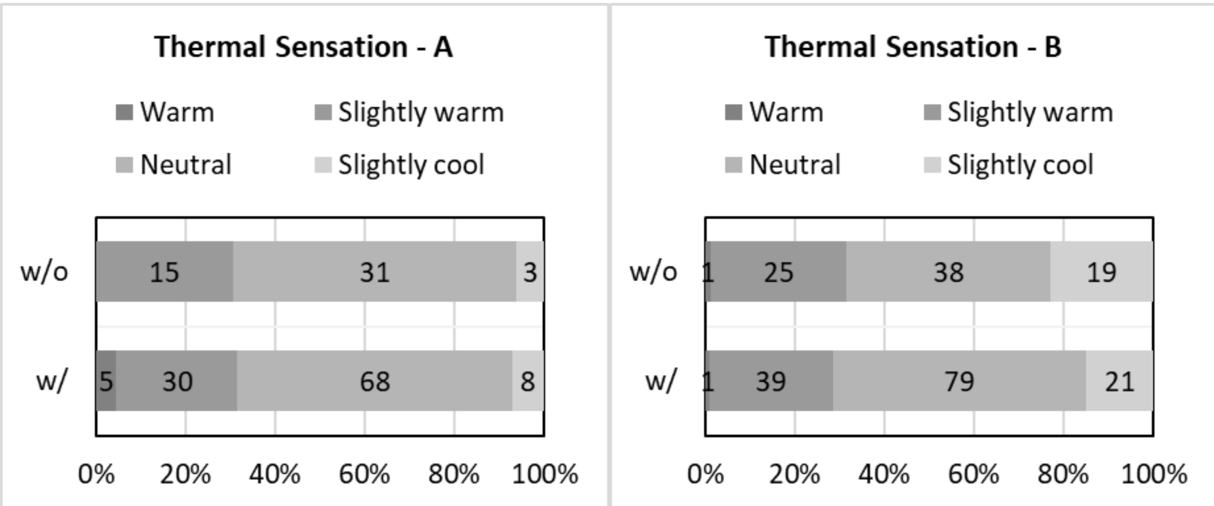



Figure 7. Thermal Sensation votes per period and office

Anyway, these differences are quite subtle and the greatest impact of fan availability was found on air movement acceptability and preference votes. As per Figure 8, the preference for more air movement was reduced by 10% in both offices, which brings the averages significantly closer to neutral point – no change. This indicates that the possibility of increasing the air movement was the main perceived effect of having desk fans available, allowing local control and adjustment to users’ preferences. The air movement acceptability also increased significantly with fans available.

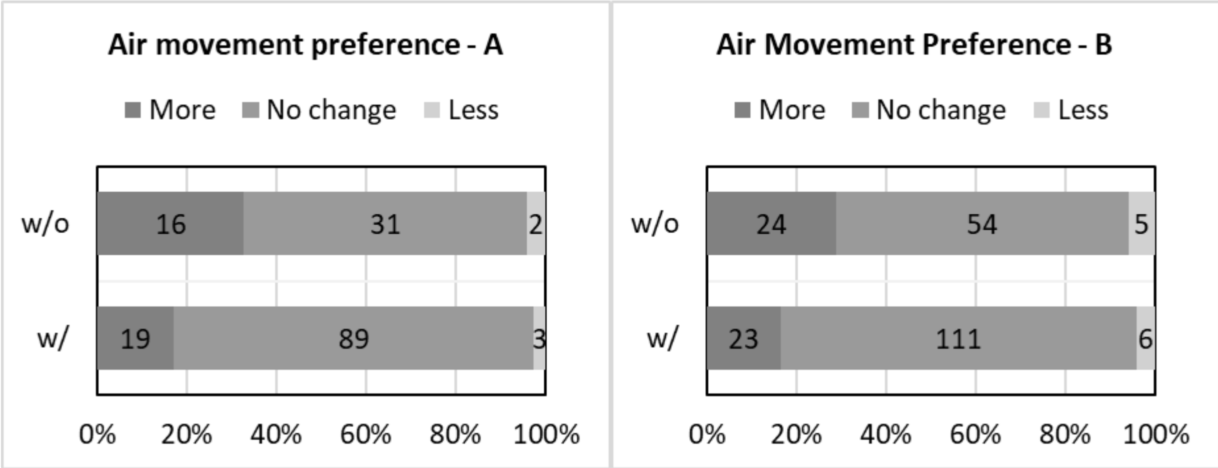



Figure 8. Air movement preference votes per period and office

A significant impact was also verified on local discomfort, as shown in Figure 9. Some kind of local discomfort was verified in 35% of responses, and most of it (20%) occurred when users had no access to desk fans. According to Figure 9, the warmth discomfort is recurrent in both periods; however, it was significantly higher when users did not have desk fans. The fans allowed the reduction of warmth discomfort in the chest, arms, back and head; the legs were less affected, but the discomfort in this region was similar. In the case of cold discomfort, no significant differences between periods were verified; however a higher occurrence is noted in the period without fans in Figure 9. It was identified that cold discomfort occurs when the air conditioning (AC) is on and never when only the desk fans are on, as can be seen in Figure 10. Even warmth and draft discomforts are higher with AC activation than with fan activation.

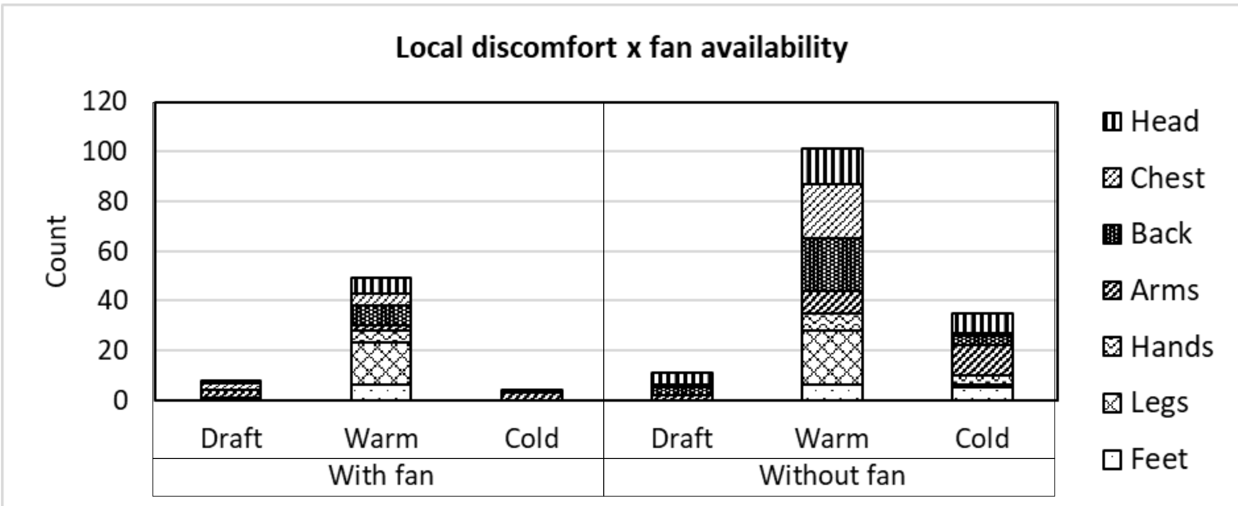



Figure 9. Local discomfort *versus* fan availability – type of discomfort and affected body part

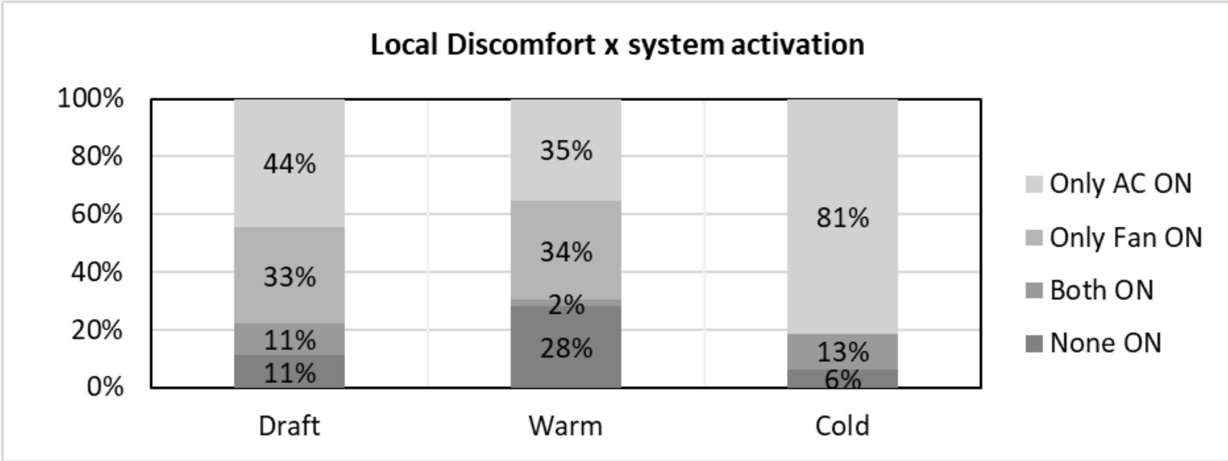



Figure 10. Local discomfort *versus* systems activation per type

Regarding thermal preference and air quality, there was no noticeable difference between survey periods. Table 5 presents a summary of the statistical tests and average votes, where p values lower than 0.10 indicate statistically significant difference of means in a confidence level of 90%.

Table 5. Summary of t-test results on users' votes

| | **Mean vote** | | **P value** | **What does that mean?** |
|---|---|---|---|---|
| | **w/ fans** | **w/o fans** | | |
| **Thermal acceptability** | 0.99 | 0.99 | 0.96 | Most considered it acceptable. No significant difference. |
| **Thermal Comfort** | 1.01 | 0.92 | 0.26 | Most considered it just comfortable with no sig. difference |
| **Thermal Sensation** | 0.21 | 0.15 | 0.45 | Most were in thermal neutrality and there was no sig. difference |
| **Thermal Preference** | -0.28 | -0.27 | 0.80 | Most preferred "no change" to cooler with no significant difference |
| **Air movement acceptability** | 0.97 | 0.92 | 0.09 | Most accepted but it was more acceptable with fan availability |
| **Air movement preference** | 0.13 | 0.25 | 0.03 | The availability of fans allowed a significant reduction of mean to a value closer to "no change" |
| **Air quality acceptability** | 0.99 | 1.00 | 0.32 | Most considered it acceptable and there was no sig. difference |
| **Draft discomfort** | 0.04 | 0.06 | 0.39 | Most had no draft discomfort and there was no sig. difference |
| **Warmth discomfort** | 0.21 | 0.35 | <0.01 | There was significant higher warmth discomfort in the period without fans |
| **Cold discomfort** | 0.07 | 0.11 | 0.27 | Most had no cold discomfort and there was no significant difference |

### 3.3. Desk fan use

During the period they were available, the use of fans varied widely among users. Figure 11 shows some users (A13, A9, A10, B7 and B10) had it turned on at more than 85% of the response time while others did not turn the fan on at all (A6, A12, B5, B9 and B11). It can also be noted a predominance of the first fan activation level among those who turned it on.

The desk fans were on in 59% and 48% of response period in office A and B, respectively, and in 60% and 67% of those votes the first level speed was chosen.

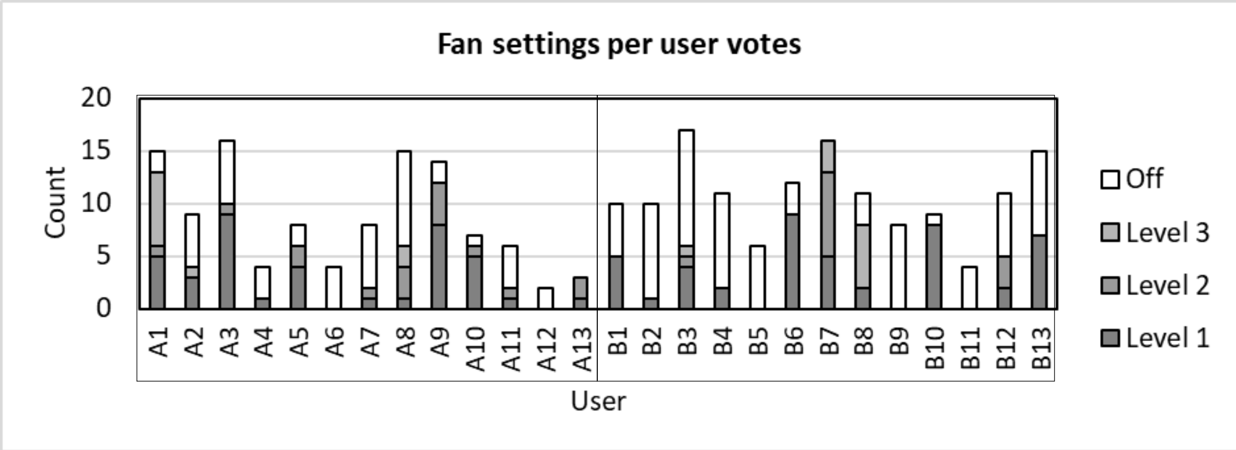



Figure 11. Fan settings per user votes during the period of fans available

People chose to locate the fan in different places of their desk, which influenced the air speed reaching the body and their affected area. Most of the votes (47%) indicated it was targeting their torso and, during the air flow measurement, it was noticed that generally the highest air speed was directed to the lower torso, as shown in Figure 12a. To change that, some users positioned the fan on top of some element to raise the air jet, as can be seen in Figure 12b. As shown in these pictures, the fan was used mainly in front of or by the side of the keyboard, so the hands and arms were indicated in 36% of answers as receiving the wind directly. The head was the least affected (5%) part because the fan's air jet was flat and straight, not generating upward air movement.

a) b)

Figure 12. Selected fan position: a) frontal air jet, b) lateral position and elevation

The targeted body part indicated by the users and the situations observed are reflected in the data of local air speed measured in different points of the body summarized in Table 6. The fans proximity to the keyboard focused the air speed in the hands, and even in the arms when located further away and by the side.

Table 6. Air velocity measured at different body parts

| Air Speed (m/s) | Minimum | Mean | St. deviation | Median | Maximum |
|---|---|---|---|---|---|
| **Head** | 0.00 | 0.07 | 0.07 | 0.05 | 0.40 |
| **Hands/arms** | 0.05 | 1.23 | 1.08 | 0.93 | 3.60 |
| **Torso** | 0.00 | 0.72 | 0.73 | 0.40 | 3.00 |
| **Ambient** | 0.00 | 0.11 | 0.07 | 0.12 | 0.3 |

### 3.4. Drivers and barriers in fan usage

At the end of the study, users were asked to indicate the main reasons for using and not using the fan. As can be seen in Figure 13, users indicated they used the desk fans primarily when arriving at their workstation to cool down from outdoor heat absorption or metabolic rate increment. It was observed that this occurred at the beginning of working day, but mainly at lunch return in the afternoon. The second reason was the reduction of hot sensation, which contrasts with the non-significance found between average sensation and thermal comfort in the periods with and without fan. The third reason indicated fits with item 3.2, according to which the possibility of increasing air movement had a greater impact on users' perception.

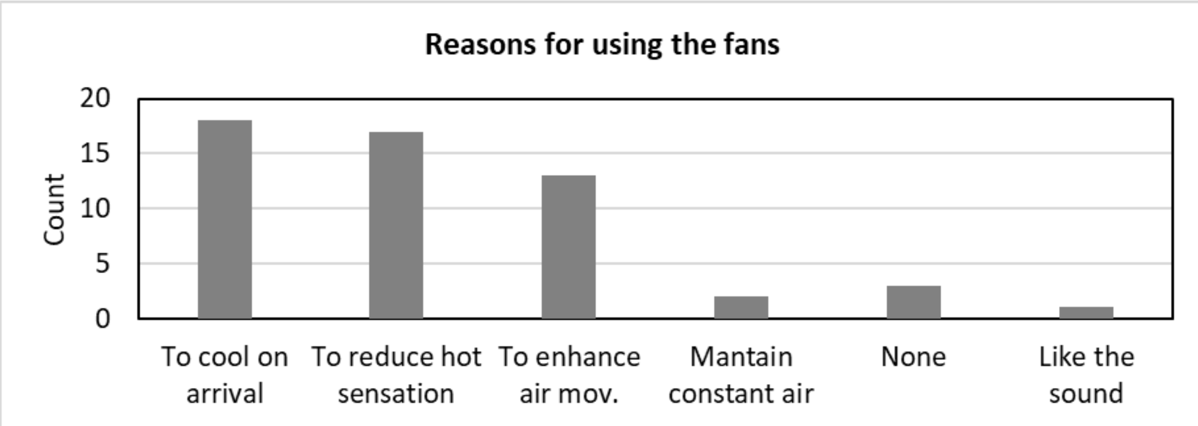



Figure 13. Reasons for using the fans

Three users found no good reason to use the fan, which can be better understood by Figure 14. The main reason indicated was the noise emission, which was also identified as the reason why users selected mainly the first activation level – the quietest. It is interesting to notice that one person indicated to like the sound of it (see Figure 13) in contrast to the most of users' opinions. The second reason indicated was the lack of demand; the users felt no need to use the equipment, probably because they felt comfortable most of the time (see item 3.2). The same number of people indicated to prefer activating the air conditioning (AC) instead of the fan; not using it because they do not like the feeling of air motion on their skin; or they used it a lot and found no reason not to do so.

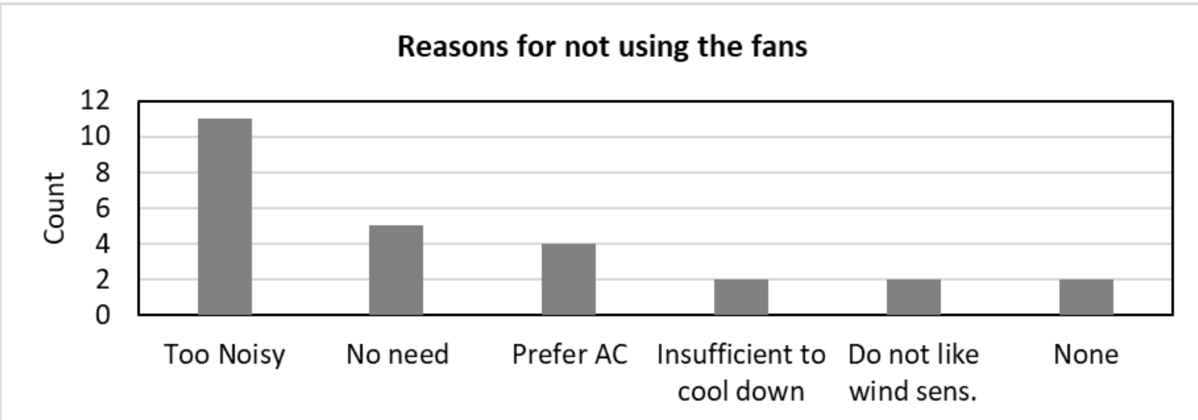



Figure 14. Reasons for not using the fans

## 4. Discussion

Fan use is considered an adaptation behaviour (Indraganti et al., 2015; De Dear and Brager, 1998), mainly with the purpose of avoiding warmth discomfort in naturally ventilated environments (Yang and Zhang, 2009; Brager et al., 2004). In this study, it was verified that the main advantage of fans was the reduction of local warmth discomfort by increasing air velocity according to users' demand. Its effect on thermal sensation and global discomfort was not as significant as expected.

Studies with personal cooling systems (PCS) have identified that the activation moment correlates more with the increase in metabolic rate and exposure to external heat than with the moment of discomfort (Shetty et al., 2016; Taheri et al., 2014; Zhai et al., 2017; Verhaart et al., 2018). According to users, the same occurred in this study; i.e., the greatest demand for using the equipment occurred on arrival at the workstation. However, this moment was not coincident with the application of questionnaires, which was performed 20 minutes after arrival. This means that the main moment of use was not registered, which might have affected the results significance.

When compared to previous studies, the results reveal a high percentage of equipment use, found in 53% of answers. The fan use is usually intermittent (Shetty et al., 2016) and total activation time corresponds to a low percentage of occupancy period. In a field study, Goto et al. (2007) noticed the activation time was less than 10% of occupancy period; and in Indraganti et al. (2015) field study, it varied from 20% to 40% according to local climate where people had control over the conditioning systems. Goto et al. (2007) indicate that fan use can also compensate for unavailability of air conditioning system control, being more frequent in offices with central cooling system. In contrast, when users have control over the systems, there is a preference for air conditioning activation instead of fans (He et al., 2018). In this study, something similar was observed; fans were used mainly when the air conditioning (AC) was turned off. Some users indicated it was insufficient to reduce the warmth sensation, which may have been a driver for AC activation. However, AC produced cold discomfort and more draft discomfort than fans. The majority of users indicated they did not to use fans because of noise emission, which may indicate that, if the equipment did not have this disadvantage, better results could have been achieved.

Desk fans are indicated as one of the most efficient PCS, producing high heat loss with low power (Luo et al., 2018; Y. He et al., 2017; Warthmann et al., 2018). In this study a 4.5 W device was used, but there are options with 2-1 W power (Luo et al., 2018; Y. He et al., 2017). To increase heat loss, Melikov et al (2013) and Simone et al (2014) indicate the fan should target the head. In this experiment, the lack of adjustment of the fan in a vertical angle did not allow to target this spot, which might have reduced its efficiency. These limitations and results corroborate the findings of Kwon et al (2019), personal control could increase thermal comfort when it meets the users' demand. Otherwise, when it does not meet such demand or there is no demand, it becomes less effective.

## 5. Conclusion

This work analyzed the results of a field study where desk fans were made available to users during the summer. It was verified a great potential for increasing users' thermal satisfaction by these devices. However, it depends on several factors, like users' willingness to use the equipment and their control over other conditioning systems. In a hybrid environment where users have total control over the equipment, desk fans availability might not be enough to increase thermal comfort and energy savings if they are not well accepted by the users, i. e. the proposition of fans as an alternative to air conditioning will depend on how receptive the users are about it. In this scenario, the design of the equipment plays an important role in allowing the necessary adjustment to be achieved, as well as controlling the negative effects that may inhibit using them. It is worth noting that, when the use of desk fans depend on user activation, they need to be as attractive as the air conditioning to the user to be considered as an alternative. One way to achieve this is to use innovative design, attractive aesthetics, technological features and versatility in adjusting the position, rotation and settings. It is also possible that other similar fans do not present the same problems identified in this study due to better design solutions.

## 6. Acknowledgment

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# The importance of sample grouping; Exploring thermal sensitivity of occupants within one building type and ventilation mode

**Despoina Teli[1] and Stephanie Gauthier[2]**

[1] Division of Building Services Engineering, Department of Architecture and Civil Engineering, Chalmers University of Technology, SE-412 96, Gothenburg, Sweden, teli@chalmers.se;
[2] Energy & Climate Change Group, Department of Civil, Maritime & Environmental Engineering, School of Engineering, Faculty of Engineering & Physical Sciences, Southampton, SO16 7QF, UK, S.Gauthier@soton.ac.uk

**Abstract:** Occupants' thermal response is influenced by their sensitivity to temperature variations, i.e. the rate of change in occupants' thermal sensation per unit change in indoor temperature. Thermal sensitivity is commonly taken as constant (Griffiths constant) in the calculation of occupants' comfort temperature. This constant is based on small differences found between buildings' ventilation modes [naturally ventilated (NV) vs. air conditioned (AC)]. However, recent research found significant differences depending on building type, ventilation mode, age, gender and climate. This paper reviews thermal sensitivity within the same building type and main ventilation mode using longitudinal surveys and monitoring data from school buildings, two in the UK (U1 and U2) and one in Sweden (S1). Results show that in two of the schools (U1 and S1) children were half as sensitive as in school U2 and the difference is statistically significant. A similar result with slightly different thermal sensitivities was derived from comparison by clusters derived from the classrooms' indoor temperatures. This outcome suggests that building ventilation mode (AC/NV), which is typically considered the main determinant of occupants' thermal experience and often the only building information recorded in field surveys, is inadequate to explain this important occupant response factor.

**Keywords:** thermal sensitivity, indoor temperature, thermal comfort, ventilation mode, buildings.

## 1. Introduction

People's thermal sensation changes with temperature and the rate of this change signifies their ability to adapt to varying thermal conditions, i.e. it is an indicator of people's thermal sensitivity. People's sensitivity to temperature change determines how quickly their thermal state departs from the comfort zone and how quickly it reaches discomfort levels or even unacceptable thresholds. It is therefore an important thermal response factor for thermal comfort but also for people's ability to adapt to rapid temperature changes, in light of the increasing warm temperature extremes and the likelihood of more frequent and longer heat waves (IPCC, 2014).

Regression analysis on thermal comfort survey data, with thermal sensation as the dependent variable and temperature as the predictor variable, gives an estimate of people's sensitivity to temperature changes (regression coefficient) and their neutral (or "comfort") temperature (temperature at which thermal sensation= neutral). When the surveys span over days or longer periods people have adapted to day-to-day changes and therefore the regression coefficient is shallower compared to short survey periods where there is little adaptive opportunity. The regression coefficient for the case where no adaptation is assumed to take place is the maximum rate of change of thermal sensation with temperature and is considered to be a standard value, the so-called 'Griffiths slope' or 'Griffiths constant'.

Initial analysis by Humphreys et al. (2007) on the ASHRAE (de Dear and Brager, 1998) and the SCATs (McCartney and Nicol, 2002) thermal comfort databases found the regression gradient to reach a maximum value of 0.4 when the standard deviation of the operative temperature during the survey period is around 1K, a value typical for short survey periods where people would have limited adaptive opportunities. The regression gradient dropped below and above 1K standard deviation of temperature, probably due to the effects of error in the predictor variable in the former case and the effect of increased adaptation in the latter (Humphreys et al., 2007). Considering that error in the predictor variable and some adaptation error will always be present, it was concluded that an appropriate value for the sensitivity to temperature changes would be higher than 0.40/K and a value of 0.50/K was chosen (Nicol and Humphreys, 2010).

Further analysis (Humphreys et al., 2010, Humphreys et al., 2013), led to the day-pooling method, where data collected in a single day (limited adaptation) were used to derive a value for the Griffiths constant from the SCATs and ASHRAE databases. This value was 0.50/K, the same as previously estimated. The difference between centrally conditioned (AC) and naturally conditioned (NV) buildings was small and not statistically significant and therefore this value was proposed for the Griffiths constant when estimating the neutral temperature from survey data.

The value of 0.5K for the Griffiths constant has been widely used in thermal comfort research. There are also studies which explored the sensitivity of the estimated neutral temperature with different values for the Griffiths constant and found its role to be important (Nguyen et al., 2012, Haddad et al., 2019) and studies that explored the applicability of the value 0.5K in other building types, i.e. schools (Teli et al., 2015) and homes (Ryu et al., 2019). A recent study investigated the validity of Griffiths constant for different contexts and found that it varies depending on building type (office, school, residential) and ventilation mode (AC/NV), recommending that different values should be used according to these categories (Rupp et al., 2019). In the previous studies, for the investigation of differences in thermal sensitivity, samples were grouped according to building type (office, school, etc.) and ventilation mode (AC/NV). To explore further these differences and the above recommendation, this paper reviews thermal sensitivity within the same building type and main ventilation mode. The analysis aims to explore the impact of sample grouping (by building type or AC/NV mode) on determining people's thermal sensitivity.

## 2. Study design

### 2.1. **Case study buildings**

The data used in the analysis are from thermal comfort field surveys conducted in three schools; two in Southampton (UK) and one in Gothenburg (Sweden). Both cities have marine west-coast temperate climate, with Köppen Climate Classification Cfb (Kottek et al., 2006). The surveys in the UK were conducted in 2011 and 2012 while the surveys in Sweden in 2016. Table 1 summarises the characteristics of the three schools.

Table 1. Characteristics of the sample of schools

| Country | School | Year surveyed | Building weight | Classroom Ventilation strategy | Class-rooms | No of questionnaires | Survey days |
|---|---|---|---|---|---|---|---|
| **UK** | U1 | 2011 | LW | All NV | 1-8 | 1,314 | 12 |
| | U2 | 2012 | MW | All NV | 9-19 | 1,676 | 14 |
| **Sweden** | S1 | 2016 | LW | 3 EV, 1 NV, 2 MVHR | 20-25 | 2,177 | 26 |

Notes:
Building weight - LW: lightweight, MW: mediumweight, HW: heavyweight.
Ventilation - NV: naturally ventilated (free-running/ no cooling in summer], EV: fan-assisted exhaust-only ventilation (no cooling in summer), MVHR: mechanical ventilation with heat recovery (no cooling in summer)

School U1 is a lightweight building constructed in 1978 while school U2 is a Victorian medium-weight building built in 1884 (Figure 1). Both UK schools are naturally ventilated through window opening. School S1 is housed in 9 buildings, seven of which were built in the turn of the 18th to the 19th century and two in the end of the 20th century. The buildings where the surveys took place have a lightweight construction. Three of the classrooms have exhaust-only ventilation (supply through wall inlets), one is naturally ventilated through window opening and two are equipped with mechanical ventilation with heat recovery. Since none of the cases involve summer cooling, it was decided to include all classrooms in the study and see whether the analysis will separate the different systems. All classrooms in all schools are heated in winter with wet central heating systems.


Figure 1. School buildings were the surveys took place. School S1 is housed in several buildings, two of which are shown here.

## 2.2. **Data collection**

A total of 5,167 pupils' questionnaires are used in the analysis, collected from approximately 650 children during 207 surveys in 25 classrooms. The questions addressed thermal sensation, thermal preference, overall comfort, tiredness, perceived air quality and clothing level at the time of the survey. The English version of the questionnaire can be found in (Teli et al., 2012). During the surveys, measurements of thermal comfort parameters were also taken, i.e. air temperature ($T_a$, ºC), globe temperature ($T_g$, ºC), relative humidity (RH, %), indoor relative air velocity ($V_a$, m/s). In this paper, children's thermal sensation votes (TSV) and the globe (operative) temperature $T_{op}$ at the time of the survey are used, in order to estimate children's thermal sensitivity (relationship between TSV and $T_{op}$).

In all surveyed classrooms data loggers were installed which recorded the air temperature and relative humidity at 5-minute intervals. These measurements are used in the cluster analysis and in the calculation of the measurement error in the predictor variable.

## 2.3. **Analysis method**

In order to investigate the impact of sample grouping on the estimated thermal sensitivity, two groupings were made: the first is by school and the second by cluster. Cluster analysis was conducted on the air temperature measurements from the data loggers in order to group the classrooms according to the temperatures that the children typically experienced. The groups of classrooms with similar indoor temperature profiles are used in order to investigate if thermal experience influences occupants' thermal sensitivity.

Children's thermal sensitivity was then estimated by school and by cluster using children's thermal sensation votes and the operative temperature at the time of the survey for single day survey runs, following Humphreys' day-pooling method. More details on the methods used are provided below.

## 2.4. **Sample grouping: cluster analysis**

From the classroom datasets with the 5-minute air temperature measurements, one month was selected and used in order to avoid prolonged periods of school holidays, term breaks etc. and have as consistent as possible outdoor weather conditions between school surveys. The most appropriate month was May. A cluster analysis of the occupied hours of the school days (08:30-15:00 weekdays) was conducted to identify groups of classrooms with similar profiles of mean daily temperature. Applying an inductive approach through unsupervised machine learning, cluster analysis is a tool to identify groups in the units of a data frame. In this analysis, each classroom is a unit and each 5-minute monthly mean temperature is a variable. As grouping is based on the distance between temperature profiles of each classroom, data was first standardised to ensure that each feature contributed proportionally to the distance between data points (i.e. 5-minute monthly mean temperature). Classrooms' temperature data were standardised by first subtracting the mean and then dividing the values by the standard deviation. The analysis was twofold. First, the number of clusters was determined using a scree plot of the within groups sum of squares by the number of clusters. Then, both K-means clustering, and Ward's minimum variance methods were applied to determine which classrooms belong to which group.

## 2.5. **Estimation of thermal sensitivity: day-pooling method**

The day-pooling method for the estimation of the regression coefficient (constant G) was formulated by Humphreys et al. (2013). The estimation process gives a weighted average of the regression coefficient for all day-surveys, which provides a more reliable statistic compared to the analysis of small day-survey samples.

There are two important parts in the procedure: the estimation of the regression coefficient and its adjustment for the presence of error in the predictor variable (measurement error of room temperature).

The estimation of the regression coefficient includes the following:

- Calculation of the variables dTSV and $dT_o$ for each response on a single day (day-survey). dTSV is the difference of the subjective TSV and the mean thermal sensation vote for the day-survey ($TSV_{(day\ mean)}$) and $dT_o$ is the difference of the operative temperature during the survey ($T_o$) and the mean operative temperature on that day ($T_{o(day\ mean)}$).
- Regression analysis of dTSV on dTo of all the day-surveys.

The estimated regression coefficient (b) is then corrected to account for measurement error in the operative temperature, using equation 1 (Humphreys and Nicol, 2000).

$$b_{adj} = b\ (\sigma^2_{dTo})/\ (\sigma^2_{dTo} - \sigma^2_{err}) \qquad (1)$$

Where $\sigma^2_{dTo}$ is the variance of the variable $dT_o$ and $\sigma^2_{err}$ its error variance. This error can be attributed to sensor limitations and to its positioning in relation to the survey respondent. The sensor limitations are hard to estimate, and the positioning error can only be approximated if there is available data for this to happen. In the absence of more appropriate data for this approximation, Humphreys et al. (2013) used the vertical difference of 1m between the globe sensors on the measuring stations in the ASHRAE database and got a value for the error variance of 0.158 $K^2$. The error variance is estimated here from the logged temperatures in the classrooms.

The significance of the differences in the estimated regression coefficients was assessed with t-testing and validated by running regression models with interaction terms on the raw data (Potthoff analysis).

## 3. Results

For the analysis, inconsistent cases (strongly contradicting thermal sensation and preference votes) were excluded (6% of the sample). More details about the exclusion criteria can be found in Teli et al. (2013). A total of 4,851 thermal sensation votes (TSV) are used for the estimation of thermal sensitivity.

### 3.1. Cluster analysis

The clustering analysis units were defined as the 25 classrooms and the variables were defined as the monthly mean of 5-minute air temperature recordings. As introduced in section 2, the analysis was twofold. A review of the scree plot determined the number of clusters, which was set at 3. Then K-means clustering and Ward's minimum variance methods were applied. Both methods resulted in the same group membership, as described in Table 2 and shown in Figure 2. Cluster 1 consists of 3 classrooms from the lightweight UK school U1 and all 6 classrooms from the Swedish school S1. Cluster 2 consists of 5 classrooms from U1 and 3 from U2. Finally, cluster 3 consists only of classrooms from the medium-weight school U2.

Table 2 Membership of classrooms by clusters (cluster 1: blue, cluster 2: green, cluster 3: yellow)

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **U1** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | | | |
| **U2** | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
| **S1** | 20 | 21 | 22 | 23 | 24 | 25 | | | | | |

Figure 2 shows the monthly mean of 5-minute air temperature profiles of the classrooms (thin lines) and the clusters (thick lines). Cluster 1 has the highest mean temperature ($T_{a\text{-}mean}$=24.2 °C), cluster 2 follows with $T_{a\text{-}mean}$= 22.6 °C and finally cluster 3 with $T_{a\text{-}mean}$=21.2 °C.

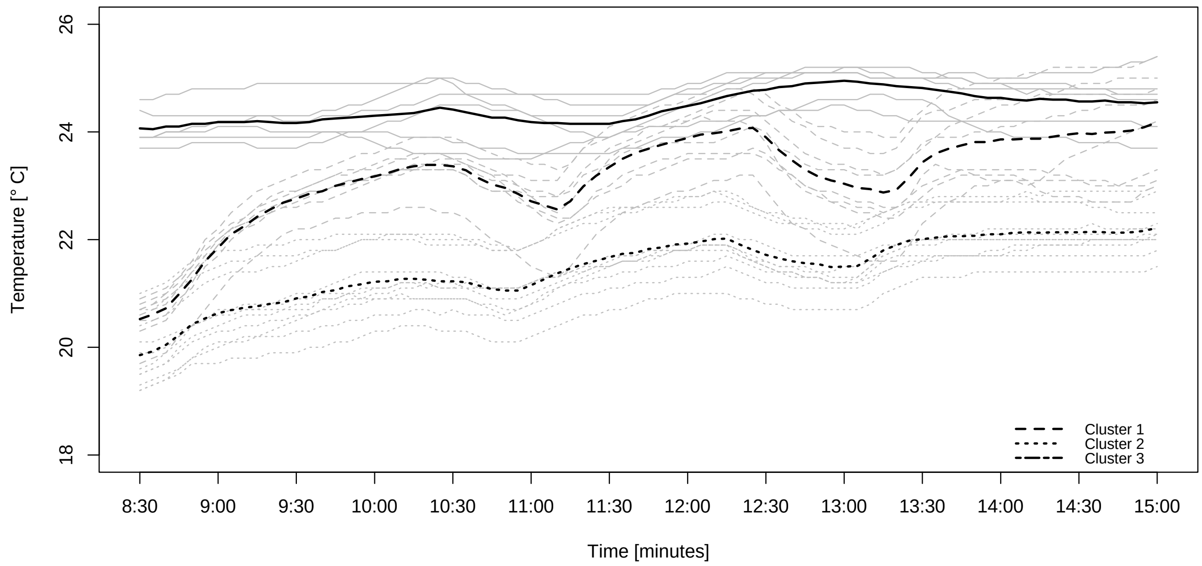


Figure 2. Monthly mean of 5-minute air temperature profiles of the 25 classrooms and the 3 clusters

Further cluster analysis applied the same method for the same unit ('classroom') but a different variable. Here, the interest lies in the temperature difference experienced over 15 minutes. As the classrooms have similar occupancy (heat gain), the difference in monthly mean temperature over 15 minutes mainly lies in fabric performance, gains and ventilation, including window opening behaviour. As introduced in section 2, the analysis was twofold. The number of clusters was set at 3. K-means clustering and Ward's minimum variance methods resulted in the same group membership. Interestingly, classrooms were grouped by their associated schools, as described in Table 3 and shown in Figure 3.

Table 3 Membership of classrooms by clusters (cluster 1: blue, cluster 2: yellow, cluster 3: green)

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **U1** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | | | |
| **U2** | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
| **S1** | 20 | 21 | 22 | 23 | 24 | 25 | | | | | |

Figure 3 shows the difference over 15 minutes of monthly mean of 5-minute air temperature profiles of the classrooms (thin lines) and the clusters (thick lines). Cluster 1 has the largest range in temperature difference ($dT_{a\text{-}mean}$=1.5°C), cluster 2 follows with $dT_{a\text{-}mean}$=0.7°C and finally cluster 3 with $dT_{a\text{-}mean}$=0.3°C.

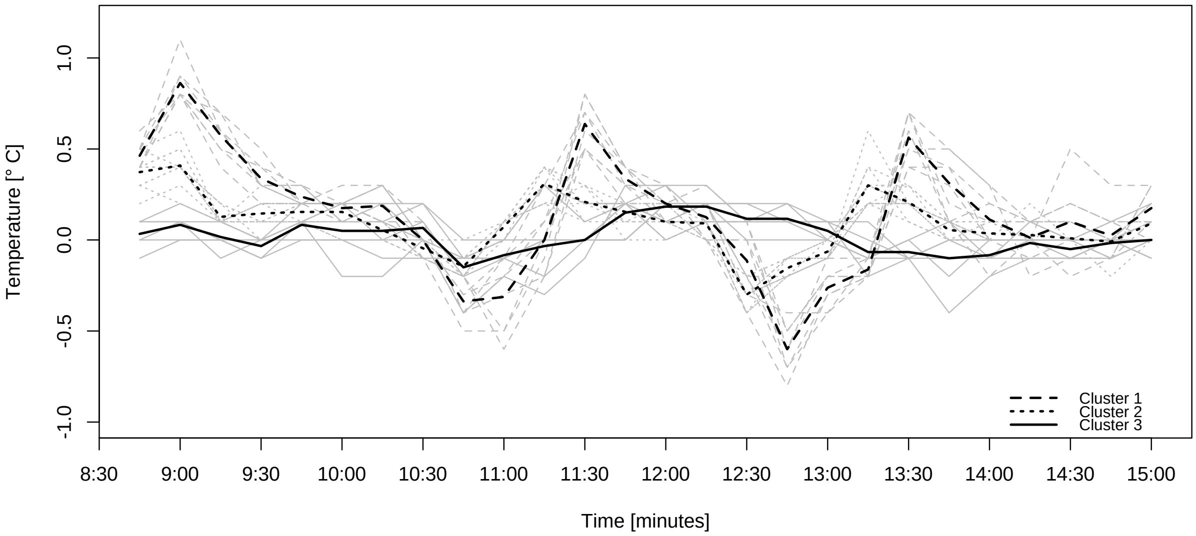


Figure 3. Difference over 15 minutes of monthly mean of 5-minute air temperature profiles of the 25 classrooms and the 3 clusters

Following the above results, thermal sensitivity is reviewed by the clusters established in both methods; (1) 3 clusters of monthly mean of 5-minute air temperature profiles (refer to Table 2) and (2) 3 schools (refer to Table 3).

