PROCEEDINGS OF THE 1ST INTERNATIONAL CONFERENCE ON COMFORT AT THE EXTREMES: ENERGY, ECONOMY AND CLIMATE

Edited by Susan Roaf and Will Finlayson

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INTRODUCTION TO THE PROCEEDINGS

In the face of ever more extreme climates the world is calling urgently for answers to questions of how people can stay not only comfortable , but also safe and healthy in our warming world. Current and future weather trends and events are, and increasingly will, threaten the survival of permanent and temporary populations not only in buildings but in the infrastructures of settlements and cities, and in our own lifestyles.

For the first time ever, we are gathering leading international figures from many fields to discuss crucial questions and ways forward on how to best provide thermal *Comfort at the Extremes* in the complex political and economic environments we occupy. Building on global networks of Comfort researchers (see: www.windsorconference.com and www.nceub.org) we are reaching out to researchers, governments, organisations and industries affected by extreme temperatures, both hot and cold, to look in detail at the nature and scale of the challenge of keeping people thermally safe, possible solutions and future opportunities. We will also explore the means to hand to build the more resilient buildings, operations and infra-structures we need to be able to withstand growing extremes. The greatest architectural challenge of our age is to change the way we design to cope with the evolving 'New Climate and Comfort Abnormal' for buildings and cities. How can we deal with economic and energy impacts of a changing climate and their technical, social and environmental manifestations? At CATE 19 both the challenges faced and potential radical solutions will be described and discussed in light of the growing realisation that we now need new approaches to the provision of *Resilient Cooling and Heating.*

The following papers from CATE 19 reflect the leading edge nature of the design, planning, technological, social and infra-structural solutions presented at the Conference. We hope they are useful to you.

SusanRoaf

Evangelia Topriska

Fergus Nicol

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The Epidemiology of Health and Mortality at Extremes

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Abstract: Epidemiological studies around the world have shown that heat exposure is an important public health issue, with heatwaves being responsible for more deaths than any other natural hazard. Historically, severe heatwaves in Europe, the United States, Russia and elsewhere, have been associated with reports of marked increases in mortality. Failure to maintain a level of thermal comfort can jeopardise the health of vulnerable members of the community, particularly the elderly, infirm, socially isolated or the very young.

Even in Australia, a country well known for its hot summer days, there is often an associated toll on human health in extreme heat, despite high rates of air conditioning. In winter, cold to very cold temperatures can also be experienced; however, much less attention is paid to maintaining warm living conditions in Australian homes. This, combined with badly designed houses, may be contributing factors to the number of deaths being higher in winter than in summer.

The aim of this paper is to discuss the temperature-mortality association, drawing on epidemiological evidence from a number of countries including Australia. The influence of the built environment on the association will be highlighted, together with suggestions for health and comfort at extremes in the future.

Keywords: Temperature, mortality, extreme heat, cold, built environment

1. Introduction

As well as influencing the thermal comfort of individuals, environmental temperature can also have considerable impacts on health and wellbeing, and in some cases can lead to death. An extensive body of epidemiological literature has shown a J-, V- or U-shaped relationship between temperature and mortality, with the number of deaths being lowest at moderate temperatures and increasing at high or low temperatures (Braga et al, 2001, Basu et al, 2002, Curriero et al, 2002, McMichael et al, 2008, Barnett et al, 2012). The overall trend is consistent in countries in the Northern and Southern hemispheres with hot and cold temperatures being associated with increased deaths. The magnitude of the effects, however, vary according to location, climate characteristics and population specific factors such as acclimatisation, adaptation and susceptibility (Braga et al, 2001, McMichael et al, 2008, Gasparrini et al, 2015).

Morbidity as well as mortality can be affected, as studies have shown during hot temperatures ambulance callouts increase (Nitschke et al, 2007, Turner et al, 2012, Zhan et al, 2018) as do cause–specific hospital admissions and emergency department visits (Knowlton et al, 2009, Zhang et al, 2013). Similar effects are seen during cold temperatures (Jegasothy et al, 2017).

Those with impaired responsiveness to environmental conditions due to advancing age or medical conditions, as well as the very young, the isolated and those with greater exposure to the elements for occupational or socioeconomic reasons, can be at increased risk of death associated with temperature extremes (Curriero et al, 2002, Schwartz 2005, Luber et al, 2008, Gasparrini et al, 2015).

2. Why does temperature affect health?

Adverse effects of temperature on health can be direct or indirect. The direct impacts result from a failure of the body to maintain thermal homeostasis. The core body temperature of humans normally varies only slightly from 37°C (Donaldson et al, 2003) due to physiological thermoregulation, a process of internal temperature control. Cutaneous thermoreceptors at the surface of the skin detect hot or cold external temperatures, triggering messages sent via the central nervous system to the hypothalamus in the brain (Vassallo et al, 1989, Romanovsky 2018). Mechanisms then result in heat loss or heat gain, in response to hot or cold environments, respectively. In extreme temperatures or for a number of vulnerability factors including age, illness (particularly cardiovascular disease), or the influence or medications, the thermoregulatory system can be overwhelmed or responses impaired, resulting in hyperthermia in hot conditions (Vassallo et al, 1989, Donaldson et al, 2003) or hypothermia in cold conditions (Bright et al, 2014), both of which can be fatal.

A direct cause of death attributable to heat is heatstroke, the most serious of the heat illnesses, where the body temperature is elevated (e.g. 40.6°C or higher) with associated central nervous system dysfunction (McGeehin et al, 2001, Herbst et al, 2014, Leon et al, 2015). Heatstroke can result in an overheating of body tissues and multi-organ dysfunction with fatal consequences (Donaldson et al, 2003, Leon et al, 2015). It is a relatively uncommon form of heat-related death however, as often excess deaths during hot weather are due to the cardiovascular consequences of heat stress rather than hyperthermia (Donaldson et al, 2003).

On the other hand, cold exposure can lead to hypothermia, defined as a decrease in core body temperature below 35°C (Bright et al, 2014, Romanovsky 2018) due to the loss of body heat not being compensated by metabolic heat production. Hypothermia can progress to a life threatening state with a high mortality rate (Knobel et al, 2001) at core body temperatures around 26-29°C (Bright et al, 2014.)

More commonly, high and low temperatures can be linked with an increased risk of cardiovascular, respiratory, and other conditions (Gasparrini et al, 2015). Studies have shown that high or low temperatures place a strain on the cardiovascular and respiratory systems (Barnett et al, 2012) and therefore related medical conditions can be triggered or exacerbated by exposure (Bennett et al, 2014). Cardiovascular mortality accounts for the greatest burden (Gasparrini et al, 2015) and individuals will cardiovascular diseases such as chronic heart disease can be at increased risk of death during heat waves (Zhang et al, 2017). This is due to thermoregulation placing a strain on the heart with changes in, for example, heart rate and blood viscosity. Heat can also increase the risk of death due to respiratory, genitourinary, and nervous system diseases (Shaposhnikov et al, 2014).

Cold weather can also contribute to deaths from cardiovascular and respiratory diseases (Barnett et al, 2012). Cold exposure contributes to cardiovascular stress by increasing cardiac workload (Barnett et al, 2005), affecting blood pressure and viscosity, plasma fibrinogen and vasoconstriction. Cold can also induce bronchoconstriction and increase the risk of respiratory infections (Gasparrini et al, 2015). The seasonality of diseases such as influenza in the winter (Bennett et al, 2014) and vector-borne diseases in warmer weather (Semenza et al, 2018) can also be indirect impacts of temperature on health.

Additionally, human behaviour can be influenced by temperature, and result in adverse health effects. Outdoor workers can incur injuries at a greater rate in non-optimal temperatures (Varghese et al, 2018), possibly due to impaired concentration and the use of very hot or cold tools. Population health studies show that motor vehicle crashes can occur in association with high ambient temperatures and heat waves[1] (Basagana et al, 2015), and violent crime, aggression, assaults, and suicide can also increase in hot conditions (Anderson et al, 1997, McGeehin et al, 2001, Page et al, 2007). On the other hand, injuries such as slips and falls tend to occur more often in cold and icy conditions (Gao et al, 2004). Finally, other weather-related hazards such as storms, blizzards, air pollution and bushfires can be associated with low or high temperature extremes and have indirect impacts on human health. Examples are cited in the sections to follow.

2.1 Heat–related deaths

Serious health effects of heat on population health can occur with exposure to prolonged periods of extremely high temperatures to which populations are not generally accustomed (McGeehin et al, 2001). The intensity and duration of the heat are therefore major determinants in the temperature-mortality association (Bouchama 2004). Here, we briefly outline some of the major heat events of recent times that have resulted in high numbers of excess heat-related deaths.

Some of the first epidemiological studies in recent decades on the heat-mortality association were conducted as a result of a severe heatwave which occurred in Chicago, USA, in July 1995. Maximum and minimum temperatures soared to record highs (Semenza et al, 1996) accompanied by high relative humidity and ozone levels. Unprecedented use of electricity resulted in power outages, roads buckled, and services were overwhelmed. Between 14-20 July there were 739 more deaths in the city than in a typical July week (Whitman et al, 1997, Klinenberg 2002). Epidemiological studies showed those most at risk of dying had medical conditions, were socially isolated and had no access to air conditioning (Semenza et al, 1996).

In the summer of 2003, Europe was impacted by a heat wave of profound proportions that resulted in approximately 70,000 deaths across 16 countries (Robine et al, 2008). The most severely affected country was France, where the death toll reportedly reached up to 15,000, mostly in Paris (Fouillet et al, 2006). Many of the heat victims were aged and living alone, with lack of mobility and pre-existing medical conditions being major risk factors (Vandentorren et al, 2006). Deaths directly related to hyperthermia, heatstroke, and dehydration increased markedly (Fouillet et al, 2006) with conditions including cardiovascular diseases, respiratory diseases and nervous system diseases also contributing to the excess mortality (Fouillet et al, 2006). With limited air conditioning in hospitals and nursing homes (Vandentorren et al, 2004) 42% of the excess deaths occurred in hospitals (Bouchama 2004). Studies have also suggested that air pollution associated with the heat (i.e. high ozone concentrations), contributed to the high number of deaths, although the extent varied by location (Bouchama 2004, Filleul et al, 2006). High night time temperatures are a major factor in heat-related deaths (NCCARF 2016) and this was evident in France during the heat wave as minimum temperatures above 25.5°C did not allow individuals to shed the accumulated heat load overnight and recover from heat-stress experienced during the day (Bouchama 2004).

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[1] The definition of 'heat wave' varies throughout the literature, but it is generally accepted that the term refers to a prolonged period of extremely high temperatures.

In Australia, the most severe heatwave of the last few decades occurred at the end of January and early February in 2009. The states of South Australia and Victoria in south eastern Australia were hardest hit. In Adelaide, the capital of South Australia, there were six consecutive days above 40°C, peaking at 45.7°C, and in Melbourne, Victoria, the highest maximum was 45.1°C (National Climate Centre 2009). As in the French heatwave six years earlier, the unprecedented minimum temperatures of 33.9°C overnight in Adelaide (National Climate Centre 2009) added to the health burden. The heat-attributed deaths totalled 58 in South Australia (Herbst et al, 2014), and ambulance callouts soared to 16 times those of regular heatwaves (Nitschke et al, 2011). In the more populous adjoining state of Victoria where maximum temperatures were 12-15°C above normal, there were 374 deaths over what would be expected (i.e. total deaths were 980 and expected deaths for the period was 606) (Department of Human Services 2009). The heatwave was also linked with catastrophic fire conditions resulting in Victoria's worst ever bushfire which claimed 173 lives (Hannan 2009).

Major heat waves were reported the following year in the northern hemisphere. In 2010 a major heatwave in Moscow, Russia, lasted for 44 days contributing to the deaths of 11,000 people. The decedents were mainly older people although there were also effects in people younger than 65 years. High excess risks of death occurred mostly for people with cardiovascular, respiratory, genitourinary, and nervous system diseases. Excess risks for other causes of death also occurred, with speculation that lack of air conditioning in hospitals and other health facilities may have played a role. Wildfires sparked by the heat occurred in forests and peat bogs near Moscow with the air pollution contributing to the death toll (Shaposhnikov et al, 2014). In May of the same year, an extreme heatwave occurred in Ahmedabad, India. Although very hot temperatures are not uncommon in India, this heatwave was associated with an excess of 1,344 all-cause deaths compared to the reference period (Azhar et al, 2014).

2.2. Cold-related deaths

Although fewer population health studies have reported the association between cold temperatures and mortality (Gasparrini et al, 2015), cold weather is also a major cause of temperature-related deaths (Chen et al, 2018). Globally, death rates are higher during winter than in other seasons (Braga et al, 2001, McGeehin et al, 2001, Bennett et al, 2014, World Health Organization 2018). A study in China reported 30% higher mortality during winter than summer (He et al, 2018) and another in the UK showed annual cold-related mortality of 61 deaths/100,000 while heat-related mortality accounted for just 3 deaths/100,000 (Vardoulakis et al, 2014). A multi-country study of 384 locations found that more temperature-attributable deaths were caused by colder than optimum temperatures, than by warmer than optimum temperatures, and that most of the world's temperature-related mortality burden is attributable to cold (Gasparrini et al, 2015).

The excess in winter mortality is mainly due to deaths from respiratory and circulatory system diseases, but deaths associated with cold seem to be more closely correlated with maximum rather than minimum temperatures during winter. This is likely due to daily minimum temperatures being recorded overnight or at day break when people are generally at home in a warmed indoor environment, whereas daily maximums occur in the afternoon when there is greater human activity outdoors. In other words, human exposure to the cold is longer during the days with low maximum temperatures, than during days when it is very cold overnight but warm during the day (Diaz et al, 2005). At least half the excess winter deaths are due to cardiovascular diseases and up to a third are due to respiratory diseases (Braubach et al, 2011).

A study of coronary events during cold periods in 21 countries showed that the rates increased during comparatively cold periods, particularly in warm climates (Barnett et al, 2005). Supporting this notion is a study in South Australia where winters are relatively mild, which showed that chronic heart failure-related morbidity and mortality peaked at the lowest temperatures in winter. This indicates that populations become acclimatised to local conditions and it is the relative extremes of temperatures in a location - that is, the extent of deviation from optimum temperatures, that are determining factors (Inglis et al, 2008).

2.3. Are heat extremes or cold extremes worse for health?

In Australia and elsewhere in the world, heat causes more deaths than all other natural hazards combined (Klinenberg 2002, Luber et al, 2008, Coates et al, 2014, Leon et al, 2015). A study in the US of the health effects of heat waves and cold waves (characterised by successive hot or cold days, respectively) on mortality showed heat waves generally increased the risk of death whereas small increases in deaths were noted with cold waves (Barnett et al, 2012). The risk also depended on the timing of the events with those occurring earlier in the warm or cold seasons being more dangerous (Barnett et al, 2012). The authors posit that populations may therefore be better able to deal with extreme cold than extreme heat as people will be able to wear extra clothes when it is cold but are limited in the number of clothing layers that can be removed in hot weather (Barnett et al, 2012).

Others have also shown that the effect of heat can be substantially larger than the cold effect (Braga et al, 2001). There is a clear and acute public health impact of heat extremes on mortality with excess deaths typically occurring around the second, third or fourth day of a heat wave (Semenza et al, 1996). This is not the case for mortality in cold extremes where there can be a lag period, with effects which are generally less marked than those of heat, persisting for days or weeks (Braga et al, 2001, Diaz et al, 2005, Gasparrini et al, 2015). Notably however, mortality risk attributable to temperature is higher for moderately cold temperatures than extremely cold temperatures (Gasparrini et al, 2015, Fu et al, 2018).