### 3.2. **Thermal sensitivity**

For each day visit to each school and each thermal sensation response (TSV), the variables dTSV and $dT_o$ were calculated. Table 4 summarizes the results from the regression analysis of dTSV on $dT_o$ to derive the regression coefficients (b) for the entire dataset, by school and by cluster. The resulting regression coefficients are first compared without the adjustment for the error in the predictor variable.

As can be seen, for all schools combined the regression coefficient is 0.28/K (Figure 4). This is close to the value Humphreys et al. (2013) derived from the NV buildings at the SCATs database (0.308/K) and considerably lower than the overall regression coefficients for SCATs and ASHRAE databases (all building types) of 0.38/K and 0.37/K respectively.

Table 4. Regression coefficients (b, thermal sensitivity) by building and by cluster

| **Dataset** | **N** | **Variance of dTo (°C$^2$)** | **Error variance of dTo (°C$^2$)** | **b** | **Standard error of b** | **R** | **p-value** | **Adjusted b** |
|---|---|---|---|---|---|---|---|---|
| **All schools** | 4581 | 0.756 | 0.227 | **0.277** | 0.022 | 0.181 | <0.001 | 0.396 |
| **By school** | | | | | | | | |
| U1 | 1224 | 0.762 | 0.154 | **0.194** | 0.045 | 0.122 | <0.001 | 0.243 |
| U2 | 1511 | 0.912 | 0.118 | **0.389** | 0.040 | 0.248 | <0.001 | 0.447 |
| S1 | 2116 | 0.642 | 0.222 | **0.220** | 0.032 | 0.152 | <0.001 | 0.336 |
| **By cluster** | | | | | | | | |
| cluster 1 | 2566 | 0.739 | 0.199 | **0.194** | 0.028 | 0.139 | <0.001 | 0.266 |
| cluster 2 | 1190 | 0.685 | 0.141 | **0.408** | 0.049 | 0.236 | <0.001 | 0.513 |
| cluster 3 | 1095 | 0.680 | 0.118 | **0.247** | 0.054 | 0.138 | <0.001 | 0.299 |

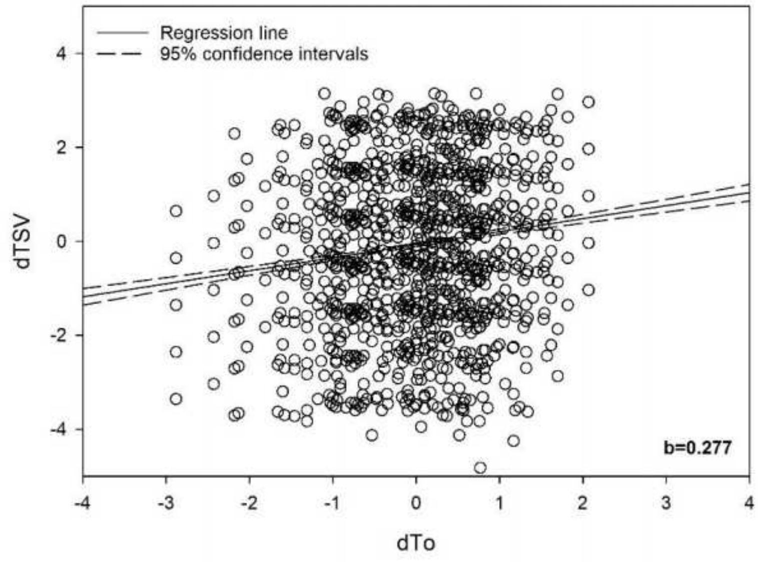


Figure 4. Regression of the day-surveys in the entire school sample.

Looking at the breakdown by school, differences can be seen. The regression coefficient for school U2 is 0.39/K, nearly double those of schools U1 and S1 (0.19/K and 0.22/K respectively), and these differences are statistically significant ($p < 0.05$). The difference between schools U1 and S1 is small and not statistically significant.

The breakdown by cluster gives a similar result but with very different groups. This time, cluster 2 has the highest regression coefficient (0.41/K) and the differences with the other two clusters is statistically significant ($p < 0.05$). Cluster 2 consists of 5 classrooms from school U1 (which had b= 0.19/K) and 3 classrooms from school U2 (b= 0.39/K). Cluster 3, with all classrooms from school U2, has b=0.25/K, which is much lower than the entire school's regression coefficient (b= 0.39/K). In both cases we get statistically significant differences, but the sample has been grouped in different ways.

The second part of the day-pooling method involves the correction of the regression coefficient for error in the measurement of the room temperature. It is therefore important to estimate its value. In this study, the estimation of error variance is based on air temperature measurements in two locations in the surveyed classrooms: at the centre of the classroom, where the thermal comfort instrument was placed, and at one of the side walls, where the data logger was installed. In most cases, the desk distribution in the classrooms covered this distance and therefore the error is considered representative. The average distance between the two locations was approximately 4m. The air temperature is used as a proxy for the operative temperature here, since only the air temperature was measured at the second location and the difference between $T_o$ and $T_a$ was overall small.

The estimation of the error variance was made for the three schools separately and then combined. The variance of the air temperature difference in the classrooms was lowest in school U2 (0.118 $^oC^2$) and highest in school S1 (0.222 $^oC^2$). The difference is quite large and likely related to the buildings' characteristics. Most of the surveyed Swedish classrooms are housed in repurposed villas (Figure 1) and have at least two walls connected to outdoors, leading to higher temperature differences between the walls and the centre of the classrooms. Such differences in the error variance of the room temperature are to be expected between different building/room samples. If the sample is treated as one, the error variance is estimated at 0.227 $^oC^2$.

The last column of Table 4 shows the estimated adjusted regression coefficients using the corresponding error variance. For the clusters, a weighted average of the error variance according to the number of classrooms from each school was used. The results confirm the observation of Humphreys et al (2016) that the estimate of the adjusted regression coefficient is sensitive to the error-variance in the predictor variable. The adjusted regression coefficients are between 15-53% higher than before the adjustment, depending on the dataset (all schools, school, cluster). For the entire dataset, the adjusted regression coefficient is 43% higher than before the adjustment.

Another aspect to consider is whether season affects the resulting thermal sensitivities. The only school where surveys were conducted in winter was the Swedish school, so the analysis is done on the S1 sample. As can be seen in Table 5, the regression coefficient for spring/summer is 40% lower than in winter. The difference did not reach statistical significance with p=0.073, which however is overall low. It appears that there is scope for further investigation on the influence of season on thermal sensitivity.

Table 5. Regression coefficients (b, thermal sensitivity) by season in the Swedish sample

| **Dataset** | **N** | **Variance of dTo (°C²)** | **Error variance of dTo (°C²)** | **b** | **Standard error of b** | **R** | **p-value** | **Adjusted b** |
|---|---|---|---|---|---|---|---|---|
| S1-winter | 2116 | 0.642 | 0.222 | **0.285** | 0.050 | 0.182 | <0.001 | 0.436 |
| S1-spring | 1148 | 0.673 | 0.222 | **0.169** | 0.041 | 0.126 | <0.001 | 0.252 |

## 4. Discussion

If the sample in this study is treated as one, representing the same building type (school) and main ventilation type (NV/no cooling), then according to Rupp et al. (2019) we should use the value 0.4/K for the Griffiths constant to estimate comfort temperatures. If the three schools are treated separately, then in school U1 thermal sensitivity is lower by approximately 40%, while in school U2 15% higher and in S1 approx. 15% lower. If the sample is divided by cluster (indoor temperature profiles experienced), the differences from the value 0.4 are -33%, +30% and -24% for clusters 1, 2 and 3 respectively. These differences are substantial, considering that the samples are from the same building type, main ventilation type and the surveys were conducted with the same research protocol.

An assumption when grouping the sample by building type or ventilation mode is that occupants experience similar conditions and have similar levels of adaptation. The results of this study however do not confirm this assumption, with significant differences in thermal sensitivities within the same building and ventilation type. The day-pooling method itself is based on an important assumption, i.e. that there is minimal to no adaptation during a working day. Although this may be close to reality for some office and school environments on which the assumption was based, it may be rather unrealistic for others, such as homes or buildings with large within-day temperature variations that instigate adaptive behaviours.

Based on Rupp et al. (2019), Griffiths constant should be treated as a variable. This study shows that the estimation of occupants' thermal sensitivity is rather sensitive to sample grouping, both in relation to the estimation of the regression coefficient and the error variance of the room temperature. It is therefore important to reflect on how reliable the resulting thermal sensitivities would be from single comfort study samples. A further issue to address is to what extent treating Griffiths constant as a variable contributes to more accurate estimations of people's comfort temperature. On a more general note, the validity in the Griffiths method needs to be revisited as an issue with large methodological implications for contemporary thermal comfort research.

## 5. Conclusions

Based on the findings of this study, thermal sensitivity varies within the same building type and ventilation mode as well as between buildings. It appears that building/space characteristics other than ventilation mode and within-day adaptive behaviour, which perhaps cannot be assumed as minimal, influence occupants' thermal sensitivity. The estimation of occupants' thermal sensitivity appears to be very sensitive to the room/building context. Grouping surveys by building type and ventilation mode for comparing the resulting regression coefficients is likely to bring statistically significant results if adequately large datasets are used but it does not necessarily mean that the resulting regression coefficients can be used with confidence in other samples of the same building/ventilation type.

Based on the findings from this analysis, there are fundamental and methodological issues to investigate before a robust recommendation on the estimation of occupants' thermal sensitivity in different contexts.


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# Numerical Simulation of a Confluent Jets System Based in Four Vertical Ducts with Energy Produced in Double Skin Facade for Winter Conditions

**Eusébio Z. E. Conceição[1,3], Mª Inês L. Conceição[2], João M. M. Gomes[3], Mª Manuela J. R. Lúcio[1] and Hazim B. Awbi[4]**

[1] FCT - University of Algarve, Campus de Gambelas, 8005-139 Faro, Portugal;
[2] Instituto Superior Técnico, Av. Rovisco Pais, 1049-001 Lisboa, Portugal
[3] CINTAL, Campus de Gambelas, 8005-139 Faro, Portugal;
[4] School of Built Environment, University of Reading, Reading, RG6 6AW, United Kingdom

**Abstract:** In this study the numerical simulation of a confluent jets system based in four vertical ducts with energy produced in Double Skin Facade, DSF, for winter conditions is evaluated. The thermal comfort, the indoor air quality, the Draught Risk, the effectiveness for heat removal, the effectiveness for contaminant removal and the Air Distribution Index, ADI, are also evaluated.
This numerical study considers an integral numerical model, that simulates the Building Thermal Response, and a coupling of a differential numerical model, that simulates the Computational Fluid Dynamics, CFD, and an integral numerical model, that simulates the Human Thermal Response. The ADI is calculated in accordance with the thermal comfort level, the indoor air quality level and the effectiveness values.
The integral Human Thermal Response model evaluates the tissue, blood and clothing temperatures distribution. The differential CFD model calculates the air velocity, air temperature, turbulence intensity and carbon dioxide concentration. Finally, the integral Building Thermal Response model evaluates the opaque, transparent and indoor surfaces temperatures.
In this numerical study, carried out in winter conditions, an office room occupied by six virtual manikins seated in six desks around a meeting table is simulated. The Heating, Ventilating and Air Conditioning (HVAC) system, based on a confluent jets system with four vertical ducts, located in the wall corners, is equipped with two lines of nozzles and the DSF is equipped with internal venetian blinds.
The evolution of indoor environmental conditions, in the DSF and in the office room, is calculated during a full winter typical day. In accordance with obtained results the thermal comfort, indoor air quality and Draught Risk levels are acceptable and the ADI increases during the day.

**Keywords:** Numerical Simulation, Double Skin Facade, Energy Production, HVAC, Thermal Comfort, Indoor Air Quality

## 1. Introduction

A DSF is a new building envelope technique that can be used to control the level of solar radiation entering in the interior of buildings. It is constituted by two layers (“skins”) separated by an air cavity. The first layer, towards to the inside, and the second layer, towards to the outside, is usually made of transparent glass. The air cavity may have shading orientable devices, such as venetian blind type, or electric power generating devices such as photovoltaic cells. The air ventilation in this cavity can also be controllable by the use of natural, hybrid (using fans) or mechanical ventilation techniques (Ghaffarianhoseini et al, 2016). The performance of the DSF depends on the type of facade, the second layer coverage, the air cavity dimensions and the integration of shading devices therein, the air ventilation strategies, the use and location of the building, among others (Poirazis, 2004).

A well detailed study about the DSF technical features, the advantages and the economic availability of the DSF use, and the DSF impact on thermal behaviour, energy efficiency and daylighting performance of the buildings can be found on the work of Ghaffarianhoseini et al (2016). In order to predict the DSF performance, building energy simulation tools can be effectively used, as referred to in the review study developed by Lucchino et al (2019). For example, the DSF naturally ventilated optimal design and thermal behaviour analysis using a new fast and accuracy CFD model can be seen in the study developed by Xue and Li (2015).

The use of DSF with shading devices integration restricts the sound transmission and direct solar radiation entering the building can be seen in Hazem et al. (2015) and Lee and Chang (2015). The DSF thermal and energy savings performance are affected by the blinds geometry, namely the air cavity dimensions, properties (reflection, absorbance and transmission) and orientation, because it biases the airflow behaviour, the air temperature and the air velocity on the DSF channel (Lee and Chang, 2015, Lee et al., 2015). Regarding to a numerical study developed by Hazem et al (2015), the building insulation efficiency is affected by some blind parameters, such as the material emissivity, the flow rate and the slat and incidence angles. The DSF thermal performance can be improved by the use of dielectric film coatings on blind outer surfaces or pastel paints on blind inner surfaces (Parra et al, 2015), or by the use of blinds with phase change material integration (Li et al, 2019). The results of an experimental study of PV cells application on a blind system embedded on a DSF system showed that there may be significant heating energy gains in winter conditions (Luo et al, 2018).

The purpose of buildings HVAC systems is to provide, simultaneously, good levels of indoor air quality and thermal comfort conditions for a relevant majority of occupants. This is guaranteed by a good air mixing within the compartment in order to reach an airflow around the occupants, which will allow to remove the heat lost by the occupants and the contaminants released in the breathing zone.

Mixed ventilation and displacement ventilation are the common fundamentals on which most HVAC systems are based (Awbi, 2003). These kind of HVAC have some problems: low energy efficiency and high airflow rates requirements on mixed ventilation systems (Yin et al., 2016); inappropriate for heating mode, draught risk at the ankle level, among others, on displacement ventilation systems (Janbakhsh and Moshfegh, 2014a; Melikov et al, 2005; Shan et al, 2016). Therefore, to solve these problems new types of ventilation systems have been developed. These include the confluent jets ventilation systems as it can simultaneously guarantee acceptable occupants thermal comfort and indoor air quality levels (Arghand et al., 2015; Janbakhsh and Moshfegh, 2014a) and improve the system energy efficiency (Awbi, 2003). The confluent jets ventilation systems produce a well-distributed airflow inside the compartment and can operate on both cooling and heating modes (Larsson and Moshfegh, 2017). The performance evaluation of the confluent jets ventilation systems can be found on the works developed by Arghand et al. (2015), Andersson et al. (2018), Cho et al. (2008), Janbakhsh and Moshfegh (2014a), Janbakhsh and Moshfegh (2014b).

The PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied) comfort indexes, developed by Fanger (1970), and adopted by international standards like ISO 7730 (2005) and ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) Standard 55 (2013), can be used to evaluate the thermal conditions in a conditioned space. These two standards define three comfort categories accordingly to the occupied spaces thermal comfort requirements: category A (−0.2 < PMV < +0.2; PPD < 6%), category B (−0.5 < PMV < +0.5; PPD < 10%) and category C (−0.7 < PMV < +0.7; PPD < 15%).

Usually, indoor air quality and ventilation performance assessment can be achieved by the use of the indoor carbon dioxide ($CO_2$) concentrations measurements (Asif et al, 2018; Laverge et al, 2011). The ASHRAE Standard 62.1 (2016) shows the relationship between $CO_2$ concentration and the ventilation rate, under steady-state conditions. Regarding this standard, a $CO_2$ concentration below 1800 mg/m$^3$ is an acceptable indoor air quality reference.

In order to assess simultaneously each occupant thermal comfort and indoor air quality levels and the performance of the ventilation system, the Air Distribution Index (ADI) is used. The detailed presentation of this index can be seen in the works of Awbi (2003) and Conceição et al (2013), respectively, for uniform and non-uniform environments.

This numerical work evaluates the HVAC, based in a confluent jets system using four vertical ducts, and an energy production system, using a DSF system. The study is made in winter typical day conditions. The thermal comfort, the indoor air quality, the Draught Risk, the effectiveness for heat removal, the effectiveness for contaminant removal and the Air Distribution Index, ADI, are evaluated.

## 2. Numerical Simulation

In the numerical simulation are used the Building Thermal Response model and the coupling of Computational Fluids Dynamics and Human Thermal Response models.

### 2.1. Building Thermal Response

The Building Thermal Response numerical model is based in a linear and a non-linear (first and second order) balance integral equations system (see as example Conceição and Lúcio, 2010).

The first order integral energy balance equations system, that simulates in transient conditions, is used to calculate the air temperature inside the spaces (office and DSF), the temperature in the venetian blind, the temperature in the transparent glasses, the temperature in the opaque bodies, the temperature in the interior bodies and the mass of contaminants. These equations consider the convection, conduction evaporation and radiation phenomena. The heat transfer by convection phenomena are calculated by natural, forced and mixed convection, through the use of dimensionless coefficients. In the radiative phenomena, the heat exchanges by radiation, the incident solar radiation, the solar radiation absorbed by glasses and the solar radiation transmitted through the glass are considered.

A combination of the linear mass and second order energy integral balance equations are used to evaluate the air velocity inside a multiple duct system connected to the spaces. The linear equation considers the airflow rate balance. The second order integral energy balance equations system, in the fluid dynamics, considers the kinetic energy, the potential energy, the energy associated with the flow pressure and the localized and continuous energy load losses. Localized energy load losses are associated with the local flow friction, while the continuous energy load losses are associated with continuous flow friction.

The building thermal behaviour numerical model was validated in winter conditions (Conceição et al, 2004), and in summer conditions (Conceição and Lúcio, 2006). In winter and summer studies were compared the air temperature, numerical calculated and experimental measured inside the occupied spaces.

### 2.2. Computational Fluids Dynamics and Human Thermal Response

The Computational Fluids Dynamics and the Human Thermal Response numerical models work in a coupling methodology.

The Human Thermal Response numerical model (please, see details in Conceição, 2000) is built by sub-models of human body thermal system, the thermoregulatory system, the clothing system and the thermal comfort. It is used to simultaneously evaluate the thermal comfort level and the body and clothing temperatures of each occupant, that simultaneously simulates a people group in transient conditions. The Human Thermal Response numerical model is validated in Conceição et al. (2006).

The CFD numerical model (please, see details in Conceição et al., 2008 and Conceição et al., 2010), that works in steady-state conditions, evaluates the air temperature, air velocity, dioxide carbon ($CO_2$) concentration, turbulent kinetic energy, turbulent energy dissipation and evaluates the indoor air quality level and the Draught Risk level. The CFD numerical model simulates isothermal (Conceição et al., 2008) and non-isothermal thermal conditions (in Conceição et al. (2010) is used the k-epsilon turbulence model and in Conceição and Lúcio (2016) is used the RNG turbulence model). In the validation (see Conceição and Lúcio, 2016) the experimental and numerical values of the chamber surface temperature, the air temperature, the air velocity, the air turbulence intensity and the DR around the occupants are compared.

The PPD and PMV indexes, developed by Fanger (1970), are used to evaluate the thermal comfort level.

The ADI, developed in Awbi (2003) for uniform environments and adapted in Conceição et al. (2013) to non-uniform environments, uses the thermal comfort number and the air quality number. The first one considers the effectiveness for heat removal and the PPD, while the second one considers the effectiveness for contaminant removal and the percentage of dissatisfied associated with the indoor air quality.

## 3. Numerical methodology

In this section the DSF prototype and the HVAC System are presented. In this numerical study, the DSF is used in the energy production and is equipped with internal venetian blind. The HVAC System is built using four vertical ducts, located in the room’s corners. Each vertical ducts is equipped with two lines.

### 3.1. Double Skin Facade prototype

Three DSF, turn to south, are installed in the virtual chamber (see Figure 1). The virtual chamber, with 4.5 m long, 2.55 m wide and 2.5 m high, is made of wood and insulated with extruded polystyrene material with a thickness of 40 mm.

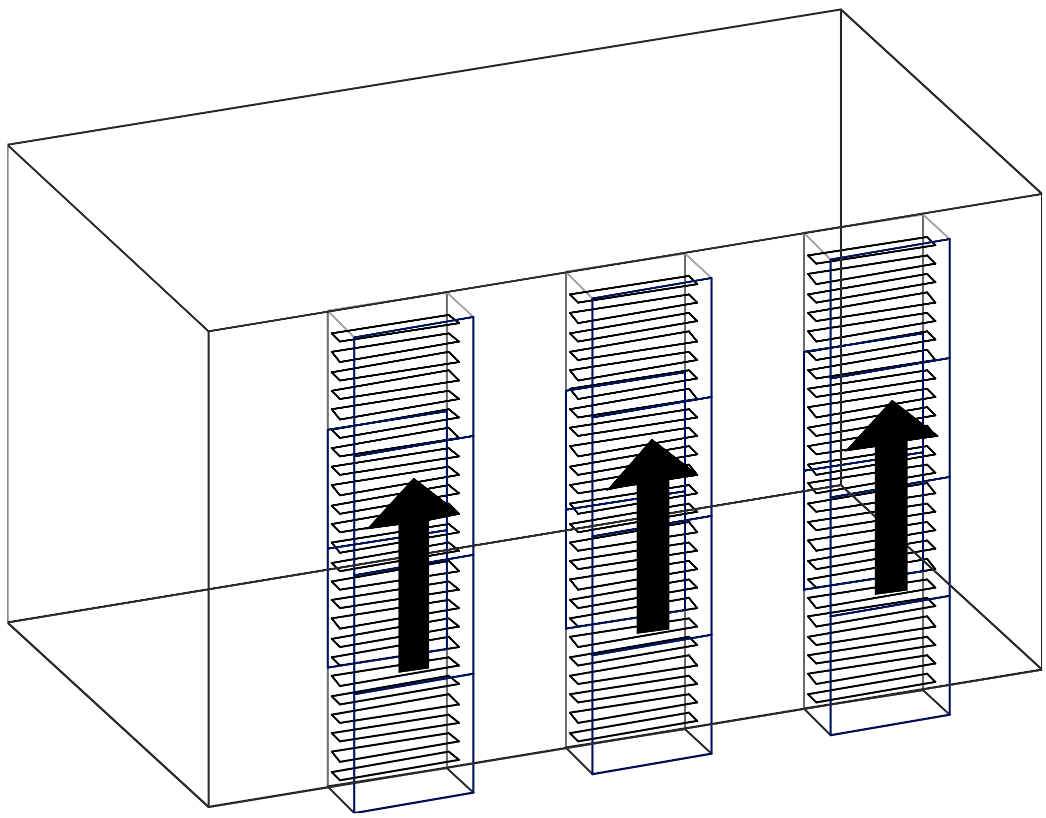


Figure 1. Scheme of the virtual chamber equipped with DSF prototype (in blue are represented the transparent surfaces and in black are represented the venetian blinds)

The three DSF, subjected to solar radiation during all day, have the following dimensions of 0.60 m long, 0.2 m wide and 2.5 m high (see figure 1). They are equipped with two transparent surfaces, each one with a thickness of 4 mm, and an adjustable set of 24 venetian blind type located between them. Each venetian blind has an average thickness of 10 mm, 0.60 m long and 0.12 m wide.

The ascending DSF airflow, where the energy is produced, that guarantees the ventilating system, is connected in a duct that is connected to the HVAC system located inside the virtual chamber.

In the numerical simulation is considered a typical winter day, occupied with 6 persons between the 8 and 12 hours and between the 14 and 18 hours.

The simulation is made during 24 hours with clean sky.

### 3.2. HVAC System

In figures 2 and 3 are presented, respectively, the scheme of the virtual chamber equipped with ventilation system based in confluent jets using in the CFD and scheme of the virtual chamber equipped with 6 persons applied in the Human Thermal Response.

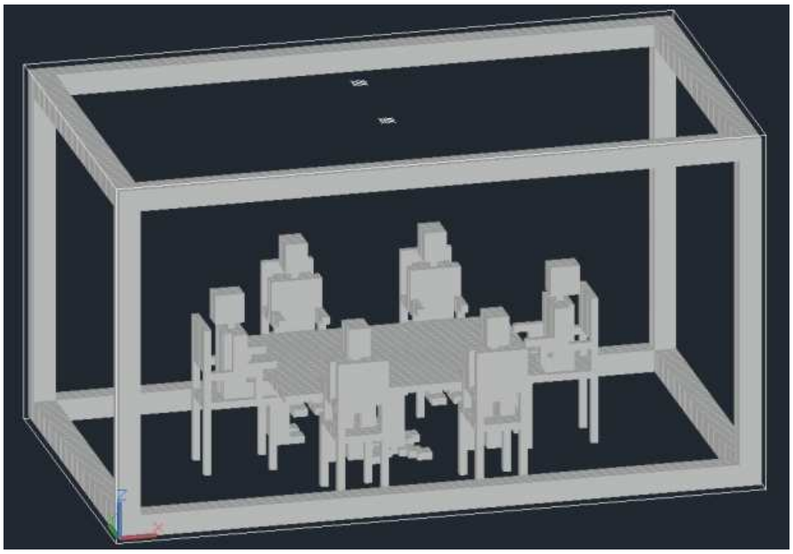


Figure 2. Scheme of the virtual chamber, equipped with ventilation system based in confluent jets, using in the CFD

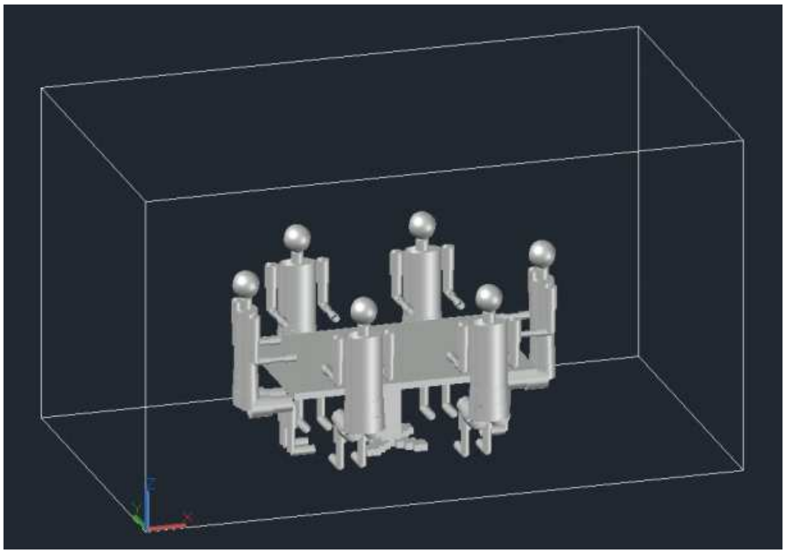


Figure 3. Scheme of the virtual chamber, equipped with six occupants, used in the Human Thermal Response

The chamber is equipped with two extractors, located in the ceiling central level, above the office table central area.

The HVAC system was built with four fans coupled to four vertical ducts of 125 mm of diameter, located at the corner of the wall surfaces; each duct contains 100 nozzles divided into 2 lines of upright nozzles forming 50 jets in each row. One line is turned to the bigger wall, while the other line is turned to the smaller wall. Each nozzles diameter is 6 mm, the distance between nozzles is 16 mm, the first nozzle is located 200 mm above the floor level and the last nozzle is located 1000 mm above the floor level.

The air velocity in each nozzle of the line turn the smaller wall is 3.5 m/s, while the line turn the bigger wall is 11.5 m/s.

The occupants 1 and 3 are located in the table top, while the other occupants are located in the table side.

## 4. Results

The results obtained in the DSF system, used to produce energy, and the HVAC System, used to improve the thermal comfort and the indoor air quality levels, are presented.

### 4.1. Double Skin Facade prototype

In figure 4 are presented the evolutions of air temperature in the outdoor environment, in the indoor occupied space and inside the DSF. The information obtained in this figure, namely at 10, 12, 14 and 16 hours, is used as input data in the HVAC system based in confluent jet system.

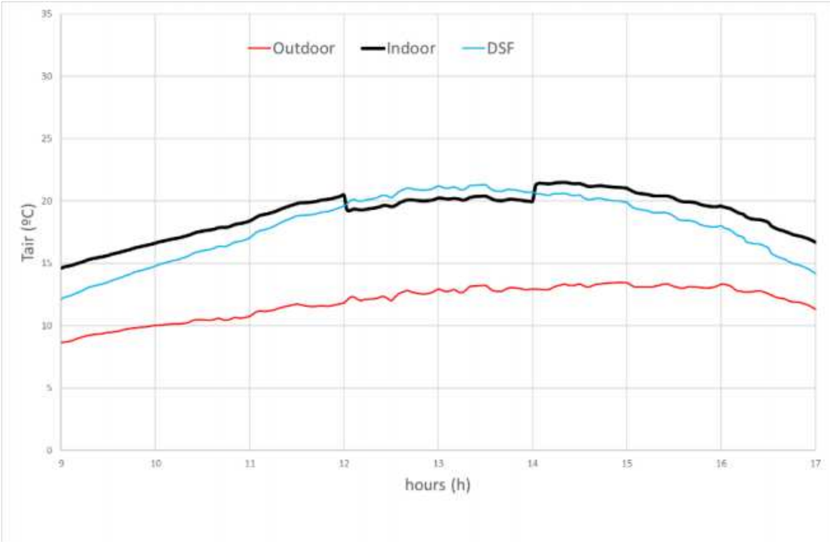



Figure 4. Evolution of air temperature in the outdoor environment, in the indoor occupied space and inside the DSF.

In accordance with the obtained results, the air temperatures of the indoor occupied and of the DSF space are higher than the outdoor environment. The air temperature of the DSF space is lower than the indoor space when the space is occupied, however the air temperature of the DSF space is higher than the indoor space when the space is not occupied.

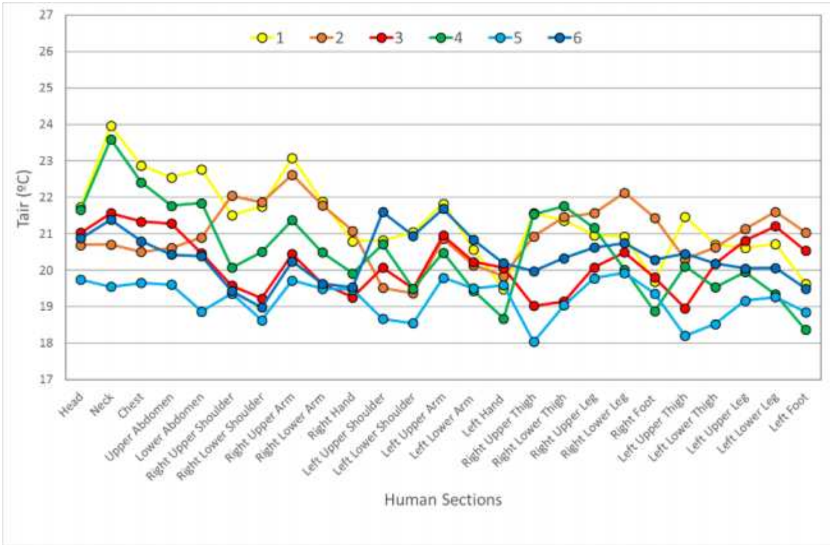
### 4.2. HVAC System

In this section the results associated to the HVAC system based in confluents jets are presented. In figures 5, 6, 7 and 8 are presented, respectively, the air temperature (figures a), air velocity (figures b) and Draught Risk (figures c) around the occupants, obtained at 10, 12, 14 and 16 hours. The inputs used in these simulations were obtained in the previous numerical forecasts in the DSF prototype simulation.

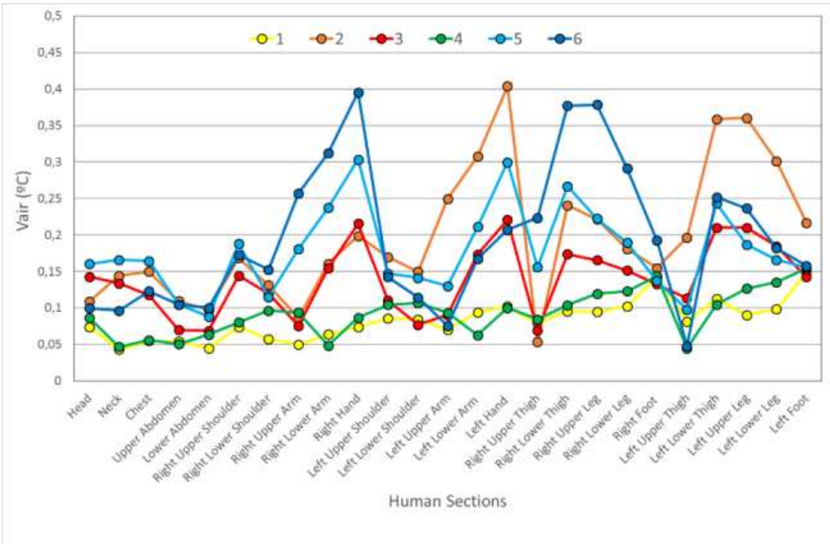
In accordance with the obtained results is possible to conclude:

- The air temperature around the occupants is slightly uniform and is lower at 10 hours, than at 12, 14 and 16 hours;
- The air velocity is slightly highest, for the four situations, in the hands and lower members;
- The Draught Risks, in general, is lower than the 20 %;
- All occupants, in general, present similar air temperature, air velocity and Draught Risk levels around the human bodies sections.

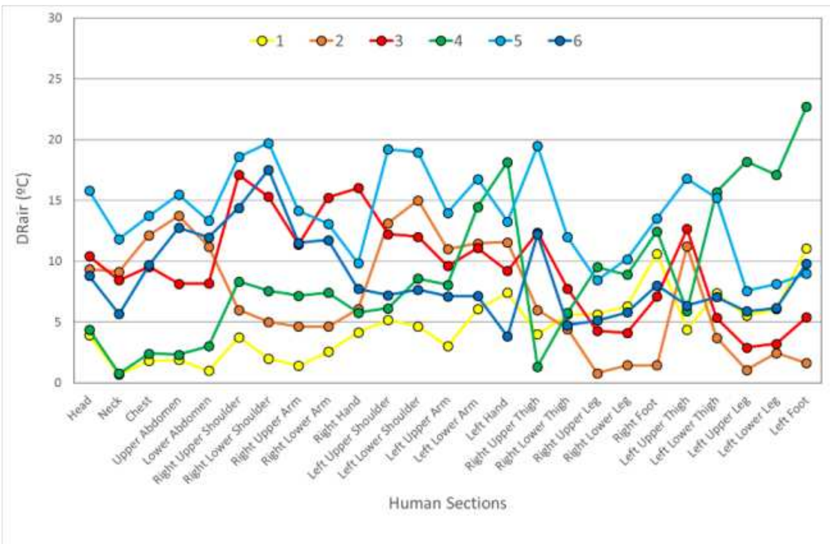
In the Tables 1, 2, 3 and 4 are presented the ADI values obtained, respectively, at 10, 12, 14 and 16 hours.




a)

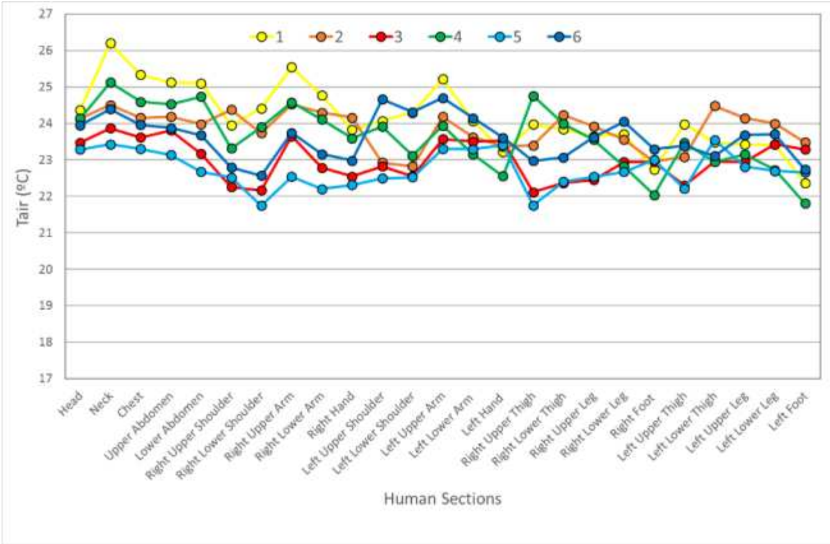



b)

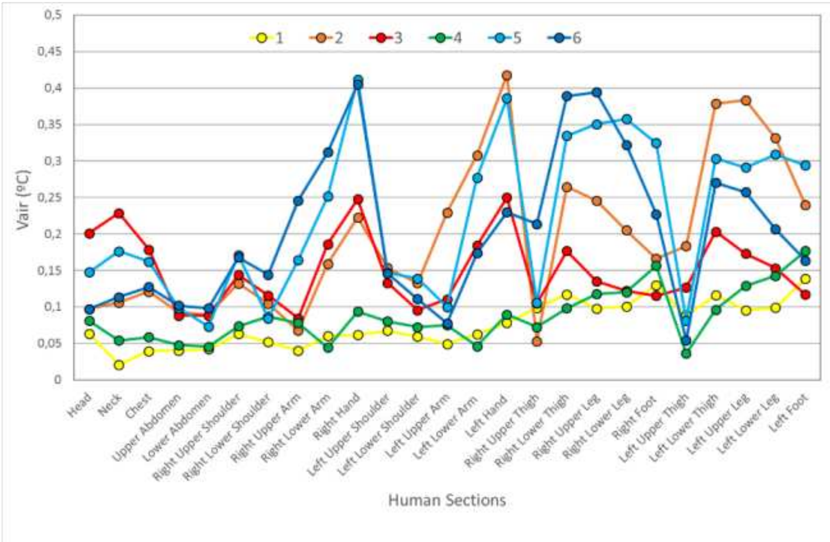



c)

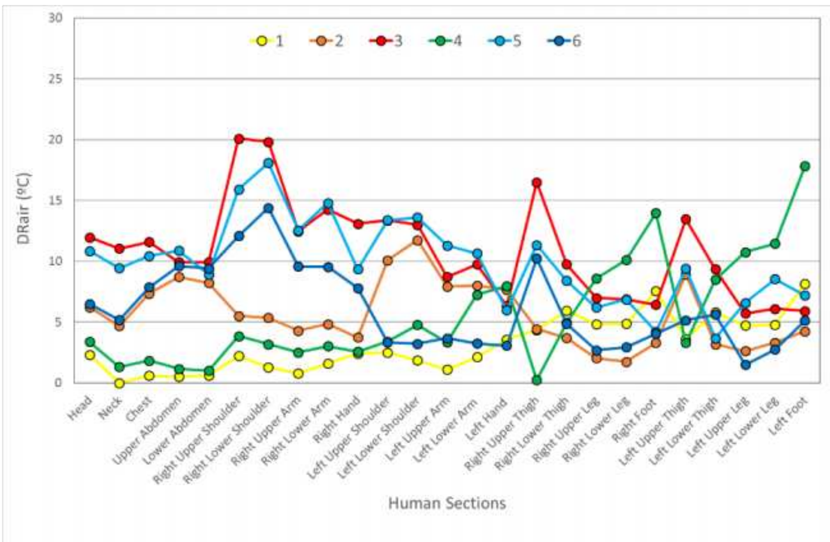
Figure 5. Air temperature (a), air velocity (b) and Draught Risk (c) around the occupants, obtained at 10 hours.




a)

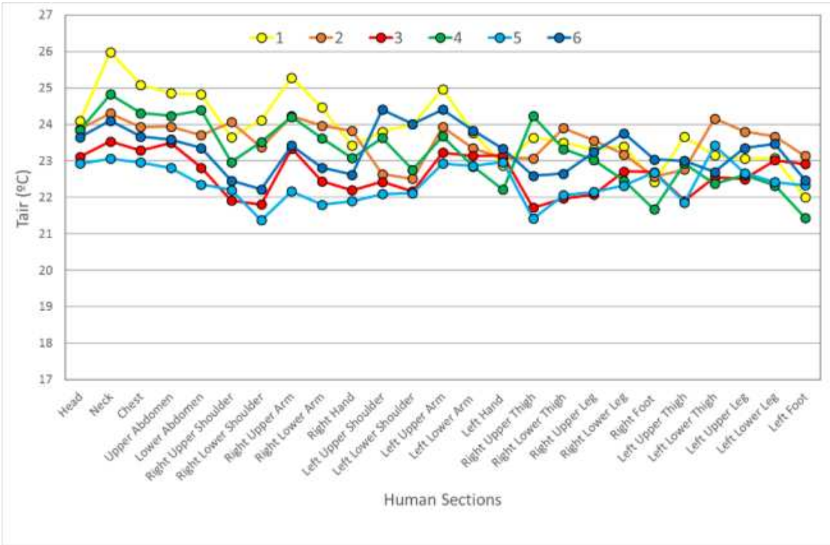



b)

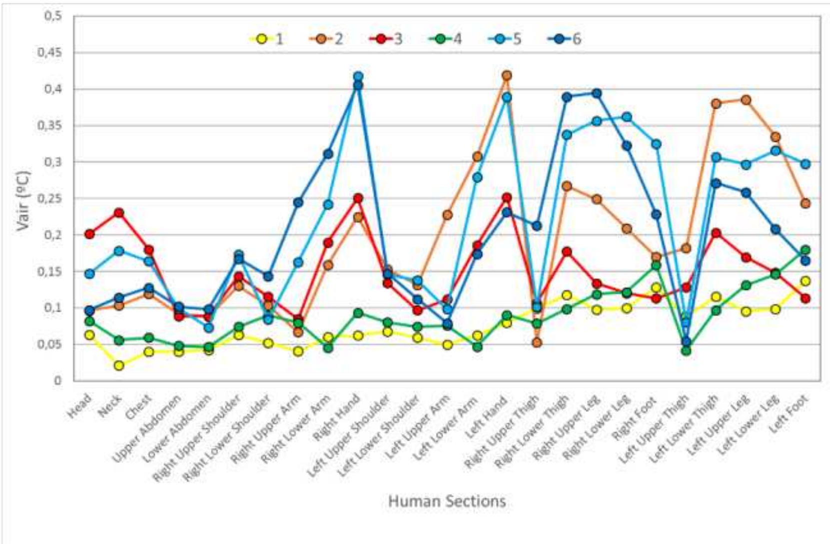



c)

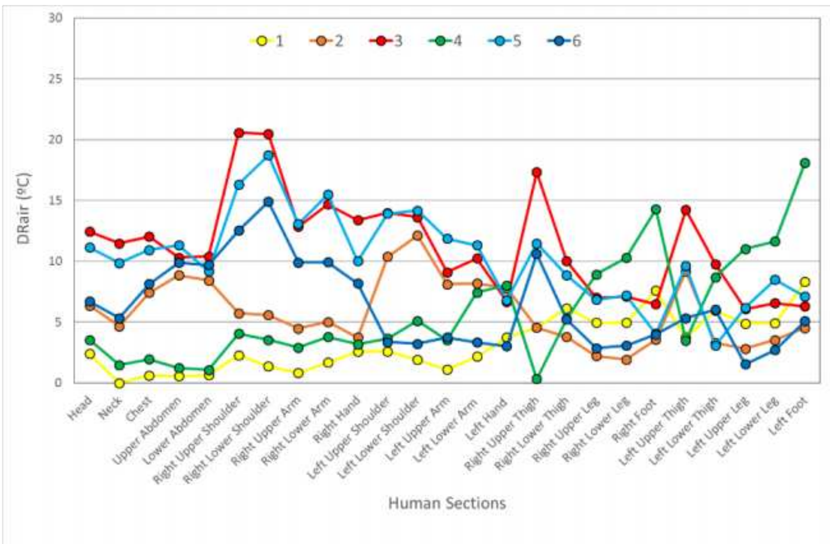
Figure 6. Air temperature (a), air velocity (b) and Draught Risk (c) around the occupants, obtained at 12 hours.




a)

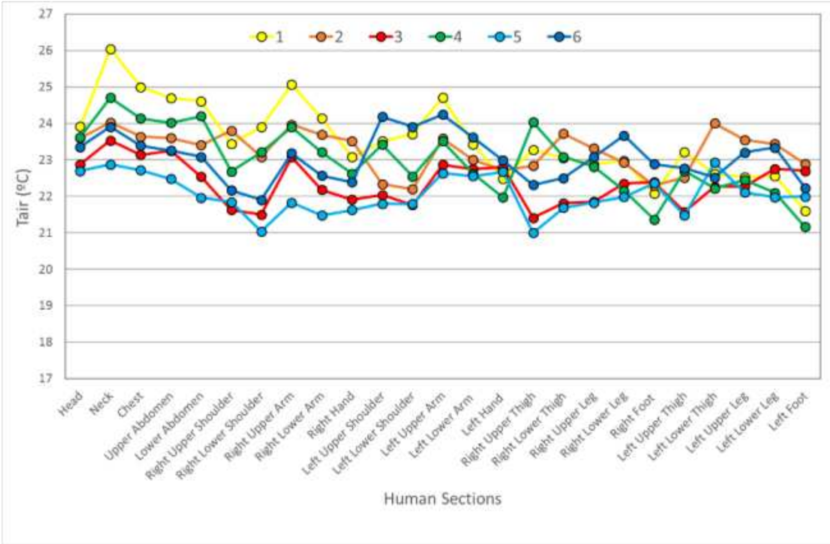



b)

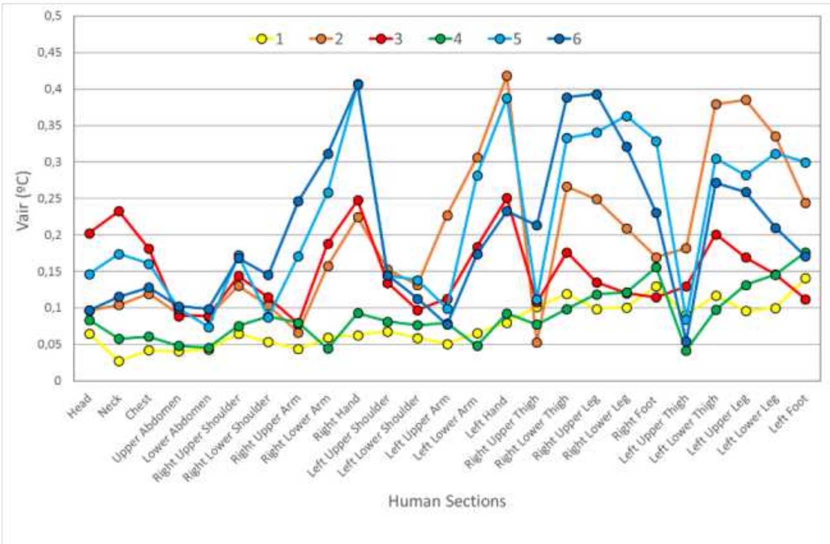



c)

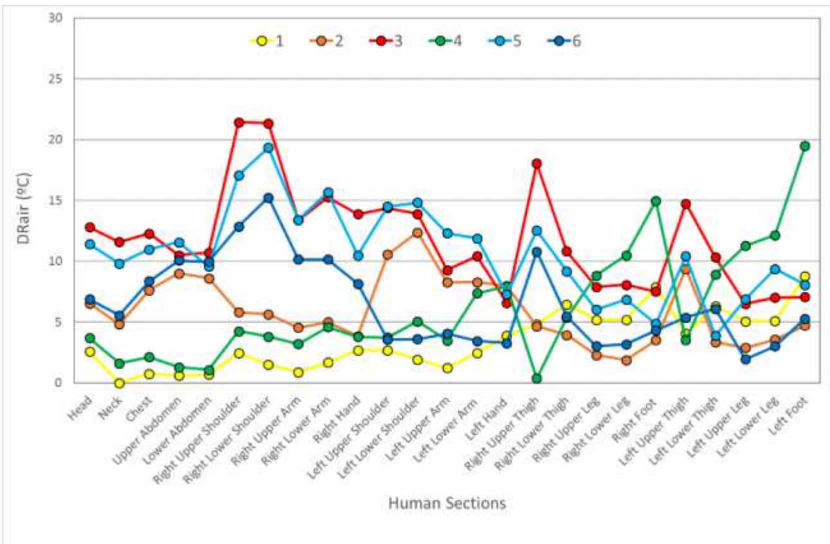
Figure 7. Air temperature (a), air velocity (b) and Draught Risk (c) around the occupants, obtained at 14 hours.




a)




b)




c)

Figure 8. Air temperature (a), air velocity (b) and Draught Risk (c) around the occupants, obtained at 16 hours.

Table 1. ADI value obtained at 10 hours

| Occupant number | 1 | 2 | 3 | 4 | 5 | 6 | Mean |
|---|---|---|---|---|---|---|---|
| Inlet Temperature (ºC) | 16,60 | 16,60 | 16,60 | 16,60 | 16,60 | 16,60 | 16,60 |
| Outlet Temperature (ºC) | 18,10 | 18,10 | 18,10 | 18,10 | 18,10 | 18,10 | 18,10 |
| Body Mean Temperature (ºC) | 21,80 | 20,84 | 20,46 | 21,14 | 19,24 | 20,48 | 20,66 |
| Effectiveness For Heat Removal (%) | 28,84 | 35,43 | 38,84 | 33,05 | 56,77 | 38,67 | 38,60 |
| PPD (%) | 10,35 | 15,68 | 15,87 | 12,60 | 23,45 | 17,15 | 15,85 |
| Thermal Comfort Number | 2,79 | 2,26 | 2,45 | 2,62 | 2,42 | 2,25 | 2,47 |
| Inlet Carbon Dioxide Concentration (mg/m3) | 500,00 | 500,00 | 500,00 | 500,00 | 500,00 | 500,00 | 500,00 |
| Outlet Carbon Dioxide Concentration (mg/m3) | 626,95 | 626,95 | 626,95 | 626,95 | 626,95 | 626,95 | 626,95 |
| CO2 in the Respiration Area (mg/m3) | 1013,60 | 916,83 | 1462,93 | 1338,04 | 1282,83 | 1149,44 | 1193,94 |
| Effectiveness For Contaminant Removal (%) | 24,72 | 30,46 | 13,18 | 15,15 | 16,22 | 19,55 | 19,88 |
| Ventilating Rate (l/s/Olf) | 57,57 | 57,57 | 57,57 | 57,57 | 57,57 | 57,57 | 57,57 |
| Percentage of Dissatisfied with Indoor Air Quality (%) | 2,55 | 2,55 | 2,55 | 2,55 | 2,55 | 2,55 | 2,55 |
| Air Quality Number | 9,67 | 11,92 | 5,16 | 5,93 | 6,35 | 7,65 | 7,78 |
| Air Distribution Index(ADI) | 5,19 | 5,19 | 3,55 | 3,94 | 3,92 | 4,15 | 4,33 |

Table 2. ADI value obtained at 12 hours

| Occupant number | 1 | 2 | 3 | 4 | 5 | 6 | Mean |
|---|---|---|---|---|---|---|---|
| Inlet Temperature (ºC) | 20,50 | 20,50 | 20,50 | 20,50 | 20,50 | 20,50 | 20,50 |
| Outlet Temperature (ºC) | 21,68 | 21,68 | 21,68 | 21,68 | 21,68 | 21,68 | 21,68 |
| Body Mean Temperature (ºC) | 24,44 | 23,92 | 23,11 | 23,95 | 22,85 | 23,67 | 23,66 |
| Effectiveness For Heat Removal (%) | 30,04 | 34,61 | 45,38 | 34,27 | 50,26 | 37,33 | 38,65 |
| PPD (%) | 5,73 | 5,07 | 5,02 | 5,28 | 5,37 | 5,01 | 5,25 |
| Thermal Comfort Number | 5,24 | 6,82 | 9,03 | 6,49 | 9,36 | 7,46 | 7,40 |
| Inlet Carbon Dioxide Concentration (mg/m3) | 500,00 | 500,00 | 500,00 | 500,00 | 500,00 | 500,00 | 500,00 |
| Outlet Carbon Dioxide Concentration (mg/m3) | 626,33 | 626,33 | 626,33 | 626,33 | 626,33 | 626,33 | 626,33 |
| CO2 in the Respiration Area (mg/m3) | 1075,59 | 1097,52 | 1529,98 | 1140,51 | 1059,61 | 1086,88 | 1165,02 |
| Effectiveness For Contaminant Removal (%) | 21,95 | 21,14 | 12,27 | 19,72 | 22,57 | 21,53 | 19,86 |
| Ventilating Rate (l/s/Olf) | 57,57 | 57,57 | 57,57 | 57,57 | 57,57 | 57,57 | 57,57 |
| Percentage of Dissatisfied with Indoor Air Quality (%) | 2,55 | 2,55 | 2,55 | 2,55 | 2,55 | 2,55 | 2,55 |
| Air Quality Number | 8,59 | 8,28 | 4,80 | 7,72 | 8,84 | 8,43 | 7,77 |
| Air Distribution Index(ADI) | 6,71 | 7,51 | 6,59 | 7,08 | 9,09 | 7,93 | 7,48 |

Table 3. ADI value obtained at 14 hours

| Occupant number | 1 | 2 | 3 | 4 | 5 | 6 | Mean |
|---|---|---|---|---|---|---|---|
| Inlet Temperature (ºC) | 20,00 | 20,00 | 20,00 | 20,00 | 20,00 | 20,00 | 20,00 |
| Outlet Temperature (ºC) | 21,34 | 21,34 | 21,34 | 21,34 | 21,34 | 21,34 | 21,34 |
| Body Mean Temperature (ºC) | 24,15 | 23,63 | 22,75 | 23,57 | 22,52 | 23,35 | 23,33 |
| Effectiveness For Heat Removal (%) | 32,21 | 36,83 | 48,56 | 37,43 | 53,07 | 39,90 | 41,33 |
| PPD (%) | 5,23 | 5,01 | 5,33 | 5,01 | 6,06 | 5,11 | 5,29 |
| Thermal Comfort Number | 6,16 | 7,35 | 9,11 | 7,47 | 8,75 | 7,81 | 7,78 |
| Inlet Carbon Dioxide Concentration (mg/m3) | 500,00 | 500,00 | 500,00 | 500,00 | 500,00 | 500,00 | 500,00 |
| Outlet Carbon Dioxide Concentration (mg/m3) | 626,19 | 626,19 | 626,19 | 626,19 | 626,19 | 626,19 | 626,19 |
| CO2 in the Respiration Area (mg/m3) | 1073,15 | 1111,63 | 1533,13 | 1135,74 | 1045,32 | 1090,31 | 1164,88 |
| Effectiveness For Contaminant Removal (%) | 22,02 | 20,63 | 12,21 | 19,85 | 23,14 | 21,38 | 19,87 |
| Ventilating Rate (l/s/Olf) | 57,57 | 57,57 | 57,57 | 57,57 | 57,57 | 57,57 | 57,57 |
| Percentage of Dissatisfied with Indoor Air Quality (%) | 2,55 | 2,55 | 2,55 | 2,55 | 2,55 | 2,55 | 2,55 |
| Air Quality Number | 8,62 | 8,08 | 4,78 | 7,77 | 9,06 | 8,37 | 7,78 |
| Air Distribution Index(ADI) | 7,29 | 7,70 | 6,60 | 7,62 | 8,90 | 8,08 | 7,70 |

Table 4. ADI value obtained at 16 hours

| Occupant number | 1 | 2 | 3 | 4 | 5 | 6 | Mean |
|---|---|---|---|---|---|---|---|
| Inlet Temperature (ºC) | 19,60 | 19,60 | 19,60 | 19,60 | 19,60 | 19,60 | 19,60 |
| Outlet Temperature (ºC) | 21,02 | 21,02 | 21,02 | 21,02 | 21,02 | 21,02 | 21,02 |
| Body Mean Temperature (ºC) | 23,89 | 23,36 | 22,51 | 23,36 | 22,20 | 23,11 | 23,07 |
| Effectiveness For Heat Removal (%) | 33,07 | 37,73 | 48,70 | 37,72 | 54,60 | 40,37 | 42,03 |
| PPD (%) | 5,02 | 5,20 | 5,80 | 5,04 | 6,94 | 5,41 | 5,57 |
| Thermal Comfort Number | 6,59 | 7,26 | 8,40 | 7,48 | 7,87 | 7,46 | 7,51 |
| Inlet Carbon Dioxide Concentration (mg/m3) | 500,00 | 500,00 | 500,00 | 500,00 | 500,00 | 500,00 | 500,00 |
| Outlet Carbon Dioxide Concentration (mg/m3) | 626,15 | 626,15 | 626,15 | 626,15 | 626,15 | 626,15 | 626,15 |
| CO2 in the Respiration Area (mg/m3) | 1072,62 | 1101,89 | 1561,08 | 1128,23 | 1084,89 | 1061,97 | 1168,45 |
| Effectiveness For Contaminant Removal (%) | 22,03 | 20,96 | 11,89 | 20,08 | 21,57 | 22,45 | 19,83 |
| Ventilating Rate (l/s/Olf) | 57,57 | 57,57 | 57,57 | 57,57 | 57,57 | 57,57 | 57,57 |
| Percentage of Dissatisfied with Indoor Air Quality (%) | 2,55 | 2,55 | 2,55 | 2,55 | 2,55 | 2,55 | 2,55 |
| Air Quality Number | 8,62 | 8,20 | 4,65 | 7,86 | 8,44 | 8,79 | 7,76 |
| Air Distribution Index(ADI) | 7,54 | 7,72 | 6,25 | 7,67 | 8,15 | 8,09 | 7,57 |

In accordance with the obtained results is possible to conclude:

- The effectiveness for heat removal increase slight during the day;
- The PPD value and the thermal comfort number are improved during the day and are lowest at 10 hours. However the thermal comfort level during the day is acceptable in accordance with the ISO 7730 (2005);
- The effectiveness for contaminant removal, the percentage of dissatisfied with indoor air quality and the air quality number are constant during the day;
- The ADI value increase during the day.

In the analysed situation, between the 10 and the 16 hours, the energy production, for this simulation, guarantee acceptable thermal comfort conditions. The airflow rate used guarantee, in the present simulation, acceptable indoor air quality levels.

## 5. Conclusions

This numerical study evaluates a confluent jets system with energy produced in DSF for winter conditions. The indoor environment variables, of the DSF and occupied space, were calculated during all day and the thermal comfort, indoor air quality and ADI were calculated at 10, 12, 14 and 16 hours.

In accordance with the obtained results the air temperature of the DSF space is lower than the indoor space when the space is occupants and is higher than the indoor space when the space is not occupants. The air temperature around the occupants is slightly uniform, the air velocity is slightly highest in the hands and lower members and the Draught Risks, in general, is lower than the 20 %. The effectiveness for heat removal increases slightly during the day, the thermal comfort level is acceptable, the effectiveness for contaminant removal are constant during the day, the indoor air quality is acceptable and the ADI value increase during the day.

In future works is suggested to analyse the influence of airflow rate in the DSF, and the influence of others HVAC systems, with different effectiveness, in the thermal comfort level, indoor air quality level and ADI.

## 6. Acknowledgements

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# Demand response of decentralized space heating using model predictive control to prevent the draught risk of cold window in an office building

Risto Kosonen[1,2*] ,Yuxin Wu[3,4], Aleksi Mäki[5], Juha Jokisalo[1], Simo Kilpeläinen[1], Sonja Salo[1,6]

[1] Department of Mechanical Engineering, Aalto University, Sähkömiehentie 4A, 02150 Espoo Helsinki, Finland
[2]College of Urban Construction, Nanjing Tech University, Nanjing 210009, China
[3] Joint International Research Laboratory of Green Buildings and Built Environments (Ministry of Education), Chongqing University, Chongqing 400045, China
[4]National Centre for International Research of Low-carbon and Green Buildings (Ministry of Science and Technology), Chongqing University, Chongqing 400045, China
[5]Oy Granlund Consulting, Helsinki, Finland
[6] Fourdeg Ltd. Helsinki, Finland

*Corresponding email: risto.kosonen@aalto.fi

**Abstract:** Demand response of district heating provides one tool for decreasing emissions in the whole energy system. However, when seeking cost savings and emission reductions, the local thermal comfort should be taken into consider. The experimental part of this study aims to examine how the demand response of space heating affects the local thermal comfort of occupants. The draught risk during the demand response was investigated by thermal manikin measurements in workstations near windows. The increase in draught risk was noticed when the window surface temperature dropped below 15 °C while the thermostat valves of the radiators were closed. The main objective of the simulation with predictive control algorithm (MPC) was to show how much the minimization of draught risk during decentralized demand response control with poor (U = 2.6 W/m²K) or energy efficient (U=1.0 W/m2K) windows has effect on cost saving potential of demand response. Results showed the DR was significantly decreased and the annual energy cost saving was also decreased by from 4.7% to 2.1% with the restriction temperature of old window (U=2.6 W/m2K) cases at 15 °C. Thus, it is necessary to use the window temperature restriction to prevent the draught risk of cold old window.

**Keywords:** Draught, Local discomfort, Cold window

## 1. Introduction

The building sector plays a remarkable role in decreasing of the overall global $CO_2$ emissions since as much as 30 % from the total global $CO_2$ emission are generated in buildings (IEA 2015). Demand response (DR) provides one possibility to tackle the problem. It can be used to decrease $CO_2$ emissions in entire energy system in addition to providing energy cost savings to building owners and energy companies. Several studies have shown that poor thermal comfort decreases employees work productivity (Li, Tan et al. 2010, Liu, Wu et al. 2017). Conditions that provide sufficient thermal comfort are stated in the national and international standards (ISO 2005, ASHRAE 2013), in which the acceptable surface temperature difference of a cold wall/window with the opposite side was no more than 10 °C. However, the thermal discomfort to drought induced by the cold window surfaces was not addressed in current standards.

The hypothesis was that, the convective downward airflows from the cold window surface could flow towards the occupant and cause draught. If at the same time the heating power of the water radiators below the window was low due to DR, the thermal plumes from the radiators would not block the downward airflows. During the demand response action, low heating powers are often used during the peak (high demand) hours when dynamic district heating price is high (Salo, Hast et al. 2019, Salo, Jokisalo et al. 2019).

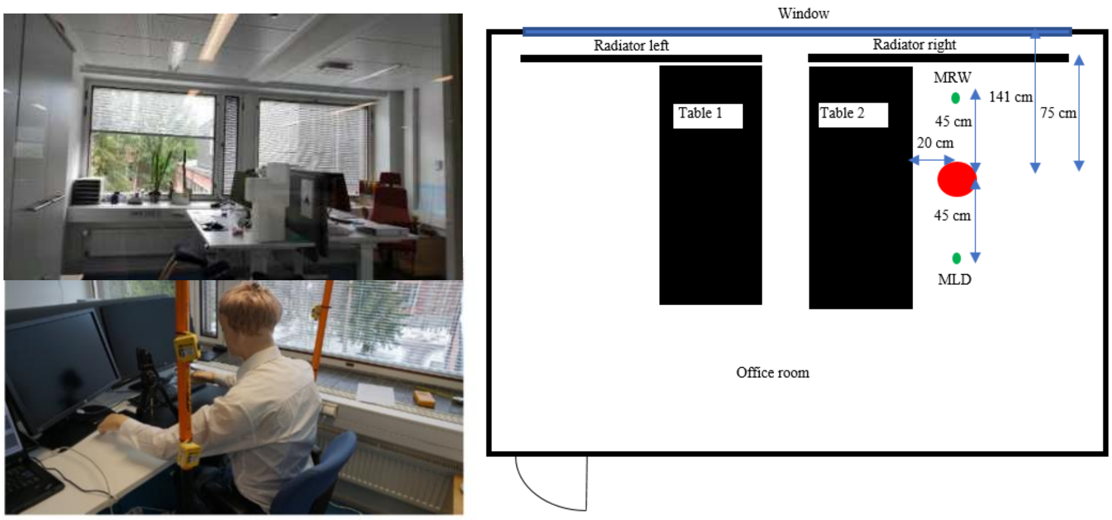
The methods used can inform further studies conducted in field condition to evaluate local discomfort caused by cold window. Data gathered can also prove to be useful for validating numerical models developed for both energy simulation and CFD models of air distribution. For poor non-energy-efficient windows the downward convective airflows would occur at the higher outdoor air temperatures than with new energy efficient windows due to higher heat losses. The results could be extended to cover different window constructions with numerical models.

## 2. Methods

### 2.1. Experimental methods on cold windows

To analyse the risk of cold window surfaces on local thermal comfort, experiments were performed in one office room of an educational building at Aalto University campus. The thermal comfort with various radiator heating setpoints and different window surface temperatures was studied in the office room.

The thermal comfort was studied in one office room with dimensions of 4.2 m (W) x 4.3 m (L) x 2.45 m (H). The measurement setup in the office room is shown in Figure 1. The room had two work stations with adjustable electric tables, chairs and common office furniture. The elevation of the tables was set to be equal to the window bottom frame (at the height 78 cm from the floor). In the office room, there were two large windows (1.8 m (W) x 1.55 m (H) and 1.9 m (W) x 1.55 m (H)). Under those windows, there were two water radiators. The thermal manikin used in the experiment was installed in front of the table further from the door (see Figure 1).




a) b)

Figure 1. Rooms studied: a) picture of manikin and measurement points; b) location of the manikin at red point. (note: MLD-measured line at left, MRW-measured line at right (window side))

Thermal manikin, build by former Helsinki University of Technology, was used to evaluate the local thermal comfort while the radiator thermostats setpoint was controlled. Manikin used in this study was size of 50 on European male index and it consisted of 24 heated body parts. Additional measurements were carried out to collect information of room air temperature, air humidity, window and radiator surface temperatures and supply and return water temperatures, ventilation air flow rates and supply air temperatures during the measurement periods. In the same time, the window surface temperature data was monitored while either cold or warm window surface conditions were reached.

### 2.2. Simulation of demand response (DR) with model predictive control (MPC)

A model predictive algorithm (MPC) was developed in this study to implement the DR of space heating. The process chart in Figure 2 presents the idea of DR with the MPC algorithm. First the input data including the weather forecast, dynamic district heating price and internal gain forecast was imported to the MPC algorithm. The MPC algorithm written in Matlab composed of the calibrated physical building model and an optimization algorithm. The optimization algorithm used the physical building model in finding the most optimal space heating temperature setpoints over the predicted time span of 12 hours.

The dynamic multi-zone simulation software IDA Indoor Climate and Energy 4.8 (IDA-ICE) was chosen to test the performance of the MPC algorithm with different DR cases. The TRY weather data was chosen since it represents current climatic conditions of southern Finland.

The studied simulation cases composed of reference cases simulated with constant setpoint of heating and demand response cases as shown in Table 4. The temperature setpoint was constant throughout the year, either 21 °C (R1), which is a normal temperature target value in Finnish building code or 21 °C (R2) which resembles a case where the heat is conserved. The DR cases (B1-B5) were simulated with temperature setpoint range of 20-23°C with and without window temperature restriction.

Table 1 Studied simulation cases

| Case | Window type | DR control | Window surface temperature restriction | Temperature setpoint range, [°C] |
|---|---|---|---|---|
| R1 | Window 1 | No | No | Cons. 21 |
| R2 | Window 2 | No | No | Cons. 21 |
| B1 | Window 1 | Yes | No | [20-23] |
| B2 | Window 1 | Yes | Yes (30%) [1] | [20-23] |
| B3 | Window 2 | Yes | No | [20-23] |
| B4 | Window 2 | Yes | Yes (30%) [1] | [20-23] |
| B5 | Window 2 | Yes | Yes (50%) [2] | [20-23] |

U-value of window glazing, [W/m²K]: Window 1 (U=1.0 W/m²K); Window 2 (U=2.6 W/m²K)

[1] The minimum power is set to 30% of the maximum power during the hour at hand

[2] The minimum power is set to 50% of the maximum power during the hour at hand

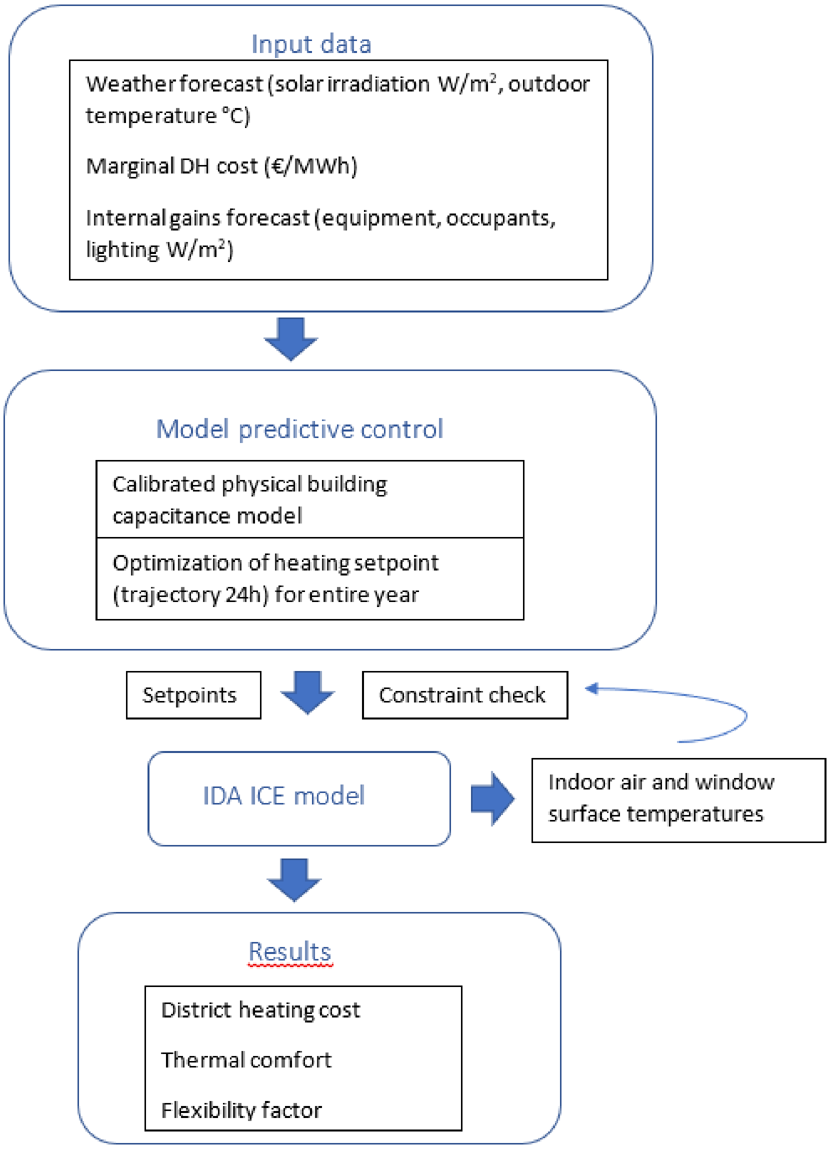



Figure 2. Process diagram of the simulation approach.

## 3. Results

### 3.1 Experimental results of restriction temperature for cold windows

When the radiator power was increased the upward plumes prevented the downward airflow. This phenomenon was further examined by measuring the equivalent temperatures with the thermal manikin. This measurement revealed that the cool window during the reduced radiator power could have a significant effect on the local thermal sensation especially on uncovered body parts e.g. hands and arms. The downdraughts and thus the local thermal comfort was most significantly sensed in the right hand which were uncovered and facing the window. In order to formulate the restrictive conditions, the equivalent temperatures in the right and left hands are analyzed in Figure 3. During the P1, the right- and left-hand equivalent temperatures differed when window surface temperature was 15 °C with valve of radiator closed, reveals that the draught occurred in this condition. During the P2, right- and left-hand equivalent temperatures differed at the beginning, but in the end the difference balanced out when window surface temperature increased to 17 °C with the valve of radiator closed. When the valve of radiator opened during P3, equivalent temperature differences balanced out and there was no draught even the window surface temperature was 15°C. It can be deduced that thermostat valves should be forced to open and heating turned ON when the window surface temperature is 15 °C or less.

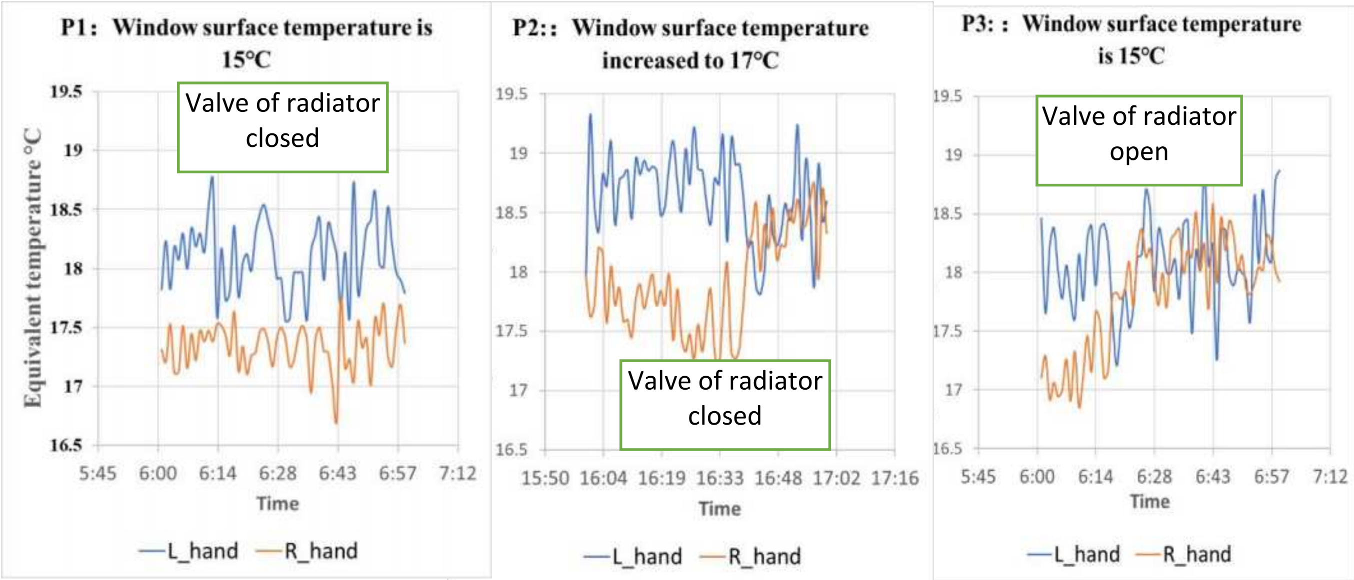



Figure 3. Equivalent temperature of the left hand (L_hand) and right hand (R_hand)

In the decentralized DR control strategy, heating power of an individual water radiator is possible to adjust separately. Technically that could be happen with electronic IoT thermostat valves that make possible to control the heating power e.g. based on the price signal. With decentralized systems, the local thermal comfort is main issue to consider. The draught risk could increase in workstations adjacent to windows during the decreased heating power mainly because of convection flow of cold window surfaces (see Fig. 4).

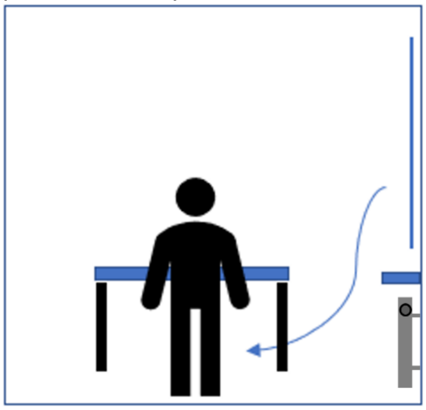


Figure 4. Convection flow from the cold window surface, if the thermostatic valve of the water radiator is closed.

Surface temperature (15°C) of inner window pane was found to be the limiting temperature in the studied room above which the thermostat valves should be opened. The window surface temperature depends on the outdoor air temperature, wind, solar radiation, indoor air temperature, window construction and properties in addition to room conditions like air flow patterns.

### 3.2 Analysis of the simulation cases

The annual heating energy consumption and cost of the simulated cases are presented in Table 2. The relative savings are calculated in reference to case R1 and R2 cases respectively. The restriction temperature of cold windows was 15°C in case B2, B4 and B5, which means that the thermostat valve was open when the surface temperature of inner window pane was below 15°C and there was heating demand in the spaces. The results were not quite different with the cold window prevent case B2. In case B3, the energy and cost saving are -4.7 and -3.8, respectively. In cold window prevent case B4 and B5, the energy and cost savings are slightly lower than that in no restriction temperature case.

Table 2. Simulation results of energy consumption and savings

| Window type | Cases | Restriction of windows | DH energy | Cost | DH energy | Cost | Cost and energy saving ratio |
|---|---|---|---|---|---|---|---|
| | | | kWh/m2 | €/m2 | % | % | - |
| Window 1 (U=1.0 W/m2K); | R1 | No | 128.3 | 8.2 | 0.0 | 0.0 | 0.0 |
| | B1 | No | 121.4 | 7.8 | -5.4 | -4.8 | 0.9 |
| | B2 | 30% | 121.4 | 7.8 | -5.4 | -4.7 | 0.9 |
| Window 2 (U=2.6 W/m2K) | R2 | No | 151.7 | 9.7 | 0.0 | 0.0 | 0.0 |
| | B3 | No | 144.5 | 9.3 | -4.7 | -3.8 | 0.8 |
| | B4 | 30% | 145.3 | 9.4 | -4.2 | -3.5 | 0.8 |
| | B5 | 50% | 147.7 | 9.5 | -2.6 | -2.3 | 0.9 |

Note: **B1, B2** refer to R1; **B3, B4, B5** refer to R2

## 4. Conclusions

This study aims to examine how the demand response of space heating affects the local thermal comfort of occupants. The draught risk during the demand response was investigated by thermal manikin measurements in workstations near windows. The thermal comfort measurements showed that the draught risk increased in workstations adjacent to windows during the decreased heating power. The increase in draught risk was noticed when the window surface temperature dropped below 15 °C while the heating was turned OFF. Thus, a window surface temperature restriction, could be taken into consider in the demand response control algorithms.

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# Balanced Heating & Cooling with Radiative Surfaces: Resilient answers to upcoming cooling needs, with new questions for the Comfort Community.