In summary, the literature shows that while there can be large increases in deaths associated with days and periods of extreme heat, these surges in mortality do not generally occur in association with days of extreme cold (Bennett et al, 2014). In fact, extremes of temperature (hot or cold) result in only a small fraction of deaths attributable to temperature. Most of these occur on days of moderately hot or cold temperatures (the latter contributing the greater burden) (Gasparrini et al, 2015), rather than on extreme temperature days that occur relatively rarely.

3. Influence of the built environment on temperature-related mortality

During extreme weather, people tend to spend most of their time indoors (Loughnan et al, 2015). Hence, the built environment can play a major role in mitigating the effects of ambient temperature on the risk of adverse health effects associated with thermal stress.

In terms of heat, there is a recognised association between high indoor temperatures and adverse health effects (Ormandy et al, 2016). In the French heat wave of 2003, 35% of the excess deaths occurred at home (Bouchama 2004, Fouillet et al, 2006). Epidemiological studies have showed living and sleeping on the top floor of a non-air conditioned building or in an upstairs room close to the roof, increases the risk of heat-related death during a heat wave (Semenza et al, 1996, McGeehin et al, 2001, Vandentorren et al, 2006). The housing characteristics associated with a higher risk of death in France included older buildings, a lack of thermal insulation, living on the top floor, the number of windows per 50m^2 and opening the windows in the afternoon instead of at any other time. High outdoor temperatures around buildings with little surrounding vegetation were also a risk factor (Vandentorren et al, 2006, Loughnan et al, 2015). Similarly, indoor environments have been implicated in heat-related deaths in the United States. In California for example, 66% of the 582 excess deaths that occurred during a heat wave in 2006 occurred at the decedent's home (Joe et al, 2016); and in Chicago, indoor temperatures in some apartment buildings and brick houses reportedly reached 120^{o}F (~49^{o}C) (Klinenberg 2002), increasing the risk of death for the occupants.

It is difficult to define a 'healthy' indoor summer temperature as this will vary by region and acclimatization of populations. As such, there is no worldwide standard indoor minimal temperature below which heat-related health effects would be expected, or indoor "maximum acceptable temperature". The World Health Organization Housing and Health Guidelines (World Health Organization 2018) suggest that the indoor minimum temperature to reduce heat-related health effects and indoor maximum acceptable temperature are 21-22^{o}C and 25^{o}C respectively, in Boston, USA. In Bangkok, Thailand, they are approximately 30^{o}C and 32^{o}C, respectively. However, in a study of indoor temperatures and comfort in domestic buildings around the world, Nicol (2017) argues that existing indoor temperatures guidelines need to be more flexible, with consideration of occupants' varying reasons for thermal preferences and reduced energy use (Nicol 2017).

There is also increasing evidence that cold indoor temperatures have adverse health consequences for health and contribute to excess winter mortality (World Health Organization 2018). Energy inefficient building design, homes that are difficult to heat due to poor design, as well as the low income of the occupants and high energy prices, can all contribute to cold indoor temperatures (Braubach et al, 2011). This can be a significant public health problem. It has been estimated in a study of 11 European countries that 38,200 excess winter deaths occur per year (12.8/100 000) due to cold housing (Braubach et al, 2011, World Health Organization 2018). It should be noted that compared with countries with severe winter climates, winter mortality can be higher in countries with milder winters where homes can be less insulated thus making them harder to heat (World Health Organization 2018). The World Health Organization recommends an indoor minimum of 18°C during winter, although this temperature may need to be higher for vulnerable groups (World Health Organization 2018).

3.1 The effect of place

It is not only the dwelling itself that can modify health risks of occupants in hot or cold conditions, it is also the location. The climate of a location together with acclimatisation and learned behaviours of the local population, play a substantial part in determining the risk of temperature-related mortality. As previously mentioned, it has been shown that people living in areas where hot weather is common fare better in heat extremes than those in cooler climates. 'Threshold temperatures' above which heat-related deaths begin to occur are generally lower in cooler cities than in warmer cities (Curriero et al, 2002, McMichael et al, 2008, Campbell et al, 2018). It follows that there is a higher heat impact in colder latitudes and a greater effect of colder temperatures on mortality risk in warmer latitudes (Curriero et al, 2002). By contrast, a study of 12 urban populations in low- and middle-income countries found that while heat thresholds were higher in warmer climates, cold thresholds, below which cold-related mortality began to increase, ranged from 15°C to 29°C and seemed to be unrelated to climate (McMichael et al, 2008). Colder countries with more extreme winter climates generally have lower excess winter deaths perhaps due to their more energy efficient housing (Braubach et al, 2011).

It is now well established that during heat events the risk of heat-related health outcomes can be higher for those living in the urban core (McGeehin et al, 2001). The urban heat island effect occurs due to the thermal mass of buildings and concrete surfaces in cities absorbing heat throughout the day and retaining and radiating heat at night (McGeehin et al, 2001, Basu et al, 2002, Luber et al, 2008). With people more likely to be at home at night, the higher night time temperatures in cities can therefore be a determining factor in the risk of heat-related health outcomes for vulnerable city residents (Laaidi et al, 2012, Campbell et al, 2018).

Spatial epidemiology studies have shown that as well as inner-city neighborhoods, residents of some suburban neighborhoods have higher risks of heat-related mortality, for geographic and socioeconomic reasons. This is particularly the case in hotter areas of cities which tend to be disadvantaged compared to the cooler and less disadvantaged areas (Smoyer 1998, Luber et al, 2008). Vulnerability can be lower in areas where there are greener landscapes and cooler microclimates where residents tend to be more affluent with higher levels of education and higher incomes (Smoyer 1998, Harlan et al, 2006). For example, in the French heatwave of 2003, while heat exposure was greater in the most urbanized areas, excess mortality rates were higher in the most deprived areas (Rey et al, 2007). Similarly, in the Chicago heatwave, heat-related deaths occurred in areas with high levels of poverty and violent crime where residents felt safer indoors, and areas where there were high proportions of older residents (Klinenberg 2002).

3.2 Australian housing stock: thermal efficiency and health

Despite Australia's reputation for outdoor fun in the summer, indoors it can be a different story as much of the existing housing stock is poorly designed for extreme heat (NCCARF 2016). A study of housing and heatwave resilience in Australia showed that the age of buildings, and presence or absence of insulation in ceiling and walls are key factors which can determine the indoor living environment. Houses with flat rather than pitched roofs had higher indoor temperatures, and higher indoor overnight temperatures were noted in buildings that had insulation only in the ceilings (Loughnan et al, 2015). During summer there is a high reliance on air conditioning in Australia and it is expected that up to 80% of Australian homes will have air conditioning by 2020 (Loughnan et al, 2015). Modern homes that are over-insulated with no eaves and little ventilation rely heavily on air-conditioning to keep cool (Hatvani-Kovacs et al, 2018) and can trap heat 'like a plastic bag' according to one expert (Sutton 2018). Current energy-efficiency measures therefore do not ensure lower energy consumption for cooling. Modern dwellings without air-conditioning however, can in fact be hazardous to human health (Hatvani-Kovacs et al, 2018).

During the aforementioned South Australian heatwave of 2009, 42 (78%) of the 54 autopsied heat-related deaths[2] occurred indoors (Herbst et al, 2014) and the mean age of the deceased was 70.4 years. In eight of the cases the indoor temperature was recorded as being greater than 40°C. Many did not have air conditioning and of those who did, less than half had

[2] "Heat-related death" here is defined as "a death in which exposure to high ambient temperatures either caused the death or significantly contributed to it" (Herbst, J., Mason, K., Byard, R. W., Gilbert, J. D., Charlwood, C., Heath, K. J., Winskog, C. and Langlois, N. E. 2014. Heat-related deaths in Adelaide, South Australia: review of the literature and case findings - an Australian perspective. *J Forensic Leg Med* 22: 73-78).

their cooling turned on (Herbst et al, 2014). The cost of electricity may have been a factor in this as subsequent studies showed that many older people are reluctant to cool their homes appropriately due to high energy costs in South Australia (Hansen et al, 2011).

Australian houses are however, arguably better designed to cope with heat extremes than cold. Much less attention is paid to maintaining warm living conditions in the winter with many houses poorly insulated and lacking central heating. Furthermore, only 2.6% of Australian homes have double-glazed windows (Bright et al, 2014) to help retain indoor warmth. These factors can contribute to poor cold-related health outcomes for occupants, and annually 33 deaths per 100,000 population are associated with cold in Australia (Vardoulakis et al, 2014).

In a media interview a senior Australian public health academic claimed that 'Australian houses are "glorified tents" which pose a health risk due to their cold indoor temperatures over winter' (Haggan 2017). Drawing on findings of an international study of temperature and mortality showing that mortality rates in Australia increase when temperatures fall below 20^{o}C (Gasparrini et al, 2015), he suggested Australian homes are partly to blame. He stated that indoor temperatures can trigger cardiovascular or cerebrovascular events in the vulnerable, yet Australian homes can be colder than those in colder climates as they 'tend to track the outdoor temperature rather than protecting inhabitants from cold' (Haggan 2017).

Supporting this notion is a study showing that the rates of deaths due to hypothermia in South Australia are comparable to those of Sweden, i.e. 3.9/100,000 and 3.3/100,000, respectively (Bright et al, 2014). Furthermore, the bulk of the deaths (84%) reported in the study occurred indoors at home addresses, unlike much colder Sweden where only 5% occurred indoors. It should be noted that the number of fatal hypothermia cases reported in South Australia was relatively low and mostly among older, socially isolated females with multiple underlying illnesses. Nevertheless, the high rate of indoor deaths shows that in Australia vulnerable individuals are at increased risk of hypothermia that is not limited to outdoor exposure (Bright et al, 2014), a fact that should be concerning not only for public health, but also the architecture and urban planning sectors.

4. The way forward for health and comfort at the extremes

The aformentioned evidence has clearly shown that temperature has an effect on health outcomes and temperature extremes can cause high mortality rates, particularly heat extremes. While everyone can be affected, those in the most vulnerable groups are most at risk, particularly in their own homes. This calls for a greater collaboration of public health experts, architects and urban planners in addressing complex thermal challenges associated with housing and health issues, particularly in the face of an ageing population, increasing urbanisation and a warming climate.

A limitation of many of the ecological studies is that outdoor air temperature typically recorded at a nearby meteorological monitoring station is used as a proxy for personal exposure. This assumes the study population are all exposed to the same (typically maximum) temperature, whereas people generally spend most of their time in an indoor environment, the temperature of which is rarely measured. Notwithstanding, the literature indicates that exposure to high overnight minimums which occur when people are generally at home, is a key determinant in heat-related deaths. The use of a single temperature metric for a large population therefore introduces a level of misclassification in terms of exposure (Basu et al, 2002). Studies using accurate measurements of temperature exposure at the individual level are comparatively rare in the broader literature, likely due to the prohibitive costs involved and small sample sizes limiting statistical inference. Further research should address this gap in knowledge to better inform policies regarding the indoor thermal environment that is conducive to the health of individuals at their home or workplaces. This information would be useful for designers of homes and buildings in particular in the face of a changing climate where temperature extremes and unprecedented weather events are expected to occur more frequently.

Humans and their built environment will need to adapt to a changing climate while taking into account energy efficiency and environmental concerns (NCCARF 2016). Buildings need to provide shelter and respite from harsh external conditions; however, it is not clear whether current building codes will still be adequate for a future climate (NCCARF 2016). Nevertheless, housing and health guidelines such as those formulated by the World Health Organization (World Health Organization 2018) should be considered in the design of future homes. In the absence of effective adaptation, it is predicted that rising temperatures in association with climate change will lead to an increased burden of heat-related mortality, and a decrease in the burden of cold-related mortality (Bennett et al, 2014, Vardoulakis et al, 2014, Guo et al, 2016). Indeed, an Australian study has shown that between 1968 and 2007, the ratio of summer to winter deaths increased from 0.71 to 0.86 (Bennett et al, 2014). While this may be indicative of longer, hotter summers, it is also possible that domestic buildings, particularly modern ones, are not providing adequate thermal protection against summer heat.

To protect the health of home occupants against the adverse health outcomes associated with higher temperatures, the designers of urban areas will need to better consider how heat is mitigated in buildings. To reduce the heat gain in existing building stock, retrofitting could be considered, using measures such as better external shading, fly screens, white roofs, double-glazed windows and ceiling vents (NCCARF 2016, Sutton 2018). However, in Australia house retrofitting will not be suitable for some poorly designed older homes, leaving air conditioning, external features and landscaping the main options to maintain safe indoor temperatures in heat extremes.

New dwellings should be designed in ways that mitigate heat with appropriate construction material that reduces retained overnight heat, and urban precincts should include green infrastructure (NCCARF 2016). An Australian study has estimated that by increasing vegetation coverage temperatures in the city of Melbourne could reduce between 0.5 and 2 °C, thereby considerably reducing heat-related mortality rates (Chen et al, 2014). Cool refuges, i.e. a room or zone in a house that is minimally affected by external temperature and has minimal energy requirements (Saman et al, 2015) could be considered for new or existing homes to provide comfort to the occupants. To be effective however, the occupants would need to understand and manage the ventilation of the room correctly (NCCARF 2016). Renewable energy sources incorporating e.g. rooftop solar panels and battery storage of generated power (NCCARF 2016) will also need to be more widely incorporated into new or existing buildings to offset the high energy costs associated with running air conditioners.

While the focus of future thermal-sensitive building design to cope with temperature extremes will no doubt be the mitigation of heat gain, in Australia there is clearly a need to also address cold indoor temperatures in domestic settings in order to reduce cold-related mortality in homes. Some of the afore-mentioned features such as better insulation should be considered in order to increase thermal comfort and reduce reliance on heating. When the use of heaters is unavoidable, the use of solar power should be encouraged to address high operating costs from running the heater. Hopefully this will improve the current housing stock of "glorified tents" (Haggan 2017) that apparently do little to adequately protect the occupants from the adverse health effects of the Australian winters.

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The limits to accepted indoor temperatures

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Abstract: One characteristic of the adaptive approach to thermal comfort is that there is not a single 'comfortable' temperature but there are a wide range of temperatures which occur in indoor environments which can be acceptable to building occupants depending on their experience and circumstances. By looking at records of indoor temperatures from field survey a variety of climates and cultures this paper explores the limits of the acceptable indoor temperature range.

Keywords: Indoor temperature, Outdoor temperature, Thermal Comfort, Acceptable temperatures

1. Introduction: looking at clouds

The paper *Temperature and adaptive comfort in heated, cooled and free-running dwellings* (Nicol, 2017) explored data from several countries which demonstrated that the range of indoor temperature in heated and cooled dwellings is greater than it is in dwellings which are neither heated nor cooled.

The analysis used 'temperature clouds' which are areas, within the indoor/outdoor temperature space which show for a particular building or group of buildings the distribution of indoor temperature which are related outdoor temperatures. This approach, using in effect, the raw data collected in a field survey is different to the accepted approach which uses statistical analysis.

This is related to the desire, particularly in buildings which are being heated or cooled (mechanically conditioned) to identify a 'comfort' or 'neutral' temperature that the occupants of the building will use to minimise their discomfort. This approach assumes that there is a constant and narrow indoor 'comfort temperature' – or 'comfort range' –which will be sought by building occupants. The data used in that paper showed that this was an over-simplification of the way people use energy to control indoor conditions, especially in Dwellings.

Nicol (2017) used data from a number of sources but principally from heated houses in England (Kelly et al 2013) and cooled ones from Dammam in Saudi Arabia (Alshaikh and Roaf 2016) which were compared with data from the diverse climate of Tokyo, Japan (Rijal et al 2015a and 2015b). The Japanese database included homes which were free-running, heated and cooled in different seasons. Remarkably the indoor summer temperatures in cooled Japanese houses seemed to coincide with those of Dammam and in the cold season the temperature of Japanese houses were like those in England.