**Peter Holzer[1] and David Stuckey[2]**

[1] IBR&I Institute of Building Research & Innovation, Vienna, Austria,
Wipplingerstraße 23/3, A-1010 Vienna, peter.holzer@building-research.at
[2] IPJ Ingenieurbüro P. Jung, Vienna, Austria,
Wipplingerstraße 23/3, A-1010 Vienna, stuckey@jung-ingenieure.at

**Abstract:** A surge of cooling is hitting the building stock, driven by economic growth, population growth in hot areas, urbanisation, climate change and other factors. Even moderate climate zones are experiencing a surge for demand for AC, both in offices and homes. Passive strategies for indoor climate control, sufficient for centuries, simply are not enough anymore. It is a severe challenge to deal with this new cooling demand, while struggling not to lose the race for the mandatory decarbonisation of our society. A promising development is the use of strategies that use balanced heating and cooling with radiative surfaces. Examples of such systems to enhance summer comfort use radiative cooling from hydronic ceilings or floors. In the case study here, the excess heat from the cooling is used to thermally recharge geothermal storage components, e.g. boreholes, reaching seasonal energy efficiency ratios of 10 and above. Based on this charging, and together with the radiative hydronic ceilings or floors, the heating and domestic hot water requirements of a house, as well as of an office or building or community can be met with brine-water-heat pumps at high seasonal COPs of up to 4.5. Several systems like this are already in operation. The feedback from users is predominantly positive. Still, comfort challenges have to be carefully addressed, such as avoiding danger of local discomfort from floor cooling or ceiling heating, avoiding exaggerated expectations towards temperature-controllability, and finally, justifyingthe application of adaptive comfort theory to these buildings, which are not fully free running.

**Keywords:** Summer Comfort, Radiative Heating & Cooling, Seasonal heat storage, borehole heat exchangers

## 1. Challenges

### 1.1. The global surge of Cooling

The world is facing a rapid increase of air conditioning of buildings. This is driven by multiple factors, such as urbanisation and densification, climate change and elevated comfort expectations together with economic growth in hot and densely populated climate regions of the world.

In the last 25 years the number and capacity of Air Conditioning (AC) Units has tripled. It is very much expected to triple again in the next 25 years. (OECD, IEA, 2018) The trend towards cooling seems inexorable therefore; it is beholden upon us to guide this development towards better and more sustainable and resilient solutions (Holzer et al, 2019).

### 1.2. The regional shift of climate zones

Climate change hits the world, challenging the liveability of some regions and rapidly changing the climate zones of places.

The author's hometown Vienna, the capital of Austria, has been within climate zone Dfb (Snow, fully humid with warm summers), since the Koeppen Geiger classification was first published in 1884 (Koeppen, 1884). In the 2006 update of the climate classification by Kottek et al in 2006, Vienna is already in climate zon Cfb (warm temperate, fully humid with warm summers) and is expected to change further to Cfa (warm temperate, fully humid with hot summers) (Kottek, 2006).

Even moderate climate zones have experienced a massive increase in the demand for AC, both in offices and homes. Passive strategies, sufficient for centuries, are simply not enough anymore to keep people thermally safe in buildings.

It is a huge challenge to deal with this new cooling demand, without losing the race for the mandatory decarbonisation of our society we must all now work for.

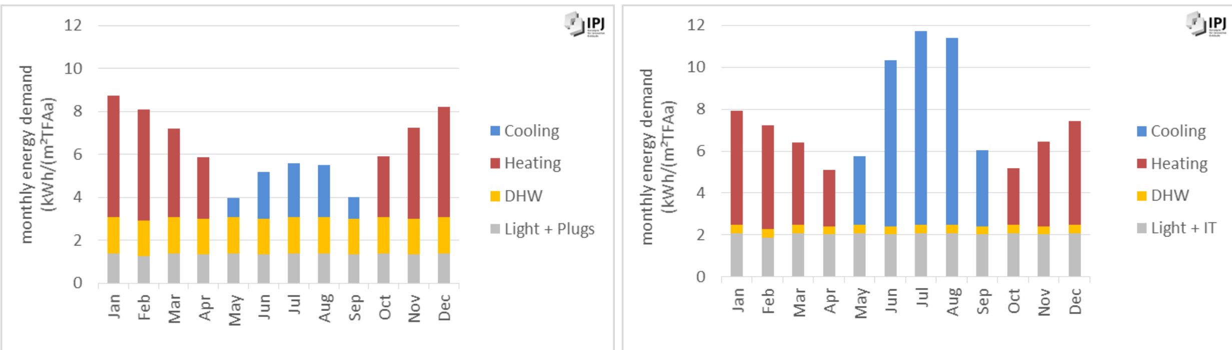
## 2. Chances

### 2.1. Balanced Heating and Cooling with seasonal storage

Even in moderate climate zones, building cooling demands have risen, but building heating demand and demand for domestic hot water remain. Depending on local climates, and the usage patterns of individual buildings , the balance between heating and cooling demand will differ.

a) b)

Figure 1 shows the monthly energy demand breakdown of a contemporary, newly built multi-storey residential building in the climate of Austria, which is currently classified as being in a Cfb climate zone (Holzer, 2020).




b) b)

Figure 1. Monthly energy demand breakdown for a) residential and b) office building

Using heat pumps, balanced heating and cooling is possible when supported by seasonal storage. The excess heat from cooling acts as a valuable thermal resource, better than releasing it into the hot city's air as thermal waste. Seasonal storage is expensive and results in high energy losses, if high exergy and high temperature differences are involved. However, it is cheap and extremely efficient if thermal storage operates close to environmental temperatures.

Ground water or borehole heat exchangers offer promising synergies with the operational requirements of such low evergy systems. Some of our key findings in the design and operation of large fields of borehole heat exchangers (BHE) are: Fields of BHE must be operated in a thermally balanced mode. They should certainly be designed using dynamic simulation, taking into account various options of load profiles. They should be operated between 0°C and 30°C medium fluid temperature. If so, they reliably cover a peak load of 40 to 60 $W_{th}$ per meter length and a storage capacity of 60 to 90 kWh per year and per meter length.

Figure 2 shows a schematic illustration of a field of borehole heat exchangers. (BLOCON, 2020)

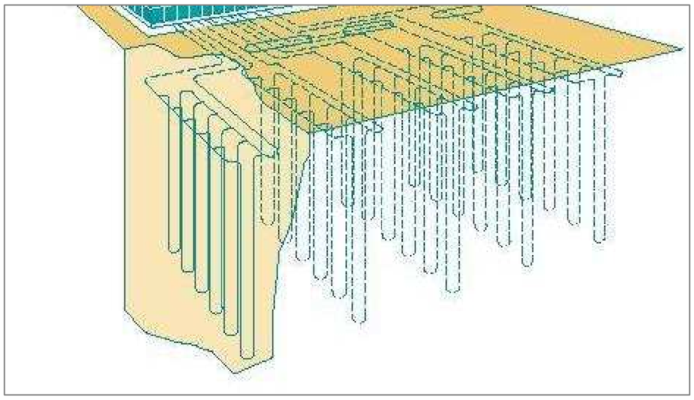


Figure 2. schematic illustration of a field of borehole heat exchangers

Depending on the balance of annual heating and cooling demands, there will often be a residual requirement for an alternative heat sink or source, in addition to those for heating and cooling. In the case of a sole heat source, it may be provided by an integrated thermal solar system. Cheapest, for sure, is a brine-air-heat exchanger, offering the chance to cover imbalances in both directions, charging and discharging, and offering very good performances during the shoulder months.

Figure 3 shows two examples of system concepts, with balanced heating and cooling, the left one using district heating to cover the imbalance between heating and cooling demand, the right one using an air-to-brine heat exchanger for the same purpose. (Holzer, 2020a)

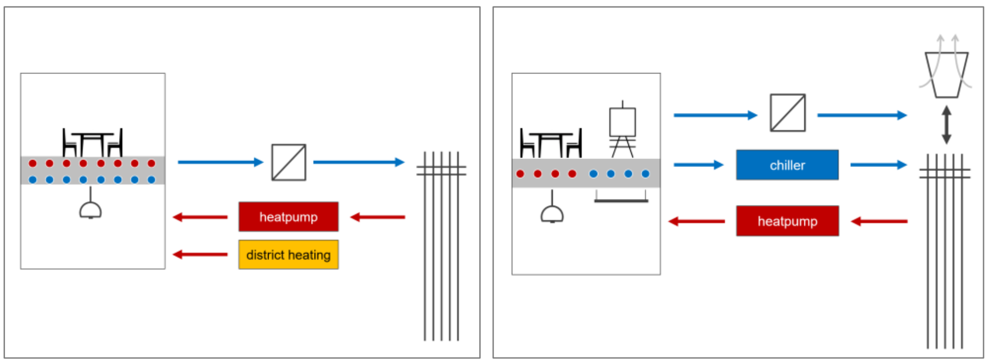



Figure 3. Two system concepts, left with district heating, right with air-to-brine heat exchanger

## 2.2. Heating & Cooling with Radiative Surfaces

The efficiency of balanced heating and cooling, using heat pump systems, stands or falls according to the temperature levels needed to operate the heating and cooling devices. Radiative surfaces offer optimal prerequisites for low temperature heating and high temperature cooling.

There is currently considerable activity in this field, resulting in good data and experience collection involving both with floor heating and cooling as well as with ceiling heating and cooling. In both cases, it is mandatory to know and accept the limitations of these systems, regarding the risk of local discomfort and – in the case of cooling – regarding condensation risk. Surface cooling and heating are well-developed technologies, with extensive knowledge available on them. Both systems offer high proportions of radiative heat transfer, especially floor cooling and ceiling heating. Figure 4 shows the heat flux of activated ceilings and floors (left heating, right cooling) as a function of the temperature difference between the surface and the room's operative temperature (Glück, 2007)

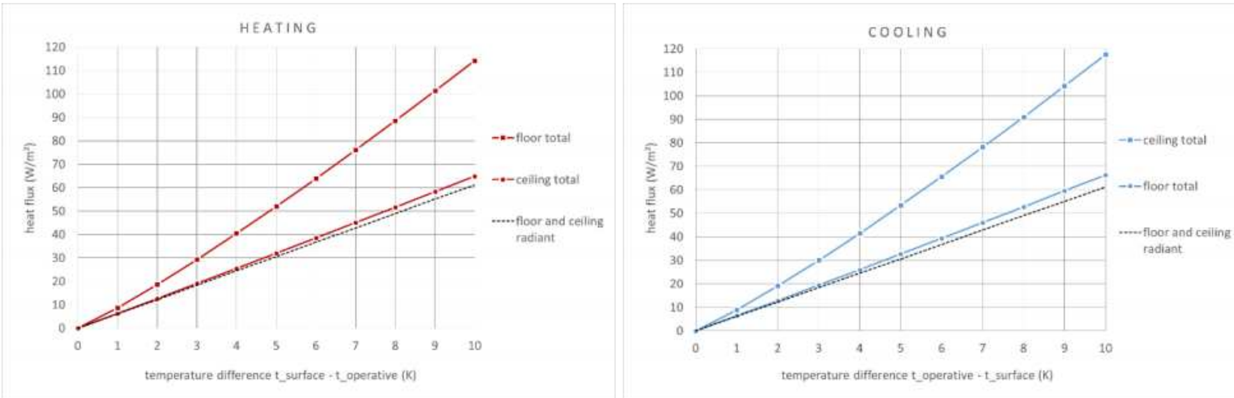



Figure 4. Heat flux of activated ceilings and floors (left heating, right cooling)

For both systems, also the risk levels of local discomfort from asymmetry of the radiant temperatures are well studied. They are internationally documented in ISO 7730:2005.

Figure 5 shows the risk of local discomfort from a warm and a cold floor. Figure 6 shows the risk of local discomfort from asymmetric radiant temperatures.

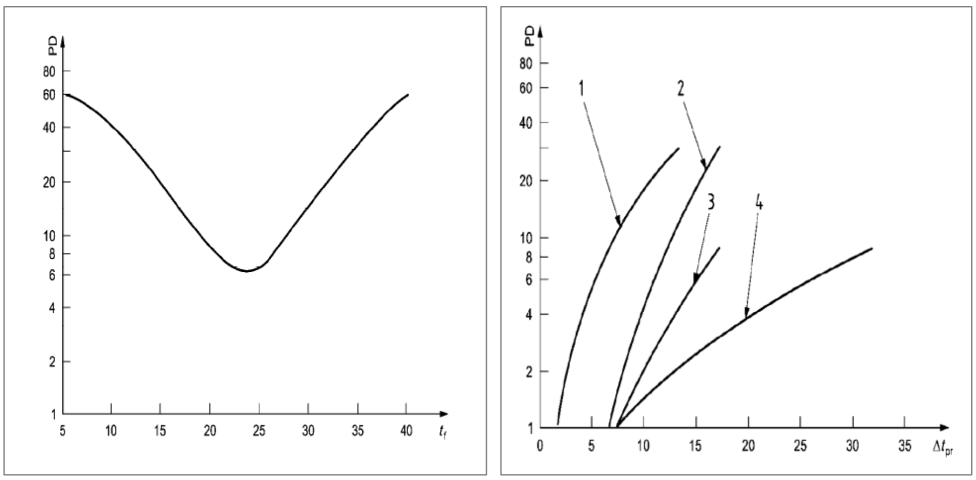



Figure 5. left: Risk of local discomfort from warm and cold floor

Figure 6. right: Risk of discomfort from asymmetric radiant temperatures (1: warm ceiling, 3: cold ceiling)

Both boundary conditions, condensation and comfort aspects, together with occupants' feedback lead to our recommendation of running hydronic ceiling and floor cooling at minimum supply temperatures of 21°C, and to run ceiling and floor heating at maximum supply temperatures of 29°C. In cooling mode, this regime leads to surface temperatures in the range of 22 to 24°C. In heating mode, this regime leads to surface temperatures of 26 to 28°C.

Accordingly, the heat flux of these systems is limited to 30 W/m² (ceiling heating and floor cooling) to these systems are sufficient for rooms with heating loads not higher than 30 W/m² (ceiling) up to 55 W/m² (floor heating and ceiling cooling).

When applying this regime, we learned to appreciate the self-regulation effect of these heating and cooling emitters: Without any technical control system, the heat-flux varies with the temperature difference, rising with the need and shutting off automatically, when the room temperature is close to the supply temperature of the fluid.

## 3. Discussion

The systems presented in this paper have proven performance and acceptance in many cases. Still there are questions to be further discussed.

### 3.1. Limitations regarding applicability to different comate zones

Balanced Heating & Cooling with Radiative Surfaces is naturally limited regarding applicability to different comate zones in two aspects:

The first limitation is from humidity. To secure sufficient effect, in cooling mode surface temperatures of down to 23°C should be allowed. This theoretically limits absolute humidity in the room of maximum 19 g/kg in conditions with a corresponding humidity outside of not more than 16 g/kg. The system is well-suited to arid and warm temperate climate zones, but is not a good solution for equatorial climate zones. (Kottek et al, 2006) This is a serious limitation. Experiments applying surface cooling, even in equatorial climate zones, combined with supply air dehumidification, turn out too vulnerable to a disturbance of this system, for example caused by open windows or doors.

The second climatic limitation of such systems comes from the need to have a definite seasonal balance between heating and cooling, or, to have at least a seasonal variation strong enough to charge or discharge seasonal storage buffers within the year. There are currently interesting attempts to discharge thermal mass of surface cooling not only seasonally, but also nocturnally, making use of low sky temperatures during different times of day and year in arid climate zones.

### 3.2. Limitations regarding maximum cooling and heating load

There are limitations regarding maximum available heating and cooling loads. They have been already discussed in this paper. Still, they are not physically rigid, but depend on the selected room temperature. As soon as a wider indoor temperature band within the room is accepted, the heating and cooling load, available from radiant surfaces will rise significantly. This raises serious questions for the future of indoor comfort: the extent to which the shift will come towards the promotion of low energy, mixed mode conditioning systems for buildings? When will this shift come? And what will be the role of supplementary personal heating and cooling appliances for use during temperature extremes in conjunction with such robust, and inflexible, low energy conditioning systems?

### 3.3. Answers posited for the Comfort Science Community?

Balanced Heating & Cooling with Radiative Surfaces, including the types of control regimes described, are very much a child of adaptive comfort theory: Such systems certainly increase genuinely low energy comfort over a year, but they certainly do not provide guaranteeable, tightly limited bands of physical indoor air properties of temperature and humidity, independent of outdoor conditions, such as are promoted through 20th century facing International Comfort Standards.

We suggest that the time has come for the building engineering community to apply widely the adaptive comfort scale, to enable and encourage the wider use of not only BHC buildings, but also all building types that involve thermal inertia and storage coupled with radiative surfaces in genuinely very low energy buildings. However international Standards actually discourage the use of Balanced Heating & Cooling with Radiative Surfaces, as they are technically not in free running mode, and thus the adaptive comfort scale, strictly speaking, is not to be applied to them. We posit that this must change and as proponents of Balanced Heating & Cooling with Radiative Surfaces argue, that these systems very much operate in free running mode, being at least invisible and soundless, constantly charging or discharging the thermal buffers without strictly controlling the physical indoor parameters. This is an ongoing and important discussion and where better to facilitate it than at the Windsor Conference.

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# Rethinking Radiant Comfort

**Eric Teitelbaum[1] and Forrest Meggers[1]**

[1] CHAOS Laboratory, School of Architecture and the Andlinger Center for Energy and the Environment, Princeton University, Princeton, NJ, 08544, USA

**Abstract:** In a warming world, staying cool will require thinking outside the air-based comfort box. Radiant cooling and personal comfort systems allow air temperature setpoints to be increased, but current comfort standards fall short of fully elucidating that full potential. Historically, radiant cooling capacity has been limited by condensation risk from the direct contact of radiant panels with humid air, and have unavoidably needed to be coupled with air conditioning. Our recent studies and experimental systems demonstrate a way to decouple the risks of radiant panels using IR transparent membranes that protect sub-dewpoint non-condensing radiant cooling surfaces. This photonically enables radiant cooling while mitigating condensation and preventing convection and condensation issues around the panel as demonstrated in our 'Cold Tube' test bed. These non-standard conditions have helped us uncover and address discrepancies between mean radiant temperature (MRT) field measurements and simulation. In order to describe the potential comfort zone differently from that which is commonly mapped on the psychrometric chart from standard comfort ranges, we present a new comfort mapping framework that allows radiation or natural ventilation to be selected as setpoints. We have discovered that calculations supporting much higher potential separation of MRT from air temperature are incorrectly calculated by current black globe correction methodologies. We demonstrate systematic error in MRT measurements using black globes. This has misinformed radiant comfort understanding, and we show here how it could systematically biased ASHRAE thermal comfort database measurements. Together, these findings help advance the field's understanding of radiant comfort, demonstrating the acceptability of comfort conditions with high (>30 °C) air temperature and low (<24°C) mean radiant temperatures. We conclude with new deductions from these models, tools, and experiments including how operative temperature misguidedly increases temperature with higher air speeds incorrectly associating warming with higher air speeds, how radiant to convective ratios of heat transfer are affected by air movement and more importantly how radiant cooling positively reinforces its relative effect while radiant heating negatively does and increases susceptibility to draft, and finally how radiant affects are highly spatialized independent of common practice of defining thermal zones with room volumes. From this evidence, we conclude that there are significant alternative conceptual frameworks not dependent on temperature proxies that can more accurately define comfort.

**Keywords:** Thermal Comfort, Radiant Cooling, Expanded Psychrometrics, Thermal Design, Globe Thermometers

## 1. Introduction and Motivation

What do we really know about comfort? Hopefully we agree that it has something to do with heat flowing from a body to its surroundings. Currently most models for comfort in buildings use empirical proxies that have lost a direct connection to physics-based models of heat transfer. They have mainly used temperature-proxies as a mechanism to simplify the complex independencies between the variables that define the heat transfer between a body and its surroundings. We revisit some of these interdependencies and have uncovered arguments for how comfort can be defined more dynamically and flexibly by leveraging the full range of interactions between a body and its surroundings, particularly with regard to radiant heat transfer.

Physics dictates that the rate of heat loss to be proportional to the temperature difference between the body and its surroundings, not singular absolute temperature-proxies. First we should focus on what we really know about temperature and the physics of heat transfer. Are temperature proxies appropriate physical metrics for comfort? How does temperature actually drive the experience of heat and comfort?

Conventionally, we know that at macroscopic scales temperature is a proxy for the average kinetic energy possessed by atoms in a system. The more kinetic energy the atoms have on average, the more momentum gases can impart on containers, the more radiation the atoms emit, and the more likely the atoms and molecules are to make people warm. As length scales decrease, statistical mechanics begins to describe temperature more and more, and exciting new phenomena can be observed. For instance, a group in 2013 proposed and observed a system that can have "negative absolute temperatures" if composed of the correct entropic ratios of energy states (Braun et al., 2013). While your thermometer would never read something below 0 Kelvin, the system could still have thermal efficiencies greater than 1. And when researchers also in 2014 demonstrated a system for daytime radiative cooling producing upwards of 100W/m$^2$ of passive cooling by restructuring light, length scales became extremely important (Raman et al., 2014).

In the built environment, macroscopic length scales dominate. However, when heat transfer occurs at interfaces, we must zoom into these interfaces to understand the interdependencies of radiation, convection, conduction, and comfort. In any discipline, temperature is at best an abstraction. Additional temperatures are then abstractions built on abstractions, which imposes problems for conceptually clean design.

For instance, the mean radiant temperature is a useful metric to compare the radiant environment in two locations (Feng et al., 2016). But it fails to provide a description of how an occupant might interact with the surfaces in a space since it does not capture geometric, material, and physiological subtleties associated with radiant heat transfer. Further, when using operative temperature to describe a radiantly cooled space, by inspection it is clear that changes in operative temperature will not proportionally scale with changes in heat lost physiologically by a person. This point will be discussed further in the methods and results. Such factors de-emphasize the importance of radiation in the built environment, compounded by the lack of fidelity of globe thermometers. The failure to assess the actual mean radiant temperature when attempting to measure this value in environments with large surface-to-air temperature gradients may have far-reaching impacts on our knowledge of thermal comfort as current research that downplays role of radiant (Dawe et al., 2020) may be based on systematically incorrect data as we will discuss.

Building physical comfort models from first principles with a framework which is first grounded in physical, not statistical or empirical, bases, allows a rethinking of radiant comfort. We demonstrated how thinking about comfort in Watts instead of Degrees, and using materials science and architectural design as a comfort methodology instead of an ASHRAE standard approach, enables a shift of the flow of heat from occupants to be overwhelmingly controlled by radiant systems, which can allow air temperatures to be setback more than ever previously demonstrated while maintaining optimal removal of watts for a novel physics-driven physiological comfort.

### 1.1. Background

We will combine and build off of work we recently published to explore the relationships and opportunities to create new potential modes of achieving and managing thermal comfort conditions for the human body across a wider range of conditions. We have found and demonstrated that common comfort metrics such as mean radiant temperature and operative temperature obfuscate the true driving forces for heat transfer by focusing on a universal temperature proxy for phenomena inherently driven by gradients across a range of temperatures (Teitelbaum et al., 2020; Guo et al., 2020; Teitelbaum et al., 2019; Houchois et al., 2019). Over the past six years we have experimentally and analytically explored a variety of challenges to heating and cooling, largely in the radiant heat transfer domain, but more recently in the broader framework on thermal comfort and all heat transfer physics relating to the human body.

A large part of this work builds on the expanded psychrometrics framework (Teitelbaum, Jayathissa, et al., 2020), which allows us to include radiant and convective variables visually to a broaden the analysis of comfort across the whole psychrometric chart. Experimentally the chart was encouraged by our work developing prototype radiant cooling systems deployed in various pavilions and installation (Aviv et al., 2019; Aviv & Meggers, 2017; Meggers et al., 2017; Teitelbaum et al., 2019). The most recent project in Singapore, the Cold Tube, provided the most unique comfort conditions well outside convention (Teitelbaum, Chen, et al., 2020). Through its evaluation we discovered several limitations and/or problems in current analyses that we will explore further in this paper.

Most recently we demonstrated that globe thermometers have systematic error, because they are not properly corrected for convective exchange with their surroundings, which significantly underestimates the real mean radiant temperature offset from the air temperature (Teitelbaum et al., 2020). Our interest in challenges with the black globe thermometers originated in our work studying novel ways to map spatial variation in MRT, and led to the publication of a replication paper (Guo, Teitelbaum, et al., 2019) of the original research by Bedford and Warner that led to the invention of the black globe in 1930's (Bedford and Warner, 1934) where we attempted to achieve the same MRT to air differences from the 30's but without high temperature industrial conditions used in the research that was originally focused on industrial hygiene, and not thermal comfort we were unable to match those conditions. We subsequently reviewed the use of the concept of mean radiant temperature more extensively, and found there to be significant discrepancies in how it was applied (Guo, Teitelbaum, et al., 2019; Houchois et al., 2019). We also discovered some serious potential mis-interpretations of operative temperature when used in combination with MRT, which we will synthesize in this paper to also consider sensitivities and variations in the ratio or relative amount of radiant versus convective heat exchange experienced by a body. In our review of previous work we found many variations on the assumed relationships to how MRT and air temperature affect comfort differently ranging from saying every degree of MRT is compensated by 1.4 degrees of air temperature to exactly the opposite (Guo et al., 2019). We have gone further to review how more physics-based models of human body metabolism can be understood using exergy analysis, which demonstrates further potential complex feedbacks (Guo, Luo et al., 2019).

We stand on the backs of giants as our work builds on a long history of groundbreaking comfort analyses and research. Although we offer many critiques and propose alternative frameworks for considering comfort, we believe the fundamental work of Bedford, Warner, Vernon, Yaglou, and others was critical in providing initial contexts for radiant heat and the body (Bedford and Warner, 1934; Vernon, 1932; Vernon and Warner, 1932; Houghton and Yagoglouu, 1923). Of course Fanger established an amazing framework for incorporating all aspects of heat transfer and thermodynamics (Fanger, 1972). In the past decades Arens, Brager, De Dear and others have all continued to refine radiant heat transfer, human physiology, and improved comfort analysis methods (de Dear et al., 1997; Arens et al., 2006; Arens et al., 1986; Licina et al., 2018). We arrive at our contemporary moment with much ongoing critical research and lively debate happening in standards and industry groups like ASHRAE. We will argue that while all of this analysis has immense value, we are in an age of huge amounts of data mixing subjective and empirical sources, and that in this moment some reflection on the basic heat transfer physics may help *push us out of our comfort zone with comfort.*

## 2. Methods

We explore the sensitivity of common comfort metrics to changes in non-standard comfort conditions. The common framework for comfort is the psychrometric chart, which enables analysis of temperature and humidity. But the psychrometric chart, although central in the definition of comfort ranges, fails to enable analysis of all comfort variables. We have proposed methods to include these additional dimensions to the psychrometric chart using the expanded psychrometric framework. We apply these methods to the consideration of the comfort metrics of operative temperature and mean radiant temperature.

### 2.1. Comfort Calculations and Mapping

We have developed a comfort evaluation tool to enable plotting additional comfort metrics on the psychrometric chart (Teitelbaum, Jayathissa, et al., 2020). The tool adds additional physics-based model of human body heat transfer to the psychrometric chart.

A standard Gagge model of human body heat transfer is put in balance with the metabolic rate (Gagge et al., 1976). The heat must be dissipated, and the temperature and humidity on the psychrometric chart are combined with the convective influence of air movement and skin wettedness to complete the exchange with air, and the mean radiant temperature is used to calculate the radiant heat transfer component. But all these variables can't fit on one chart, so the expanded psychrometric methods holds air movement constant and demonstrates possible comfort by calculating the necessary MRT across the entire psychrometric chart to achieve a balance with the metabolic rate and plotting a contour map of that potential (example Figure 1). This provides a wider physics based approximation of potential thermal comfort independent empirical bounds. In addition, the MRT can be held constant and air speed can be plotted to achieve comfort. This tool has been made interactive online at www.comfortch.art and www.ashrae.cool.

The resulting tool eliminates the need for a standard "comfort zone" on the psychrometric chart, but also creates some non-standard comfort conditions. These include ones with higher-than-acceptable air speeds (though potentially acceptable for some applications where occupants are given control of air speed), and more importantly it predicts very specific comfort scenarios visually with air temperature and humidity conditions currently considered to be universally uncomfortable, but for which higher or lower MRT can enable comfort.

We use this tool as a method to explore how our previous work building unique radiant cooling and heating pavilions can be considered also as mechanisms to demonstrate non-standard thermal environments that are also comfortable even though they don't fit standard comfort models. It helped guide design and analysis of the Cold Tube.

### 2.2. Cold Tube

The Cold Tube pavilion was created in Singapore to explore radiant cooling below the dew point in the hot humid tropics with novel photonic panels that prevent condensation, and we use the output of very non-standard MRT and air-temperature combinations as a method to frame the analysis of non-standard comfort criteria. Figure 1 demonstrates an expanded psychrometric chart with the range of values where comfort conditions were achieved on the expanded psychrometric chart, which will be used to expand consideration for comfort conditions in the Results.

Accurately measuring the mean radiant temperature in the Cold Tube pavillion proved a difficult task because of the high degree of separation between the mean radiant temperature and the air temperature. We had already exprienced challenges trying to replicated the work of Beford and Warner when they created the first globes as part of an *Energy and Buildings* replication issue, but we had not yet suspected a fundamental error with the technique (Guo et al., 2018). It wasn't until systematically comparing measurements of with calibrated pyrgeometers measuring precise W/m$^2$ of longwave radiation that we recognized a problem. Black globe thermometers as discussed in Teitelbaum et al. (2020) are not adequately corrected for free convection or mixed mode convection effects, and as such deviated significantly from our 6 pyrgeometers (Apogee SL-510-SS) ground truth oriented along the cardinal directions. A photo of this setup can be found in Teitelbaum et al. (2020).

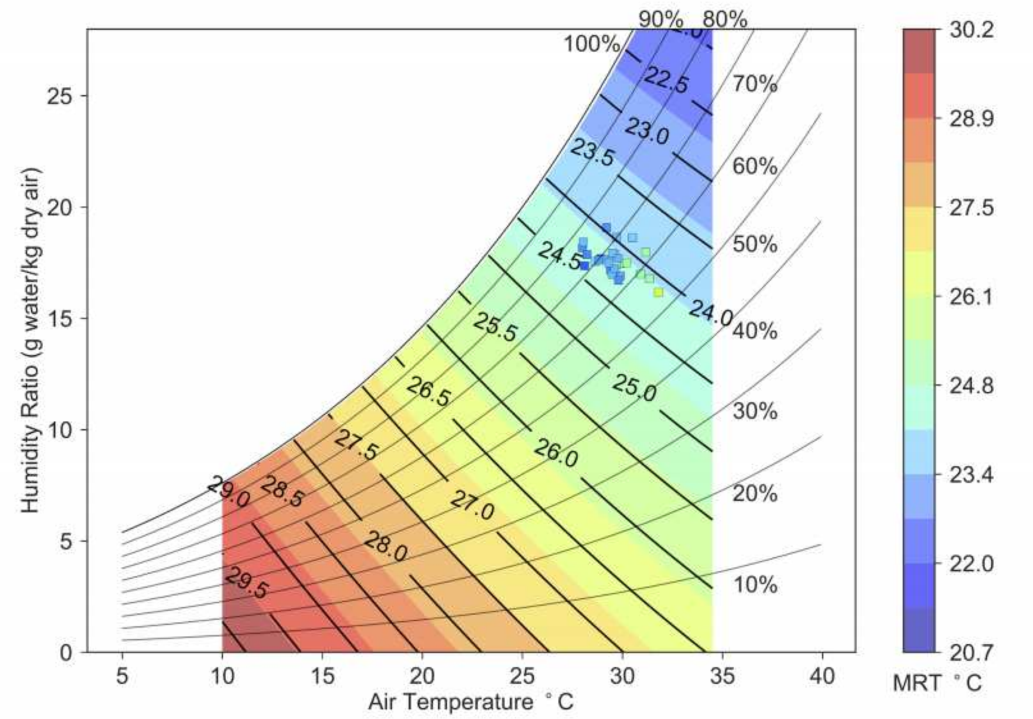


Figure 1: Designing the comfort setpoints into the Cold Tube pavilion based on the expanded psychrometrics framework. The datapoints clustered around an air temperature of 30 °C and relative humidity of 70% are shaded with the color corresponding to the actual measured mean radiant temperature. Comparing the data point's color with the background gives an approximation of how close the condition is to achieving the calculated human body heat balance.

The real mean radiant temperature data was not subject to degradation from convection due to the physics to the pyrgeometer, and much higher separations of MRT from air temperature were confirmed. Preliminary data was collected from the operational Cold Tube, shown in Figure 1. Low mean radiant temperatures were achieved without condensation or unwanted air conditioning using 17°C chilled water to produce a 23.9 °C average mean radiant temperature. This high temperature cooling method has implications for low-exergy system design.

### 2.3. Analysis of existing MRT Data ASHRAE

To demonstrate the systematic error that not accounting for free convection might have broadly on calculated mean radiant temperatures and subsequent thermal comfort derivations and analyses we explored effect on data in the ASHRAE Thermal Comfort Database II (Licina et al., 2018). Data was filtered by selecting air temperature and globe temperature with a coincident air speed less than or equal to 0.1 m/s. 45,164 data points fit this criteria. For these points, mean radiant temperature was back-calculated using the globe temperature, air speed, and air temperature with the ASHRAE method (ASHRAE, 2013) and only a free convection correction (Teitelbaum et al., 2020) for a globe diameter of 0.04 cm (ping-pong ball).

### 2.4. Analysis of Operative Temperature as metric

Operative temperature was calculated using equation (1), where the radiative and convective heat transfer coefficients were calculated using the approach outlined in Teitelbaum, Jayathissa et al. (2020). There are several methods to calculate the operative temperature, however this one was chosen due to its attempted fidelity at physiological heat transfer models by using actual radiative and convective heat transfer coefficients.

$$T_o = \frac{h_r T_r + h_c T_a}{h_r + h_c} \qquad \text{Eq. 1}$$

### 2.5. Analysis of variations in the ratio of radiant to convective heat transfer

We used the same methods for calculating the components of heat transfer from radiant surfaces and surround air in the expanded psychrometric chart to look specifically at the way the convective vs radiant heat transfer vary. Specifically we explore the ratio of convective to radiant exchange. These are calculated at two different wind speeds, 0.16 m/s and 0.5 m/s, and also for two different metabolic rates, 1.2 met and 2 met.

### 2.6. Spatial analysis of radiant heat transfer

After evaluating the challenges in properly incorporating radiant heat transfer into comfort evaluations, we also consider the way radiant heat transfer uniquely varies spatially. As view factor and surface temperature are different for any point in a room we again use the Cold Tube project to project the variation of the MRT in plan. We produce data using a scanning mean radiant temperature sensor (SMART) that we developed to produce a point cloud of various and surfaces (Houchois et al., 2019; Aviv and Houchois, 2019). This type of data will allow description of changes in the thermal experience across a singular space, again breaking the commonly held notion that rooms are conditioned as singular volumes.

## 3. Results

### 3.1. Cold Tube Comfort Analysis

Inside the Cold Tube, survey participants were generally comfortable, with only 20% of participants with the pavilion 'on' reporting a thermal sensation warmer than neutral (greater than 0). With the Cold Tube 'off', 73% of the surveyed population was too warm. This indicates that shading inside the Cold Tube was not responsible for the perceived cooling effect, but instead thermal radiation. Survey data is plotted in figure 2a. The coincident average air speed was 0.26 m/s. This low air speed, high air temperature and humidity when fed into the expanded psychrometrics heat balance model predicts that 34% of heat transfer was due to convection and the remaining 66% was due to thermal radiation.

While we are not aware of another human-made example of this environment (the ASHRAE Thermal Comfort Database II does not have such an environment), such a comfort zone was predicted by the adaptive thermal comfort model. However, conventional methods for producing the environment would rely on elevated air speed and air conditioning, the Cold Tube demonstrator is a successful example of using radiation to manipulate thermal comfort votes.

However, as shown in figure 1b, there is a quantifiable discrepancy between the operative temperature when using the mean radiant temperature as calculated by the ASHRAE standard correction equation versus the ground truth as measured with the pyrgeometer. This discrepancy is explained in Teitelbaum et al (2020) as the lack of incorporation of the effects of free convection when air speeds are low. As the coincident average air speed was 0.26 m/s, free convection was significant on the surface of the globe thermometer. There was an average difference of 1.8 °C between the two methods.

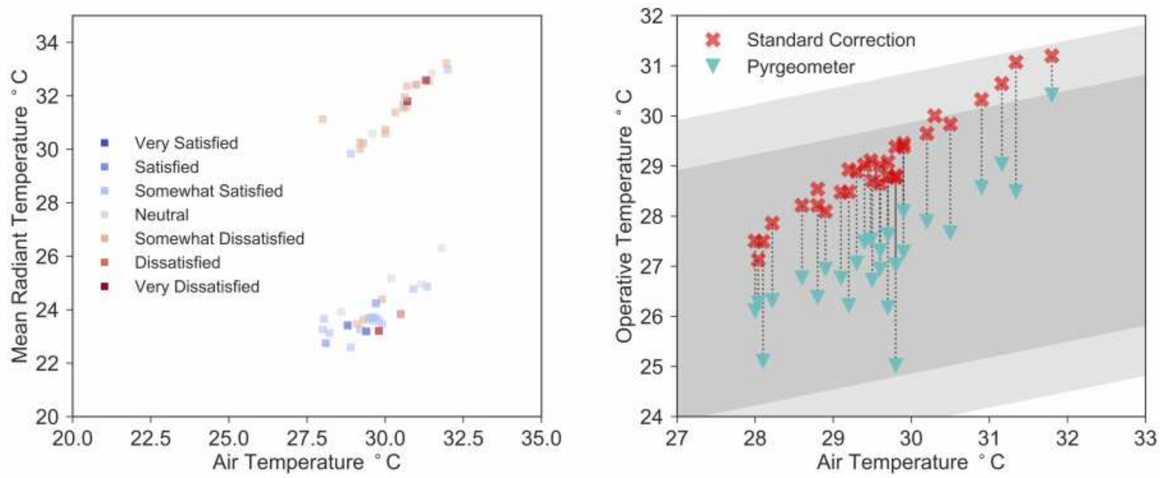


Figure 2a (left): Thermal comfort survey results from the Cold Tube plotted as air temperature versus mean radiant temperature. There are two visibly distinct domains, the 'off' and 'on' population. Thermal sensations in the 'on' cluster had a mean vote of -0.05, indicating a slightly cool average perception despite an average air temperature of 30 °C. 2b (right): When plotted within the adaptive comfort framework, there is a 1.8°C average error between the mean radiant temperature as calculated with the standard correction equation (red) and the measured ground truth reading from the pyrgeometer.

While the discrepancy does not pull certain data fully outside the adaptive comfort zone, there is certainly the potential for such a phenomena to occur with this mechanism, particularly as the air speed approaches 0.

### 3.2. Results of analysis of ASHRAE comfort database

Using 45,164 data points with an air speed less than 0.1 m/s from the ASHRAE Thermal Comfort Database II, a comparison between an empirically derived free convection correction (Teitelbaum et al., 2020), and the ASHRAE standard was performed. There was an average difference between these methods of 0.4 °C. More importantly, the difference was skewed in favor of radiation, meaning when correcting for free convection, there was 1.4 °C average separation between the air temperature and mean radiant temperature, compared to 1.0 °C separation between these two metrics with the standard correction. This result is summarized in figure 3.

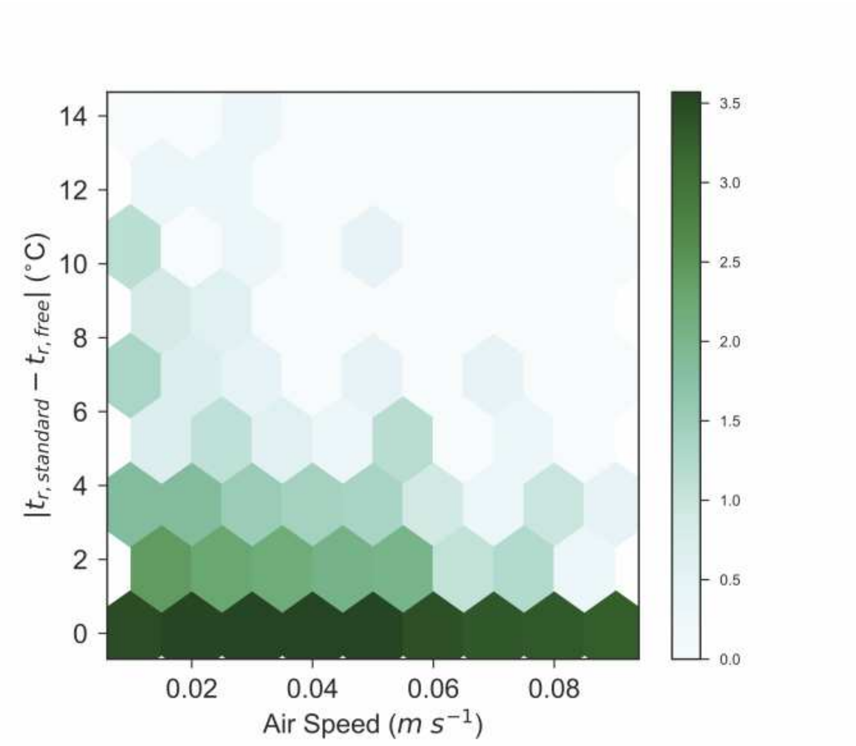


Figure 3: A logarithmic scatter-histogram of air speed versus the absolute difference between the standard and free convection corrected mean radiant temperature readings. The color intensity is the exponent of 10 for the frequency measurements contained by each block. Coincidentally, the data appear to converge near 0.1 m/s. This convergence is dependent on globe thermometer diameter, with a standard 40 mm diameter ping pong ball used here.

### 3.3. Operative Temperature Mischaracterizations

The data presented previously in Figure 2b is an example of a systematic error associated with free convection around globe thermometers that can systematically under represent thermal radiation's effect on comfort. This mechanism will be present at low air velocities. When the air speed increases substantially, above 0.2 m/s to 2 m/s, there is another mechanism at play that skews the analysis of comfort conditions.

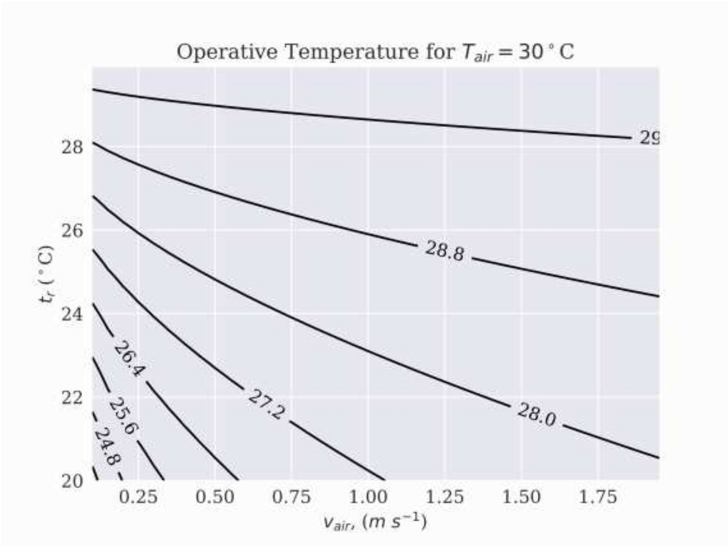


Figure 4: The operative temperature, provided by the contour lines on the chart, increases as the air speed increases, a conceptual inconsistency with the driving force for heat transfer about the human body.

By inspection of the operative temperature equation (eq. 1), there is an inverse relationship effect with heat transfer and temperature that is not representative of the real effect of air movement. As the air speed increases, removing more heat through convection from a person, the operative temperature will increase if the mean radiant temperature is below the air temperature according to the equation and shown in Figure 4. This is computationally consistent with the method, since it is based on a changing heat transfer coefficient for convection that increases relative to the radiant heat transfer. But it is completely inconsistent as a proxy for comfort. The effect is plotted in figure 4 at a constant air temperature of 30 °C, and a variable mean radiant temperature from 20-30°C and an air speed varying from 0-2 m/s. The resulting operative temperature contours are plotted as labelled lines.

The highest rate of change in figure 4 is at low air speeds and low mean radiant temperatures, where the resulting operative temperature is roughly the average of the air temperature and the mean radiant temperature. But then as the air speed increases, the increase in operative temperature counterintuitively impacts the result of a high powered radiant system. Such an inconsistency is consistent within the operative temperature framework, but not for a radiant thermal designer attempting to design a system that takes advantage of the advancements in radiant panel technologies like those we demonstrated in the Cold Tube. There are no points in the ASHRAE database to demonstrate the magnitude of this type of error.

One final minor final point of error with operative temperature - often when operative temperature is used with comfort plots in ASHRAE, it is used as the x-axis for the psychrometric chart. If operative temperature is to have any radiant component that would be completely independent of any impact on water vapor psychrometrics. Only actual air temperature should be on the x-axis of a psychrometric chart.

### 3.4. Physics-based feedbacks on radiative vs convective comfort impacts

Another result that came out of our analysis of radiant and convective heat transfers in our experiments and expanded psychrometric comfort simulations was the varying relative impacts of convection and radiation on people. As previously mentioned there have been several generalized ratios proposed that we have reviewed in previous work (Guo et al., 2019).

Of course the physics dictates that depending on the temperature difference between the air and the body surface, the air speed the relative amount of convection will change and for radiation the surface temperature of the surroundings will change the ratio. The physics do not dictate the the surface and air temperature change in a uniform way to create a constant ratio.

We plotted the ratio of convective to radiant heat transfer for a person in Figure 5 for two different air speeds. The left plot shows data with an air speed of 0.16 m/s, a standard value for typical indoor office working environment. The right shows the value for a wind at 0.5 m/s. The left plot shows that along the dashed line of air-temperature equal to MRT, the ratio is close to 1:1. But as soon as the MRT begins to drop below the air-temperature, radiation begins to dominate, which implies that radiant cooling positively reinforces the relative impact of radiant heat transfer on comfort. Conversely, radiant heating has its impact reduced as the MRT increases above the air-temperature. In addition if the air speed increases, the MRT impact is further reduced. As the convection coefficient increases it will also increase the relative impact of any temperature difference between teh air and the human body surface. Therefore a person in a radiantly heated space will be more physically more sensitive to draft.

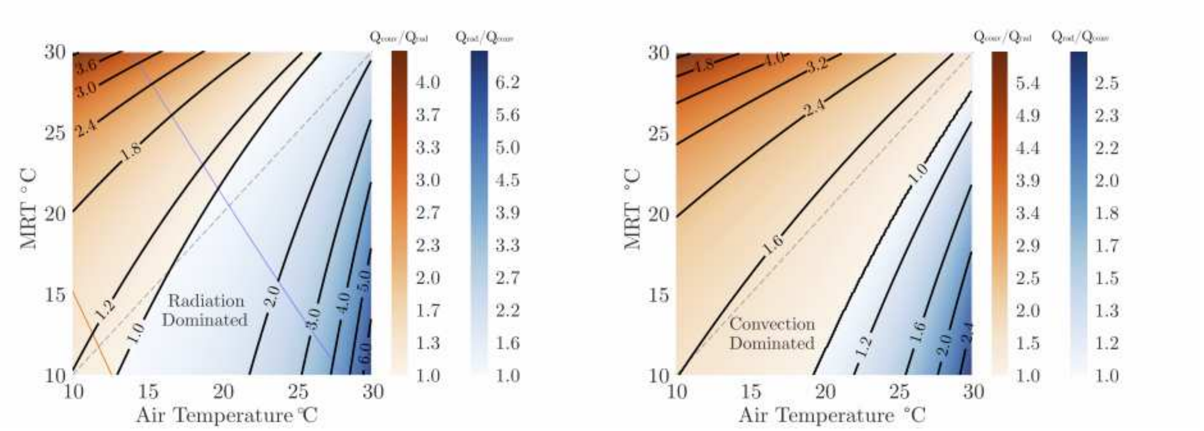


Figure 5: Illustration of the change in the relative ratio of heat transfer to a body by radiation or convection. Iso-lines plotted are ratio of convective to radiative. The dashed line is where MRT equals T-air. Left plot is for office low-air-movement conditions assuming air velocity of 0.16 m/s. Left also plots the heat balance for two different metabolic rates with 1.2 mets in blue and 2 mets in red. Right plot shows the increased convection at 0.5 m/s.

The left plot of Figure 5 also shows the lines of constant metabolic rate, so if the aim was to create heat transfer to consistently maintain removal of 1.2 mets (blue line) or 2 mets (red line), those conditions would need to be met. This shows that for radiant cooling comfort could be met in conditions similar to the Cold tube with a ratio of radiant cooling nearly 3 times that of convective cooling. If you imagine standing by a wood stove in a cold cabin you can also see how metabolic rate can be managed in cold air temperatures and high MRT, but you also must recognize that any change in air movement significantly shifts the ratio more toward convection making drafts problematic in these scenarios.

### 3.5. Spatial variation of comfort due to MRT variations

Aside from convective errors, the component of radiant analysis that is traditionally overlooked for calculation simplicity is the spatial variation of mean radiant temperature. The spatial variation within the Cold Tube pavilion is of the same magnitude as the convective errors exposed in this paper. Therefore, for a true physics-based model of thermal comfort, many additional factors must be taken into account, an approach simplified if left in watts rather than abstracted temperatures.

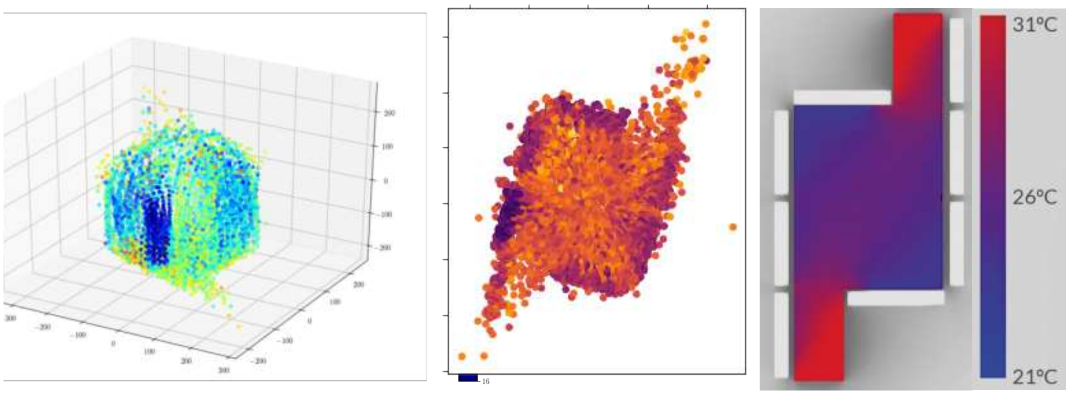


Figure 6: The mean radiant temperature variation in the Cold Tube, as measured using the SMART sensor we developed in a point cloud of surface temperatures (left) that are displayed in plan (middle), and used to calculate the variation in MRT as viewed in plan (right).

For example, even in the Cold Tube, an environment designed to maximize radiant heat transfer from the surfaces to the occupants, there is a spatial variation of the mean radiant temperature inside based on the view factor weighting of the surrounding surfaces. This effect is shown in Figure 6. Further, this model was developed from the real surface temperatures abstracted to a point, however this is still not the complete picture because the human body is not a point but a set of points arranged in surfaces with variable view factors to the surroundings.

## 4. Discussion and Conclusion

So what does this all mean for designing comfort systems in the built environment? We have demonstrated a few failure mechanisms for existing technologies that can underestimate or downplay the role of radiation in the built environment. We recognize our research bias as we are explicitly interested in radiant systems, and have being explicitly developing and analyzing new systems and sensors to analyze radiant heat transfer. We believe there is enough evidence to validate our nervousness that the role of radiant heat transfer is underplayed, and potentially systematically incorrectly considered in comfort analyses.

Currently we are working with independent research colleagues to validate our findings on globe thermometers. We hope to create a much improved correction that can also do a good job of approximating mixed-convection error. We will also use the same collaborations to validate our scanning and mapping techniques for radiant heat transfer spatial variation and for non standard comfort conditions.

We will also continue to work to disseminate our findings to active groups in the standards community, and are proactively engaging with ASHRAE and ISO (Measurement committee and 7726 standard respectively). The standard ASHRAE measurement method (ASHRAE,

2013) completely neglected free convection and the ISO method (ISO, 2011) only allows for a binary selection of free or forced convection with no mixed-mode model, which would arguably be the most common type of convective flow around a globe. This puts into question many thousands of datapoints used in empirical models based on globe thermometer derived MRTs. In recent extensive and excellent analysis by Dawe (Dawe et al., 2020) showed that 200,000 datapoints, (many from ASHRAE Thermal Comfort II database (Licina et al., 2018)) had air and radiant temperature median difference of only 0.4, which is coincidentally the same as our average. Our corrected average difference was a full degree higher, and our preliminary consideration of mixed convection models indicates that perhaps a much larger set and much higher error could exist in for those data points with air speeds between 0.1 and 0.5 m/s. This would also have implication for ISO 7726 based analyses where globes are corrected for free convection, but there still lacks an appropriate mixed-convection correction.

In addition we are working to improve how designers and architects engage with radiant heating and cooling. The radiant/convective ratio of 1.4 was actually first found by the author when teaching a building systems class in a textbook in NUS, and then in *Design with Climate* by architect Victor Olgyay, but although we found some other references from the 1930's we have still failed to uncover what experimental data led to those conclusions, which have now propagated through the architecture of radiant systems for almost a century without validation. We hope the expanded psychrometric framework and expand not just the comfort zone, but also the opportunities for innovation in building systems and architectural design where radiant systems are strategically activated in building surfaces.

Beyond radiant, the expanded psychrometrics framework also allows more extensive consideration of air movement, and we have recently submitted more extensive analysis of the potential of Cold Tube style panels to enable more natural ventilation. Besides are movement we are also exploring how humidity and skin wettedness relationships feedback on the effectiveness of air movement. These relationships are also very non-linear and significantly change how "good" air movement feels. These works build on our technical research on liquid desiccant systems in parallel, which create additional system-pathways to rethink not just radiant systems, but all of thermal comfort. Refocusing on watts of heat the body needs to shed to stay comfortable instead of universal temperature proxies is a first step. Building new systems, sensors and controls that use contemporary technology to appreciate the full spatial and temporal factors driving our body's heat transfer is something we strive for.

### 4.1. Conclusions

In summary we have demonstrated how many comfort calculations, particularly those relating to radiant heat transfer, have become susceptible to inappropriate utilization, and improper representation of heat transfer physics. In many situations a simple failure to recognize the temperature differences the body experiences instead of our absolute temperature proxies for comfort has limited our ability to fully resolve thermal comfort.

We have developed demonstration projects, and alternative comfort tools in an attempt to recapture some of these non-standard opportunities to address and design thermal comfort. It is important to revise some of our measurement techniques and comfort analysis methods to better represent what is really experienced and to provide better design guidance. New technological advances, alternative design paradigms, and rewarding thermal experiences can be unlocked in doing so. This will unlock large step-changes in the efficiency of managing indoor climates conveniently mitigating emissions causing outdoor climate change.

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# Exploring the Brazilian Thermal Comfort Database: an overview on the main contributions

**Carolina Buonocore[1*], Maíra André[1], Greici Ramos[1], Renata De Vecchi[1], Christhina Maria Cândido[2], Roberto Lamberts[1]**

[1] Laboratory of Energy Efficiency in Buildings, Department of Civil Engineering, Federal University of Santa Catarina, Brazil;
[2] Department of Architecture, Design and Urban Planning, the University of Sydney, Australia.
[*] Corresponding author: carolina_buonocore@yahoo.com.br

**Abstract:** Significant data from thermal comfort studies conducted in indoor built environment have been included in databases worldwide, e.g. the ASHRAE Global Thermal Comfort Database II, where Brazil holds a relevant position. The records include a total of 10,925 thermal comfort votes, coming from field studies mainly conducted in offices and schools. Thus, this paper aims to present the database, describing its characteristics and main results from a preliminary analysis. The method was based on the standardization and treatment of raw data from field studies, and some analysis of thermal perception responses and environmental variables were performed. The results highlighted some important variations in thermal perception among people from different climates in Brazilian territory, which is also influenced by the current ventilation system mode. People from Brazilian tropical climates showed a neutral thermal sensation balance close to 27.4 °C of mean operative temperature; meanwhile, those from subtropical climates were close to 24.4 °C. The overall thermal preference tended to cooler than neutral, particularly in naturally ventilated environments. The contributions of this investigation are mainly related to the gaps identified in the database, such as limited climate types and building typologies. Thus, the database expansion would provide valuable information to be analysed and further incorporated in the Brazilian Standard.

**Keywords:** Indoor thermal comfort, Brazilian thermal comfort database, Field studies.

## 1. Introduction

In thermal comfort studies, significant data from field investigations conducted in indoor built environment have been included in databases worldwide. In countries with large territorial extension, diverse climatic characteristics and various cultural aspects, there is a concern about how those parameters would influence people's thermal perception in occupied spaces. Thus, increasing the number of representative thermal comfort data from different regions has become a key point to the discussion and comparison of the results about occupants' thermal perception and related behaviours.

The main initiatives of documenting human thermal perception through "right-here-right-now" subjective evaluation and the related thermal environmental variables by means of field measurements are the ASHRAE Global Thermal Comfort Databases (De Dear, Brager and Cooper, 1997; De Dear *et al.*, 2016; Földváry Ličina *et al.*, 2018). The ASHRAE II Database added approximately 82,000 new sets of data collected until 2015 (Földváry Ličina *et al.*, 2018), expanding the global database to a number close to 108,000 votes (Databases I and II together). The countries with the biggest amount of thermal comfort data in current ASHRAE II Database are India (n = 16,110), USA (n = 8,546) and China (n = 8,235).

Brazil holds a relevant position in the ASHRAE II Database, as it is the fourth country in terms of data amount (n = 7,390). It is also the only representing South America in the global database so far. The need to document and explore the results set of this Brazilian data has motivated the creation of project focused in a national database in 2014, entitled “Brazilian Thermal Comfort Database”. The Brazilian Database is still under construction and has added new data from field studies performed after 2015, which are not included in ASHRAE Database II.

The discussion of the main results, gaps and contribution of the current Brazilian database is the main subject of the present work. The raw data from field investigations were treated and standardized and some analysis related to thermal perception responses and indoor environmental variables were performed. It is expected that the future efforts regarding thermal comfort field evidence in Brazil may be pointed out based on the characterisation and the preliminary results from Brazilian database.

## 2. Methods

The Brazilian thermal comfort database[1] is a set of information related to the indoor thermal environment (physical variables measured) and the occupants’ characterization and thermal perception. The data collected came from field studies conducted in indoor environments during their daily occupation – “real” environments with occupants performing their habitual activities.

For the time being, the documented data was obtained through field studies in universities classrooms and offices. This kind of environment usually guarantees that a considerable number of subjects have a similar profile and were using the same space at the same metabolic rate. According to the international measurement protocols recurrent in base surveys (De Dear, Brager and Cooper, 1997; De Dear and Brager, 1998; ASHRAE, 2010), the physical variables related to the indoor thermal environment (air temperature, mean radiant temperature, relative humidity and air velocity) should be recorded by appropriated and previously calibrated instruments, while the subjective responses from the occupants should be documented through questionnaires. The methods adopted in the field investigations must be in accordance with proposed standards by the project (which can be accessed in the project link[1] below). The thermal comfort field investigations whose data were included in the database are classified as Class II from De Dear, Brager and Cooper (De Dear, Brager and Cooper, 1997), since the measurements of indoor environmental variables were performed at a single measurement height. Regarding the subjective information, personal anthropometric characteristics such as gender, age, weight and height were filled in by the buildings’ occupants.

Thus, the metabolic rate and the clothing insulation were estimated according to the auxiliary tables of ASHRAE 55 (2017) standard. The occupants were requested to address their sensation, preference and acceptability related to the current thermal environment and air movement (right-here-right-now questionnaires). The researchers were aware of possible changes in activity and/or clothing from the occupants during the field investigations, as well as the monitoring of environmental controls (air-conditioning, fans, windows, doors etc.) available for thermal adaptation. Particularities of methodological procedures adopted in each field study can be found in detail by assessing the references in Table 1.

[1] Access link: http://www.labeee.ufsc.br/projetos/base-brasileira-de-dados-em-conforto-termico (Accessed: 12 December 2019)

Table 1. Brazilian thermal comfort field studies in added in the national database

| **Title / Portuguese (English) – available link** | **Reference Author (year)** | **n data** |
|---|---|---|
| *Análise dos níveis de conforto térmico em um edifício de escritórios na cidade de Maringá* (Analysis of thermal comfort levels in an office building in the city of Maringá) - http://www.labeee.ufsc.br/node/211 | **Gomes** (2003) | **567** |
| *Aceitabilidade do movimento do ar e conforto térmico em climas quentes e úmidos* (Indoor air movement acceptability and thermal confort in hot-humid climates) - http://www.labeee.ufsc.br/node/156 | **Cândido** (2010) | **2,075** |
| *Condições de conforto térmico e aceitabilidade da velocidade do ar em salas de aula com ventiladores de teto para o clima de Florianópolis/SC* (Thermal comfort conditions and acceptability of air speed in classrooms with ceiling fans in the climate of Florianópolis/SC) - http://www.labeee.ufsc.br/node/290 | **De Vecchi** (2011) | **2,507** |
| *Avaliação de conforto térmico em edificações comerciais que operam sob sistemas mistos de condicionamento ambiental em clima temperado e úmido* (Thermal comfort evaluation in commercial buildings operating under mixed-mode conditioning systems in temperate and humid climate) - http://www.labeee.ufsc.br/node/657 | **De Vecchi** (2015) | **2,688** |
| *Conforto térmico em ambientes de escritórios naturalmente ventilados: pesquisa de campo na cidade de Florianópolis por meio da abordagem adaptativa* (Thermal comfort in naturally ventilated office environments: field research in the city of Florianopolis through the adaptive approach) - https://repositorio.ufsc.br/xmlui/handle/123456789/156885 | **Pires** (2015) | **455** |
| *Análise das condições de conforto térmico no clima quente e úmido de São Luís (MA): estudos de campo em salas de aula naturalmente ventiladas e climatizadas* (Analysis of thermal comfort conditions in the hot and humid climate of São Luís (MA): field studies in naturally ventilated and air-conditioned classrooms) - http://www.labeee.ufsc.br/node/734 | **Buonocore** (2018) | **2,680** |
| *Potencial de incremento do conforto térmico dos usuários em escritórios com o uso de ventiladores de mesa durante o verão* (Potential for increasing users' thermal comfort in offices through the use of table fans during the summer) - http://www.labeee.ufsc.br/node/739 | **André** (2019) | **383** |

## 2.1. Standardization and treatment of raw data

In the preparation of the unified database, raw data from field studies conducted in Brazil were grouped and coded. An electronic spreadsheet model for data standardization and other field surveys' guidelines can be found on the project's website. The climate characteristics, occupants' information and thermal assessment, indoor and outdoor environmental variables should be registered by the researchers and submitted in a spreadsheet.

In this standardized spreadsheet, each row must correspond to a user's point-in-time perception response and the total number of rows is the total of data records (n). The indoor operative temperature was calculated for the entire sample based on the recommendations of ASHRAE 55 (2017). The outdoor variables (air temperature and relative humidity) were obtained through the meteorological station closest to the survey site. Finally, a procedure for excluding discrepant data was adopted in the full spreadsheet, according to the criteria as follows:

- Simultaneous "unacceptable" and "comfortable" votes for the thermal environment;

- Simultaneous “unacceptable” vote for the thermal environment and “no change” vote for the thermal preference;
- Simultaneous “uncomfortable” vote for the thermal environment and “no change” vote for the thermal preference;
- Simultaneous “unacceptable” and “no change” votes for the current air movement.

A total of 175 votes (1.6% of the total 11100 raw data) fell into at least one of the conditions mentioned above. Thus, those votes were excluded, and the resulting sample is composed of 10,925 votes. The Welch's T-Test (Spearman's method for non-normal distribution samples and categorical variables) and the Mann-Whitney Test were adopted in the comparison of unpaired samples’ means and medians. The hypothesis tests were performed in R programming language through RStudio interface. The significance level adopted in the tests was 5% (p-value < 0.05).

## 3. Results

### 3.1. Brazilian database characteristics

The database currently has 10,925 valid votes, which are distributed in the cities as illustrated in Figure 1. Most of the data was collected in the city of Florianopolis (Southern region of Brazil), with 5,704 votes added. In the Northeast region – São Luis and Maceio cities – more than 4,000 votes were computed. According to the Koppën-Geiger climate classification (Kottek *et al.*, 2006), the group of data correspond to three existing climate types in Brazil: Aw, Am and Cfa (Figure 1).

Among the data from the Cfa climate in Brazilian database, there is a predominance of winter and autumn seasons, which corresponded to 71% of the data. In tropical climates, there was a balanced amount of data in the two seasons: 45% of the votes were collected during the rainy (or wet) season, and 55% were reunited during the dry season.

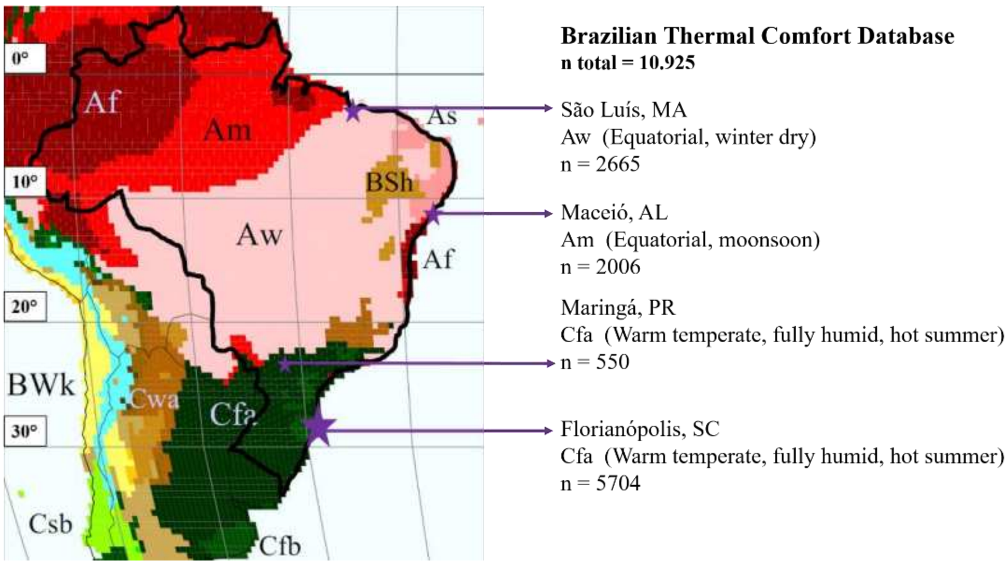


Figure 1. Characterization of Brazilian Database and Koppën-Geiger climate classification. Source: adapted from Kottek et al (Kottek *et al.*, 2006)

From Figure 1 it is possible to identify all Brazilian climate types and the recorded data from each city. There are three main climates, divided into nine specific climate types as follows: equatorial/tropical (Af, Am, As and Aw), arid (BSh) and warm temperate (Cfa, Cfb, Cwa, Cwb). The database is composed of numerous sets of data from tropical (A) and temperate (C) climates, which are predominant in Brazilian territory. Some of the specific Koppen climate types remained out of the thermal comfort field campaigns so far, particularly the drier climates (BSh, Cwa and Cwb).

The room cooling systems and the operation modes are shown in Figure 2. The spaces assessed in the field campaigns were mainly based on naturally ventilated (NV – 37%) or mixed-mode (MM – 40%); MM buildings could be operated with air conditioning and/or natural ventilation. The other 23% of the data were collected in constantly air conditioned (AC) environments. The operation modes verified throughout the field investigations were air conditioning (AC), natural ventilation (NV), natural ventilation with fans simultaneously (NV with fans), only fans operating (fans only), and air conditioning with fans simultaneously (AC with fans). During the occupancy time, natural ventilation (NV) was the predominant operation mode in MM environments (≅32%). There was a significant number of responses occurring with fans on, particularly AC with fans (≅28%). The "Fans only" group in MM (≅24%) represent the moments of only fans operating while windows were closed – see De Vecchi (De Vecchi, 2011) for more details.

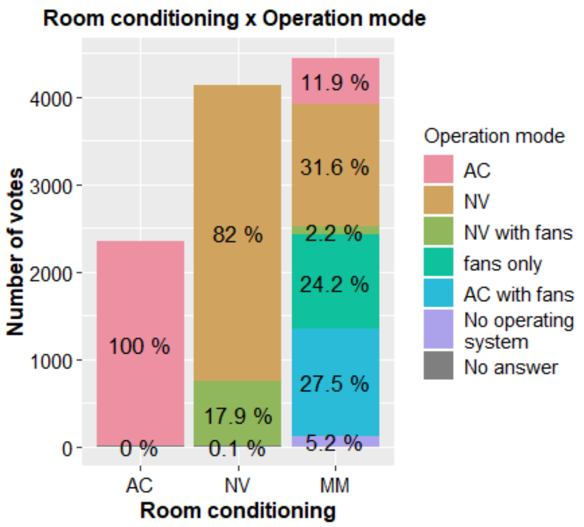


Figure 2. Number of votes obtained in each room conditioning type and percentages of each operation mode

Regarding the use of the spaces in which field studies were carried out, 62% corresponded to educational buildings (undergraduate classrooms – CR – and design rooms – DR), while 38% of the votes were collected in offices (OF). In Figure 3, the groups with ages under 20 years and between 21-30 years were predominant, noticeably in educational rooms. Regarding the occupants' gender, 60% are females and 40%, males. Females' participations predominated in educational spaces, while in offices the percentages of males and females were very similar.

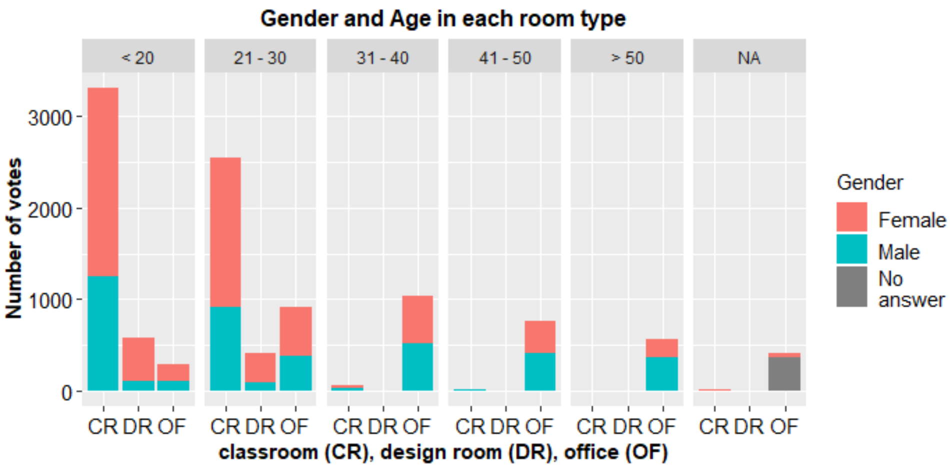


Figure 3. Occupants' gender and age in each room type

The maximum, median and minimum recorded values of body mass index (BMI), metabolic rate and clothing insulation, as well as 1st and 3rd interquartile intervals, are represented per room type in Figure 4. BMI's distribution was similar in educational spaces and presented a higher median value in the office rooms' sample (Figure 4a). In general, the occupants presented a normal nutrition level – between 18.5 and 25.0 kg/m² (*Body Mass Index - BMI*, 2019). The metabolic rate distribution (Figure 4b) presented small variation among the room type samples due to the predominant sedentary activities performed (overall mean value = 1.1 met and overall standard deviation of 0.1 met); in the design rooms (DR), occupants average metabolic rate was 1.2 met.

Regarding the total clothing insulation, variations among seasons and room types were identified. In general, there was a predominance of users with light clothing, such as trousers and short-sleeved shirt (0.5 clo). The clothing insulation values were mainly higher than 0.5 clo in winter, while in the other seasons, they usually remained below 0.5 clo. According to Figure 4c, clothing insulation values varied the most in offices (from 0.2 to 1.5 clo). The median value was the lowest in classrooms and highest in offices, probably because of the dress code usually adopted in each room type.

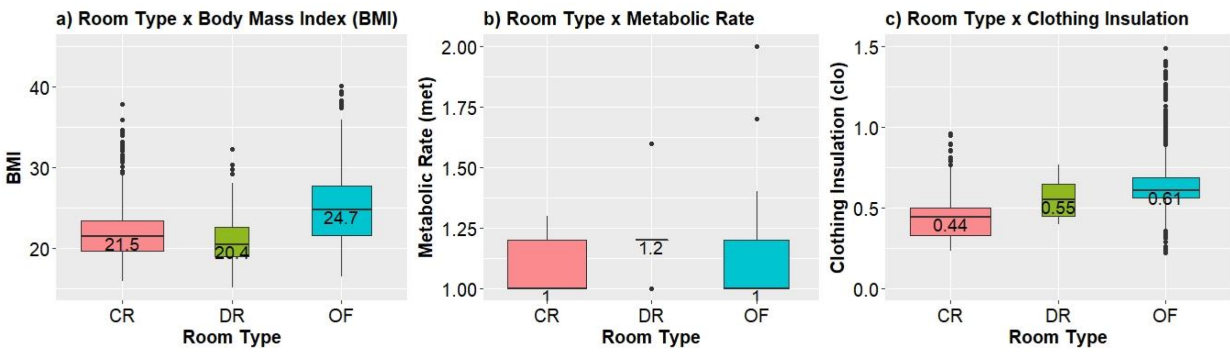


Figure 4. Occupants' BMI (a), metabolic rate (b) and clothing insulation (c) in each room type

Regarding the indoor environmental variables (Table 2), there was a large variation between minimum and maximum values from the whole database sample. However, the mean and the median values were close, and the standard deviation values were little. The air velocity values registered were predominantly low (mean value = 0.26 m/s) although some higher values were measured (standard deviation = 0.29 and maximum value above 4 m/s). Air velocity values above 2 m/s were verified in 37% of the overall sample, mainly in spaces with fans on.

Table 2. Summary of indoor environmental variables for the whole database sample

| Values | Ta (°C) | RH (%) | Va (m/s) | To (°C) |
|---|---|---|---|---|
| Maximum | 32.9 | 89 | 4.17 | 32.9 |
| Median | 25.8 | 64 | 0.18 | 25.7 |
| Mean | 25.9 | 64 | 0.26 | 25.9 |
| SD (+/-) | 2.9 | 11 | 0.29 | 2.8 |
| Minimum | 15.4 | 23 | 0.00 | 16.6 |

The indoor environmental conditions analysed are strongly related to the climates in which field surveys were carried out, as shown in Figure 5. A smaller variation in the operative temperature from tropical climates (Am and Aw in Figure 5a) was observed, while the temperature amplitude recorded in the subtropical climate (Cfa in Figure 5a) was higher. However, 50% of the recorded operative temperature values were between 25-30 °C in Am/Aw climates and between 23-26.5 °C in Cfa. The average operative temperature in tropical climates was 27.6 °C, and in the subtropical climate was 24.6 °C.

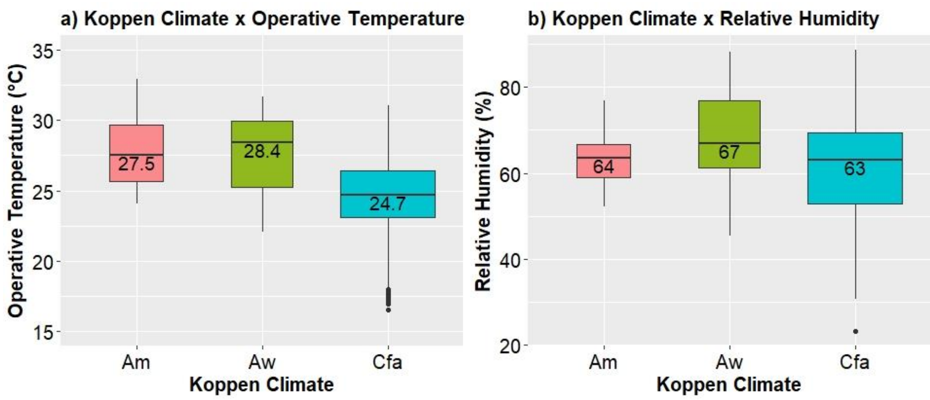


Figure 5. Indoor operative temperature (a) and relative humidity (b) registered in each Koppen climate type

Although the Aw climate typically presents an annual rainfall index lower than that from Am climate, the relative humidity mean, median and interquartile values from the Aw sample were higher than those from the Am sample (Figure 5b). As expected, larger variations in indoor relative humidity were verified in the Cfa climate, while in tropical climates at least 50% of the recorded values were above 60%. The differences between the median values of operative temperature and relative humidity in each Koppen climate sample (Am, Aw and Cfa) were statistically significant (p-value < 0.05).

### 3.2. Brazilian thermal perception

The occupants' thermal sensation vote (TSV) as a function of indoor operative temperature and in different Koppen climates is illustrated in Figure 6. The values in red represent the mean operative temperatures in each TSV sample. The average temperatures that corresponded to each thermal sensation in Cfa climate were lower than the average temperatures in tropical climates. Neutral votes (0) were achieved when mean operative temperature was around 24 °C in Cfa and 27 °C in Am/w. For instance, a mean operative temperature around 27° C resulted in a neutral thermal sensation (0) in tropical climates and a warm thermal sensation (+2) in the subtropical climate.

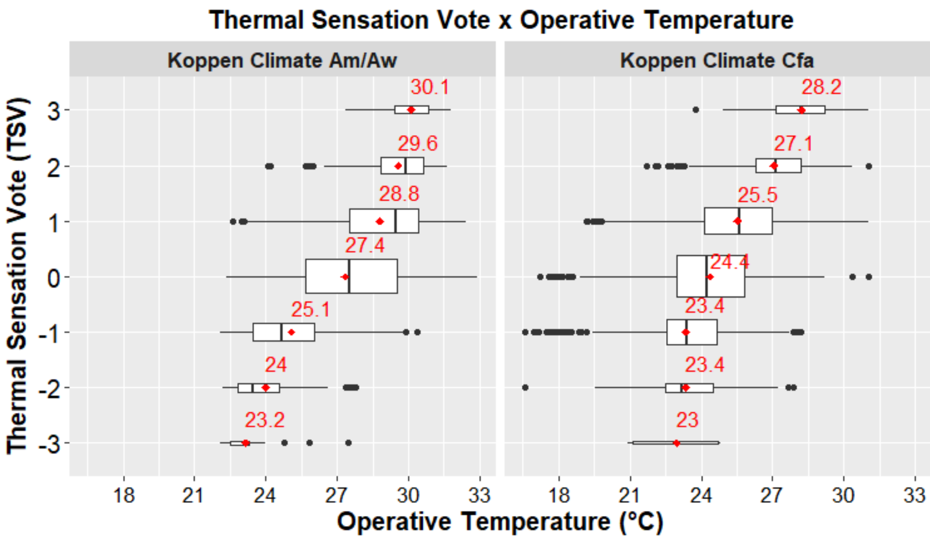


Figure 6. Thermal Sensation Vote's distribution in each Koppen climate

Different thermal responses regarding warmer and cooler sensations were observed among the analysed climates. In the cold side of the scale, a smaller operative temperature variation between the slightly cool (-1), cool (-2) and cold (-3) votes was observed in Cfa sample, if compared to the tropical (Am/w) samples. For instance, there was a difference of 1 °C between the average neutral (0) and slightly cold (-1) samples' operative temperature in Cfa climate, while in tropical climates it was equal to 2.3 °C. In the warm side of the scale, the opposite situation has occurred. The mean operative temperature required to feel warmer in tropical climates was higher than the one required in the subtropical climate.