Information was also presented which suggested that people are comfortable in a wide range of temperature in mechanically conditioned (heated or cooled) dwellings. Nicol (2017) suggested that the reason for such a wide range was the individual differences in clothing worn, income and lifestyle as well, perhaps, as differences in physiology and body build. In buildings not using mechanical conditioning the occupants must find other ways to suit the environment to their preference (through changes in air movement, shading, windows etc) or themselves to the environment (through changes in clothing, posture, activity etc) so that their thermal needs are matched to their local environment by one or other strategy or a mixture of the two. In these free-running circumstances the range of possible comfortable environments is often smaller than in the conditioned environments where using energy the building occupants can make bigger changes in the environment.

In this paper a similar technique is used to determine the possible, or limits of acceptable range of indoor temperature from the results of field surveys of thermal comfort. Limiting acceptable temperatures are taken to include those that might be acceptable in unusual or extreme conditions such as power outages, heat waves and so on when the use of any existing mechanical heating or cooling is not possible, or it is inadequate to deal with conditions that they were not designed for. Such emergency conditions are predicted to become increasingly common as extreme weather arises more frequently as a result of climate change.

1.1. Conditioned and free-running buildings

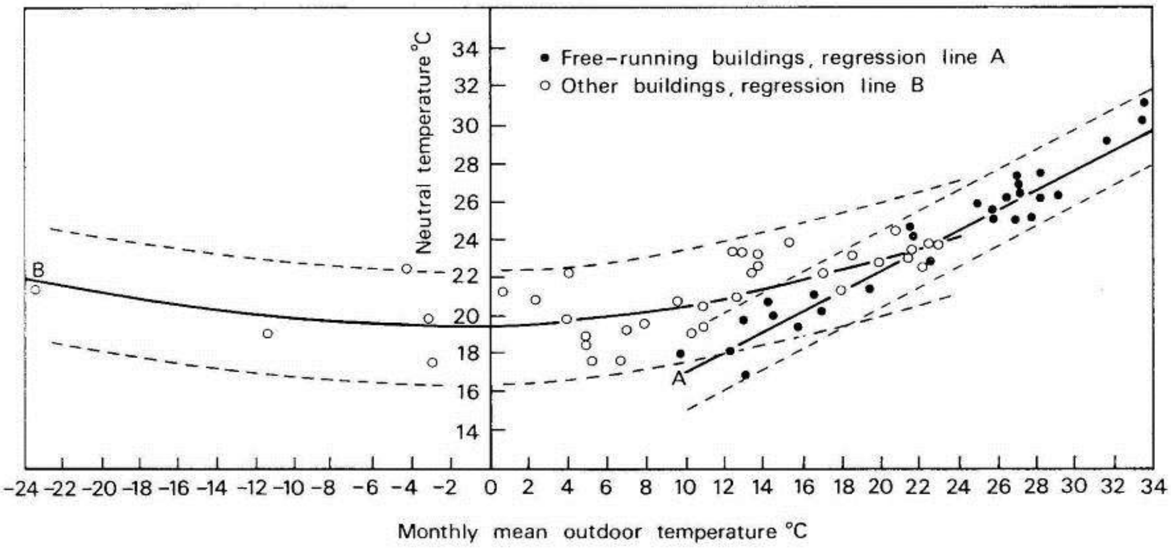

Figure 1. The relationships demonstrated by Humphreys between mean indoor temperature and mean outdoor temperature. Each mark is the graphs is the mean from a whole field survey (from Humphreys 1978)

Humphreys (1978) suggested that the comfort temperature inside a mechanically conditioned building would be essentially independent of the outdoor temperature but the mean comfort temperature rises on either side of 0°C as the temperature drops below or increases above zero. The effect is shown in Figure 1, In heated buildings this increase in heating might be to compensate for the increasingly inhospitable outdoor climate and in the cooled buildings because of the acclimatisation of the occupants, or maybe because of the inefficiency of the cooling system.

Humphreys additional remarkable finding was that the neutral[1] temperature in free-running buildings was linearly related to the outdoor temperature (Figure 1). The strength of this relationship was later used to develop ways in which standards such as ASHRAE 55 (2004) and EN15251 (BSI 2007) could be developed to ensure comfort in free-running buildings

In his paper Humphreys was using a different type of graph than is used in this paper. He was plotting the mean values of the outdoor temperature from a whole comfort survey against the neutral temperature(s) derived from the survey. As a result, a lot of the variation

[1] Humphreys used the term Neutral Temperature (i.e. the temperature at which the comfort vote is most likely to be 'neutral') this temperature is more often referred to as the comfort temperature.

in temperature and comfort vote is smoothed and is lost in the diagram. The temperature clouds shown in this paper, recorded from a whole survey or buildings, would in Humphreys' paper be reduced to a single point.

Humphreys (2016 chapter 27) suggests that office workers in both Europe and Pakistan can achieve a high degree of comfort at temperatures within 3 or 4°C of the annual mean indoor temperature and this suggests that "within a population seasonal drifts in the indoor temperature of less than seven or eight degrees are well tolerated and are consistent with a very high level of thermal comfort" (p282).

2. Temperatures in buildings with mechanical conditioning

The results described in this paper are not analysed precisely they seek to demonstrate a trend rather than trying to set up a precise description of a phenomenon which is in any case imprecise and changeable. Figure 2 introduces the concept. The plot of all the concurrent indoor and outdoor temperatures collected in a particular survey are shown as an area or cloud on the indoor/outdoor temperature graph.

The clouds are not strictly comparable. Some are measurements taken in one season and some in another, some relating to buildings which are mechanically cooled and some which are heated. Some show data which are collected from several buildings in a particular season or city and some from a single building. The data which forms the clouds is nevertheless all from occupied buildings. The aim is to see whether there is a pattern in the occupied buildings and whether there is evidence that some indoor temperatures are too extreme for human occupation.

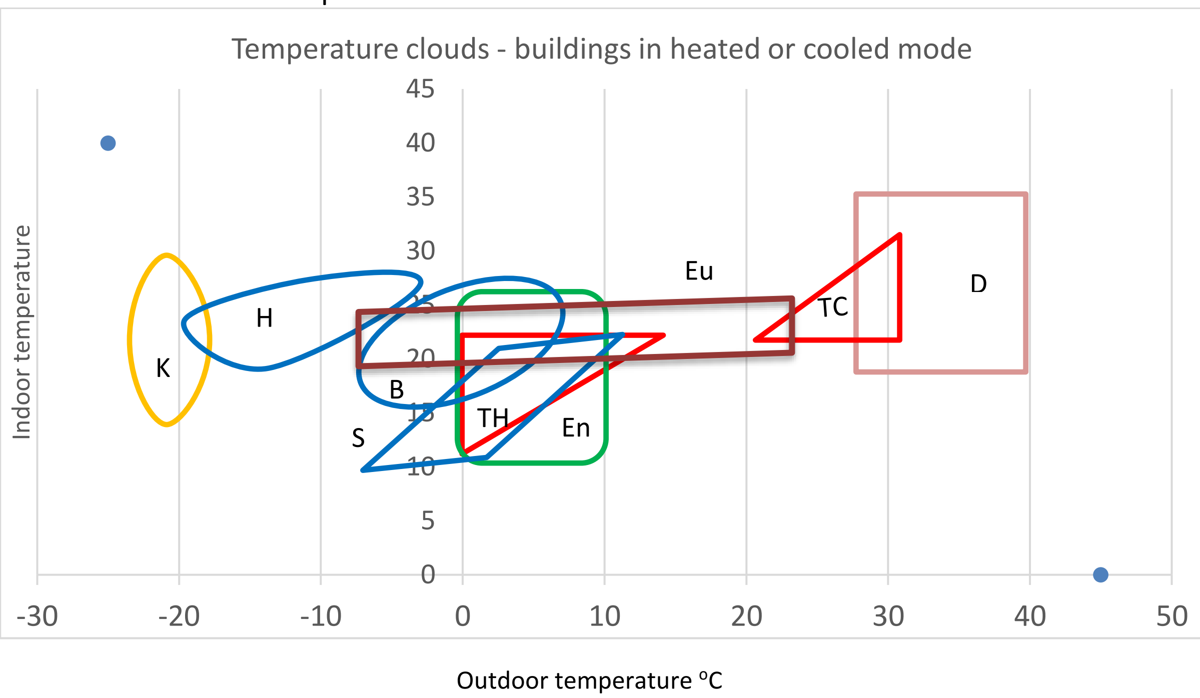

Figure 2. Temperature clouds from surveys in various parts of the world from buildings which were mechanically cooled or heated at the time of the survey. Key: blue: China (Harbin (H), Beijing (B), Shanghai (S) in winter (Cao et al 2016), yellow Russia (Khabarovsk winter (K) Borovikova 2013), green England (En) (Kelly et al 2013), red Japan (Tokyo (TH heating, TC cooling) Rijal et al 2015), Brown Saudi Arabia (Dammam (D) Alshaikh 2016), Purple European offices (McCarney et al 2002)

Figure 2 shows temperature clouds which have been collected from surveys in conditioned buildings in different parts of the world. In this figure heating is assumed to be turned on when the mean outdoor temperature is below 10°C and cooling (if available) when it exceeds 20°C. The method of data collection for each of the sets of data can be found in the references given in the caption for the figure. The figure suggests that an indoor temperature of 20-25°C is achieved by some of the building occupants in all the datasets whether heating or cooling is being used. This is particularly true of the European (Eu) data from offices where the conditioning systems used are closely controlled to European standards EN 15251 which recommends indoor office temperatures of 20-25°C in winter and 23-26°C in summer

Figure 2 supports Humphreys' (1978) finding that there is a fall in the indoor temperature at outdoor temperatures close to zero. The logic of the adaptive model suggests that the lowest indoor temperatures will occur when the outdoor temperature is close to the temperature at which the occupants begin to use mechanical heating. This fits the adaptive approach better than a rather arbitrary 0°C. this effect was commented upon by the researchers from China (Cao et al 2016) when they found that among the three Chinese cities the lower the outdoor temperature the higher were the indoor temperatures. This finding is further reinforced by the results from Khabarovsk in Eastern Russia.

The indoor temperatures recorded in Figure 2 run from about 10°C (England and Shanghai) to 35°C in Dammam. Rather few Dammam results were measured above 30°C and the graph of discomfort given in Figure 3 suggests that heat discomfort becomes widespread at indoor temperatures above 30°C. These are airconditioned buildings and the comfort limit of 30°C may be lower than it could be because the occupants have expectations which are affecting their subjective response to the building. Figure 3 also suggests that there is discomfort from heat in air-conditioned dwellings in Dammam. notice also that figure 3 shows that there is also significant cold discomfort in this climate with indoor temperatures below 25°C.

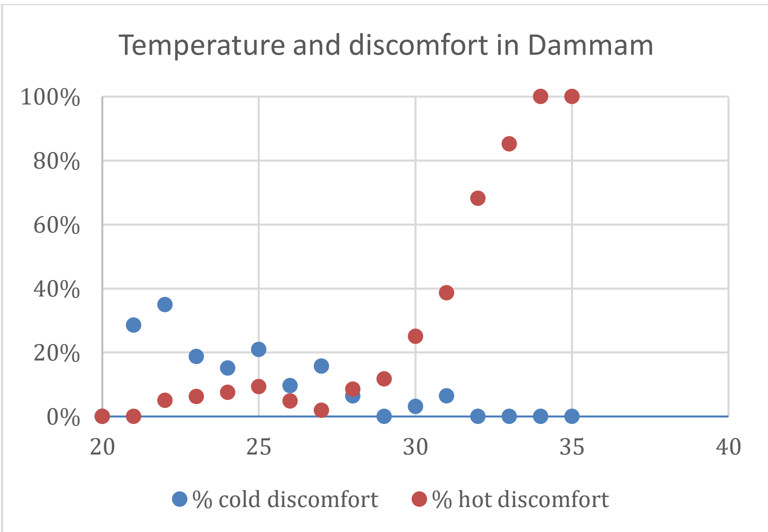

Figure 3. Discomfort from cold and heat at different temperatures in dwellings in Dammam (data from Alshaikh and Roaf 2016)

3. Temperatures in free running buildings

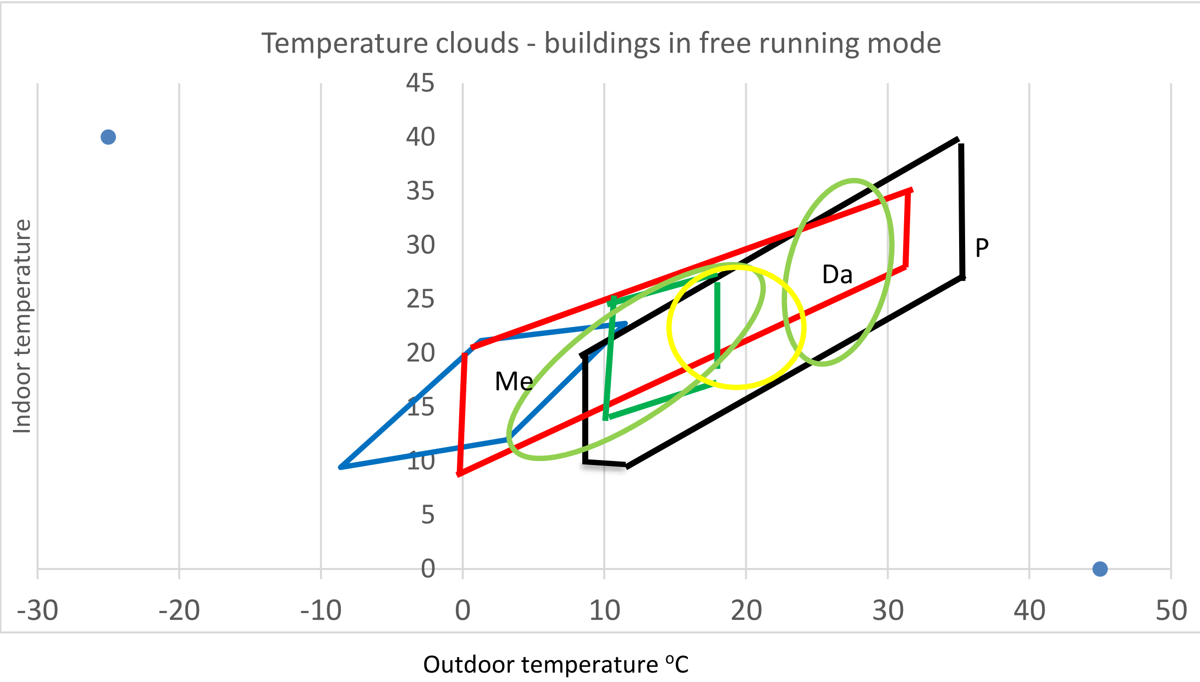

Figure 4. Temperature clouds from various parts of the world from buildings which were free-running at the time of the survey. Key: blue: China (Shanghai, winter, Cao et al, 2016), yellow Russia (Moscow summer Borovikova 2013), dark green (England summer Kelly et al 2013), red Japan (Tokyo all seasons Rijal et al 2015), Light green Australia (Melbourne (Me), Darwin (Da) Daniel et al 2016), black Pakistan all seasons (P Nicol et al 1999)

Temperature clouds from free running buildings in a variety of climates are shown in Figure 4. The indoor temperatures run from below 10ºC to almost 40ºC and outdoor temperatures from 0ºC to 35ºC. The data from Japanese dwellings (red) and Pakistani offices (black) come from data gathered throughout the year. Results from Japan during periods when the dwellings are heated or cooled can be found in figure 2. The comfort cloud for Shanghai is shown in both figure 2 and figure 4 because many buildings in that city have no mechanical conditioning system even in the cooler season. This means tend to wear thicker clothing. The data from Australia was collected throughout the year but in two distinct climate zones, Melbourne (Me) in the south and Darwin (D) in the north. Buildings from the UK and Moscow are assumed to be free-running in summer and follow the general pattern of other buildings in this free-running group.