Occupants' thermal acceptability was also different among the addressed climates, as depicted in Figure 7. In general, people from tropical climates (Am/w) expressed less dissatisfaction regarding the coldest thermal sensations, if compared to people from subtropical climate (Cfa). Thermal acceptability in the "warm" TSV (+2) was surprisingly high among the occupants in Am/w climates. Those results suggest distinct aspirations from people living in different Brazilian regions. The inhabitants of tropical climates expressed different acceptability levels to warm and cool thermal sensations, positively to the cooler and negatively to the warmer ones. In subtropical climate, the dissatisfaction levels with warm and cool TSV's were similar.

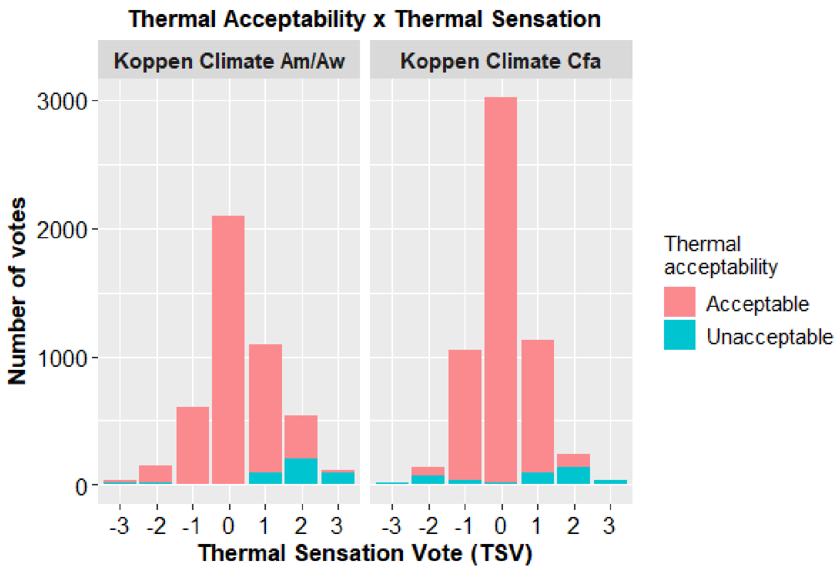


Figure 7. TAV x TSV in each Koppen climate

The "probit" percentage of dissatisfied people was addressed in a comparison between two sets of samples from the ASHRAE II Database, as shown in Figure 8. The data was filtered and limited to the humid subtropical climate (Cfa), as it is the only Brazilian climate type appearing in the interface so far. Thus, the sample in blue is composed of Brazilian data, and the sample in pink represents the World data (including Brazil). When evaluating the dissatisfaction with warm (+2) and cool (-2) TSVs, there is a noticeable difference between the samples. The probability of dissatisfaction in the Brazilian sample was higher for warmer thermal sensations (more than 50%), while it was higher for cooler thermal sensations in the World sample. The addition of tropical climate data from Brazil in the global database might accentuate that difference, since high unacceptability with the warmer thermal sensations was detected in the "A" climate sample.

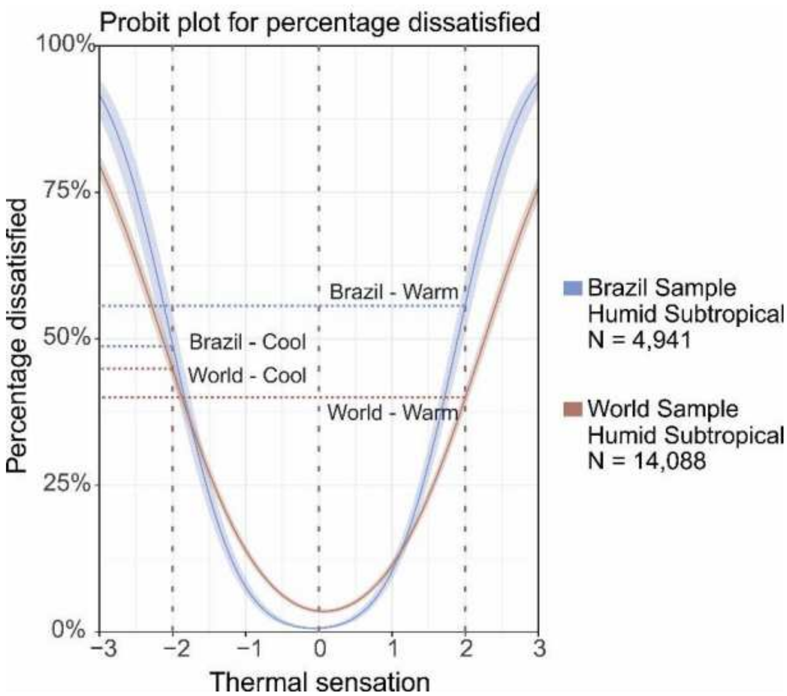


Figure 8. Comparison between Brazil and World samples in the ASHRAE II Database. Source: adapted from *ASHRAE Global Thermal Comfort Database II Visualization* (2018)

Occupants' thermal preference was assessed in Figure 9. The thermal preference vote was collected in 83% of the data from Brazilian database (n=9095). By analysing these data, it was noticed that the relation between thermal sensation and thermal preference was significantly influenced by the conditioning mode of the environment. In general, there was a higher number of users feeling uncomfortable by cold in air-conditioned environments (AC), when compared to naturally ventilated environments (NV) – the percentage of users who preferred the environment to be warmer in AC was higher than in NV.

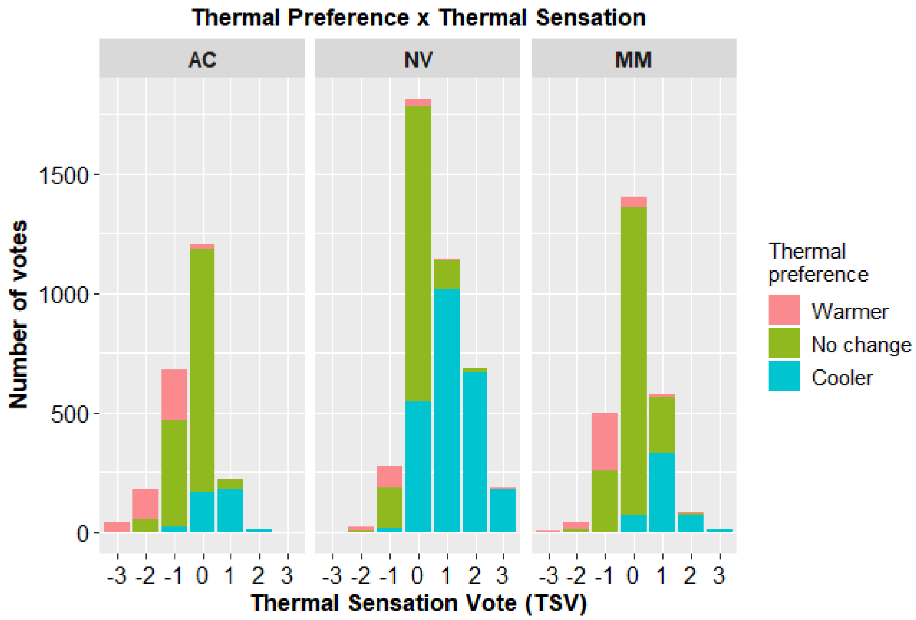


Figure 9. TPV x TSV in each room conditioning available

The thermal preference votes of subjects who declared to be neutral presented variations among the cooling operation modes. The overall preference under the neutral votes was "no change", followed by "cooler". This was verified particularly in NV environments – the preference to be cooler was more evident if compared to MM or AC environments. However, among the "slightly warm" TSV sample (+1), the predominant preference was to be cooler in all operation modes.

## 4. Discussion

The preliminary analysis from thermal perceptions in Brazilian database highlighted an overall preference for cooler environments and overall high acceptability levels in climates characterized by elevated air temperature and humidity. However, significant influence of climate particularities and cooling conditioning modes on thermal perception votes was also verified. Therefore, it can be assumed that thermal comfort requirements are different between people from tropical and subtropical climates (Figure 6 and Figure 7), and between occupants from air-conditioned and naturally ventilated spaces (Figure 9). Additionally, a preliminary comparison between Brazil and World samples in the ASHRAE Database II (Figure 8) highlighted a particularity of perception from the Brazilian sample available in the global database so far. The database has joined up a significant number of votes to corroborate this point. Nevertheless, to which extent the added data properly represents (or no) the diverse climatic and cultural contexts existing in Brazil is a question that must be considered when new efforts of thermal comfort field studies are idealised.

The explored data was collected in three Koppen-Geiger climate classifications that cover a significant extent of the national territory and represent the main climate types – equatorial/tropical and temperate/subtropical. As shown in Table 2 and Figure 5, the conditions of indoor temperature presented some variations within the database, but the mean and median values of relative humidity were close among the studied climates (between 60-70%). Some areas of the Brazilian territory are characterised by drier and colder climate conditions, which are still underexplored. Moreover, the preliminary analysis presented must advance into a more detailed assessment between the environmental variables measured and the perception votes collected, as the developed model in the ASHRAE Global Database II (Földváry Ličina *et al.*, 2018). Relative humidity and air velocity values may be assessed in conjunction with an indoor temperature parameter in future investigations with the whole Brazilian database as matter.

The room types currently addressed are restricted to undergraduate rooms (educational use) and offices. Thus, some occupant characteristics such as activity level and predominant age may present little variation among the samples, as shown in Figure 4b. Thermal comfort studies in the Brazilian residential sector were recently conducted, focusing on occupant behaviour related to adaptive resources such as the air-conditioning usage. The future data to be added in the national database may be applied in thermal preference and comfort assessments within the full amount of data. Additionally, assessing the thermal comfort issue in diverse building types would contribute to reunite variated occupant characteristics regarding social and economic profiles found in the national territory. No questions about personal income have been included in the questionnaires so far.

The consolidation of the Brazilian thermal comfort database and its related analysis are important requirements to the National Standard, which must be continuously revised and improved as already verified by previous studies such as Candido *et al.* (2010), and the findings of De Vecchi *et al.* (2015). The last cited publication suggested a clothing adjustment zone to be incorporated in the adaptive zone of the proposed Brazilian Standard NBR 16401-2. From the preliminary results, thermal comfort evaluation methods in buildings with diverse conditioning modes must be distinguished since occupants' thermal perception in AC, NV and MM buildings has varied. The applicability of the methods for determining acceptable thermal environments should be extended to the personal and physical conditions found in the database sample; particularly the clothing insulation values – a great amount of them was below 0.5 clo in classrooms.

## 5. Conclusion

The present work aimed to depict the Brazilian thermal comfort database by describing its characteristics and the main thermal perception results from a preliminary analysis. The database is being built up based on the standardization and treatment of raw data from field studies conducted in real occupancy spaces. The analysis performed so far has associated the main thermal perception responses and the respective measured environmental variables.

Based on the results of this paper, it can be concluded that the occupants' thermal perceptions within Brazil's territory presented relevant variations due to the influence of climate particularities and cooling conditioning modes. Brazil is a large and varied country in its geographical, climatic, social and economic dimensions, which must be considered in environmental assessments performed in occupied spaces. The main highlights from the preliminary results are as follows.

- People from tropical climates (Koppen's A classification) presented a neutral thermal sensation balance close to 27.4 °C of mean operative temperature, meanwhile those from subtropical climate (Koppen's C classification) were close to 24.4 °C. Occupants from tropical climates seems to be more tolerant to the warmest thermal sensations, once the mean operative temperature required to feel warmer in tropical climates was higher than the one required in the subtropical climate;
- Overall thermal acceptability was high, especially under warm and cool conditions in tropical climates. The former represented an undesired but acceptable situation, while the latter was generally acceptable in the occupants' assessment. Instead, people from subtropical climate expressed almost the same dissatisfaction with warm and cool conditions indoors, if compared to people from tropical climates;
- People from Brazilian humid subtropical climate (Cfa) tend to be more dissatisfied with the warmer thermal sensations, whilst the World sample from humid subtropical climate tend to be more dissatisfied with the cooler thermal sensations;
- Thermal Preference Vote's distribution has varied among the available conditioning mode (AC, NV and MM). The overall thermal preference tended to cooler than neutral, particularly in naturally ventilated environments, where occupants were more susceptible to hot discomfort. Conversely, some cold discomfort was detected noticeably in air-conditioned spaces.

Although the results gave an overview of the thermal perception in Brazilian buildings, some gaps were pointed out in the database characterisation. Therefore, to reunite representative evidence from field investigations, expanding the database is a current priority. The future studies on the subject can be classified in two: field survey campaigns considering the variability of climates and building typologies, which would enable the access to diverse occupants' profiles and characteristics; and comparisons between the sets of data corresponding to Brazilian and World databases, highlighting Brazil's particularities regarding the preferred environmental conditions, preferred cooling conditioning modes, air movement evaluation and overall acceptability/comfort perceptions.

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# Establishing a global database for outdoor thermal comfort survey: A pilot study of standardisation of methodology

**Kevin Ka-Lun Lau[1], Eduardo Krüger[2]**

[1] Institute of Future Cities, The Chinese University of Hong Kong, Shatin, Hong Kong
[2] Universidade Tecnologica Federal do Parana, Curitiba, Brazil

**Abstract:** In the last two decades, studies of subjective thermal comfort have been widely conducted in the urban environment, covering different cultures and climatic regions. However, shortcomings can be observed mainly with respect to protocols used in terms of assessment scales of thermal perception, calculated thermal indices and instrumental setup used for micrometeorological measurements. Such data may vary considerably across studies due to constraints at field sites and the availability of instruments, making it difficult for inter-comparisons between studies and climatic regions, calibrations of thermal indices and a true understanding of people's thermal perception in outdoor settings. There is a need for standardisation of methodology and guidance for conducting field surveys in outdoor spaces with implications on climate-sensitive urban design, public health measures and adaptation of humans to a changing climate. The objective of this pilot study is to develop a standard methodology for outdoor thermal comfort surveys towards the creation of a worldwide outdoor comfort database. The progress of this pilot study is reported in this paper and future developments are also introduced.

**Keywords:** Up to five

## 1. Introduction

Climatic effects on the comfort of building occupants have been widely studied in the last few decades (Olgyay, 1963; Givoni, 1976; Nicol and Raja, 1996) and it was found that climatic effects are associated with the health and well-being, as well as productivity and living quality of building occupants (Huntington, 1945). Olgyay (1963) pointed out the constituents of the physical environment act directly upon human body which tends to achieve biological equilibrium through physical and psychological reactions. Hence, human comfort is determined by the energy exchange between human body and the climatic environment of the surroundings, which aims to achieve the "comfort" conditions as defined by integrating climatic variables such as temperature, humidity, air movement and radiation.

The shorter time spent (e.g. in the range of minutes) in the outdoor environment also influences the thermal exposure. Höppe (2002) suggested that the steady-state assumption of indoor thermal comfort does not provide realistic assessments for outdoor settings. His previous study based on the Instationary Munich Energy-Balance Model (Hoppe, 1989) showed that thermo-physiological parameters such as skin and core temperatures take at least one hour in outdoors to achieve the steady-state level. The complex outdoor environment also creates large variations in thermal conditions that the outdoor space users are exposed to. Lau et al. (2019a) showed that subjective thermal sensation changes considerably when pedestrians travel outdoors and suggested that the environmental conditions exposed have a lag effect on thermal perception of pedestrians. Therefore, the assessment of human thermal comfort in outdoor environment requires a different methodological framework and analytical approach in order to address the distinctive relationship between subjective thermal sensation and environmental conditions experienced by outdoor space users.

### 1.1. Subjective assessment of the thermal environment

Human thermal comfort is generally studied by using questionnaire surveys to obtain a subjective assessment of the thermal conditions that the respondents are exposed to. There are a wide range of subjective assessment scales for the thermal environment, including perceptual or affective, global or localised, instantaneous or covering certain period of time (ISO 10551, 2019). The object of judgement also varies from the environment to the person of assessment, from general conditions to specific components such as temperature and air movement, from permanent to temporary situation. The ISO 10551 provides five subjective judgement scales to describe a person's thermal state, including thermal perception, thermal comfort, thermal preference, personal acceptability and personal tolerance. The ASHRAE Standard 55 (2017) also provides a scale for thermal perception (commonly known as the ASHRAE 7-point scale) and thermal acceptability (Table 1). However, these standards were not designated for general outdoor conditions and their applications in previous studies vary considerably for local context.

Table 1. Protocols for subjective perception of thermal environment (Johansson et al., 2014).

| Parameter | Standard | Interview question and measurement scale |
|---|---|---|
| Thermal sensation or perception | ISO10551 | 'How are you feeling now?'<br>7 Point scale: cold (-3), cool (-2), slightly cool (-1), neutral (0), slightly warm (+1), warm (+2) and hot (+3)<br>9-point scale: above plus 'Very cold' (-4) and 'Very hot' (+4) (mainly for use in extreme environments) |
| | ASHRAE | 'What is your general thermal sensation?'<br>7-Point symmetrical thermal perception scale (equal in wording to the ISO 10551) |
| Thermal comfort (affective evaluation) | ISO10551 | 'Do you find this environment…?'<br>4-Point: comfortable (0) as the point of origin followed by slightly uncomfortable (1), uncomfortable (2), very uncomfortable (3) |
| Thermal preference | ISO10551 | 'Please state how you would prefer it to be now'<br>7-Point: much cooler (-3), cooler (-2), slightly cooler (-1), neither warmer nor cooler (0), a little warmer (+1), warmer (+2) and much warmer (+3) |
| Personal acceptability | ISO10551 | 'On a personal level, this environment is for me…'<br>Two-category statement: acceptable rather than unacceptable (0) and unacceptable rather than acceptable (1)<br>Continuous scale: clearly acceptable, just acceptable, just unacceptable and clearly unacceptable |
| Personal tolerance | ISO10551 | 'Is it…?'<br>5-Point: perfectly tolerable (0), slightly difficult to tolerate (1), fairly difficult to tolerate (2), very difficult to tolerate (3) and intolerable (4) |

Currently there are no standard guidelines for subjective assessment of the outdoor thermal environment, so the use of questions and measurement scales vary across studies. The ASHRAE 7-point scale was commonly used (Krüger and Rossi, 2011; Lau et al., 2019b) while 5-point (Nikolopoulou and Lykoudis, 2006; Metje et al., 2008) and 9-point scales (Kántor et al., 2012) were also used in some studies. There is usually a middle point in the assessment scale, but the terms used to describe this middle point include "neutral", "comfortable", "neither cool nor warm" and "acceptable". The assessment of other meteorological components, such as solar radiation, air movement and humidity, was also used in some studies (Stathopoulos et al., 2004; Villadiego and Velay-Dabat, 2014; Lau et al., 2019b). Moreover, the personal state of thermal comfort (affective evaluation) and thermal preference was sometimes included in the thermal assessment (Oliveira and Andrade, 2007; Ng and Cheng, 2012). The inconsistencies in subjective scales and wordings used lead to possible errors in comparison between the results of different studies.

Personal factors such as gender, body weight, and skin colour were also found to be associated with the subjective assessment of the thermal environment (Krüger and Drach, 2017). It suggested possible variations in thermo-physiological adaptation to the thermal environment. Previous studies also suggested that human behaviour is another determinant of thermal perception (Knez and Thorsson, 2006) while reason for visit and cultural background were widely regarded as psychological mechanism of thermal adaptation in outdoor environment (Nikolopoulou et al., 2001). However, these factors were not addressed by all the studies and the methods of assessment need to be standardised to produce more accurate and reliable results.

### 1.2. Thermal comfort indices for the outdoor environment

More than 100 different thermal indices have been developed to describe the heat exchange between human body and its surrounding environment (Błażejczyk et al., 2012). Energy balance model of human body was developed and widely used in the 1970s to 1980s, with a number of biometeorological indices developed for the assessment of thermal stress and strain (Höppe, 1997). One of the commonly used indices was Predicted Mean Vote (PMV) which provides a practical and easily programmable heat balance model of human body (Fanger, 1970). It has since been a widely adopted biometeorological index to describe the predicted mean thermal perception under indoor conditions. Pickup and de Dear (2000) developed a physiologically valid outdoor comfort index (OUT_SET*) by adapting the indoor comfort index SET* to outdoor settings. This involves an estimation of the amount of solar radiation absorbed by the human body and hence determine an outdoor mean radiant temperature.

The Munich Energy-balance Model for Individuals (MEMI) was later developed to incorporate individual heat fluxes, body temperatures, sweating rates and skin wettedness into the assessment of the thermal conditions of the human body in a physiologically relevant way (Höppe, 1984). It also forms the basis of the Physiological Equivalent Temperature (PET) which is defined as "the air temperature at which, in a typical indoor setting (without wind and solar radiation), the heat budget of the human body is balanced with the same core and skin temperature as under the complex outdoor conditions to be assessed (Höppe, 1999, p.71). PET has been used in studies of outdoor thermal comfort in different climates and urban settings (Lin, 2009; Ng and Cheng, 2012; Krüger, 2017).

Another commonly used thermal index which has been widely used in the last decade is Universal Thermal Climate Index (UTCI). UTCI is defined as "the air temperature which would produce under reference conditions the same thermal strain as in the actual thermal environment" (Błażejczyk et al., 2010). It is therefore a one-dimensional quantity which represents the human physiological reaction to the actual thermal conditions defined by multiple dimensions. It was developed based on the UTCI-Fiala model which was adapted to predict human responses to outdoor climate conditions. The model also considers behavioural adjustments of the clothing insulation with outdoor air temperature as well as the effect of air movement, walking speed and clothing's thermal and evaporative resistances (Havenith et al., 2011). UTCI has been widely used in the assessment of outdoor thermal environment (Bröde et al., 2012; Krüger et al., 2017; Oh et al., 2019).

### 1.3. Micrometeorological measurements

The measurement of micrometeorological conditions is an integral part of outdoor thermal comfort studies since it provides observed data for comparing to subjective thermal perception. Oke (2006) presents a set of guidelines for meteorological observations in urban areas while ISO 7726 (1998) and ASHRAE Handbook of Fundamentals (ASHRAE, 2017) also provide a description of instruments that suit thermal comfort measurements for indoors. However, additional considerations are necessary for the exposure of instruments, the measurement of wind speed, and the estimation of mean radiant temperature (Tmrt; Johansson et al., 2014).

Temperature and humidity sensors may be affected by radiation sources like solar radiation and heated urban surfaces, leading to overestimation of the air temperature. As such, shielding and ventilation are required to minimise the radiative exchange between the instrument and its surroundings and avoid the accumulation of warm air around the probe. Cheng et al. (2012) argued that the radiation shield may not be sufficient to prevent overestimation of air temperature so correction to the results may be required. Wind speed is also an important variable in the assessment of thermal comfort and the type of sensors may affect the accuracy of measurements. Two-dimensional anemometers are commonly used but the turbulence in outdoors may result in an underestimation of actual wind speed.

$T_{mrt}$ is a critical variable in the assessment of thermal comfort, particularly during warm and sunny weather conditions (Mayer and Höppe, 1987) since it represents the aggregated short- and long-wave radiation fluxes in the surroundings that a human body is exposed to (Johansson et al., 2014). It can be determined by two common approaches, namely integral radiation measurements with the inclusion of angular factors and global thermometer combined with measurements of air temperature and wind speed (Thorsson et al., 2007). The large variations in the use of instruments cause inconsistencies and issues in comparison between studies.

### 1.4. Objectives of the study

The present study aims to: (1) prioritise the elements of outdoor thermal comfort studies such as subjective thermal sensation, affective evaluation of thermal comfort, thermal preference for better understanding of human thermal comfort at international level; (2) develop an internationally recognised standard methodology for conducting field studies of outdoor thermal comfort; and (3) establish a database of outdoor thermal comfort surveys by collating existing data from studies conducted in different climates. The methodological framework of this study was presented, and the progress of this study was also reported in this paper. Future developments of this study are also introduced.

## 2. Data Acquisition

### 2.1. Identification and acquisition of relevant data sources

At the preliminary stage, a literature review was conducted to identify relevant data sources for the inclusion in the database. Articles indexed in journal databases such as PubMed, Web of Science, Scopus and SpringerLink were retrieved and shortlisted for relevance, using relevant keywords including (but not limited to) “outdoor thermal comfort”, “human thermal comfort”, “thermal perception”, “thermal assessment”, “outdoor environment” and “questionnaire survey”. The authors of relevant studies were contacted for their interest in contributing to the database. At the same time, contribution to a pilot study was called in the newsletter of the International Association for Urban Climate in mid-2019 (http://www.urban-climate.org/wp-content/uploads/IAUC072.pdf).

Data obtained from shortlisted studies have to fulfil the following criteria in order to be included in the database. A template, consisting of unit of measurement, code names, and coding conventions, was provided for data contributors.

- Data should be collected from field surveys and experiments conducted in semi-outdoor or outdoor environments.
- Metadata of the study are required, including (but not limited to) dates of questionnaire survey and micrometeorological measurements, number of samples, climate zone and background climatic information, and types of urban settings (with pictures of study site, when available).
- Both subjective (questionnaire survey) and instrumental (micrometeorological measurement) data are required and they should be simultaneously collected to obtain the right-here-right-now response from the respondents.
- The questionnaire survey should consist of subjective assessment of the thermal environment, metabolic rate and clothing level of the respondents, immediate thermal history (if any), biometric information, and demographic background of the respondents.
- The micrometeorological measurements should include four fundamental parameters for calculating thermal comfort indices, namely air temperature, humidity, air movement, globe temperature (or three-dimensional measurements of radiation fluxes for calculating mean radiant temperature, $T_{mrt}$). Technical specifications of instruments/sensors and detailed instrumental settings will also be required.
- Raw data are required, i.e. not from processed or published data. However, data must have been published in peer-reviewed journals or conference papers. Therefore, publication metadata should be provided. Coding of the data should also be clearly defined by data contributors.

### 2.2. Study areas and climatic background

In this pilot stage, 11 studies were included in this pilot study with three studies from Europe (Szeged, Warsaw and Athens), two studies from South America (Guayquil and Curitiba), two studies from Australia (Melbourne), and three studies from Asia (Hong Kong) (Figure 1). They cover different background climates according to the Köppen-Geiger's climate classification (Kottek et al., 2006), ranging from Group A (tropical climate), Group B (dry climate), Group C (temperate climate), to Group D (continental climate), so this pilot study provides a variety of physiological acclimatisation and psychological adaptation. A total of 21,254 data entries were obtained. Details of the data sets are listed in Table 2.

### 2.3. Collection of field data

The study sites of all surveys were public spaces commonly visited, including public squares, pedestrian streets, urban parks, university campuses, and residential districts. Structured questionnaires were administered to study people's subjective assessment of the thermal comfort conditions while micro-meteorological measurements were simultaneously performed. Questionnaire surveys were conducted in summer for all studies and in winter for six studies, with seven of them covering transitional seasons. In Guayaquil, surveys were conducted in wet and dry seasons due to the insignificant seasonal differences in air temperature.


Figure 1. Locations of the studies included in the pilot stage.

Table 2. Details of the studies included in the pilot stage.

| Study | Study Area | Latitude, Longitude | Climate Zone | Season | Survey Location | Survey Days | Time Period | Sample Size |
|---|---|---|---|---|---|---|---|---|
| ARMI16 | Tempe, United States | 33.42° N, 111.94° W | Bwh | 1,2,3,4 | Campus | | 07h-19h | 1284 |
| ATKO12 | Szeged, Hungary | 46.25° N, 20.14° E | Dfb | 1,2,3 | Park, square, street | | 10h-18h | 5288; 517 |
| CHLA17 | Melbourne, Australia | 37.81° S, 144.96° E | Cfb | 2 | Park | | 09h-16h | 3293 |
| ERJO18 | Guayaquil, Ecuador | 2.19° S, 79.89° W | Aw | 1,2 | Arcade, square, park, waterfront | | 11h-20h | 544 |
| ESYU19 | Hong Kong | 22.32° N, 114.17° E | Cwa | 2,4 | Park | | 07h-17h | 454 |
| KALI13 | Warsaw, Poland | 52.23° N, 21.01° E | Dfb | 1,2,3,4 | Square | | 11h-16h | 818 |
| KAPA13 | Athens, Greece | 37.98° N, 23.73° E | Csa | 2,3,4 | Square, street | | 11h-22h | 1706 |
| SASH16 | Melbourne, Australia | 37.81° S, 144.96° E | Cfb | 1,2,3 | Campus | | 09h-17h | 1023 |
| EDNG12 | Hong Kong | 22.32° N, 114.17° E | Cwa | 2,4 | Park, Residential, Street | | 07h-19h | 2674 |
| KELA18 | Hong Kong | 22.32° N, 114.17° E | Cwa | 2 | Park, Residential, Street | | 10h-17h | 1998 |
| EDKR11 | Curitiba, Brazil | 25.43° S, 49.27° W | Cfb | 2,3,4 | Street, Square, Crossroads | | 10h-16h | 1655 |

### 2.3.1. Micro-meteorological measurements

Field measurements of micro-meteorological conditions included air temperature ($T_a$; °C), relative humidity ($RH$; %) and wind speed ($v$; ms$^{-1}$) in all studies. Measurements of thermal radiation, in terms of globe temperature ($T_g$; °C) and/or global solar radiation, were also conducted for the estimation of mean radiant temperature ($T_{mrt}$; °C). Sensors were placed close to the respondents with the same exposure to solar radiation and at about 1.1 m above ground surface in most cases, which corresponds to the average height of the centre of gravity of a standing man (Mayer and Höppe 1987).

Table 3 presents the summary statistics of the meteorological variables measured in the 11 studies. Due to the diversified climatic background, there are large variations in air temperature. Apart from Study 4 and 10 which were conducted in the tropical region (Guayaquil, Ecuador) and sub-tropical region (Hong Kong) in summer. Maximum air temperature was over 30°C with Study 1 up to 43.4°C (Tempe, Arizona).

Table 3. Summary of the meteorological conditions of the studies.

| **Study** | **ARMI16** | **ATKO12** | **CHLA17** | **ERJO18** | **ESYU19** | **KALI13** | **KAPA13** | **SASH16** | **EDNG12** | **KELA18** | **EDKR11** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *Air Temperature (°C)* | | | | | | | | | | | |
| Max | 43.4 | 38.0 | 40.6 | 34.3 | 35.7 | 30.0 | 39.3 | 34.5 | 38.7 | 38.9 | 30.7 |
| Mean | 24.8 | 21.4 | 24.9 | 29.1 | 23.4 | 12.0 | 25.1 | 22.0 | 26.9 | 33.3 | 19.9 |
| Median | 25.7 | 21.1 | 23.7 | 28.8 | 22.4 | 12.5 | 25.2 | 21.5 | 26.2 | 33.1 | 20.2 |
| Min | 10.2 | 6.9 | 15.8 | 25.5 | 11.9 | -6.7 | 7.1 | 12.2 | 11.6 | 29.8 | 6.4 |
| Std Dev | 8.5 | 6.3 | 5.2 | 2.2 | 7.1 | 11.1 | 8.6 | 5.1 | 5.7 | 1.5 | 5.5 |
| *Relative Humidity (%)* | | | | | | | | | | | |
| Max | 40.2 | 82.1 | 99.9 | 73.1 | 87.8 | 85.8 | 79.4 | 80.9 | 86.3 | 89.3 | 93.2 |
| Mean | 23.3 | 39.7 | 56.4 | 63.3 | 70.3 | 55.6 | 50.4 | 49.2 | 62.3 | 63.7 | 56.4 |
| Median | 20.0 | 37.5 | 61.1 | 64.8 | 74.1 | 54.8 | 48.1 | 49.8 | 63.3 | 63.1 | 56.3 |
| Min | 11.0 | 14.8 | 14.6 | 49.2 | 45.8 | 25.2 | 22.6 | 18.0 | 28.7 | 45.6 | 23.5 |
| Std Dev | 9.5 | 12.6 | 17.1 | 6.7 | 10.8 | 15.5 | 14.2 | 12.2 | 11.0 | 7.7 | 12.9 |
| *Wind Speed (m/s)* | | | | | | | | | | | |
| Max | / | 4.22 | 3.70 | 2.77 | 2.18 | 1.90 | 9.33 | 6.27 | 6.85 | 3.21 | 3.28 |
| Mean | / | 1.16 | 1.25 | 1.13 | 0.69 | 0.73 | 0.81 | 1.63 | 1.15 | 0.97 | 1.14 |
| Median | / | 1.06 | 1.09 | 1.02 | 0.65 | 0.76 | 0.64 | 1.48 | 0.97 | 0.94 | 1.07 |
| Min | / | 0.10 | 0.00 | 0.44 | 0.00 | 0.00 | 0.25 | 0.19 | 0.03 | 0.07 | 0.00 |
| Std Dev | / | 0.54 | 0.72 | 0.48 | 0.47 | 0.37 | 0.74 | 0.81 | 0.77 | 0.42 | 0.56 |
| *Mean Radiant Temperature (°C)* | | | | | | | | | | | |
| Max | 85.8 | 70.9 | 77.2 | 78.9 | 77.6 | 86.9 | 44.7 | 51.0 | 79.3 | 81.2 | 72.3 |
| Mean | 39.8 | 33.2 | 46.7 | 47.9 | 31.1 | 20.1 | 28.1 | 28.2 | 34.8 | 39.8 | 31.3 |
| Median | 34.2 | 30.5 | 48.6 | 47.0 | 30.5 | 16.3 | 30.4 | 27.5 | 31.4 | 34.4 | 27.2 |
| Min | 0.3 | 2.7 | 8.8 | 24.5 | 14.4 | -13.0 | 8.5 | 9.7 | 2.5 | 29.8 | 9.8 |
| Std Dev | 18.5 | 13.3 | 14.6 | 14.9 | 8.7 | 19.7 | 9.5 | 9.0 | 13.2 | 10.0 | 13.9 |
| *Physiological Equivalent Temperature (°C)* | | | | | | | | | | | |
| Max | 70.7 | 53.9 | 55.6 | 51.1 | 48.4 | / | 43.9 | 42.1 | 43.8 | / | 45.5 |
| Mean | 32.2 | 23.1 | 31.8 | 35.9 | 25.0 | / | 25.0 | 21.1 | 25.8 | / | 21.7 |
| Median | 29.7 | 22.9 | 32.0 | 34.9 | 27.3 | / | 26.0 | 20.5 | 26.7 | / | 20.5 |
| Min | 5.3 | 3.6 | 11.8 | 24.0 | 10.6 | / | 1.7 | 7.4 | 2.9 | / | 3.6 |
| Std Dev | 14.0 | 8.4 | 8.2 | 7.2 | 8.3 | / | 10.0 | 7.0 | 7.9 | / | 9.0 |
| *Universal Thermal Climate Index (°C)* | | | | | | | | | | | |
| Max | 51.9 | 45.2 | 46.2 | 43.8 | / | 34.1 | 39.3 | 37.9 | 45.2 | 44.7 | 37.6 |
| Mean | 27.8 | 23.8 | 30.2 | 34.2 | / | 13.7 | 25.7 | 19.9 | 29.4 | 37.5 | 22.5 |
| Median | 26.5 | 24.1 | 30.5 | 33.6 | / | 13.9 | 26.9 | 19.7 | 28.8 | 37.0 | 21.9 |
| Min | 6.3 | -0.6 | 14.5 | 24.6 | / | -13.9 | 3.0 | -3.6 | 9.8 | 34.0 | 5.0 |
| Std Dev | 9.6 | 6.5 | 5.6 | 4.7 | / | 12.9 | 8.9 | 7.3 | 7.4 | 2.0 | 6.9 |
| Number | 1284 | 5805 | 3293 | 544 | 454 | 818 | 1706 | 1023 | 2674 | 1998 | 1655 |

Thermal comfort indices are important to provide an objective assessment of the thermal environment. As pointed out by de Dear (1998), there are potential sources of "noise" in the thermal comfort indices since different versions of computer algorithms may have been used to calculate such indices. In order to avoid these inconsistencies, three thermal comfort indices commonly used by outdoor thermal comfort studies, namely PET and UTCI, were calculated from the raw data of micrometeorological measurements acquired from data contributors.

The software RayMan (Matzarakis et al., 2007) and BioKlima (Błażejczyk, 2011) were used to calculate PET and UTCI, respectively. RayMan is developed for the calculation of short- and long-wave radiation fluxes on the human body. It takes into account the complex geometry of urban structures and can be applied in urban planning and street design. The output of the model includes Tmrt for the assessment of the urban bioclimate by using thermal comfort indices such as PMV, PET, SET*. BioKlima consists of different methods of bioclimatic studies and provides easy calculations of more than 60 various biometeorological and thermophysiological indices. The mandatory inputs of meteorological variables include air temperature, relative humidity, globe temperature, wind speed, metabolic rate and clothing level (thermal insulation). Personal factors such as height and weight can also be included for the calculation of the thermal comfort indices.

### 2.3.2. Questionnaire surveys

Structured questionnaires were conducted to obtain information about subjective assessment of the thermal environment, as well as personal parameters and behaviours, usage of outdoor spaces. Although the overall content of the questionnaires was adjusted to local contexts, this pilot study focuses on the subjective assessment of the thermal environment.

Table 4 describes the thermal assessment scales used in the 11 studies included in this pilot stage. Eight studies adopted the ASHRAE 7-point scale for the respondents to report their thermal sensation vote (TSV). It was originally designed for indoor studies but has been widely used for outdoor studies in the last two decades (Spagnolo and de Dear, 2003; Knez and Thorsson, 2006; Lin et al., 2009; Lau et al., 2018). Previous studies used this scale to correspond to the PET categories particularly developed for Central Europe (Matzarakis and Mayer, 1996; Matzarakis et al., 2009). In three of the studies (ARMI16, ATKO12, and ERJO18), two additional votes ('very cold' and 'very hot') were used to represent the wider range of thermal conditions in the outdoor environment. In particular, the respondents in Szeged were asked to report TSV on a 9-point scale with a 0.1 increment.

The respondents were also asked to report their affective evaluation of overall thermal comfort in seven studies, though different evaluation scales were used. ARMI16 used a 4-point unipolar scale with three levels of uncomfortable votes and one class of comfortable vote. ATKO12 and SASH16 used a 7-point symmetric scale while ESYU19 adopted a similar scale without a 'neutral' option. KAPA13 applied a 5-grade symmetric scale while EDNG12 and KELA18 adopted this scale with the middle vote denominated.

Preference to the current thermal conditions was also asked in most of the studies (except EDNG12). All of them adopted symmetric scales with a neutral option. Seven studies used three classes to represent 'want warmer', 'remain unchanged' and 'want cooler' (McIntyre, 1980). ARMI16, ESYU19, EDKR11 applied seven classes from 'much cooler' to 'much warmer'. Thermal acceptability was only asked in three studies with a 6-point symmetric scale without a 'neutral' option adopted by ESYU19. SASH16 and KELA18 used two classes to represent 'acceptable rather than unacceptable' and 'unacceptable rather than acceptable'. In addition, only three studies asked the perception of different meteorological parameters (such as wind, humidity and solar radiation).

Table 4. Thermal assessment scales used in the 11 studies.

| Study | Thermal Sensation | Thermal Comfort | Thermal Preference | Thermal Acceptability | Perception Vote | Remarks |
|---|---|---|---|---|---|---|
| ARMI16 | 9-point | 4-point (0 to -3) | 7-point (-3 to +3) | N/A | N/A | |
| ATKO12 | 9-point | 7-point (-3 to +3) | 3-point (-1 to +1) | N/A | WSV, SSV, HSV | TSV is on 9-point scale with 0.1°C increment |
| CHLA17 | 7-point | N/A | 3-point (-1 to +1) | N/A | N/A | |
| ERJO18 | 9-point | N/A | 3-point (-1 to +1) | N/A | N/A | |
| ESYU19 | 7-point | 6-point (-3 to +3) | 7-point (-3 to +3) | 6-point (-3 to +3) | N/A | |
| KALI13 | 7-point | N/A | 3-point (-1 to +1) | N/A | N/A | |
| KAPA13 | 7-point | 5-point (-2 to +2) | 3-point (-1 to +1) | N/A | N/A | |
| SASH16 | 7-point | 7-point (-3 to +3) | 3-point (-1 to +1) | 2-point (0 or 1) | N/A | |
| EDNG12 | 7-point | 4-point (-2 to +2) | N/A | N/A | WSV, SSV, HSV | |
| KELA18 | 7-point | 4-point (-2 to +2) | 3-point (-1 to +1) | 2-point (0 or 1) | WSV, SSV, HSV | |
| EDKR11 | 7-point | 4-point (0 to -3) | 7-point (-3 to +3) | 2-point (0 or 1) | N/A | |

### 2.4. Data harmonisation

Subjective thermal perception is often compared to objective micrometeorological measurements in order to understand the subjective-objective relationship of thermal assessment. As different assessment scales (e.g. number of points on the scales) were adopted by previous studies, there is a need to harmonise the datasets obtained from different studies.

In this study, the method proposed by Dawes (2002) was adopted to rescale the data obtained by different assessment scales since it produces similar mean and variance values. For instance, the data obtained from 9-point scale were rescaled by applying a rescaling factor to reduce the spread from nine to seven classes. The rescaled data were evaluated against the original data based on the mean, standard deviation, kurtosis and skewness values.

## 3. Analytical Procedures

### 3.1. Identification of key elements in outdoor thermal comfort surveys

Subjective assessment of the thermal environment includes thermal perception, thermal comfort (affective evaluation), thermal preference, personal acceptability and tolerance (ISO 10551, 2019). Data before and after harmonisation will be tested among subjective assessment and objective measurements for the sensitivity in thermal assessment (Task 5).

The non-parametric Spearman's rank correlation coefficient will be used to determine the correlations among subjective assessment and objective measurements, which indicates the significant elements in thermal assessment with respect to micrometeorological conditions that the respondents are exposed to.

Linear regression analysis will then be conducted to investigate the relationship between both original and binned values of meteorological variables and thermal comfort indices. Linear models will be developed to examine how well subjective thermal assessment can be predicted from observed meteorological measurements.

The models will be validated using two approaches. Firstly, studies from similar climatic regions or similar urban settings will be divided into training and validation datasets. This ensures the applicability of the models in a relatively consistent climatic and environmental conditions. Secondly, the entire datasets will be randomly divided into training (80%) and validation (20%) datasets in order to evaluate the overall predictability of the linear models. The parameters identified will be included in the draft standard methodology which will be further tested by selected research teams in different climatic regions.

### 3.2. Testing of the draft standard methodology

The key elements identified in Task 5 will be included in the draft standard methodology which will consist of subjective thermal assessment and micrometeorological measurements. The testing of the draft standard methodology will be conducted in selected countries by corresponding research teams in order to test its feasibility and identify if there are any issues or difficulties.

The questionnaire surveys will include the assessment scales and elements determined by the linear models in Task 5 to form the subjective part of data collection. At the same time, the instrumental settings will also be provided for testing the draft standard methodology. The testing will be conducted in different seasons in order to examine the applicability of the draft methodology in both extreme and transitional conditions. The target sample size is 100 responses per round in order to maintain sufficient samples to compare between different studies and refine the methodology if necessary.

### 3.3. Establishment of the online database

Based on the findings obtained in Tasks 3-5, the key elements of human thermal comfort in outdoors will be identified and used in establishing the online database. Browser-based applications will be used since it has readily available and easy-to-use visualisation and user interface. Open-source JavaScript libraries will be used to visualise the data based on the data analysis conducted in Task 5. The primary focus of the database is to provide information about the conditions that are perceived as comfortable so that the users such as urban planners and designers can take into account these conditions in their practices.

Four types of information will be included in the database. First, subjective assessment of thermal comfort will be provided to indicate how people perceive their thermal comfort under specific conditions. Second, the corresponding meteorological conditions will be provided in order to allow users to understand what conditions are required to achieve thermal comfort. Third, demographic information will be included for any specific use or design of outdoor spaces. Finally, the urban settings where the data were collected will be specified.

During the process of development, a website with online forum will be established to provide an online platform for communication between researchers and contributors. The questions or issues encountered during the process will be shared and data contributors can answer or raise any questions they concern. This online platform can also engage potential users during the development process in order to maximise the applicability of the online database.

## 4. Way Forward

The primary objective of developing this global database for outdoor thermal comfort survey is to provide the empirical basis for establishing outdoor thermal comfort models by understanding the influential elements of human thermal comfort in the outdoor environment. However, the content of the database has a large potential beyond this due to the large amount of high-quality field data that can be used to explore the issues regrading human thermal comfort in the outdoor environment. The followings are some examples of potential applications of this global database.

The database provides numerous possibilities for developing empirical relationships between different assessment scales of subjective thermal perception. Human thermal comfort research has been using a wide range of subjective assessment scales, for example, the seven-point ASHRAE thermal sensation scale, thermal acceptability and preference assessment. The database therefore provides a platform for evaluating the assumptions behind different assessments and the applicability in outdoor settings.

The contextual effects were studied in some previous work but there have been no comprehensive understandings of how these effects influence subjective thermal perception in different climates. Therefore, there are opportunities for researchers to investigate the characteristics of the outdoor environment and their relationship with human thermal comfort of pedestrians and users of outdoor spaces. Urban planning and design professionals can be informed with the findings and they can enhance the design of outdoor spaces in order to encourage their usage, which in turn has implications on human health and well-being, as well as energy consumption of buildings.

Since the data provided by researchers have been previously published in peer-reviewed academic journals and undergone the process of quality check, they are reliable and ready to use for scientific and design work. The database also allows professional practitioners to extract relevant information for their design. For example, design professionals can acquire the understanding of thermal comfort requirements for specific urban contexts and climatic regions without conducting the field work themselves.

The long-term goal of the database is to establish a standard methodology for conducting outdoor thermal comfort research. The draft version of the standard methodology provided in the later stages of the development of the database allows robust testing of the methodology. It also facilitates comparison of results between different climatic regions and urban settings in order to enhance the understanding of outdoor thermal comfort. This potentially contributes to the discussion of the difference between indoor and outdoor studies, which has been widely discussed in the last two decades.

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# Comfort, Cooling and Critical Accountability: a teaching tools and research odyssey

**Ola Uduku[1], Gillian Treacy[2] Yiqiang Zhao[3] and Satish BK[3]**

**[1] Manchester School of Architecture, Manchester, M15 6BR o.uduku@mmu.ac.uk**

**[2] Edinburgh College of Art University of Edinburgh**

**[3] ESALA University of Edinburgh, Edinburgh EH1 1JZ yiqiang.zhao@ed.ac.uk**

**[4] Architecture School, University of Plymouth Satish.bk@plymouth.ac.uk**

Abstract:

**Comfort, Cooling and Critical Accountability: a teaching tools and research odyssey**

How do we ensure the next generation in the building profession are best equipped to respond to the challenges of providing comfort in a rapidly heating world? As environmental science educators it is our job it is to pass this responsibility to the next generation. For those whose work will be in the global 'south' this task is especially crucial as we know that achieving thermal cooling is more energy consuming and harder to achieve than through heating. In today's world with greater communications and IT usage might this become easier to achieve? The internationalisation of students in universities also means that the research and teaching of environmental design courses to students whose ultimate work and practice location will be sites in the "tropical south", needs to be addressed. Today there is a great need to revisit the notion of a tropical design syllabus and associated design courses to be taught to Western universities' international student cohorts. Here we review the history of tropical education across the world. It then considers the current status of environmental design teaching, taking into account the incorporation of new tools for environmental science pedagogy; environmental modelling, environmental apps, applications such as AI and VR. Finally, it suggests how future environmental design teaching might benefit from incorporating new pedagogy to deliver sustainability-focused environmental science teaching, to tomorrow's practitioners and researchers.

**Keywords:**

Environmental design pedagogy, internationalization, digital teaching tools

## INTRODUCTION

Over various periods for more than five years the co-authors of this paper taught environmental design at year two level, at Edinburgh School of Architecture, (ESALA) at the University of Edinburgh. They taught to student audiences from international backgrounds, many of whom came from, or had lived in the global 'South' . The environmental design course taught was one of the first to embrace an internationalisation of its curriculum by engaging students with research tasks which enabled them to consider other climate considerations, and the issues related to sustainability in contemporary design. The course also allowed the introduction of new forms of environmental measurement using 'apps' and basic modelling techniques. This paper discusses case study instances of this, and then goes on to explore the challenges this early attempt at globalised environmental design teaching produced and what future changes and issues will need to be dealt with.

The paper runs as a discussion with case study examples being given by the co-authors and the drawing of a conclusion and literature review in the course of the text. We see this as an initial attempt at a larger body of work likely to result in a monograph on environmental design and thermal comfort teaching to global audiences in transnational institutions.

### 1.0 Context

This is a joint paper collated to describe the experiences and instances of teaching which has informed a thematic approach to thermal comfort teaching to mostly undergraduate students at the University of Edinburgh from c. 2012 – 2017, when the co-ordinator of the teaching left to take up a chair in Architecture at Manchester. In 2011 the architecture schools at Edinburgh College of Art and Edinburgh University had just merged to become the 'super' school ESALA, and this resulted in the unification of different teaching methods in Environmental design, amongst other subject areas.

This was seen as an opportunity more than a challenge to re-imagine what an environmental design course might offer to students from increasingly international backgrounds. Edinburgh University is a Russell group institution, of which ESALA is now a part. The school regularly has more than 40% international student enrolment in its undergraduate architecture course.

The previous environmental design courses that had been taught at Edinburgh College of Art, and the University had up until the merger had remained largely unaltered from the development of the RIBA-ARB required teaching competencies in relation to environmental design and building physics tuition for architecture students as had been defined in the late 1980s. The opportunity thus arose to review the curriculum and develop a more 21$^{st}$ century student-focused environmental design programme with a new, younger academic teaching team. It also allowed us begin to consider and engage with emerging key themes in teaching, pedagogy and contemporary ways of measuring environmental design performance and analysis.

This paper focuses only on the thermal comfort aspect of teaching, but the curriculum that was developed also radically overhauled teaching in the area of daylighting and lighting comfort, mainly through the efforts of our colleague Gillian Treacy. There was also some overlap in this area as initial work on apps development and thermal modelling analysis was undertaken in conjunction with Treacy, (Treacy and Uduku, 2015).

### 2.0 Thermal Performance and Design Teaching at Edinburgh; *Uduku, Satish BK, and Treacy*

At ESALA, from 2011 onwards, teaching at second year level in environmental design has taken place exclusively in semester one over an 8 – 10 week period. It involved a condensation of a wider teaching programme which had taken place before at Edinburgh University for its second-year students, and a partially studio based teaching programme that had been introduced for ECA students which again ensured that in the past teaching of environmental design took place for a longer part of the academic year.

Both systems had also initially focused on exam-based systems where students were tested on their knowledge of building physics themes such as the calculation of U-values, and thermal load at various period in buildings. A review of student outcomes and knowledge highlighted early to us that students often 'crammed' environmental formulae to pass examinations, with very little of this information being applied to their architectural designs in studio. This directly contravened the contemporary pedagogic related to student centred learning, and agency in their application of the environmental knowledge gained to their design aspirations in studio. Furthermore, much of the work being undertaken was case study focused, and involved examples which were either Edinburgh-located or at best focused on Europe, and consequently the environmental design requirements for northern climatic conditions. This was despite the increasing number of international students who now made up the student body.

Our task then was to 'internationalise" the curriculum and also consider how best through our teaching to embed key 'gateway' concepts in environmental design teaching to our international students who we recognised as being the 'generation X' Digital Natives, who would and could use technologies innovatively. What follows is the presentation of a number of tuition case studies which various collaborators on this paper have used that exemplify this approach. The final part of the paper pulls these strategies together and describes the teaching approach which we simultaneously and sometimes individually achieved over this period of teaching at ESALA at the University of Edinburgh.

### 3.0 The Environmental Design Case Study

This non digital intervention involved our changing a small building case study that had been focused solely on working on environmental conditions in a shaded square in Edinburgh University to expecting all students to conduct an environmental case study of a small building in one of a number of different climatic zones. This was used as an 'end of teaching' examination where students could analyse the case study building using the thermal analysis and other environmental design measurement tools to come up with a credible environmental analysis of the small building in its climatic setting.

As a final formative evaluation teaching tool, this proved particularly successful in assessing student understanding of themes and concepts taught over the term, and importantly gave the course relevance to students from different climate zones to Europe. The best student work often foregrounded students whose work in studio would also go on to achieve critical success, with many of such students going on to win end of year awards for their work in more than just the environmental design course we were involved in delivering.

Examples here are given of Satish BK's tutored case study work, in this case an environmental analysis of the Richard Murphy's Dance Base Studios in Edinburgh, by, this is contrasted with Ola Uduku's tutored Tropical Dwelling Case Study, in Indonesia.

**Fig. 1 Dance Base. Case Study (Edinburgh)** **Fig. 2 Tropical Dwelling Case Study (Indonesia)**

### 4.0 Digital Tools for Teaching

In this section we discuss the evolution and incorporation of the development of the use of digital tools, from basic models to apps for teaching the environmental design course at ESALA. Whilst much of the initial process was initiated by Treacy and Uduku, Zhao has been involved in its further development and has incorporated this in his PhD studies. He provides a commentary of his his further development of the EdenApp mobile application as a thermal comfort evaluation model which he has tested amongst ESALA students. This model is being considered for use within a more global context with collaborating schools in Africa and elsewhere in the future.

### 4.1 IES 'Lite' for Architects

In 2012 Uduku and Treacy acquired an RKE development grant to develop a 'stripped-down' form of the thermal modelling programme IES, which we called IES-Lite. The ambition of the project was to create IES-lite as a an undergraduate-friendly thermal modelling programme which could be used by our 2$^{nd}$ year architecture students to engage with the thermal analysis of their designs using only basic features of the IES programme. We had previously used the Cambridge University, Martin Centre's, mini 'LT' programme to consider issues such as shading and overheating, but had found this has significant limitations. (Baker and Steemers, 1996) IES lite gave students the chance to use different climate files to consider different locations in the world, they could also change building materials and facades and gauge levels of  cooling or overheating, and therefore thermal discomfort, and finally it enabled them consider shading and daylighting.

We trialled the use of the programme for two teaching years with  limited success. The climate data files were the most useful part of the programme as students could get some idea of the thermal comfort and required ventilation (in air changes per hour) that their buildings would need. Also, the programming of shading worked well as different times in the year and day could be calculated accurately with the programme algorithms to show realistic views of shading. The particularly complicated nature of the programme however meant that it would never be an easy analysis for non-fully technology and arithmetically focused students, and so we went on to consider other options.

### 4.2 EdenApp

EdenApp evolved from our experience of IES lite, as a different method of engaging students with environmental measurement and evaluation. First of all it focused on lighting and assessment of the daylight factor. As documented elsewhere it enabled students work with their mobile phones to determine lighting levels and then undertaken in real time the calculation needed to determine the daylight factor in the space being considered. A further part of the app was developed to show students if the factor meant that the areas were either too bright or too dark for optimal visual comfort. Further iterations of the app were developed to consider temperature, noise levels, and there are still future ambitions to develop a comfort chart; similar to the Olgyay Chart (Olgyay, 1963) which might respond to climate variations across the world.

EdenApp has been successful in its ambition and follows on from our learning from IES-lite, the app is very much focused at the education market, and has clear basic teaching objectives. We found its development however was challenging as we neither were app programmers, Phd student Yiqiang Zhao joined the team and helped with the further development of thermal analysis which he describes later on in this paper. We were mainly however reliant on an early “technopreneur -programmer**”,** Cosmin Dumitrache, who helped transform our ideas for the app into reality, with a further grant received from the University of Edinburgh. The weakness of support in the Edinburgh University system for this form of development unfortunately meant that as he left for Silicon Valley the development of the programme slowed down considerably.  EdenApp still has a liminal presence on apple education tools, and occasional requests to use it are received from across the world, there is the ambition to work further on its development in future.

### 4.3 EdenApp Thermal Comfort – Yiqiang Zhao

The success of EdenApp – Lighting sensor increased the possibility of developing from more perspective.  As a result, EdenApp – Thermal Comfort was developed for thermal comfort calculation (Zhao, Uduku and Murray-Rust, 2017). By adding some basic parameter and connected with Bluetooth sensors, it could provide real-time Predicted Mean Vote (PMV) calculation, which is the metric for indoor thermal comfort in ISO 7730 and ASHRAE 55. We tested the app but found out that several parameters such as globe temperature and low-speed wind speed need a professional sensor for measurements.  Furthermore, the cost is quite high compared with traditional temperature sensor and anemometer.

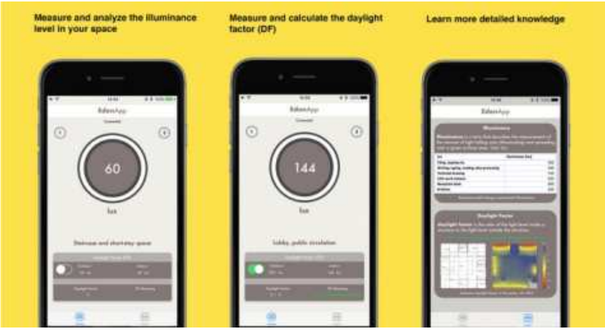


*Figure 3: EdenApp – Lighting*

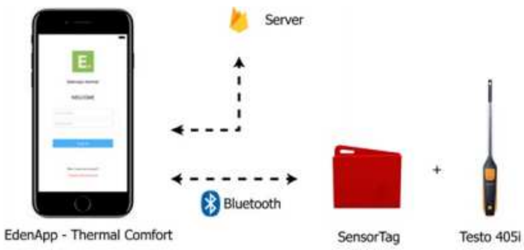


*Fig. 4: EdenApp – Thermal Comfort*

The price, feasibility, stability and connectivity will all influence the accuracy of reading and student's user experience. Since we realised that sensor had become a crucial part of the whole learning process, based on Smart Thermal Comfort (STC) sensor box (Zhao *et al.*, 2018), we developed a portable version which could measure air temperature, globe temperature, relative humidity, hot-wire air velocity and illuminance (Figure 4 left). It could give users an accurate real-time environmental data dashboard. To further increase mobility, we used Arduino-based circuit and Bluetooth Low Energy (BLE) technology to made the latest version of portable EdenApp sensor box and fully integrated with mobile app (Figure 4 right). It cost only £40.

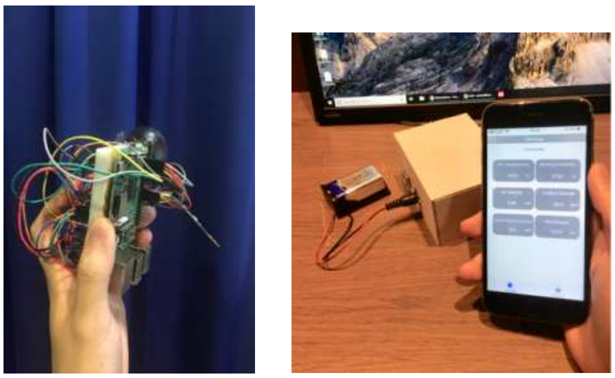

*Fig. 5: EdenApp portable sensors, first generation (left), current version (right).*

Compared with traditional expensive and limited measurement facilities in university's lab, EdenApp could significantly reduce the cost of facility while remain the same function and accuracy. By linking with smart phone, it could give each student more interests and opportunity to join the study game, using real-time measurement tool to learn those invisible environmental parameters. There is no time or space limitation, just open the app and sensor whenever they want.

In 2018 we tested the thermal comfort app in several field trips for undergraduate architecture students in ESALA. The aim of the trip was to let students measure environment parameters in different buildings and get a basic understanding of how thermal comfort standard works. For example, one of the sites was St Albert's Catholic Chaplaincy in Edinburgh. This is a mixed-mode one-floor building with mechanical heating system. Our visit took place in November when windows were all closed and heating system was working properly. A number of five-student groups each worked with a portable sensor set. They conducted measurements, comprising air temperature, relative humidity and air velocity data using the portable sensor, metabolic rate and clothing level. These were entered by the students through the app. Then the PMV was calculated within the app. Within each group, students discussed the range of each environment parameter, and the comparison between PMV and their own actual thermal sensation vote. Tutors then answered student's questions. The process worked well but we found out many students reported the PMV result was not accurate. This was despite the sensors having been calibrated before use and students having had instructions before using the sensor sets.

The PMV model used for the sensor set had been devised within a laboratory environment whilst the adaptive model was generated based on the student generated field study data. There was thefore a paradigm shift from using the PMV to adaptive modelwhich better considers occupants' ability to adapt themselves to suit their surrounding environment. The PMV model still serves well in mechanical HVAC system building whilst the adaptive model is better suited for tropical areas where mechanical ventilation is not in use. In places such as the UK especially winter, PMV is still the only way in ISO or ASHRAE standard to predict thermal comfort. However the PMV model was based on average data which is difficult to predict for individual thermal comfort levels (Kim, Zhou, Schiavon, Raftery, & Brager, 2017; Liu, Schiavon, Das, Spanos, & Jin, 2019). In education, after students measuring the environment data, calculating the PMV result and comparing with their actual thermal sensation vote, many of them asked the question: "[the] PMV is not accurate, why?"; "I feel much colder than the PMV result, can the model adjust based on different buildings?"; "Why not use a smart home sensor in the room [being measured] and let the AI self-learn optimize the heating? "

When facing these questions, it is difficult for teaching-based fellow to realize or explain. There are several options: 1. We could say that's the shortcoming of current standards. The details are quite complicated and need time to solve. 2. We could draw a PDD distribution diagram to explain how PMV applying to multiple-occupied space. 3. We could explain the latest framework to predict individual thermal comfort.

For example, Personal Comfort Model is a new framework to localise thermal comfort within individual level. By using Internet of Things (IoT) sensor and Machine learning, the model self-learns occupant's comfort preference, relearns the pattern in different buildings and apply the setting in HVAC control system. Meanwhile, using EdenApp shows the students how the whole data collection process works.

Our students are part of a younger generation who have a totally different educational experience of growing up in a technologically advanced world than their teachers. They are extremely interested in discovering and using new technologies such as sensors, AI, personalisation service and so on. Amongst these three options, EdenApp creates the opportunity to attract students engaging with the course in a real-time and field-based way. This method shortens the learning curve and increase the possibility of student's independent study skills rather than traditional passive lecture or tutorial-based learning process.

### 4.4 21st Pedagogy in Environmental Design – Thermal Comfort Teaching

Whilst this has in many ways been a learning journey for both the lecturers, tutors and staff who have been involved in the evolution of environmental design teaching at ESALA, the changes to pedagogy and teaching were well received by students. Overall satisfaction, as measured by student feedback was good, with 10 – 12 students, (approximately 10%) of each cohort achieving A+ grades in the environmental appraisal which students were expected to carry out.

We have found that students are ready to engage with digital methods of teaching and the use of the various evolutions of the EdenApp, for daylighting and more recently thermal comfort measurements has been easy to follow. The most difficult part of the process has been finding the sensor attachments for the mobile phones. Lighting sensors were easy to source, as they already existed for photography applications, more specialist sensors required more extensive research, but as discussed by Zhao there are more specialist sensors that work as arduino based sensor kits were adapted to develop the thermal comfort sensor.

The main challenge to teaching we found however was the adoption of new pedagogic methods across different architecture school curricula. For many schools there remains the tension between incorporating environmental analysis and teaching into the studio or leaving its pedagogy as a separate element of the taught curriculum, which is sometimes outsourced altogether in teaching to specialists. In this model the use of experimental apps such as EdenApp are unlikely to be introduced as the specialist link with such programmes is purely delivery related. In other instances, environmental design teaching, although integrated in the studio pedagogy, is taught strictly to textbook themes, with historic examination-based tasks still in use.

We feel that through our longitudinal experience with student cohorts in Edinburgh that the development and use of different 'tech' approaches to teaching can be relatively easily incorporated into undergraduate curricula and importantly the different pedagogic focus has made its uptake and popularity with students a positive experience. The challenges to its further development are less technological but more links to research and teaching at a PG level.

This is a fundamental issue across architecture teaching at part one or undergraduate level. Research led teaching is considered difficult to engage with in first- and second- year teaching more because there is a reluctance to explore and challenge what is considered 'core teaching' which focuses on gateway concepts to understanding. In environmental design this largely covers the building physics issues such as thermal comfort lighting and acoustics. As lecturers and tutors we have been able to engage specifically with this and demonstrate that it is possible to be research focused and creative with our teaching and thus transform curriculum delivery at this level.

The building of a strong research team to carry the project on however requires more critical thinking at departmental research strategy and teaching management level. The integration and development of research teams whose work integrates into architectural teaching remains a relatively new phenomenon across architecture schools. What is needed is a commitment at research level to maintain and develop research teams who can work to constantly engage with various parts of the architecture teaching and curriculum development so as to ensure that these respond both to new trends in teaching technology and pedagogy – so this does not rely on staff interests only and therefore can often lack sustainability and long term development.

In the case of ESALA, this experience suffered this fate. From 2017 onwards, the initial teaching and research team dispersed. The lead co-ordinator left to take up a chair in Architecture, at a different institution. The lighting specialist moved to another part of the University, and has further developed her own interests in lighting teaching with students in Interior design. Most of the graduate tutors who had worked with the programme have now completed their PhDs, and went on to develop their careers elsewhere. The core team of environmental design researchers and tutors who had been involved in developing these pedagogic changes thus were disbanded. Yiqiang Zhao however does continue to work with EdenApp and other applications in his soon to be completed PhD at the University of Edinburgh.

In the meantime, the ESALA teaching programme at undergraduate level retained much of the analogue, non app-based interventions, but in essence no longer directly engages in the integration of environmental science research in its teaching. If we are to develop and support local interest in environmental design and performance analysis amongst architects, without engaging undergraduates early in understanding this using environmental tools they are conversant with we are losing the initiative in this process. Furthermore with the internationalisation of teaching and shared use of digital platforms the potential for involving transnational teaching and research collaboration is now truly global.

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# The Windsor Conferences in Context

**Susan Roaf**[1]

[1] Heriot Watt University, Scotland, UK. s.roaf@hw.ac.uk

**Abstract:** The context of the eleven Windsor Conferences on thermal comfort is set within two horizons. The first is that of the long history of the building regulations our civilisations have invented to control the living and working conditions of it citizens over time. Over centuries these have been gradually moulded by shifts in the demographic, social, economic and political structures of nations. Regulations were also changed rapidly by extreme events like plagues, fires, floods or extreme storms. The second, shorter, horizon is that of the unprecedented pace of change that has shaped all our lives since the first Windsor Conference in 1994. Important stepping stones that have occurred in the intervening years are outlined, and in light of the step changes experienced in those twenty-six years, key lessons are reviewed. It is then proposed that the current system of developing international and national standards are changed in order to be Fit for Purpose in the very different world we live in, in our heating world.

**Keywords:** Comfort, Adaptation, Resilience, Affordability, Climate Change

## 1. Comfort: The Long View

Why exactly are we interested in Thermal Comfort? Essentially, because the temperatures people occupy in their living and working lives can have an enormous effect on the physical and mental health, well-being and productivity of individuals, societies, economies and entire political systems. The extent to which societies experience, or avoid, thermal stress is an under-recognised attribute of their own, overall, success.

What role does politics play in shaping the thermal conditions experienced by populations? '*Civilisation'* is commonly measured, in part, by the level of control held by the centre, over its civilians, through the activities of its armed or active services, or through judicial controls like regulations. The COVID-19 pandemic has clearly shown us how national control responses to such a threat range widely from 'troops on the streets' to optimistic 'social conditioning' strategies, from a spectrum of regimes ranging from Totalitarian states to Liberal Democracies. The impacts of political choices made on the outcomes of COVID outbreaks in different countries are now being measured in mortalities on one hand, and money on the other. Political decisions are demonstrably arrived at using a balance, on which the health and well-being of a population weighs down one end, and the health of an economy, and the Status Quo of the financial and political interests that prop it up, the other. The cry of *Quis custodiet ipsos custodies* sounds out now, as it has done through the centuries: *Who guards the guardians*? Because the answer to that question ultimately determines which way that balance swings.

Since earliest records, we see building regulations being used to manage contemporaneous priorities in successive civilisations. The Babylonia *Code of Hammurabi*, carved into a stone stele in around 1754 BC[i], proclaimed that the law of 'an eye for an eye' -

'a life for a life' - would be applied to builders and their upper class clients, while a mere silver coin was required to be paid out for the death of a worker. The laws of Rome and Byzantium largely dealt with land ownership and its infringements, keeping the moneyed urban classes managed and controlled. The 6th century AD *Institutes of Justinian*[ii] still underpin much of modern Western property law today showing that still to be a priority.

For three millennia the European legal system evolved slowly, gaining pace as cities expanded rapidly with increasing trade and the industrial revolution, resulting in ever more crowded settlements and new work settings that fed the need for new regulations to protect the health of the working classes, and the wealth of those who benefitted from their labour.

An early example of urban regulation in Britain was the 12th century London *Assize of Building,* that dealt largely with disputes between neighbours, and remained little changed until the 15th century when Dick Whittington was Mayor. What changed it then?

The flea born, bacterial pandemic, Bubonic Plague, arrived in London in 1347 and continued to intermittently infect its citizens for the next three and a half centuries. It culminated in The Great Plague, an outbreak in 1665-66 that killed an estimated 100,000 Londoners within 18 months, almost a quarter of the population. New ordinances dealt with the risk of fire, and disease emanating from unsanitary timber framed, thatched roofed buildings with wattle and daub walls, ideal breeding grounds for vermin such as rats and mice on which the plague bearing fees could thrive. Citizens were ordered to build in cleaner brick with tiled roofs, but the temptation, as always, was to build cheaply as possible. It was not until after the Great Fire of London in 1666[iii] that the London building codes were fully revised, and then rigorously enforced to require solid Party Walls between all buildings[iv].

The Plague had petered out by the end of the 17th century, by which time it had killed around a third of Europe's population, and led to a heightened awareness of the high costs of uncleanliness. Tougher sanitary enforcement resulted across Europe. There grew a great fear of health effects of the *miasma*[v], the great stink, manifested in outbreaks of fetid air. Health boards and local government adopted rigorous control of street cleaning and the disposal of dead bodies, opened public baths and regulated water supply and maintenance.

By the early 1700s Scientists began to look in detail at the constituents of air, its toxicity, and the *effects of air on human bodies*[vi]. Over the next century, assisted by the growth of analytical medicine, work began on the thermo-regulatory systems of the body with a pioneering publication in 1814 by John Davey on his experiments on body heat[vii].

By the 19th century, novel and often expensive engineering approaches were being built by trade-rich nations to systematically improve the outdoor street environments and air within cities through better ventilation, drainage, street cleaning, clean water supply, and the burial of garbage[viii]. For those within buildings three approaches were applied to the effort to decrease indoor air pollution, and improve the thermal comfort of occupants.

The first was to improve open fire, boiler and stove efficiencies and create efficient water based heat circulations systems within buildings. The second was to develop more advanced internal natural ventilation systems to exclude and expel indoor air pollution, and manage the movement of heat and coolth around buildings. As commercial and government buildings grew ever larger, so did the need for, and sophistication of, these systems in the increasingly factory littered, and open-fire heated, cities of Europe and America[ix].

The third was to fast track the design of climatically better buildings to enhance indoor thermal comfort, notably across suburban America. Between 1850 and 1950, and often building on the design knowledge from their native lands, or the experiences garnered from three centuries of European colonisation of lands with unfamiliar climates, immigrants from

Europe rapidly evolved a new vernacular vocabulary of climatically, and locally, appropriate buildings forms and construction practices, across the sub-continent. Shading and ventilation strategies, and the thermal landscaping[x] of the rooms within a building, were key to the ability of occupants to make and keep themselves affordably cool, or warm, at different times of day, and different seasons of the year in the very different climates across America[xi].

The early 20th century also saw an explosion of research into the thermal conditions of building occupants in relation to their ventilation[xii], heating and cooling systems[xiii], and health in buildings[xiv]. Mill and factory workers were at high risk of ill-health and early death, and so became the focus of pioneering studies published in 1929[xv], 1926[xvi] and 1929[xvii] by bodies like the Industrial Research Boards on Fatigue and Health in London. The deaths of soldiers on military parade grounds[xviii], and workers in factories[xix] and deep mines[xx] sparked many studies examining the physiological limits of heat stress at work.

Children were always seen as a key cohort for investigation because of their physiology, immaturity and vulnerability[xxi]. The Elderly were not of particular interest to early comfort researchers, possibly because there were fewer of them, or perhaps because they had a short life expectancy then anyway. Hospital patients were another vulnerable group of particular interest, with research accelerated by the rapid development of new treatment approaches, for instance for Tuberculosis, and new approaches to hospital design[xxii].


*Figure 1. Cover of the Aerologist Magazine, December 1931 showing the Crossroads of comfort, with either / or choices of ways to go, giving no possibilities of having both AC and Natural Ventilation together in the sales pitch. The fight was on to either keep the windows open or closed. Closed won! (Source: the cover of Gail Cooper, 1998).*

## 2. Mechanical Comfort

By the middle of the 20th century America had careered, headlong, into the air-conditioning age. Dirty outside air could be shut out, filtered, heated or cooled and even humidified to provide healthy and comfortable indoor conditions. The technology was expensive, and was initially installed in high value buildings in the Roaring 1920s when people flocked to air-conditioned hotels, bars, cinemas, banks and shops for the 'Zest' delivered from machines and ducts, in places that encouraged people in America to spend, spend, spend[xxiii]. In offices and factories, sales of air-conditioning systems were fueled by promises of more *productivity,* and reduction of waste in produced products[xxiv]. It also had a less wholesome backstory, founded in the work of American 'climate determinists' on the early 20th century like Ellsworth Huntington who claimed that white men exposed to very hot conditions would inevitably be reduced to nothing more than backward natives[xxv], an incentive to spend, then, indeed.

By the 1950s the increasingly affluent middle classes were being sold the dream that their hard work should also bring them enhanced *Quality of Life* in their own air-conditioned (AC) homes. Some were even being persuaded they no longer needed opening windows, but could rely on AC for comfort 24/7/365[xxvi]. The multiple benefits of having climatically appropriate buildings went out the window. They were no longer needed. Comfort research in the last half of the 20th century was largely dominated by the drive to refine the language, and technologies that described and produced thermal comfort as a product deliverable as air from machines via ducts and vents. Increasingly architects were persuaded that windows had to be fixed shut to make the AC Dream, the American Dream, happen 'efficiently'.

Figure 2. The air-conditioned dream, and possibly an argument about the thermal settings of the AC or the cost of the bill for it? She, in her attractive dress, is obviously cold with folded arms, while he, in his wool suit, is more relaxed, unconcerned about conserving body heat (Source: www.gottman.com ).

Related research in the last half of the 20th Century was largely done in laboratories in the US and Europe. It was aimed at providing clear evidence for the best temperature settings for thermostats, adjusted to ensure that as few people as possible complained about their thermal environment, and that productivity levels remained high. The numbers needed by engineers supplying, fitting and servicing the machines needed to be simple enough to be understood and correctly applied. Much effort, and expensive lobbying, went into writing very simple temperatures into national and international standards. Where once AC managers were advised by ASHVE (later ASHRAE) to adapt the settings to the local climate and conditions over the year, as shown in Figure 3, the industry then moved to requiring and promoting fewer, less flexible settings. Thermostat temperatures were typically changed from summer to winter settings on fixed dates, regardless of the weather outdoors, and sometimes not changed at all. This use of the same comfort temperature all year, or season, relies on the proven ability of buildings occupants to adapt to the experienced indoor temperatures provided, largely by using clothing choices, where permitted. Such inflexible thermostat setting regimes not only often lead to discomfort, but also to energy wastage.

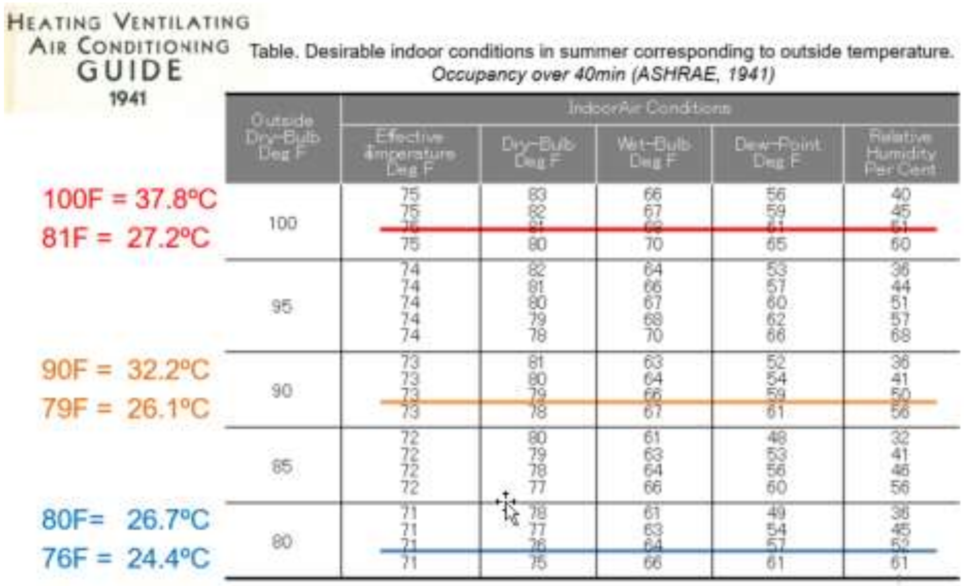
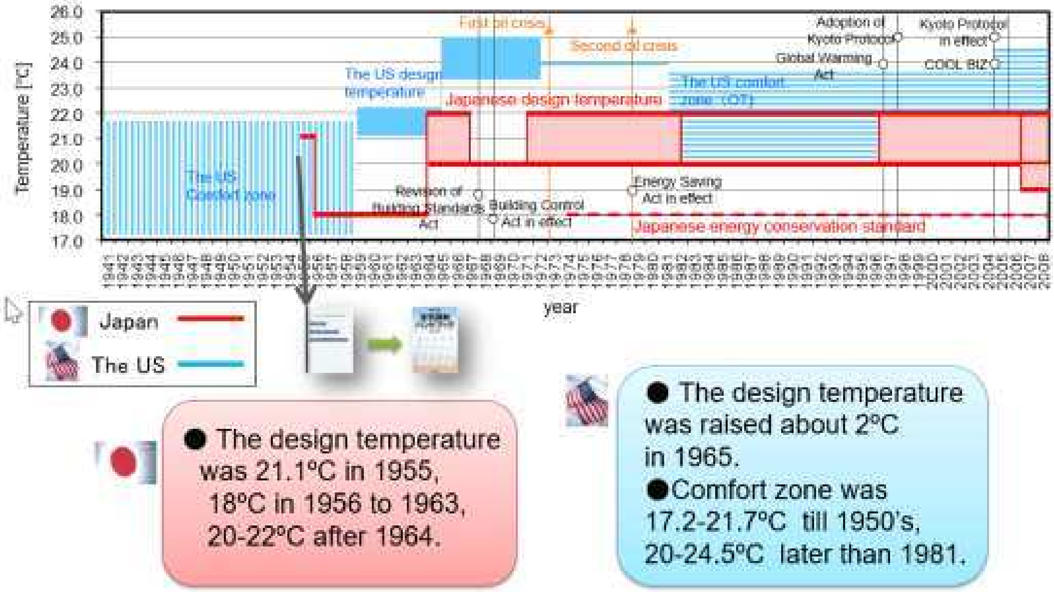



Table. Desirable indoor conditions in summer corresponding to outside temperature.
*Occupancy over 40min (ASHRAE, 1941)*

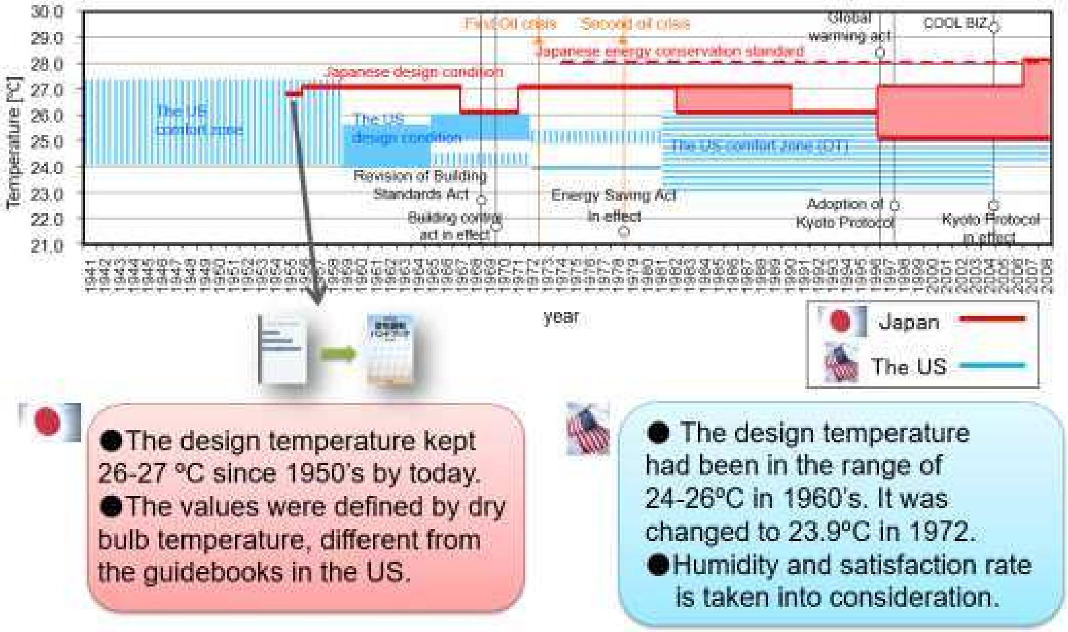
| Outside Dry-Bulb Deg F | Indoor Air Conditions | | | | |
|---|---|---|---|---|---|
| | Effective Temperature Deg F | Dry-Bulb Deg F | Wet-Bulb Deg F | Dew-Point Deg F | Relative Humidity Per Cent |
| 100 | 75 | 83 | 66 | 56 | 40 |
| | 75 | 82 | 67 | 59 | 45 |
| | ~~76~~ | ~~81~~ | ~~68~~ | ~~61~~ | ~~51~~ |
| | 75 | 80 | 70 | 65 | 60 |
| 95 | 74 | 82 | 64 | 53 | 36 |
| | 74 | 81 | 66 | 57 | 44 |
| | 74 | 80 | 67 | 60 | 51 |
| | 74 | 79 | 68 | 62 | 57 |
| | 74 | 78 | 70 | 66 | 68 |
| 90 | 73 | 81 | 63 | 52 | 36 |
| | 73 | 80 | 64 | 54 | 41 |
| | ~~73~~ | ~~79~~ | ~~66~~ | ~~59~~ | ~~50~~ |
| | 73 | 78 | 67 | 61 | 56 |
| 85 | 72 | 80 | 61 | 48 | 32 |
| | 72 | 79 | 63 | 53 | 41 |
| | 72 | 78 | 64 | 56 | 46 |
| | 72 | 77 | 66 | 60 | 56 |
| 80 | 71 | 78 | 61 | 49 | 36 |
| | 71 | 77 | 63 | 54 | 45 |
| | ~~71~~ | ~~76~~ | ~~64~~ | ~~57~~ | ~~52~~ |
| | 71 | 75 | 66 | 61 | 61 |

Figure 3. The 1941 American ASHVE Guide on desirable indoor summer temperatures. These were recommended to track the outdoor temperatures, to be manually adjusted at the building level to adapt to the weather conditions locally (Source: Professor Shinichi Tanabe[xxvii]).