Unlike the sets of data from the conditioned buildings where the clouds seem to be separated, in free-running buildings there is a great deal of overlap between one record and another. The difference between the indoor conditions in different buildings at any particular outdoor temperature are likely to be caused largely by differences in building construction and layout, perhaps modified by the lifestyle and expectations of the occupants

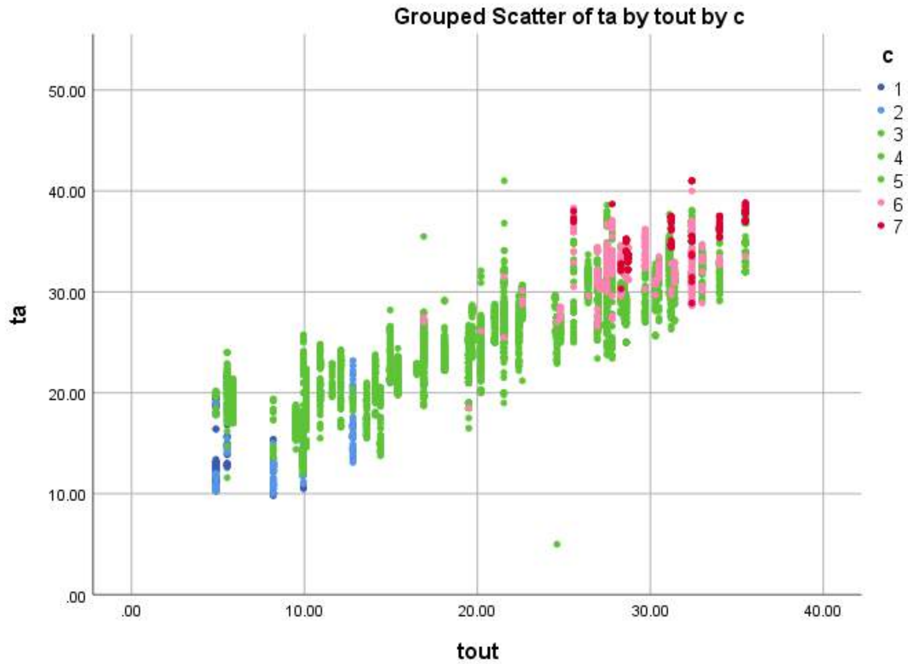

Figure 5. Comfort votes among the Pakistan data. Notice that heat discomfort (pink and red) occurs above about 30°C and above 35°C form most of the dataset (Nicol et al 1999). The highest temperature (tout > 32°C are from Multan, the coldest (tout < 8°C) from Quetta

Figure 5. shows the temperature cloud for the Pakistani data from all areas of the country and times of year. Each point shows the indoor and outdoor temperatures and the colour of the point indicating the comfort vote on the ASHRAE scale. Throughout the year and in the different parts of country the subjects are neutral except when the indoor temperature is less than about 15°C or above about 30°C. Outside these limits the subjects become increasingly subject to discomfort.

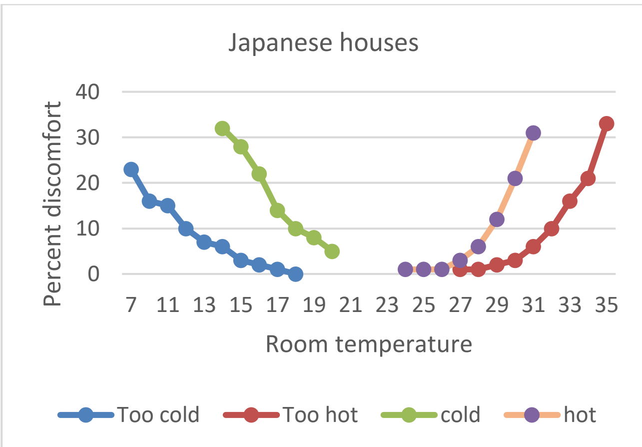

Figure 6. The effect of emergency conditions on the percent acceptable when the acceptable range for the SHASE vote is increased from votes 3-5 (hot/cold) to 2-6 (too hot/too cold)

Figure 6 is similar to figure 7 in Nicol (2017) showing the percentage of thermal discomfort at different indoor temperatures in the Japanese houses. The two closest curves take discomfort as being defined by votes 1 and 2 (cold) and 6 and 7 (hot). Most Japanese and Pakistani occupants of free-running buildings are comfortable. 86% of Japanese and 78% of Pakistani responded with votes of 3, 4 or 5 with the remainder about equally divided between hot and cold discomfort.

4. Comfort or survival in an Emergency

The Intergovernmental Panel on Climate Change (IPCC) expects increasing climate change to cause an increase in the frequency of extreme weather events. During these events the concerns begins to change from comfort to survival. One consideration is the timescale in an emergency compared to the time-period over which the data which form a cloud was collected. People may be prepared to put up with extreme conditions for a relatively short period of time, such as a heatwave lasting a couple of weeks, where conditions might be unacceptable if they persist over a longer period

A case in point is introduced by Thapa et al (2018) which reports on measurements of comfort and thermal acceptability of the thermal environment in emergency shelters provided after the 2015 earthquake in Nepal in 2015. "The thermal acceptance was higher than 90%, if the respondents were asked directly; this was considered due to the survival from the disaster. The logistic-regression analysis applied to quantify the relationship between the thermal acceptance and indoor globe temperature revealed that 80% of the people would accept the indoor thermal environment if the indoor globe temperature is higher than 11 °C in winter and lower than 30 °C in summer in temporary shelters".

The Thapa study suggests that 'comfort' as defined by Fanger (1970) as votes of 3. 4 or 5 on the ASHRAE scale may be too narrow for emergency situations. Researchers asking subjects who were victims of the 2015 earthquake found that votes between 2 and 6 were acceptable in these circumstances. This means that whereas in normal times for temperature range for 90% acceptable is 17-29^{o}C in emergency situations this range may rise to 11-32^{o}C. (see figure 6).

5. Discussion and conclusions

This paper uses the 'temperature clouds' methodology Nicol (2017) to look at the relationship between indoor and outdoor temperature. The method seeks to avoid the simplifications inherent in using statistics such as means of operative or comfort temperatures in the handling of comfort data. The use of these statistics but can give a mistaken impression of the relationships being investigated. In addition, many of the accepted statistical relationships assume the normal distribution of the variables. Data such as that collected in field surveys related to actual physical phenomena do not occur in such an ordered stochastic way and therefore the accepted relationships (such as the use of standard deviation to estimate dispersion) may give misleading results. In many cases the error introduced by this approximation will be small but it should be borne in mind

The work of Humphreys (1978) is supported in two ways: firstly, the general shape of the relationship between indoor and outdoor temperature is curvilinear in buildings with mechanical conditioning. The indoor temperature increases as the outdoor temperature becomes either lower or higher than about 0-10^{o}C. Secondly in free-running buildings there is a linear relationship between indoor and outdoor temperature

The maximum indoor temperature for acclimatised building occupants as suggested by the temperature clouds illustrated in this paper is 30-35^{o}C The minimum indoor temperature acceptable to acclimatised subjects is 10^{o}C. The same temperature limits apply in both conditioned and free-running buildings.

Whilst all the temperature clouds in figures 2 and 4 pass through the indoor temperature range 20-25^{o}C, this may not always be the case. Most of them spend large periods of time outside this narrow range, especially if there is a large seasonal temperature range[2].So it should not be taken as an indication that the 20-25°C is necessarily the temperature range to aim for, at some times of year or in particular buildings it may be uncomfortable. This is particularly the case when the building is in Free-running mode and the occupants must adapt to what is largely a given indoor temperature (by changes of clothing and activity or use of fans, shading etc) with minimal use of energy.

Not all the temperatures that exist in a building are necessarily comfortable to all occupants, but it suggests that comfort is possible at that temperature in that environment.

Further work is necessary to explore the comfort clouds approach to temperatures in buildings. In particular in developing methods to define more precisely the limits of particular clouds, and the interpretation of the different shapes they take.

6. Acknowledgements

Thanks are due to the various people who have allowed me to visit their data and use it in an unusual analysis. I hope the results are of interest and of use. It is clear that this approach needs a lot more work but even at this level it yields some interesting insights for the future.

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[2] For instance in the cloud for Pakistan the data from the hot dry city of Multan is almost all greater than 25°C

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Passive Survivability:
Keeping Occupants Safe in an Age of Disruptions

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Abstract: Passive survivability is defined as the ability of a building to maintain habitable conditions during an extended power outage or loss of heating fuel. There have been ongoing efforts in the United States to address this issue since Hurricane Katrina caused extended power outages in New Orleans in 2005. This paper reports on such efforts—focusing especially on the suite of pilot credits on Resilient Design in the U.S. Green Building Council's LEED Rating System. These recently updated and re-released (November 2018) pilot credits offer three compliance paths to demonstrate passive survivability. While these methodologies and metrics for passive survivability will almost certainly evolve in the coming years, they provide an important starting point for this critically important discussion.

Keywords: Passive survivability; Resilience;

1. Introduction

Passive survivability refers to the idea that certain buildings, especially houses and apartment buildings, should be designed and built to maintain habitable temperatures in the event of an extended power outage or interruption in heating fuel.

The concept of passive survivability emerged following Hurricane Katrina in the Gulf Coast of the United States in the fall of 2005 when several chapters of the U.S. Green Building Council organized and led a series of *design charrettes* in an effort to guide the reconstruction that would occur following the storm's destruction to enhance sustainability. More than 100 designers, planners, municipal officials, and others, including more than 30 from the Gulf Coast, were brought together at the 2005 Greenbuild Conference in Atlanta for several days of brainstorming about the Katrina response.

Among the outcomes of these charrettes was *The New Orleans Principles*, a document that articulated ten principles that could guide this process of recovery in New Orleans. *The New Orleans Principles* included the following:

Principle #8 – To Provide for Passive Survivability: Homes, schools, public buildings, and neighborhoods should be designed and built or rebuilt to serve as livable refuges in the event of crisis or breakdown or energy, water, and sewer systems.

The concept of passive survivability occurred to charrette organizers who had watched on television as New Orleans residents were evacuated to The Superdome (an enclosed sports stadium) in the City and then, a day or two later, had to be evacuated from the Superdome because it was too hot inside. The building wasn't designed to maintain habitable conditions without mechanical systems supplying cooling.

Similarly, among homes on the Gulf Coast that lost power for an extended period of time but weren't flooded, there were reports that *older homes*, built prior to the advent of air conditioning, were more livable than newer homes, built after air conditioning systems became ubiquitous. Those older homes were built using *vernacular architecture*—architecture that made sense for the hot, humid bioclimate of the American Southeast.

These older homes had features like wrap-around porches that shaded the windows from direct sunlight, tall ceilings that resulted in temperature stratification, geometries and fenestration that channeled cooling summer breezes through the occupied space, and outdoor living spaces where residents could spend time during the hottest weather.

Once mechanical cooling (air conditioning) systems were introduced in the mid-20th Century, the principles of vernacular architecture were left behind. The same ranch houses began to be built everywhere, and designs that maintained reasonable comfort *passively* were forgotten.

Participants of the Atlanta design charrettes reasoned that Hurricane Katrina would not be the last storm event to cause a prolonged power outage, and they argued that homes (and certain other buildings) should be designed and built to keep occupants safe if they are unable to evacuate during disasters or power outages and have to shelter in place.

Providing for passive survivability was a way to help ensure that people would remain safer. It was a life-safety priority not only for homes and apartment buildings, but also for schools and other public buildings that are designated to serve as emergency shelters.

2. Passive survivability is more important in an age of climate change

As climate change advances, the design criterion of passive survivability becomes increasingly important. Among the impacts of climate change are more intense topical storms, winter storm events, coastal flooding exacerbated by sea level rise, inland flooding, heat waves, drought, and wildfire. A frequent primary or secondary impact of any of these events is loss of power.

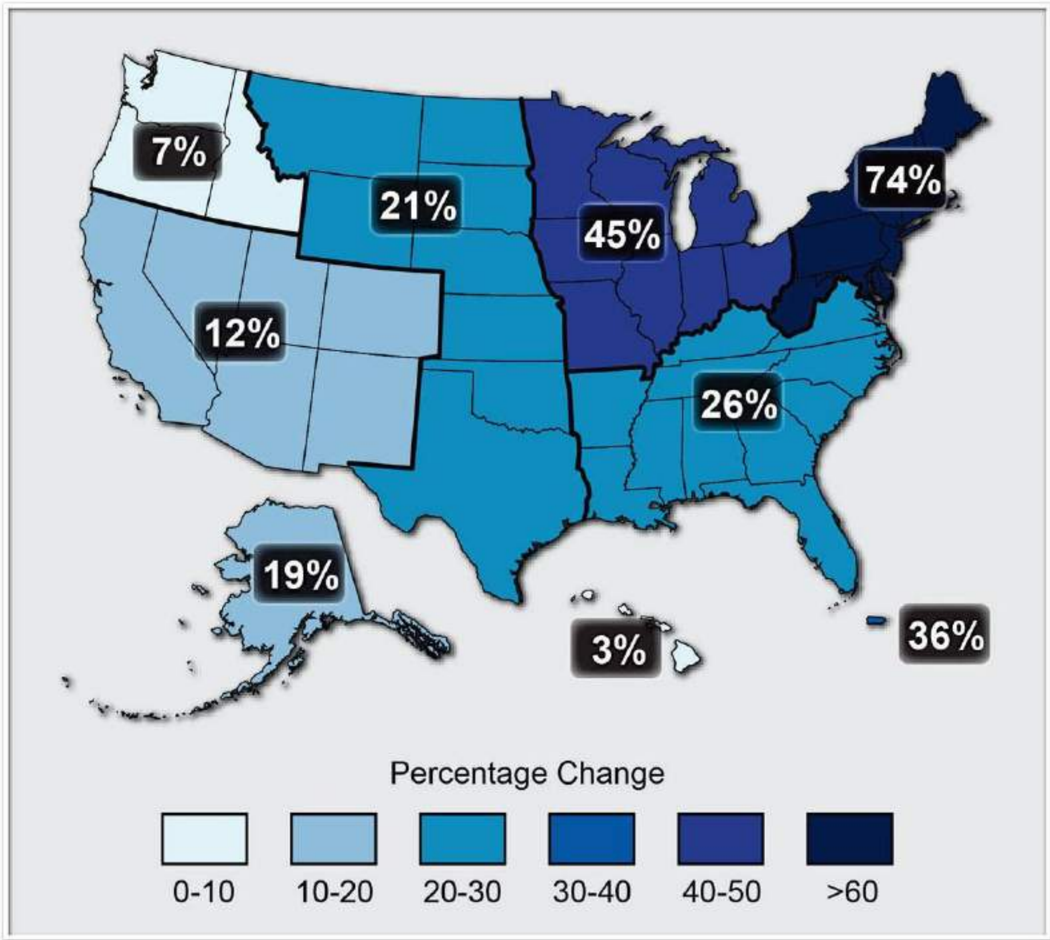

Figure 1. The percent increase in very heavy precipitation events (defined as the heaviest 1% of all daily events) from 1958 to 2011 for each region of the United States. Source: National Climate Assessment, 2014, U.S. Global Change Research Program.

Heat waves and drought, both of which are expected to become more common with climate change, result in power outages in a number of ways. In hotter weather, air conditioning use increases, and this can put more stress of the power grid, while overhead electrical distribution lines thermally expand and may sag, coming in contact with vegetation and short out or cause fires.

With extended drought, there may be shortages of cooling water for thermoelectric power plants because of falling water levels in reservoirs; this can result in power plants having to shut down or go into a reduced power-output mode—which can put stress on the power grid. During the extended heat wave and drought in Europe in 2003, more than a dozen power plants either shut down or curtailed output.