Comfort standards were not immune from political pressures, and Figure 4 shows how standards over time have been amenable to alteration as a result of geo-political 'events'. The comfort zones in the US and japan are shown to have moved over time between 17$^0$C and 28$^0$C for acceptable winter and summer settings. Step changes in the standards notably happen suddenly as the result of major global shocks like an Oil Crisis, Climate Change imperatives and accidents like the Fukushima nuclear disaster in Japan. However, at any one time the actual acceptable temperature limits allowed by the standards can be as narrow as one or two degrees. Obviously, such narrow comfort zones are only achievable in summer in fully air-conditioned buildings, with the windows closed. Building design has been hugely affected by the premise that there is a single comfort temperature, or zone. This thinking validates the 'International Style' of architecture, in which the building is almost irrelevant and HVAC systems can be used from the steppes of Siberia, to the desert cities of the Gulf States, with the same comfort zones applied to the controls. Exemplified by hugely energy profligate, glass, steel and concrete structures[xxviii], such building types were born in the fossil fuel and nuclear ages, when people were promised that energy in the future would be 'too cheap to meter'. Energy from non-renewable sources now becomes more environmentally costly year on year, and it's devastating emissions are on a fair way to destroying the global climate. Things had to change, and the Windsor Conferences have informed that change.




a)




b)

*Figure 4. Comparison between the recommended a) Winter and b) Summer indoor temperatures in the Japanese (Red) and US (Blue) Standards (Source: Shinichi Tanabe, Tanabe Laboratory, WASEDA University, Japan[xxix]).*

By the early 1990s it was widely believed, and promoted, that Ole Fanger's steady-state heat balance equation method[xxx] involving Predicted Mean Votes (PMV) and Predicted Percent Dissatisfied (PPD) could be used without modification, anywhere in the world. This global scope was further reinforced by the inclusion of PMV/ PPD in various comfort standards, most notably ISO 7730 (1984) and ASHRAE 55-1992, lending the model an authority that HVAC engineers, and others responsible for delivering thermal comfort inside buildings, strongly needed in an increasingly litigious age[xxxi]. There is no doubt that the very limited range of temperatures allowed for indoors in such standards (c. $20^{0}$C-$26^{0}$C) can be relied upon to be relatively safely adapted to, even by populations to whom such temperatures may be alien, but the cost in heating up, or cooling down, whole buildings to the narrow comfort bands prescribed by the standards, was being increasingly questioned.

### 3. Adaptive Comfort

In parallel to the PMV and laboratory research, a small group of researchers based at the Building Research Establishment (BRE) outside London were quietly working on a different approach to comfort. Building on the pioneering thermal research done in outposts of the British Empire in the very different climates of Australia[xxxii], Singapore, Iraq and India, they were looking at the temperatures occupied by real people in the homes and offices they lived and worked in[xxxiii],[xxxiv]. The first international conference dedicated to Thermal Comfort was held at the BRE in 1972[xxxv] when Fergus Nicol and Michael Humphreys[xxxvi] showed for the first time their graph demonstrating the huge range of temperatures found to be acceptably comfortable by adapted populations in different climates, to a noticeably incredulous audience. They suggested that thermal comfort was part of a feed-back system which helped maintain the thermal balance of bodies with their occupied environment.

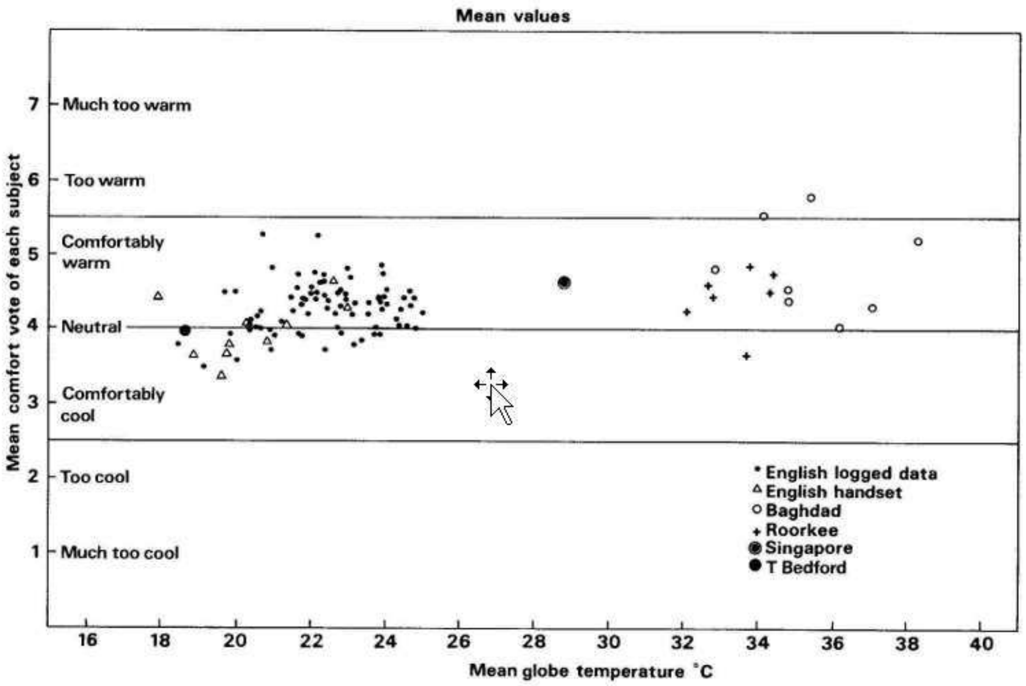



*Fig. 8. Monthly mean comfort votes including data from various sources*

Figure 5. This influential diagram showing the wide spread of comfort votes in surveys from different cultures and climates was shown at the 1972 conference at the BRE (Source: Nicol and Humphreys, 1973).

Humphreys went on in 1978 to propose the link between outdoor temperatures and indoor comfort[xxxvii] which has informed so much of the subsequent work on adaptive comfort and related standards. This conference really marked the beginning of what has become known as adaptive thermal comfort, and underpinned its founding premise that:

*If change occurs such as to produce discomfort, people react in ways which tend to restore their comfort.*

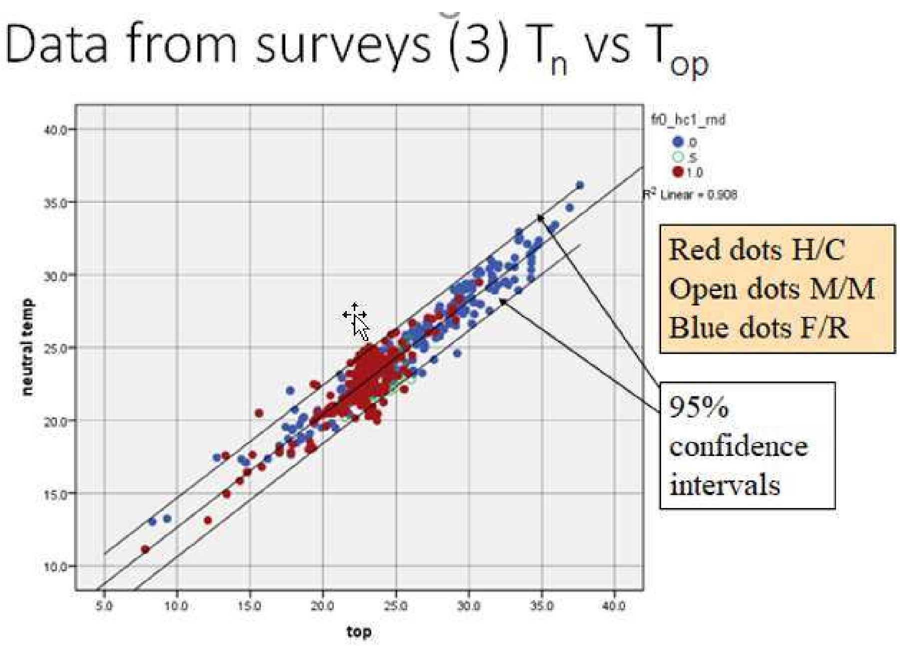



Figure 6. Neutral temperatures and the mean operative temperatures (top) for buildings operating in (blue) Natural Ventilation (FR) mode; Mixed Mode (open points) and (red) in Heating or Cooling modes. (Based on Humphreys et al., 2013[xxxviii]).

By the late 1970s both Michael Humphreys and Fergus Nicol, had retired from the field to pursue other careers. Meanwhile excellent work on adaptive comfort was carried forward by Andris Auliciems and Richard de Dear in Australia[xxxix] and Gail Brager and Ed Arens at the University of California, Berkeley.

Twenty-one years after the first conference, in June 1993 Nigel Oseland and Gary Raw hosted a second international conference at the BRE on 'Thermal comfort: past, present and future'[xl]. There proved to be a healthy interest in the subject, and a number of interesting papers were submitted and published in the proceedings of the event, with only a few on the subject of adaptive thermal comfort. A notable exception was the paper by Richard de Dear using ASHRAE-sponsored research to show how laboratory-based comfort models were unreliable in naturally ventilated buildings.

Climate Change was becoming a global concern, not least in the spotlight of the Rio Conference on the Environment in 1992. Greenhouse gas emissions became the focus of research and legislation, just as the fashion for ever more highly glazed and serviced buildings exploded, despite the fact they were clearly shown to emit the most greenhouse gases of any building type[xli]. London, for instance, had few air-conditioned, fixed window, buildings in 1980. By the 1990 nearly all new office blocks were highly serviced, with thin tight-skinned envelopes. Building regulations over the next three decades were to push new commercial buildings into using ever more highly serviced systems to meet ever narrower temperatures requirements, driving up emissions from them[xlii], and ensuring that national greenhouse gas emission targets could never be met, as has now been proved to be the case[xliii].

In 1992 the Thermal Comfort Unit at Oxford Brookes University was set up by Fergus Nicol, Susan Roaf and Michael Humphreys, with a view to widening the horizons of comfort research by promoting the adaptive approach, and re-enabling the natural ventilation of buildings. It was against this backdrop that the 1st Windsor Conference was held, from which ten subsequent conferences evolved, each addressing the evolving challenges of their times. The Proceedings for the conferences can be accessed online from: www.windsorconference.com

Figure 7. Cumberland Lodge

## 4. Comfort: The Windsor View

The 1st Windsor Conference on *Standards for thermal comfort* was held at Cumberland Lodge in August 1994, over three days and set in a luxurious country house, donated by the Late Queen Mother to the nation as a venue for 'change making' events after the 2nd World War. This historic location and ethos of the Lodge, the wonderful food and close social proximity of delegates, have all contributed to the forging of ideas and forming of friendships that have fostered and disseminated influential new approaches to the growing challenges of providing comfort in the 21st Century. Notable at this first meeting was the diversity of cultures and climates represented. There were architects, engineers and researchers present approaching the subject from their many different angles. It was a forum where regional voices emerged clearly, telling their own very different comfort stories, recorded in their fieldwork. It was really exciting first hearing of people in Bangkok being perfectly comfortable in temperatures of $35^0$C, and to see the incoming tide of new datasets that would later be included in the 1998 ASHRAE database of field studies. Research reflecting work done in laboratories still prevailed, but a door opened at Windsor into a much richer range of discussions on comfort. Key papers, and discussions, were captured in a resulting book on *Comfort Standards* published in 1995[xliv].

Seven years later in 2001 the 2nd Windsor conference on *Thermal comfort standards for the twenty-first century* was held. Set against the optimism of the new century, and still growing global economies the second conference attracted delegates from all branches of the thermal comfort world including Ole Fanger and Bjarne Olesen from the Danish Technical University. Selected papers from the conference were developed as a special issue of *Energy and Buildings* (Volume 34 (6) 2002), jointly edited by Fergus Nicol and Ken Parsons of Loughborough University. One highlight of the conference was the presentation by Gail Brager and Richard de Dear on the meta-analysis of data on which was based the new adaptive standard in ASHRAE Standard 55-2004. This marked the historic loosening of the growing hold of prescriptive temperature standards on designers, enabling them to open the windows of their buildings again, while still adhering to regulated comfort limits.

In 2004 the world was still reeling from the 9/11 triggered war in the Middle East, and the catastrophic impacts of 2003 European heatwave, in which buildings had failed to keep their occupants thermally safe and over 52,000 excess deaths were recorded[xlv]. The focus of the 3rd Windsor Conference in 2004 was on the Post Occupancy Evaluation (POE) of Buildings, the systematic evaluation performed in terms of energy use and occupant satisfaction.

A special Issue of *Building Research and Information* (BRI) on 'Building Performance Evaluation' resulted (Volume 33(4), 2005), edited by Nicol and Roaf. It included important papers by Bill Bordass and Adrian Leaman and many other POE stars including Wolfgang Preiser, Jacqueline Vischer and George Baird who have all written influential books on the subject. Fun was provided in a Saturday evening POE Challenge set by the delegates from the US Society of Building Science Educators (www.sbse/org). This conference established a clearer, practical, link between building design, facilities management and comfort research.

In 2004 the Network of Comfort and Energy Use in Buildings was also started at the LEARN Unit at London Metropolitan University (NCEUB – www.nceub.org ), originally with around 300 members, about one third of them from outside the UK and about two thirds of them from an academic background. Membership is now over 700. The site continues to promote ideas, opportunities and events on the environmental performance of buildings.

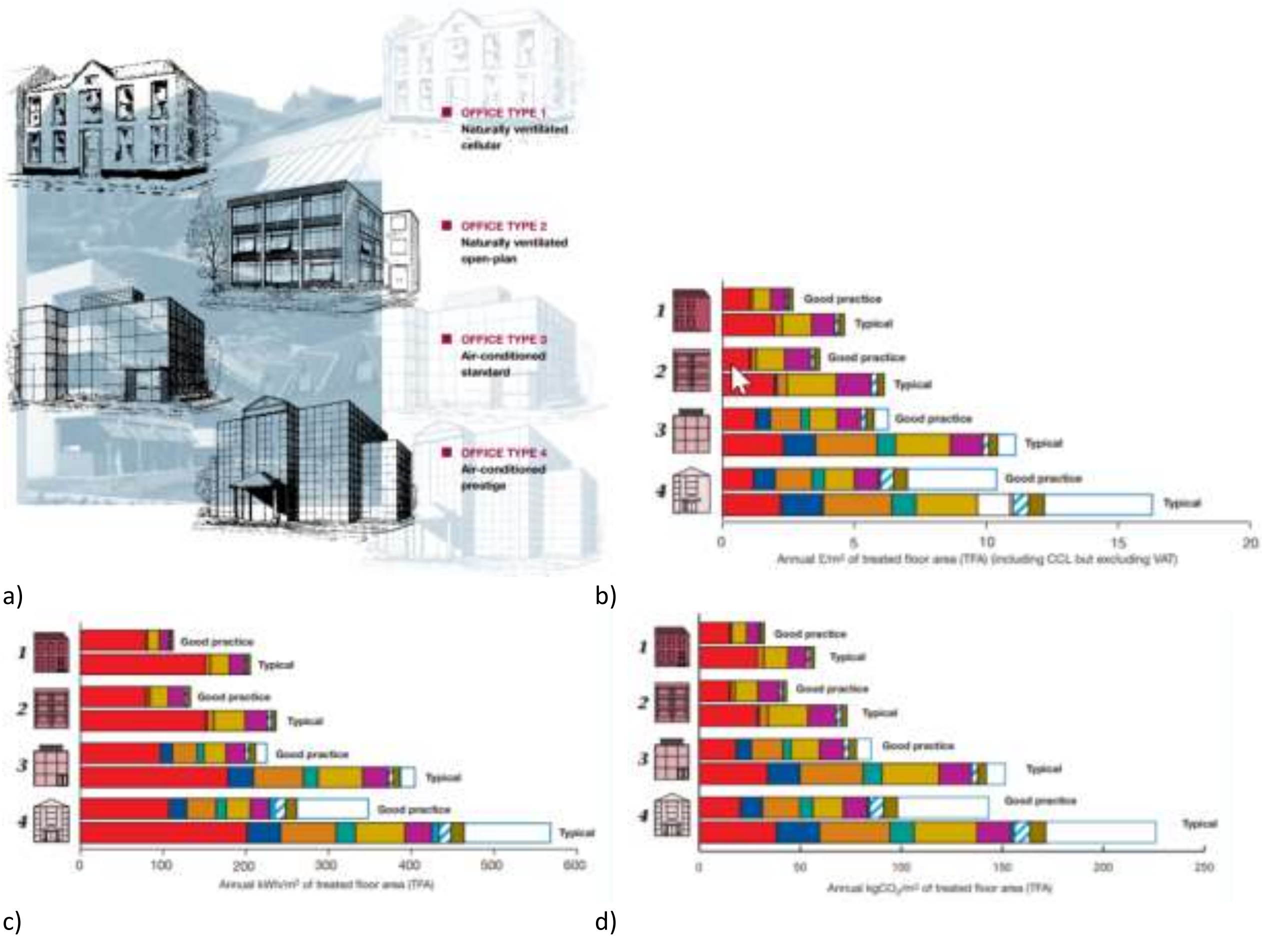



Figure 8. For four different office types from naturally ventilated (NV) cellular; NV open plan; Air-conditioned (AC) standard and AC prestige showing b) energy costs; c) energy use and carbon dioxide emissions in and from each, in the 1992 ECON 19 document of the UK best Practice Programme written by Bill Bordass[xlvi]

From extreme heatwaves to super-storms, Hurricane Katrina in 2005 awoke concerns about the scale and pace of climate change, and the role of buildings in driving global emission was increasingly under scrutiny. The 4th Windsor Conference in 2006 on *Comfort and energy use in buildings* looked at the energy implications of comfort paradigms, and was attended by 66 delegates from 22 countries. A special issue of *Energy and Buildings* with the same title and edited by Fergus Nicol, was published (Volume 39, no 7, July 2007), based on selected papers from the conference.

Figure 9. Delegates from the 5th Windsor Conference in 2008

In 2008 the Global Economic Crisis was peaking, and the focus of the 5th Windsor Conference was on *air-conditioning and the low carbon challenge.* Inherent in the discussions was the growing issue of how to provide affordable comfort to the many, as even the US middle classes began to disappear in the wake of their housing crisis[xlvii]. The fastest, and most effective way to lower emissions is, of course, to open the windows in an office or home condition or ventilate it [xlviii]. How is that to happen in the US now when some 80% of all homes and nearly 100% of offices have air-conditioning, and new buildings are made largely of chipboard, steel, timber and glass? The conference, part funded by the EU Common Sense project had 77 delegates. A special issue of *Building Research and Information* on 'Cooling in a low carbon world', was published, edited by Fergus Nicol (Volume 37 (4) 2009). The growing contributions of the Chinese scientists was much appreciated, as they presented their own national, evolving, thermal comfort standards that sensibly encourage natural ventilation.

By 2010 the wider impacts of the global recession concentrated thinking for the 6th Conference in 2010 on *Adapting to Change – New Thinking on Comfort*. Held in April, it was attended by 88 delegates. The new thinking began with the opening evening keynotes when Ed Arens from the University of California spoke on 'California Dreaming – Future directions for Thermal Comfort' and Richard de Dear from the University of Sydney on 'Thermal Comfort in Natural Ventilation – A Neurophysiological Hypothesis'.

Two major emerging themes were thus sewn into the minds of the audience: the common sense and ultra-low energy benefits of using local *personal environmental technologies* like local fans of heaters, to heat and cool people where appropriate, rather than resorting to conditioning whole buildings to keep a few people happy. De Dear fascinated on subject of Allesthesia, the sensual driver for rewarding the body for returning to homeostasis, thermally safe conditions. Both talks set the tone for the following sessions, and were complemented in the other keynote by Michael Humphreys on the relationship between indoor and outdoor temperatures. A special issue of *Building Research and Information* called 'Adaptive Comfort' was published (Volume 39 (2) 2011).

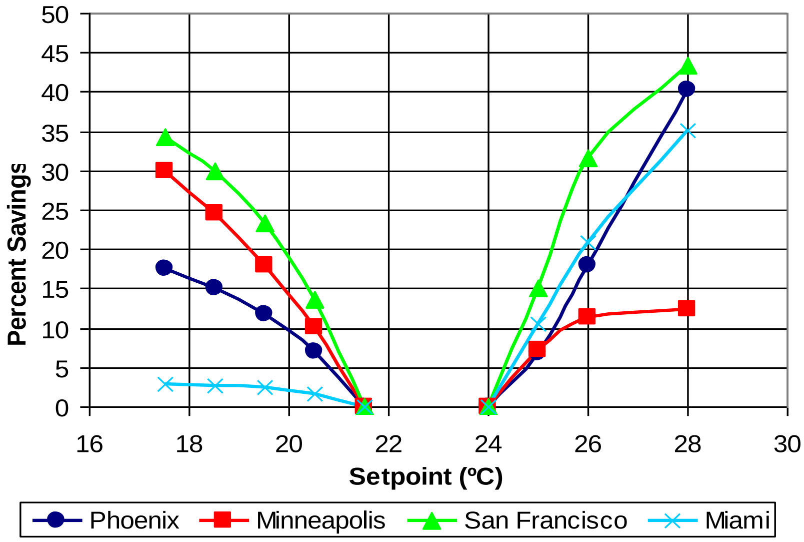



Figure 10. An influential diagram presented by Arens showed the possibility of huge energy, and hence cost savings by widening the heating and cooling set points in four different US cities in different climates. Temperatures between 18$^0$C and 28$^0$C are widely recognised as being suitable for natural ventilation of spaces. (Source: T. Hoyt et al. 2009[xlix]).

The Fukushima Daiichi nuclear disaster on the 11$^{th}$ March 2011 was the wake-up call for genuine *Resilient Comfort* thinking. The 7$^{th}$ Windsor Conference in April 2012 aptly flagged the importance of *The changing context of comfort in an unpredictable world.* Shinichi Tanabe presented a paper showing how Japan had immediately responded to the threat to the whole Japanese energy system by limiting the use of AC in government buildings to indoor temperatures over 28$^0$C, leaving people to cope using changes in behaviours, clothing, working practices etc. Having more than 100 delegates for the first time meant a change from the practice of every paper being heard by all delegates. There were four workshops on the hot topics of *Standards for the Indoor Environment*; *Designing Comfortable Buildings for the Future*; *Personal Control in Office Buildings* and *How to Make Low energy buildings that Really Work*. Special issues of *Architectural Science Review* on 'The wicked problem of designing for comfort in a rapidly changing world' (Volume 56 (1)) and *Building Research and Information* on 'Adaptive comfort' were published (Volume 41 (3) 2013).

Figure 11. Delegates at the 7$^{th}$ Conference in 2012

Three strong themes that stood out in 2014 at the 8th Windsor Conference on *Counting the Cost of Comfort in a Changing World:* the need to affordably address the problem of overheating in buildings; the need to look at affordably protecting vulnerable populations like children and the sick and elderly and a welcome revival of papers on the physiology of comfort. 120 people attended the 8 sessions and 9 workshops on subjects including field work from cold and hot climates, and the ongoing debate on comfort standards, particularly in relation to expectations. A highlight paper was on 'thermal mavericks' in Melbourne and Darwin in Australia, whose environmental zeal was reflected in the greatly expanded comfort zones they occupied, reinforcing the importance of attitude in comfort experiences and costs.

The use and management of local adaptive opportunities was a popular theme, including when and how people opened windows and used fans. Another interesting development was the findings by Pallubinski and van Marken Lichtenbelt that thermal change can be beneficial in our everyday lives, and that thermal stasis may be not only expensive to achieve, but can run counter to the best health interests of occupants. An unvarying environment may not just be psychologically boring, but may also reduce the ability of individuals to physiologically cope with environmental change. A range of papers developed from those presented have appeared in subsequent issues of *Building Research Information* (Vol 43.3) and *Architectural Science Review* (Vol 58.1) and an article about the conference appeared in REHVA European HVAC Journal for June 2014 (Vol 51.4).

The 9th Windsor Conference in 2016 was about *Making Comfort Relevant*. Thermal comfort issues were increasingly being recognised as playing crucial roles in keeping building occupants safe, heathy, productive but the challenge posed at this conference was how to connect the work of comfort researchers to tangible improvements in the real world. Traditionally this had been done via the medium of standards and regulations, but these were increasingly seen as detached from the lives, and comfort opportunities of most ordinary people.

Elizabeth Shove from Lancaster University spoke on the *Concept of Comfort*, questioning whether the Comfort Standards that are international espoused today are still fit for purpose in a changing world. A growing number of researchers from industry attended in in the 130 delegates who took part. 90 papers were presented in plenary sessions and 9 themed workshops. Bjarne Olesen and Ken Parsons opened the deliberations with a talk on the history of International Comfort Standards.

The breadth of the conference topics can be judged from some of the Sessions titles: Comfort in Hotter Climates; Smart Comfort; Behaviour and Aging as well as workshops called: Putting People in Building Comfort Models; the Role of Clothing, Domestic Comfort and Teaching and Tools and Statistics for Comfort. There was also welcome news of new comfort laboratories opening about the world and a Comfort Quiz on Saturday night all about Clos!

Two special journal issues were developed from some papers from the conference: *Building Research and Information* (Vol 45.7 – Rethinking Thermal Comfort) and *Architectural Science Review* (Vol 60.3 – Running Buildings on Natural Energy: Design Thinking for a Different Future).

Figure 12. Delegates at the 2018 Windsor Conference (Source: Ashak Nathwani)

Questions about the roles and relevance of comfort science raised at the 9th conference were again discussed at the 10th conference on *Rethinking Comfort*. Rising to the huge challenges posed by changing economies, societies, buildings, technologies and the heating climate this conference simply asked delegates to think hard about where comfort research had come from, and where it should be aimed at now? In 2018 the growing interest in comfort from a range of new quarters became apparent. A 125 delegates attend and the papers into seven sessions and nine workshops to provide an opportunity to discuss topics in greater depth, and to explore detailed issues of methodology, experimental design, semantics, real world constraints, impacts and new thinking and approaches.

A talk by Kris de Decker on *Low Tech Comfort: Heating People not Buildings* looked at traditional methods of providing comfort in different countries. He usefully spoke to the new interest in lower-tech means of heating and cooling buildings from radiant systems to evaporative misting systems for hot cities. Roberto Lambert's talk on his own *Economic social and cultural experiences of thermal comfort from field studies in Brazil,* shed light on a country where many are poor and low cost conditioning strategies, like simple natural ventilation strategies, and appropriate dress codes, are included as valid comfort components within the national standards. He showed that comfort standards can included provision for highly serviced building as well as promoting a low-tech range of adaptive comfort opportunities to be operationalised at the building design stage.

Sessions and workshops dealt with a range of topics from new approaches to heating and cooling people; personal control; perceptions and adaptive behaviours; usage and interpretation of comfort scales, and the evolving field of personal comfort models. Survey results were presented from hot and cold climates; different building types including schools, offices and homes and the influence of diversity factors in the experience of comfort. Studies on comfort sleep, IEQ, energy, health and physiology showing the large expansion in the scope of the subjects covered in the conference over the last 22 years.

A number of journal articles based on the papers have been published and the papers presented all appear in full, in the Windsor 2018 Conference Proceedings (on line at: www.windsorconference.com) and the deliberations of the Workshop attendees are captured and published on line in the Windsor 2018 Legacy Document.

An exciting development in 2018 was the rapid organising by some of the younger Middle East-based delegates of a satellite conference on Comfort at the Extremes. Held in Dubai on the 10th to 11th April 2019, the Proceedings and Legacy Document are available on www.comfortattheextremes.com. Speakers covered the health and mortality implications of extreme temperatures, and in particular building and city level design solutions to them.

The Legacy document on the CATE19 website showed the huge challenges for humanity in trying to keep people thermally safe in a heating world. Papers covered studies of people dying of heatstroke on city streets, on excess deaths in Australian homes during heatwaves and in the refugee camps of Jordan and Bangladesh. It is a very different world out there in the field of Extreme Comfort and importantly CATE 21 will be held in Oman in October 2021. How fitting that the work if the IEA EBC Annex 80 on Resilient Cooling also met then in Dubai, ably led by Bjarne Olesen and Peter Holzer (http://annex80.iea-ebc.org/).

## 5. The Windsor Stepping Stones

The papers outlined in the Introduction to these Proceedings of the 11th Windsor Conference, can be usefully looked at in the light of two very different time horizons:

*The first* is that of the long history of the building regulations our civilisations have invented to control the living and working conditions of their citizens over time. Over centuries these have been gradually moulded by shifts in the demographic, social, economic and political structures of nations. Much more sudden changes in regulations have been triggered by unpredicted extreme events like plagues fires, flood or extreme storms.

*The second* horizon is that of the unprecedented pace of global change that has shaped all of our lives since the first Windsor Conference in 1994. The stepping stones from there to here are clear in retrospect, although were not always recognised as significant at the time.

**Stepping Stone 1:** The Rio Conference of 1992 reset development priorities to elevate *Climate Change Mitigation* to being of primary legislative importance, due to the global need to urgently lower energy use in, and greenhouse gas emissions from, buildings.

**Stepping Stone 2**: The 2003 European heatwave, the first extreme climate disaster of the many that have followed, made us understand the fundamental importance of *Adapting our Buildings and Cities* to withstand the escalating force of climate related events.

**Stepping Stone 3:** The Global Economic Crisis showed how fragile all our economies are, even the apparently strongest of them. The phenomenon of the 'disappearing middle classes' of our societies, as inequality grows, will inevitably mean that the *Affordability* of comfort will become a primary concern for the 95% of the world's populations with falling incomes.

**Stepping Stone 3:** The Fukushima nuclear disaster, triggering national power outages and shortages of a catastrophic scale, demonstrated that the 20th energy supply paradigms are extremely brittle, fostering the need to design much more *Resilient* buildings that can keep people safe and healthy, even when power systems fail.

**Stepping Stone 4:** The global COVID pandemic has highlighted for us that fixed window buildings with shared ductwork systems can be not only unhealthy, but can also spread infections. Only with extremely expensive mechanical systems with high, and for the many unaffordable, installation and running costs might vulnerable occupants be kept safe during disease outbreaks in them. Opening windows must now be seen as a leading design option for enabling people to *Safely Survive* during pandemics in the buildings they live and work in.

**Stepping Stone 5:** All of the above have highlighted the growing *inequalities* in the world today and the plights of the poor, from those who sleep on the streets, or in the refugee camps, to the old dying in care homes, or even friends over the road who have lost their jobs or businesses in the COVID crisis. The enormous *Diversity* that exists in cultures, climates, societies, economies and political systems must now be recognised, and addressed in our comfort standards. We can no longer treat humanity as a monolithic bloc to whom one comfort single standard applies, even if it promotes the economic interests of a major global industry. The weights on the balance have now shifted. That time is over.

## 6. Comfort: The Future

Fergus Nicol, Michael Humphreys and Susan Roaf began the Windsor Conferences with two rather simple aims: to widen the horizons of comfort research by promoting the adaptive approach, and to enable all normal buildings to be naturally ventilated again.

Over eleven conferences we have achieved so much more than we dreamed possible. The hugely nuanced range of Windsor learnings have left us all much wiser, and better prepared to help our societies, and our shared civilisation, to affordably survive in the very different future we all face. Things will have to change radically to do this.

We must raise our ambitions far beyond the 20th Century 'Business-as-Usual' focus on comfort as something that is a thermal product from machines, via ducts, sold by the kWh. Issues of what actually constitutes comfort, discomfort and thermal stress for the diverse populations of our planet will increasingly lie at the heart the health and well-being challenges faced by all our societies in a heating world. Ways forward to new thinking on indoor environments in buildings in the future will be well informed by what we have learnt at the eleven Windsor Conferences about:

**People:**

- *There is no such thing as a 'comfort temperature'*. Everybody is different, the old, the young, those with different cultures, climates, physiognomies and daily lifestyles. People habituate to the thermal environments they occupy over a day and year. Children in one school adapt to different temperatures than those in an adjacent school of a different construction. People in an AC office will have different neutral temperatures to those in a naturally ventilated one next door. We adapt.
- *People adapt to a wide range of temperatures.* Nicol shows in his paper above that adapted people around the world find temperatures from $10^0$C-$35^0$C acceptable in their own homes. We do not, and cannot, know better than they do about what they feel. We are limited in our understanding but our own experiences.
- *Thermal delight* is undervalued by lazy modern designers. The comfort ambitions of architects have almost universally been reduced to a bare minimum, as they blindly accept the engineer's definitions of comfort, validated by crude modelling tools and black box rating systems. They have been thus led to depriving people of a whole gamut of sensual delights that can arise from the interactions between sun, wind, fabric warmth and coolth, that create rich thermal pleasures in different seasons.
- *Behaviours and expectations of building occupants* are key to the management and improvement of indoor comfort, particularly where numbers of people are involved.
- *The Physiology of comfort* is crucial in explaining how temperatures affects the health and well-being of people.

**Buildings:**

- *Use too much energy.* The shift over the past half century toward highly serviced, over glazed and fixed window buildings means they both use too much energy, and they consequently emit too many greenhouse gases. Inherent in most building regulations is the *Energy Efficiency Fallacy*. To hide the truth of unacceptable levels of energy use in buildings, they are cleverly classified for their consumption within ‘classes’. An efficient Prestige AC building is judged only against others of its type. Absolute performance of energy use in, and emissions from, every building should be put on a common scale eg. kWh/m$^2$/a, and annual energy use reported and published.

- *Overheating.* Extremes of temperature are now being experienced in many modern buildings, even in colder climates, due to persistent and costly flaws in modern design practices that are promoted with crude simulation packages and licenced by current comfort standards and rating systems. Catastrophic consequences may result during power outages, population Lockdowns or when people can no longer pay for comfort.
- *Next generation buildings will be different*. The idea that it is sensible, or acceptable, to mechanical condition buildings all year, 24/7/365, cannot continue. Windsor has demonstrated the economic, and comfort sense of designing buildings that can be run for as much of the day, or year, as possible, heating and cooling people in buildings, not just spaces in them, using energy storage, radiant and personal technologies etc.
- *The New vernacular.* The form, fabric and construction of buildings themselves must be culturally, climatically, and economically appropriate to their local context so buildings can be part of successful climate solutions, not just major climate problem.

**Comfort Standards:**

- *International Standards should be re-thought.* The idea that the same temperature that is applied to an office, or home, in North America is appropriate in Sri Lanka or Bangladesh is simply wrong. Cynically, this idea serves only the international air-conditioning industry who largely control the process of writing standards, at huge such a huge cost to humanity, particularly in poorer, warmer climates.
- *Local city level or national standards should replace them.* The energy profligacy of having the same European indoor temperature standard for northern Sweden as for Southern Spain is no longer affordable financially, or in greenhouse gas emissions.
- *Opening windows are essential*. All buildings should have at least some opening windows, and be habitable in natural ventilation mode, at the very least during periods of overheating, during power outages and during pandemics when recirculated air from mechanical systems can spread infection between rooms.

Civilisation is about control, and who has it. For the last half century, we have largely ceded control of national and international comfort standards to those who are either paid by the mechanical conditioning industry to research, or write the comfort standards, or those who are paid for their work according to how much servicing equipment they include in buildings. It is now up to the politicians to put together a new cohort of standard makers, who can reshape fairer comfort standards and regulations that benefit all, not least by helping to avoid climate catastrophe. These may be physiologists, doctors, behavioural psychologists, technologists, and those who will design the *New Normal* for the construction industry.

In 2020 control is shifting: to the angry young people from Extinction Rebellion who want save the global climate and their futures in it; to the people who are helpless in COVID lockdown as their spaces overheat; to those losing faith in politicians; to the people desperate because they have lost their jobs and can no longer keep their families adequately fed, let alone pay for comfort; to the religious leaders who can call people en masse to prayer and to action. The balance of history is shifting and the weights on the scale are moving fast – people v. economy – profit v. survival. Change is coming.

The last twenty-six years of comfort research presented at the Windsor conferences has laid solid foundations from which to build such change. Thank you all for your contributions.

Figure 13. Looking through the great window at Cumberland Lodge, to the benches that we should have sat in April 2020 for our team photo, the croquet lawn we should have played on, out to Windsor, and the world beyond (Source: Sue Roaf).

**Acknowledgements:**
For their help with this text, and so much more, I would like to thank my two, dear, fellow Comforteers, Fergus Nicol and Michael Humphreys, on whose giant shoulders it has been an honour, privilege and pleasure to stand for these last thirty years.

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Figure 14. The future: Delegates at the 2019 Comfort at the Extremes Conference in Dubai share a meal in a traditional Arab house in Bastakiyah, Dubai (www.comfortattheextremes.com)

# WINDSOR 2020

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