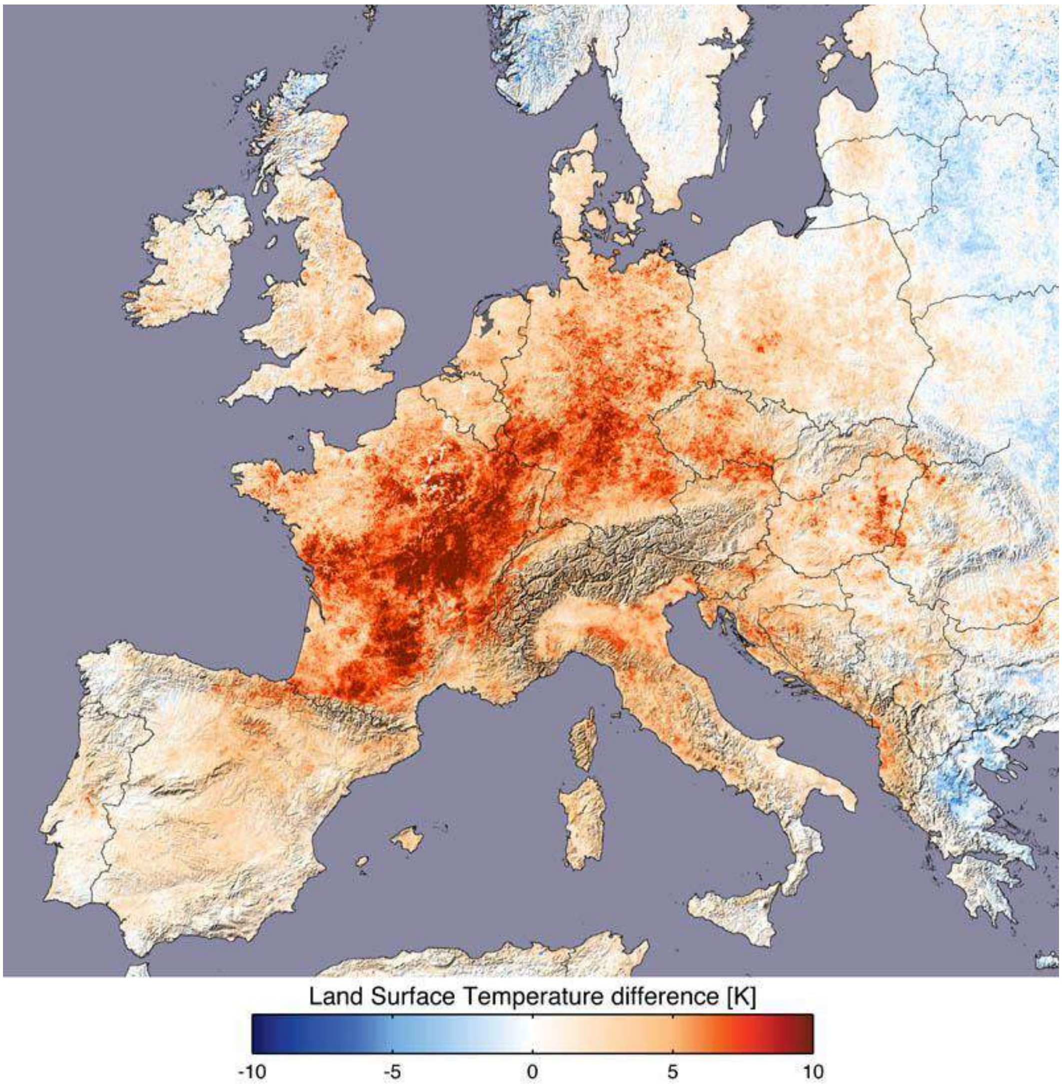

Figure 2. Elevated temperatures in Europe in °C in the summer of 2003. During this heat wave, power output in France was reduced due to elevated temperatures of rivers that nuclear power plants relied on for cooling. Source: NASA Earth Observatory.

We also face vulnerabilities that are not related to climate change, such as earthquakes, coronal discharges from the sun (space weather), and anthropogenic events such as equipment failures, terrorism, and warfare. With weather-related power outages, there is typically advance warning that leads to evacuations; with these other power outages the impact can be greater, because residents have not evacuated and must shelter in place.

During the 2003 heat wave and drought in Europe, for example, France lost approximately 4,000 MW of power generation, the equivalent of four large nuclear power plants, due to elevated river temperatures and reduced cooling capacity. During a more extensive heat wave or drought, the impacts of such power outages could be very dangerous, especially because air conditioning loads are greatest during hot weather.

3. Initiatives to address passive survivability

In the United States, the issue of passive survivability has begun attracting significant attention in some cities, and various research institutions are beginning to focus on this issue. A few such initiatives are described below.

3.1. New York City Greening the Codes Task Force, 2008 – 2010

In advancing the PlaNYC initiative to make New York City more sustainable and reduce its carbon footprint 30% by 2030, Mayor Michael Bloomberg and City Council Speaker Christine Quinn engaged the Urban Green Council in 2008 to lead an effort to "green" the City's building codes. The NYC Green Codes Task Force, with over 200 members, was assembled to carry out this initiative, and their final report was issued in February 2010.

Concerned about vulnerability to power outages during hot weather, the Resilient Design Institute, which was represented on this Task Force, argued for passive survivability to be incorporated into the City's building codes.

There are 111 proposals included in the final report, divided into ten categories. One of the nine proposals in the Building Resilience category (BR6) is to "Analyze Strategies to Maintain Habitability During Power Outages." The specific recommendation in BR6 is to "Undertake a comprehensive study of passive survivability and dual-mode functionality, then propose code changes to incorporate these concepts into the city's building codes. Also include a study on refuge areas in sealed buildings." While the recommendation was only *to study* the issue, at least it got the concept onto the agenda.

3.2. Addressing metrics of passive survivability

While the Resilient Design Institute (RDI) had been advancing the concept of passive survivability since 2005, the organization only had a vague sense of what passive survivability actually meant. We reasoned that more energy-efficient buildings would maintain habitable temperatures better than conventional buildings, but we didn't really know what "habitability" meant or even how it should be measured. In an effort to answer these questions, RDI convened a one-day workshop in New York City in May 2013.

Eighteen leading engineers, architects, and other experts addressed these questions and others, in a full, intensive day of brainstorming and discussion. While the workshop itself did not result in specific answers to these questions, it led to a technical paper by two of the participants and a third coauthor in the peer-reviewed journal *Building Research & Information*: "Overheating and passive habitability: indoor health and heat indices."

3.3. New York City's Building Resiliency Task Force, 2012 – 2013

Following Superstorm Sandy in the fall of 2012, New York City sought to address resilience through a wide range of measures. As with the Greening the Codes initiative several years earlier, Mayor Bloomberg and City Council Speaker Quinn engaged the Urban Green Council to convene a task force to address resilience. The Building Resiliency Task Force, with over 200 members, including a representative from the Resilient Design Institute, was convened in late-2012, and their final report was issued in June 2013.

The report of the Building Resiliency Task Force includes 33 specific proposals organized into four categories: Stronger Buildings; Backup Power; Essential Safety; and Better Planning. The section on Essential Safety includes six proposals, including two that relate specifically to passive survivability: Ensure Operable Windows in Residential Buildings (#26) and Maintain Habitable Temperatures Without Power (#27). Relative to operable windows, New York currently has a requirement for operability, but it is in conflict with a law relating to child safety (fall protection) that limits the window opening size. The proposal for ensuring that habitable temperatures are maintained during power outages has not been addressed by the City to date.

3.4. Baby It's Cold Inside report

In February 2014 the Urban Green Council published *Baby It's Cold Inside*, a concise report of thermal modeling conducted for Urban Green by the engineering form Atelier Ten. In the report, six different residential building types common in New York City were examined relative to interior temperature conditions over week-long power outages during typical (not extreme) summer and winter conditions. Separately, these buildings were modeled, first, assuming typical building stock at the time and, second, assuming the buildings were built to modern energy codes.

The results of this modeling showed that standard buildings quickly reach unsafe conditions during extended power outages, both in winter and summer, while more energy efficient buildings maintain more habitable conditions. Temperature charts from the report for winter conditions are shown in Figures 3 and 4, below. This report helped to convey the seriousness of this issue and the importance of addressing passive survivability—not just in New York City, but in most locations.

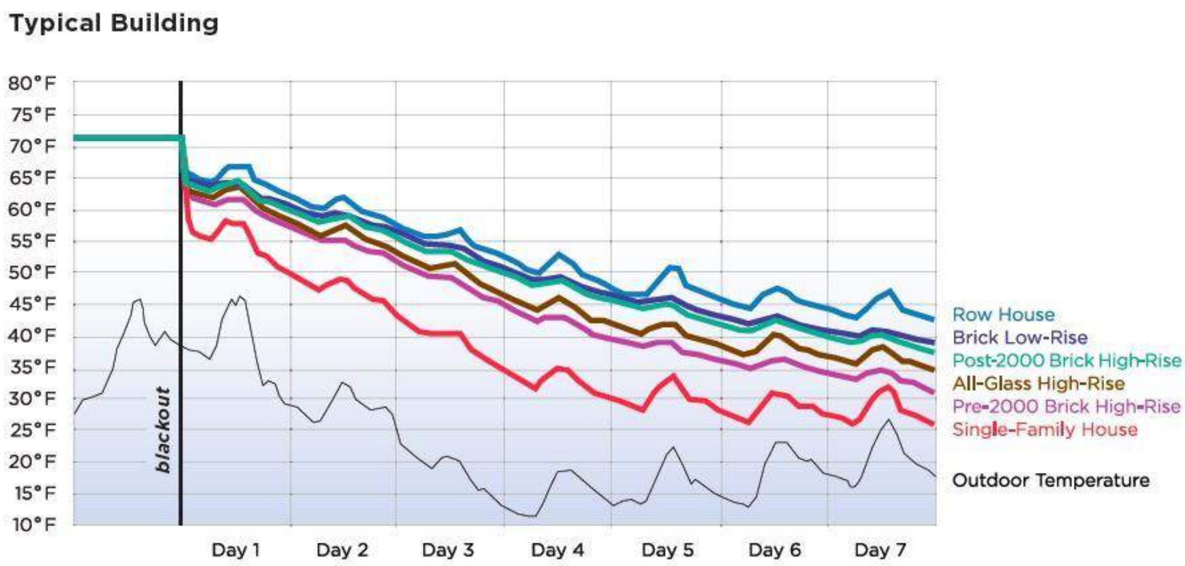

Figure 3. Indoor drift temperatures for different types of buildings based on thermal modeling by Atelier Ten, assuming typical construction practices for existing buildings in New York City. Source: *Baby It's Cold Inside*, Urban Green Council, February 2014.

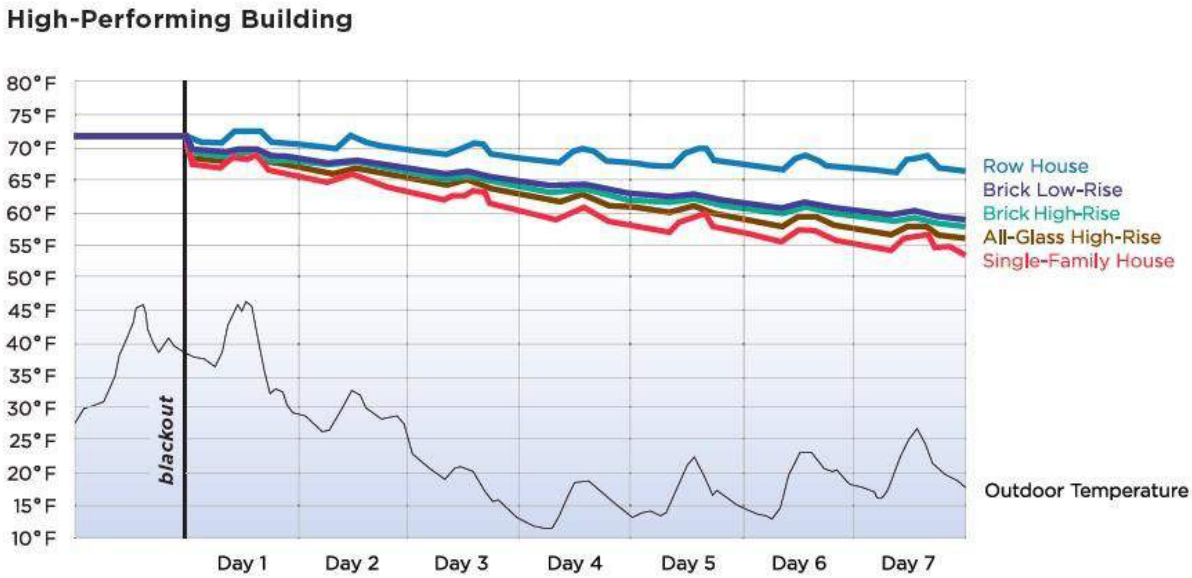

Figure 4. Indoor drift temperatures for different types of buildings based on thermal modeling by Atelier Ten, assuming energy-efficient construction practices (meeting current energy codes) for the buildings in New York City. Source: *Baby It's Cold Inside*, Urban Green Council, February 2014.

3.5. LEED pilot credits on resilient design

In November 2015 the U.S. Green Building Council rolled out a suite of three LEED pilot credits on Resilient Design. The LEED Rating System (Leadership in Energy and Environmental Design) has helped advance green building worldwide since its introduction in 2000, but it hadn't addressed resilient design. The Resilient Design Institute led an effort to change that through a two-year process to develop pilot credits on resilient design. The pilot credits were available for one year, then taken down as the U.S. Green Building Council moved toward adopting the RELi Rating System as its resilience platform (see below). There remained strong interest in the LEED community for addressing resilience directly in LEED, however, and revised versions of the three pilot credits became available again in November 2018.

There are three LEED pilot credits on Resilient Design: the first requires assessment of vulnerabilities at a site; the second requires mitigating the most significant threats (allowing a project two earn up to two points for addressing the greatest threats at the project location); and the third credit can be earned by addressing either passive survivability (thermal safety) or back-up power—earning one point for each. The different compliance paths that can be used to demonstrate passive survivability are addressed later in this paper.

3.6. RELi Rating System

RELi is the resilience platform that the U.S. Green Building Council has adopted. It is a wide-raging and comprehensive rating system that addresses a wide range of resilience issues, including thermal safety (RELi's terminology for passive survivability). Prior to the re-release of the LEED pilot credits on resilient design, the RELi Steering Committee worked on aligning the requirements for those aspects of resilience that are addressed in the pilot credits. As a result, the compliance paths for demonstrating thermal safety in RELi are identical to those of the pilot credits.

4. Defining the "habitability zone" and metrics of passive survivability

A key aspect of demonstrating that a building will maintain conditions of passive survivability is defining what constitutes habitable, or safe, conditions in buildings that lose power. How hot is too hot and how cold is too cold? This is a far different question than what constitutes comfort—it is about survivability. Just as energy engineers refer to a "comfort zone" in designing mechanical systems for buildings, we can think of a "habitability zone" as those conditions that will generally keep people safe is buildings during power outages.

When the group of experts convened by the Resilient Design Institute considered this issue in May 2013, they quickly realized that those habitable conditions are not only about air temperature (dry-bulb temperature); they are also about relative humidity and mean radiant temperature. During an extended power outage, a building at 85°F in Phoenix, with 15% relative humidity will be far different than a building at 85°F in Atlanta with 95% relative humidity, because the cooling effect of evaporation of moisture from an occupant's skin is impeded by higher relative humidity.

For this reason, experts who focus on passive survivability prefer less-common thermal metrics that factor in relative humidity and mean radiant temperature. These include Standard Effective Temperature (SET), Wet-Bulb Globe Temperature (WBGT), and for high temperatures: Heat Index. These metrics of thermal conditions are used in the different compliance paths for demonstrating that a building will achieve passive survivability. Unfortunately, these metrics were created primarily for outdoor conditions; they are not ideal metrics of indoor climatic conditions—but for now, they are what we have to work with.

Using the SET metric for thermal conditions, the developers of the LEED pilot credit on passive survivability identified a *habitability zone* for adults of average stature and physical condition as follows: a low of 54°F SET and a high of 86°F SET (12°C SET to 30°C SET)—and the pilot credit defines how much deviation there can be from this range. Another compliance path in this pilot credit provides not-to-exceed temperatures using either WBGT or Heat Index.

Note that maintaining temperatures and relative humidity within these boundaries will not guarantee safety for everybody. Differences in age, physical health, and physiology can mean that one person does fine at the high or low end of this thermal habitability range, while another individual cannot survive in those conditions. Individual with higher Body Mass Index (BMI), for example, may do fine at temperatures well below this thermal habitability zone, while being at risk in hot weather at temperatures well within the thermal habitability range.

5. Methodologies for assessing passive survivability

Both the revised 2018 LEED pilot credit on resilient design and the RELi Rating System v.2.0 provide three compliance paths for demonstrating passive survivability. The first two of these methodologies require thermal modeling specific to passive survivability. Requirements are laid out in a technical appendix to the LEED pilot credit *Passive Survivability and Back-Up Power During Disruptions*.

5.1. Compliance path 1: Standard Effective Temperature

With the SET methodology, thermal modeling has to demonstrate that deviations from the "habitability zone" of 54°F SET to 86°F SET (12°C SET to 30°C SET) during winter and summer design weeks must be no greater than the referenced number of degree-days (or degree-hours). Those limits are as follows:

During peak summer conditions (cooling season) for residential buildings, the building can exceed 86°F SET for no more than 9°F SET-days (degree-days), or 216°F SET-hours, over a four-day period. (In metric, residential buildings cannot exceed 30°C SET by more than 5°C SET-days (120°C SET-hours) over a four-day period.

With non-residential buildings, greater deviation from the habitability zone is permitted, given the expectation that workers will leave the building and head home during an extended power outage. During peak summer conditions, the building cannot exceed 86°F SET for more than 18°F SET-days, or 432°F SET-hours. (In metric, non-residential buildings cannot exceed 30°C SET for more than 10°C SET-days (240 °C SET-hours).

During the heating season, passive survivability requirements for residential and non-residential buildings are the same. Temperatures cannot fall below 54°F SET for more than 9 °F SET-days (216 °F SET-hours) during a four-day period in peak heating conditions. (In metric, the building cannot fall below 12°C SET for more than 5°C SET-days (120 °C SET-hours).

This terminology gets confusing. °F SET-days and °F SET-hours are degree-days and degree-hours in Fahrenheit degrees, using SET rather than air temperature as the metric. Here's how °F SET-hours are derived:

For the summer cooling season: Add up the difference between the building's modeled interior temperature (in SET) and 86°F, only if the interior SET is greater than 86°F, for all hours of the four-day period during the extreme hot week. For example, If on day one of that extreme week, there is an afternoon stretch where the temperatures rise to 87°F SET between 1-2 pm, to 90°F SET between 2-3 pm, to 88°F SET between 3-4 pm, before dropping below 86°F SET at 4 pm, you would come up with a total of 7°F SET-hours for that day. Those SET cooling degree-hours would be added up for each of the four days to come up with the total deviation. As long as the total is no more than 216°F SET-hours for that four-hour period (for a residential building), the passive survivability requirement would be met.

For the winter heating season: Add up the difference between the building's modeled interior temperature (in SET) and 54°F, only if the interior SET is less than 54°F, for all hours of the four-day period during the extreme cold week. The total SET heating-degree-hours for that four-day period cannot not exceed 216°F SET-hours or 9°F SET-days.

With metric, the calculations are the same, deriving °C SET-days and °C SET-hours for the four-day peak periods in summer and winter.

5.2. Compliance path 2: psychrometric analysis

The second compliance path relies on psychrometric analysis and establishes not-to-exceed temperatures using either Heat Index or WBGT metrics; these thresholds differ by building type and season. Heat Index is a metric that was developed by the National Weather Service in the U.S. to better represent comfort in outdoor conditions, because it factors in relative humidity. For summer conditions, thermal modeling must demonstrate that residential buildings will not exceed the "Extreme Caution" threshold in the Heat Index metric, or approximately 90°F (32°C) Heat Index. With non-residential buildings, that threshold is increased to the Extreme Danger threshold, or about 103°F (39°C) Heat Index.

With the WBGT metric (which differs somewhat from Heat Index, but factors in relative humidity and mean radiant temperature) during summer conditions, thermal modeling must demonstrate that the building will not exceed 83°F WBGT (28°C WBGT). For non-residential buildings, those temperatures cannot exceed 88°F WBGT (31°C WBGT).

During the heating season (winter), relative humidity is less of a factor, and a standard air temperature metric (dry-bulb temperature) is used. Thermal modeling must demonstrate that the building temperature will not fall below 50°F (10°C)—for either residential or non-residential buildings.

5.3. Compliance Path 3: Passive House certification

The third way in which the LEED pilot credit point on passive survivability can be earned does not require separate thermal modeling. Instead, the project has to go through *Passive House* certification and demonstrate that natural ventilation can be achieved.

Passive House is a certification system for ultra-efficient buildings that was developed in Germany by the Passivhaus Institute (PHI). To earn Passive House certification, a building must be extremely well-insulated, and such buildings typically include other passive features that help to minimize energy consumption, such as passive solar heating. The reasoning for including Passive House certification as a compliance path for demonstrating passive survivability is that such houses are so energy efficient that they are likely to maintain habitable temperatures for a power outage lasting many days.

In the LEED pilot credit on passive survivability, either the International Passive House standard may be used, or a modified version tailored for the U.S. may be used: Passive House Institute U.S. (PHIUS). The rating systems are slightly different, with the PHIUS standard better factoring in cooling loads in U.S. climates, but either is a good indicator of a building that will maintain habitability in the U.S.

This is not to suggest that Passive House certification is easy. It is an arduous process and requires its own, sophisticated thermal modeling. But it is now a well-established system, and it is often easier for design teams to understand than the complex methodologies employed in Compliance Paths 1 and 2.

In addition to Passive House certification, this third compliance path for the pilot credit on passive survivability requires that *natural ventilation* be provided for the building. This requirement is included because it is possible to build a Passive House that relies 100% on mechanical ventilation that will not operate during a power outage. The natural ventilation requirement can be satisfied with operable windows or other means, and it is clearly described in the pilot credit appendix.

Other certification systems for *net-zero-energy* performance do not comply with the requirements of the LEED pilot credit on passive survivability, because net-zero-energy performance can be achieved by adding a lot of solar panels to a building that has only mediocre energy performance. During a power outage, most solar systems do not operate, so the fact that a building achieves net-zero-energy performance is no guarantee that it will maintain habitable conditions.

These methodologies for assessing passive survivability are likely to evolve as we gain more experience in modeling passive conditions in buildings, but at least they provide a starting point for testing and comparing how we can track this important building performance criterion.

6. Achieving multiple benefits: synergies between resilience and sustainability

Buildings that achieve passive survivability will be far more energy efficient and, therefore, more sustainable than typical buildings. It is very difficult to achieve passive survivability performance, as defined here, without a highly energy-efficient building envelope as well as other features that will reduce operating energy use.

Passive survivability may also appeal to a wider audience than sustainability or green building. The motivation to achieve passive survivability can be one of life-safety, not just "doing the right thing." And although adaptation to climate change is an important motivation for pursuing passive survivability, one doesn't have to believe in global warming to want to keep his or her family safe—this can be a factor in the United States, where there remains skepticism in some circles about the reality of climate change.

As more frequent storms cause more frequent power outages, the motivation to design and build for passive survivability is likely to grow. Each new storm or outage-causing event—for example Hurricane Katrina in 2005; Sandy in 2012; Harvey, Maria, and Florence in 2017; and Michael in 2018—builds motivation for creating buildings that will keep people safe. As the global climate warms, those motivations are likely to keep increasing.

Finally, while passive survivability is a climate *adaptation* response, the strategies for achieving this performance will save operating energy and therefore reduce carbon dioxide emissions. In other words, implementing passive survivability measures will help to *mitigate* climate change, even as it helps us adapt to it.

7. The path ahead: the research and standards-setting agenda for passive survivability

There is tremendous need for additional research on key aspects of passive survivability.

From a human health and safety standpoint, we need a better understanding of human physiology and how indoor thermal conditions during power outages can affect us. What is the *thermal habitability* zone in a building without power? How hot is too hot, and, how cold is too cold? How does age (especially the very young and the elderly), illness, and body weight affect our ability to survive thermal extremes in buildings without power? How do relative humidity and mean radiant temperature affect human health and safety?

We need to refine the metrics that can be used for assessing passive survivability in buildings. The metrics currently used to assess these thermal conditions, including *Standard*

Effective Temperature, *Wet-Bulb Globe Temperature*, and *Heat Index*, were all developed for use in assessing *outdoor* conditions. How should we model thermal conditions *inside* buildings that lose power? Can existing thermal modeling tools serve this function, or do new tools need to be developed?

We need to develop easy-to-use, clear methodologies for assessing passive survivability/thermal habitability. The methodologies developed for the LEED pilot credit on Passive Survivability (reported in this paper) provides a good starting point, but these need much more thorough vetting and testing in real-world applications. Are these approaches realistic? Are they achievable? Are they understandable? What worksheets or calculators are needed to streamline this process?

Finally, we need to develop language and procedures for passive survivability so that these methodologies can be incorporated into building codes and/or other regulatory frameworks. If a municipality wants to incorporate passive survivability requirements into its building codes, as has been suggested in New York City, how do they go about doing that?

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Thermal Adaptation of Buildings and People in Very Cold Climate of Nepal

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Abstract: A thermal comfort survey and a thermal investigation were conducted in traditional houses, during the winter in the Mustang district of Nepal. The thermal measurement was conducted in 9 houses for 7 days. The thermal comfort surveys were carried out over 4 days, gathering a total of 1,584 thermal sensations from 36 subjects. The results show that passive heating effects are found in houses with thick brick wall and mud roof, 2) residents are highly satisfied with the thermal condition of their houses, 3) the mean comfort temperature is 10.7 °C and 4) the comfort temperatures are different according to the thermal environment of the evaluated spaces. These findings reveal that people are well adapted to the thermal environment of traditional vernacular houses, as a result of which the comfort temperature is lower than the thermal comfort standard.

Keywords: Nepal, Himalayas, Winter, Adaptive building design, Adaptive thermal comfort, Comfort temperature

1. Introduction

The different and sometimes extreme climate conditions necessitate specially adapted types of housing, which incorporate a variety of passive heating methods designed to keep indoor environmental conditions thermally comfortable. In the cold climatic region of Nepal, traditional houses are designed to exploit building elements such as small window and thick brick wall. There is no known, substantial research on thermal mitigation in traditional Nepalese houses. However, such research is imperative if this low-energy consumption lifestyle is to continue. By introducing new techniques into existing houses in cold climate of Nepal, it would be possible not only to support a comfortable thermal environment, but also to build a sustainable society based on energy conservation. Research into environmental qualities and performance of the traditional buildings has been carried out in recent years (Meir & Roaf 2006). Generally speaking, the thermal performance of traditional dwellings is better than that of modern dwellings (Ahmad et al. 1985, Algifri et al. 1992, Pearlmutter & Meir 1995).

In order to improve the traditional houses and to establish indoor temperature standards, we have been doing research in the sub-tropical, temperate and cold climate zones of Nepal (Rijal et al. 2010, Rijal 2012). Although we have already conducted research in one cold climate zone (the Solukhunbu district) of Nepal, we have again focused on another cold climate area (Mustang district, Lomangtang). The reasons for this are; firstly, due to the high altitude of this Himalayan region, it has a low outdoor air temperature (minimum air temperature –22.5°C, H.M.G. of Nepal 1995), high wind velocity and low sensory temperature. To protect inhabitants from the cold, courtyard houses are built connected to each other. The houses are also constructed with 450 mm thick dry brick walls and small windows. Secondly, as the area is located in the rain shadow on the northern side of the Himalayas, there is no effect from monsoons and the precipitation is low (113 mm, H.M.G. of Nepal 1995). Consequently, the houses have flat roofs in which small holes are made for lighting and ventilation. Finally, due to the low precipitation, firewood is very scarce. Residents therefore burn livestock dung (yak, goat and horse) for cooking and heating.

These three factors present significant differences from the previous research area (Solukhumbu district). Lomangtang is an interesting research area from the viewpoint of thermal comfort and how the people manage to live thermally comfortably in such an extremely cold climate. The purposes of this research are to;

- clarify the indoor thermal environment of the houses,
- evaluate the thermal satisfaction of the residents,
- establish the comfort temperature of the residents, and
- show the relation between the comfort temperature and the thermal environment.

2. Methodology

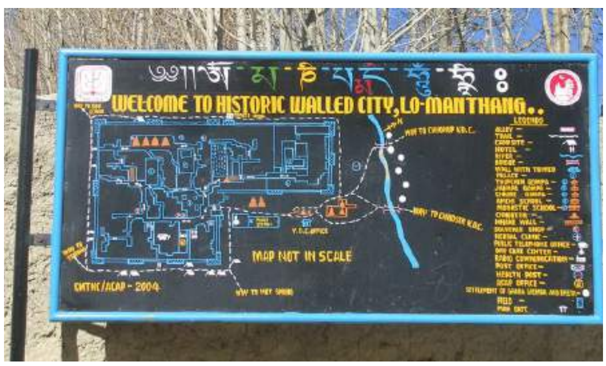
2.1. Research area

Lomangtang (3,705m), the study area, is located in the Mustang district of Nepal (Figure 1, Table 1, H.M.G. of Nepal 1995). The climatic zone of this area is cold. It took 4 days to get there on foot from Josmom airport. To avoid mountain sickness, we adapted by walking slowly and reducing our levels of physical activity.

In Nepal, summer is in May and winter is in January (Figure 2). Because of the landlocked nature of the country, the climate is dry and hot in summer. However, in the sub-tropical climate zone, relative humidity is 53% in May and it can feel cool in the shade (Rijal et al., 2003). It is warm in winter during the daytime because Nepal lies in low latitudes (26° to 30°N) and insolation is high.

Figure 3 shows the plan and view of investigated houses. Most houses are 2-storey courtyard houses, built from sun dried brick (approx. 450 mm thick). Houses are constructed using the natural materials available in the area. The houses have few windows – these are also small. Small holes are found in the roof for ventilation and lighting. The 1st floor is used for sheltering cattle and storage, and the 2nd floor is used for living space. The kitchen is used not only for cooking but also for living and dining. In some houses, it is also used for sleeping. Because of the low temperatures, people spend most of their time in the kitchen, keeping warm by burning livestock dung (yak, goat and horse). Residents have begun using iron stoves for cooking and heating instead of the traditional open-hearth stove. The iron stove improves indoor air quality; however it requires more energy than the open-hearth.

(a) Map of Nepal



(b) Map of Lomangtang

Figure 1. Locations of the survey area

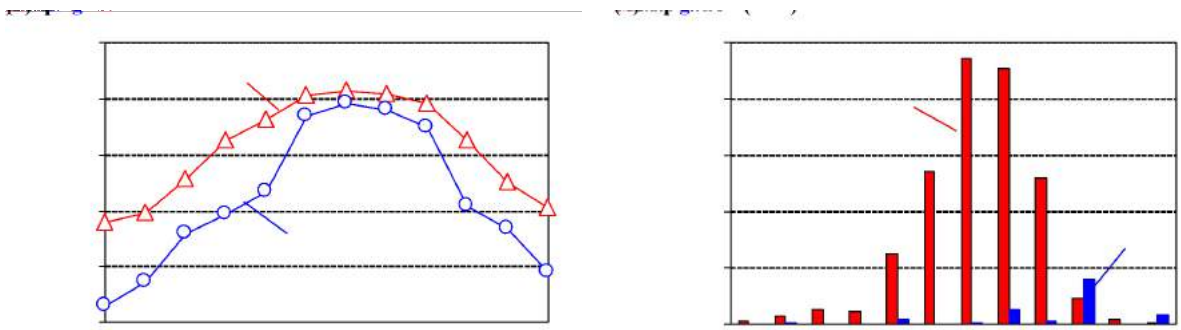
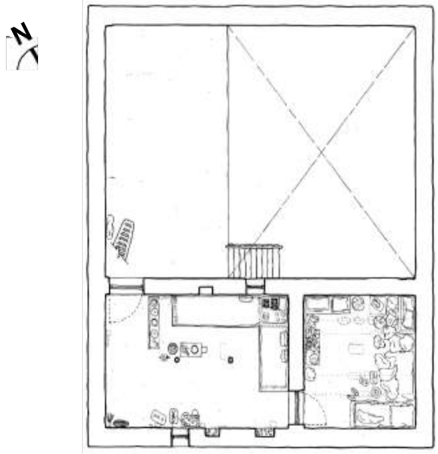
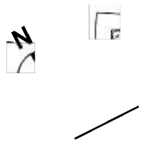


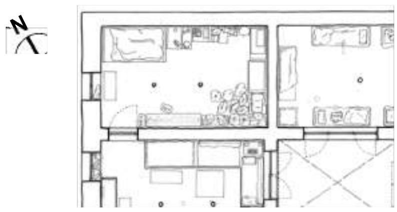
Figure 2. Climate of the investigated areas: (a) Outdoor air temperature and (b) Precipitation.



(a) House A



(b) House B



(c) House C

(d) Overall view

(e) Courtyard

(f) Street

Figure 3. Plan and view of the investigated houses (2F)
(The LDK (Living/Dining/Kitchen): Space of thermal comfort survey)

2.2. Thermal measurement

The thermal measurements were conducted during the winter, January 2005 (Rijal & Yoshida 2005, 2006). The conditions measured were air temperature, relative humidity, globe temperature (15 cm diameter), wind speed, wind direction and solar radiation (Figure 4). Outdoor environmental conditions were measured at a height of 1.5 m above roof level. Indoor conditions were measured in the centre part of the rooms at a height of 0.6 m above floor level. Indoor air temperature was measured around the floor level (0.1m above the floor level) and ceiling level (0.1m below the ceiling level). Surface temperature and heat flux were measured at the centre of the floor, wall and roof. All data were recorded at intervals of 5 minutes. Measured data were calibrated.

(a) Outdoor (b) Indoor

Figure 4. View of outdoor and indoor measurements

2.3. Thermal comfort survey

(1) Scale

The English and Nepalese thermal comfort questionnaires are shown in Table 1. The questionnaire was translated into Nepali, the official language of Nepal, so that people could be interviewed. Some of the male and female subjects could not speak Nepali very well and the questionnaire was translated for them by local people fluent in Nepali. To evaluate the wide range of thermal environments in which the Nepalese live, a 9-point thermal sensation scale was used. The meaning, relationships and evaluation methods of the questionnaires were explained in advance to all the subjects either individually or in groups to improve the accuracy of the responses.

(2) Subjects

The mean age, height, body surface area and clothing insulation are shown in Table 2. 36 healthy local men and women were selected as subjects. Ages ranged from 17 to 60 years old (Figure 5). The mean age was 46.4 year for the men and 37.8 year for the women. At the time the questionnaire was conducted, the subjects were either sitting down resting, or sitting down and working (Figure 5(d)). The residents are in the habit of wearing the same clothes for many days. Therefore, the subjects were asked to wear the same clothes during the investigation period (4 days) and if they wanted to change clothes, they were asked to wear similar clothes to the previous ones. Clothing insulation values were calculated by measuring the weight of the clothes (Hanada et al., 1981, 1983). The clo value of female clothing (mean 5.96 clo) is higher than that of male clothing (mean 2.87 clo) (Table 2).

However, due to the high weight of the traditional clothing of this area, the clo value estimate may not be precise (Figure 5). It is said that a clo value of 7 is necessary when 'at rest' in –20 °C (Inoue, 1981), which is relevant to the high clo values and low outdoor air temperature (minimum –22.5 °C) of this research.

The physiques of Nepalese people are similar to those of the Japanese, therefore body surface areas were estimated using the formula for the Japanese (Kurazumi et al., 1994). Because of heavy weight of the clothes (mean 5.4 kg, maximum 8.6 kg), they were excluded from the weight and body surface area calculations. The body surface areas are 1.57 m^2 for men and 1.44 m^2 for women. Daily allowances were paid to the subjects appropriate to the cost of living of the investigated area.

Table 1. Scale for the thermal comfort survey.

(a) English		(b) Nepali	
(1) Thermal sensation	(2) Overall comfort	(१) चिसो-तातोको अनुभव	(२) चिसो-तातोको आनन्दपन
-4. very cold	0. comfortable	-४. धेरै जाडो	०. आनन्द
-3. cold	1. slightly uncomfortable	-३. जाडो	१. अलिकती असुविधा
-2. cool	2. uncomfortable	-२. चिसो	२. असुविधा
-1. slightly cool	3. very uncomfortable	-१. अलिकती चिसो	३. धेरै असुविधा
0. neutral	(3) Thermal preference	०. ठिक्क	(३) न्यानो-शितलको चाहाना
1. slightly warm	-2. much warmer	१. अलिकती तातो	-२. न्यानो चाहिन्छ
2. warm	-1. slightly warmer	२. तातो	-१. अलिकती न्यानो चाहिन्छ
3. hot	0. no change	३. गर्मी	०. एतिकै ठिक्क छ
4. very hot	1. slightly cooler	४. धेरै गर्मी	१. अलिकती शितल चाहिन्छ
	2. much cooler		२. शितल चाहिन्छ
(4) Skin moisture	(5) Activity	(४) शरिरको पसिना	(५) शरिरको कार्यशीलता
0. none	1. lying down	०. छैन	१. पल्टिरहेको
1. slightly	2. sitting resting	१. अलिकती छ	२. बसेर आराम गरिरहेको
2. moderate	3. sitting working	२. केही मात्रामा छ	३. बसेर काम गरिरहेको
3. profuse	4. standing	३. धेरै छ	४. उभिरहेको
	5. moving around		५. उभिएर काम गरिरहेको
(6) Do you have any cold / hot part in the body?	(7) Can you accept the present cold / hot environment or not?	(६) तपाईको शरिरको कुनै भाग चिसा र तातो छ ?	(७) तपाई अहिलेको जाडो / गर्मी वातावरण खप्न सक्नु हुन्छ कि हुदैन् ?

(a) House A (n=12)

(b) House B (n=11)

(c) House C (n=13)

(d) Indoor environment of the house B

Figure 5. Residents and instruments for thermal comfort survey

Table 2. Outline of the investigated residents

Investigated house	Subject		Age [year]		Height [cm]		Weight [kg]		S [m^2]		CI [clo]	
	M	F	M	F	M	F	M	F	M	F	M	F
1) A	3	9	47.0	38.9	164.0	154.2	52.0	44.4	1.56	1.41	3.25	6.04
2) B	4	7	40.8	31.3	162.3	155.3	53.9	46.4	1.57	1.44	2.63	5.20
3) C	3	10	53.3	41.3	160.0	155.5	58.1	50.1	1.59	1.48	2.80	6.41
Mean	10	26	46.4	37.8	162.1	155.0	54.6	47.1	1.57	1.44	2.87	5.96

S: Body surface area ($S=100.315\ W^{0.383}\ H^{0.693}$, W: Weight (kg), H: Height (cm)), M: Male, F: Female, CI: Clothing insulation ($CI_M=0.000558w+0.068$, $CI_F=0.00103w-0.0253$, w: Cloth weight (g))

(3) Evaluation method

The survey was carried out by the author. Every hour subjects were gathered in the space to be evaluated 15 minutes before recording their answer so that they would have time to adapt to the environment before answering. Questionnaires were started 15 minutes before the hour in house A, on the hour in house B and 15 minutes past the hour in house C.

Thermal sensations were taken by approaching the subjects individually and collecting the answers orally, as many subjects cannot read. To get an accurate response, questions such as, 'How do you feel in this place now?' were asked. Some subjects answered 'It is colder/warmer than before.' They were asked not to compare their sensations to previous ones, but rather to choose an answer provided on the scale. If they could not differentiate the values on the scales, they were asked to rate the sensation numerically. If there were any ambiguous answers, the interview was repeated. When the questionnaire was completed, the subjects were permitted to leave the evaluated space. However, most of them stayed around the evaluated space. Subjects were asked to describe their sensations while together according to their own feelings, as mutual influences on the answers were expected.

(4) Period

The survey was carried out over 4 days (Table 3). A total of 1,584 thermal sensations were gathered. The sensations were gathered at intervals of one hour. There is no electricity supply in the winter and residents go to bed at around 20:00. Therefore the sensations were collected only during the daytime (Table 3).

Table 3. Description of investigated house, space and period

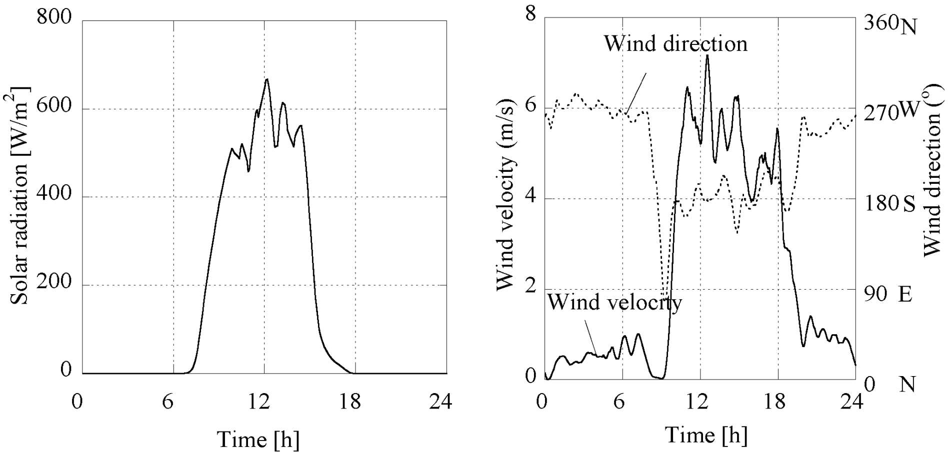
Investigated house	Description of the house				Evaluated space	Survey period (2005)	
	Storey	Wall	Roof shape	Roof material		Date	Time
1) A	2	Sun dried brick	Flat	Mud	LDK (2F)	5 ~ 8 Jan.	7:45 ~ 17:45
2) B	2	Sun dried brick	Flat	Mud	LDKB (2F)	5 ~ 8 Jan.	8:00 ~ 18:00
3) C	3	Sun dried brick	Flat	Mud	LDK (2F)	5 ~ 8 Jan.	8:15 ~ 18:15

L: Living, D: Dining, K: Kitchen, B: Bed

3. Thermal adaptation of buildings

3.1. Relation between the outdoor environment and building design

Figure 6 shows the solar radiation, wind velocity and wind direction of one of the investigated days. Most of the houses have a courtyard and the balcony is connected to the courtyard to obtain the maximum solar radiation inside the house. Due to the high solar radiation (maximum 705 W/m^2, Figure 6), the residents spend time in the sunniest areas such as roof top, balcony and street to feel thermally comfortable. Due to the high wind velocity (maximum 9.1 m/s in daytime, Figure 6), the houses are connected to each other and only a few windows are found in the external walls. This might be helpful to avoid the strong wind penetrating indoors, and thus create a warmer indoor environment in winter.



(a) Solar radiation (b) Wind velocity and wind direction.

Figure 6. Variation of solar radiation and wind climate.

3.2. Comparison of thermal environment of the heated and non-heated room

As we described above, people used the kitchen for dining, living and sleeping purposes and thus we have classified this as a heated room, and other rooms are classified as a non-heated room. The thermal environment of the heated and non-heated room was evaluated by the air temperature and humidity. The air temperature increased by up to 15 to 20 °C during the cooking and heating time (Figure 7(a), left). The temperature variation of the non-heated room is almost constant throughout the day (Figure 7(a), right). The variation of absolute humidity is similar for the both room types. The daily mean air temperature (relative humidity) was -3.1°C (36%) outdoors, 4.1°C (43 %) heated room, and 0.5°C (57 %) non-heated room (Figure 7(a)(b), Table 4). It is an uncomfortable thermal environment from the thermal comfort point of view, but people have accustomed themselves to live in these environments.

(1) Indoor and outdoor temperature difference

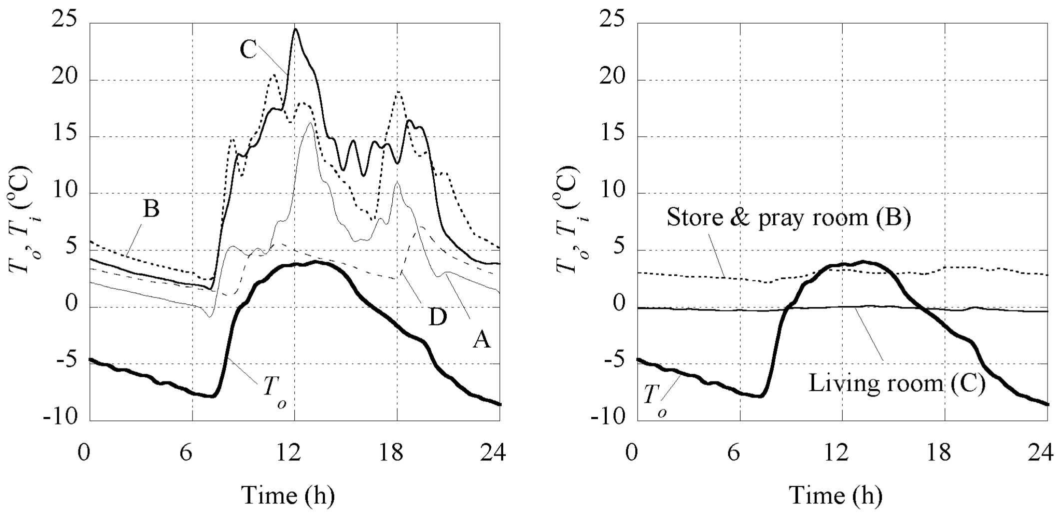
Table 4 shows the indoor and outdoor temperature difference. The indoor air temperature in the heated room was 4.9K higher than outdoors in the daytime and 9.6K higher than outdoors in the night time. The reason might be that people spend most of their time in the kitchen burning animal dung. The thick brick wall might be also effective in keeping houses warm in winter. Residents also adjust the openings, for example doors and windows are shut in winter.

As for the non-heated room, the indoor air temperature was 0.8K higher than outdoors in daytime and 6.4K higher than outdoors in night time (Table 4). There is no internal heat gain in these rooms, and thus the indoor and outdoor temperature difference is much lower than in the heated rooms. People do not spend so much time in the non-heated rooms, and thus the indoor environment is mainly related to the thermal performance of the building.

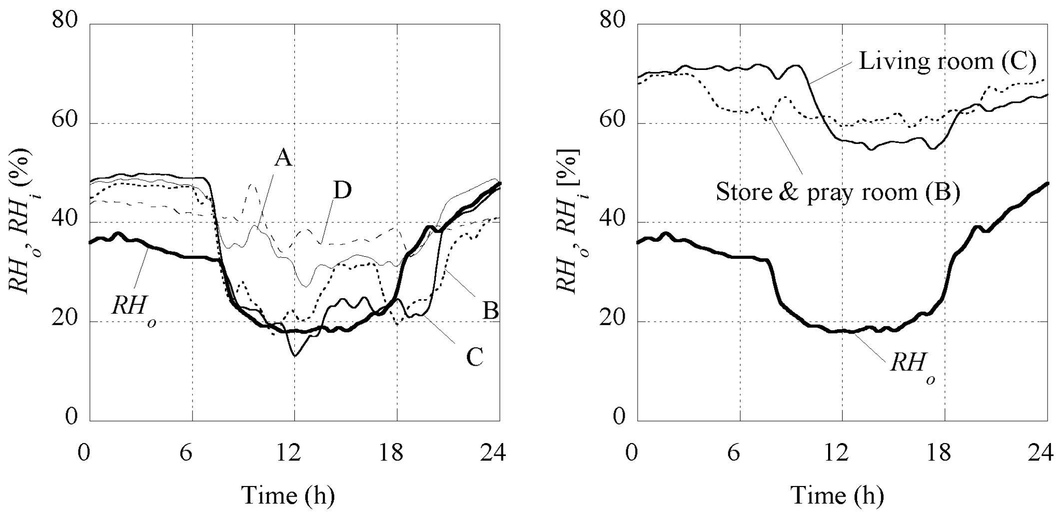
(2) Indoor and outdoor humidity difference

Table 4 shows the indoor and outdoor humidity difference. The indoor absolute humidity in the heated room was 1.9 g/kg' higher than outdoors in daytime and night time (Figure 7(c)). The reasons might be that water vapour is generated from cooking and the moisture may discharge from the thick brick wall.

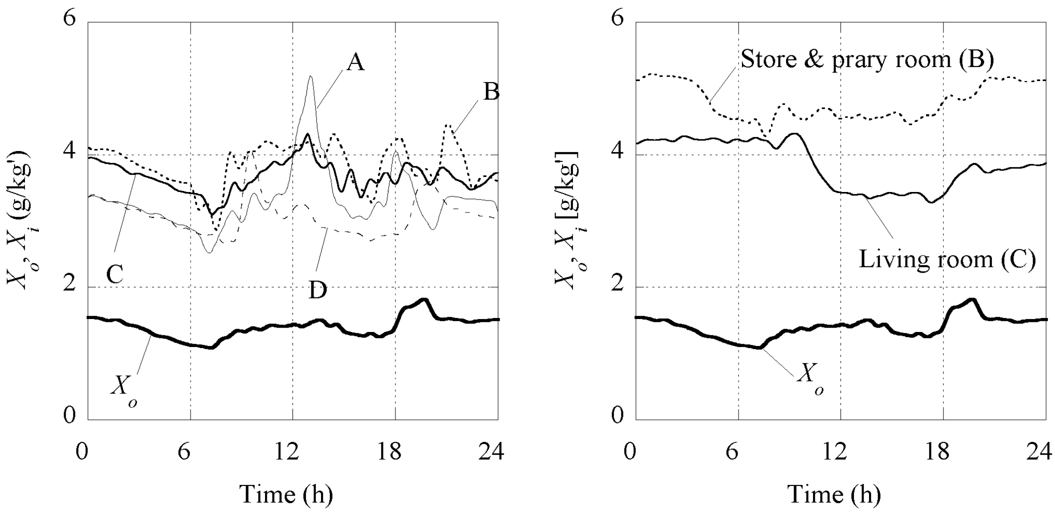
As for the non-heated room, the absolute humidity was 1.9 g/kg' higher than outdoors in daytime and 2.1 g/kg' higher than outdoors in night time (Table 4). The results show that a certain moisture control effect is found in thick brick walls, which is to say that indoor moisture absorption occurs when outdoor humidity is high and indoor moisture discharge occurs when outdoor humidity is low.



(a) Air temperature



(b) Relative humidity



(c) Absolute humidity

Figure 7. Variation of air temperature and humidity (left: with heating, right: without heating).

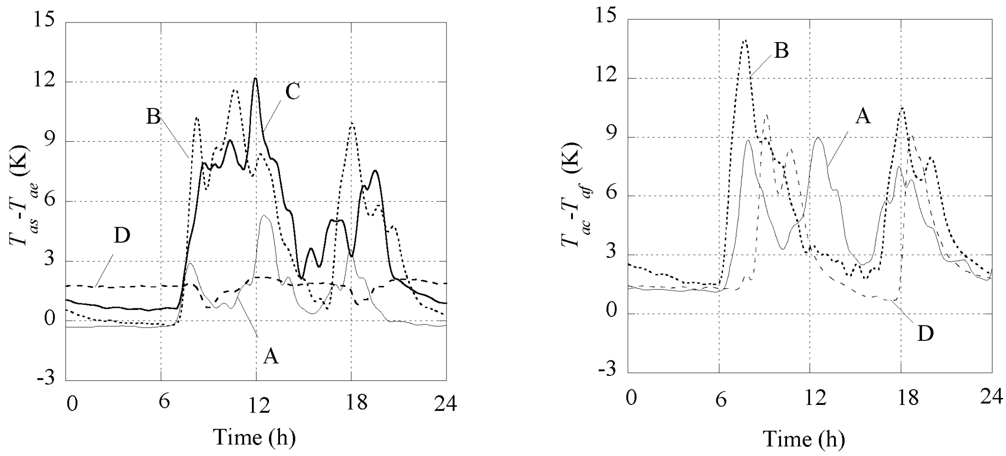
Table 4. Thermal environment of the investigated houses (5-8 January, 2005)

Space	Classification	Room	n	T_i (°C)			T_i-T_o (K)			RH_i (%)			RH_i-RH_o (%)			X_i (g/kg')			X_i-X_o (g/kg')		
				DM	DT	NT	DM	DT	NT	DM	DT	NT	DM	DT	NT	DM	DT	NT	DM	DT	NT
Outdoor	T_o, RH_o, X_o			-3.1	-0.4	-5.8				36	29	43				1.6	1.6	1.7			
Semi-open			1	-1.0	-0.8	-1.2				53	50	56				3.0	2.9	3.1			
Indoor	Heated room	Kitchen*	9	4.1	4.5	3.8	7.2	4.9	9.6	43	41	44	7	13	1	3.5	3.5	3.5	1.9	1.9	1.9
	Non-heated room	Living**	1	-0.3	-0.3	-0.3	2.8	0.1	5.5	67	67	67	31	39	24	4.0	4.0	4.0	2.3	2.4	2.3
		Store+	3	2.3	1.9	2.6	5.3	2.4	8.3	60	58	61	24	29	18	4.3	4.1	4.6	2.7	2.5	2.9
		Pray room	2	-0.4	-0.6	-0.3	2.7	-0.2	5.5	45	44	46	9	15	3	2.6	2.5	2.7	1.0	0.9	1.0
		Mean		0.5	0.4	0.7	3.6	0.8	6.4	57	56	58	21	28	15	3.6	3.5	3.8	2.0	1.9	2.1

n: Number of investigated houses, T_i & T_o: Indoor & outdoor air temperature, RH_i & RH_o: Indoor and outdoor relative humidity, X_i & X_o: Indoor and outdoor absolute humidity, DM: Daily mean, DT (Daytime): 6:00~18:00, NT (Night time): 0:00~6:00 & 18:00~24:00, *: 6 houses are also used for sleeping, **: Mainly use for summer, +: 1 house used for sleeping and 2 houses used for pray room.

3.3. Air temperature distribution of the heated room

Figure 8 (a) shows the air temperature difference between the environment around the stove (T_{as}) and entrance (T_{ae}) and Figure 8 (b) shows the air temperature difference between the area around the ceiling (T_{ac}) and floor (T_{af}). The trend of the horizontal or vertical temperature difference is almost similar. The vertical air temperature difference is significantly high (up to 14K) during the cooking and heating time, which was greater than the ASHRAE thermal comfort standard that is 3K. It was 3.5K (daytime) and 3.0K (night time) (Table 5). The results are similar to the previous study which was conducted in the temperate climate of Nepal (Rijal et al. 2001). The results show that a significant amount of hot air is accumulated around the ceiling which indicates a wastage of heat energy.



(a) Horizontal temperature difference (b) Vertical temperature difference

Figure 8. Horizontal or vertical difference temperature in the heated room.

Table 5. Temperature difference and humidity difference in the heated room.

Description	Period	n	Daily	Daytime	Night time
Horizontal air temperature difference (T_{as}-T_{ae}) (K)	4-10 Jan.	4	2.3	2.9	1.7
Horizontal relative humidity difference (RH_{as}-RH_{ae}) (%)	4-10 Jan.	3	-5.0	-5.0	-4.0
Horizontal absolute humidity difference (X_{as}-X_{ae}) (g/kg')	4-10 Jan.	3	0.0	0.1	-0.1
Vertical air temperature difference (T_{ac}-T_{af}) (K)	4-10 Jan.	6	3.2	3.5	3.0
Surface temperature difference between ceiling and roof (T_{sc}-T_{sr}) (K)	5-10 Jan.	2	9.8	6.0	13.6

T_{as}, RH_{as} & X_{as}: Air temperature, relative humidity & absolute humidity around the stove
T_{ae}, H_{ae} & X_{es}: Air temperature, relative humidity & absolute humidity entrance
T_c & T_f: Air temperature around the ceiling & floor
T_{sc} & T_{sr}: Surface temperature around the ceiling & roof
n: Number of investigated houses

3.4. Thermal insulation performance of roof

To evaluate the thermal insulation performance of the roof, the ceiling surface temperature (T_{sc}) and roof surface temperature (T_{sr}) were compared. The results are shown in Figure 9 and Table 5. The ceiling surface temperature in daytime and night time are 6.0K and 13.6K higher than the roof surface temperature. Consequently, it can be said that mud roof is highly effective for thermal insulation.

3.5. Thermal performance of floor and wall

To evaluate the heat loss and heat gain from the floor and walls, the variation of the heat flux was analysed. The results are shown in Figure 10 and Table 6. The variation of the heat flux is similar in the floor and walls. The mean heat flux was -6.5 W/m^2 in daytime and -3.1 W/m^2 in night time. The results showed that heat loss from indoors to floor or walls occurred in both daytime and night time. However, the maximum heat flux from floor and walls to indoors was 3.7 to 16.2 W/m^2 in night time (Table 6). The reason might be that the floor and walls store the heat in daytime which gradually flows indoors in night time. Thus, the thick brick walls and floor are effective to create a warm indoor environment in winter.

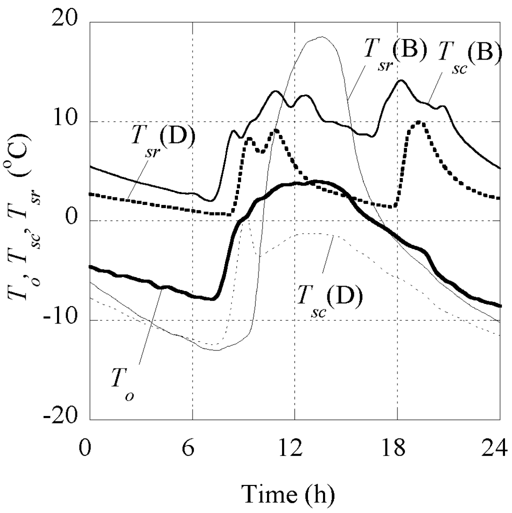


Figure 9. Variation of outdoor air temperature, ceiling and roof surface temperatures.

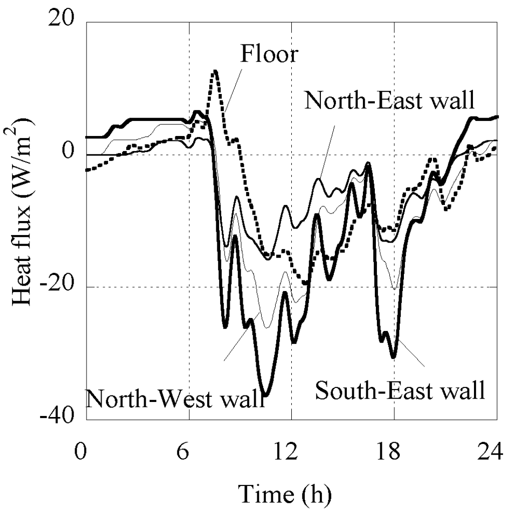


Figure 10. Variation of heat flux of the floor and walls.

Table 6. Heat flux of the floor and walls in the heated room (5-10 January 2005).

Indoor measurement surface (n=1)	Heat flux (W/m²)				
	Daily mean	Daytime	Night time	Max.	Min.
North-East wall	-3.8	-4.9	-2.7	3.7	-19.7
North-West wall	-5.4	-6.5	-4.3	7.3	-28.1
South-east wall	-6.8	-10.1	-3.5	9.3	-42.4
Floor	-3.2	-4.4	-1.9	16.2	-19.7
Mean	-4.8	-6.5	-3.1	9.1	-27.5

n: Number of dwelling, -: Indoor to outdoor flow

4. Thermal adaptation of people

4.1. Thermal environment of the houses A, B and C

The mean indoor and outdoor air temperature, globe temperature and relative humidity are shown in Table 7. The daily mean outdoor and indoor air temperatures (relative humidity) were –2.4°C (30%) and 6.0°C (38%) respectively. The results show that the indoor air temperature and humidity are higher than the outdoor. The indoor air temperatures are also higher that the globe temperature. Daytime indoor air temperature and globe temperature are higher than at night. The opposite applies to relative humidity. It can be said that residents are living in a thermal environment far below the accepted thermal comfort standard.

Table 7. Thermal environment of the houses A, B and C (5-8 January, 2005)

Space	House	Air temperature (°C)			Globe temperature (°C)			Relative humidity (%)		
		DM	DT	NT	DM	DT	NT	DM	DT	NT
Outdoor		-2.4	0.6	-5.4	-	-	-	30	23	37
Indoor	A	3.9	5.5	2.4	3.5	4.9	2.1	38	34	43
	B	7.4	8.1	6.6	6.9	7.7	6.1	36	33	39
	C	6.7	8.9	4.5	6.0	8.1	4.0	39	32	45

Mean	6.0	7.5	4.5	5.5	6.9	4.0	38	33	42

DM: Daly mean, DT: Daytime (6:00 to 18:00), NT: Night time (0:00 to 6:00 & 18:00 to 24:00)

4.2. Thermal satisfaction

In order to evaluate the overall characteristic of thermal sensation vote, we applied the same method as Fanger (1970), Humphreys and Nicol (1970), ASHRAE Standard 55 (2013), and Nicol et al. (1999) used in their research. All of them have suggested the central three categories of TSV votes including neutral can be assumed as 'comfort zone' or 'satisfied' and the rest as 'dissatisfied' or 'discomfort'. We have classified the following 'thermal comfort zone': ±1 for thermal sensation (on a 9-point scale), ±1 for thermal preference (5-point scale); and 0. & 1. for overall comfort (4-point scale) as in the PMV (±0.5 on the 7 point ASHRAE scale). The 'thermal comfort zone' of thermal sensation is wider than the PMV because residents are accustomed to living in a natural environment and have a wider comfort zone than the subjects of an artificial environment (climate chamber experiment). Although the 'thermal comfort zones' include discomfort scales, it is assumed that residents achieve thermal satisfaction by adjusting several passive methods.

To clarify the thermal comfort of the residents, thermal sensation, thermal comfort and thermal preferences were analyzed. The distribution of thermal responses is shown in Figure 11. The mean values of the thermal comfort survey and the globe temperatures are shown in Table 8.

Table 8. Thermal responses and temperatures.

House	No. of sample	Thermal sensation				Thermal preference				Overall comfort				T_{gm} (°C)		T_{gmn} (°C)	
		Mean	S.D.	N	±1	Mean	S.D.	Nc	±1	Mean	S.D.	C	0.&1.	Mean	S.D.	Mean	S.D.
1) A	528	-1.2	0.9	23	68	-1.1	0.5	6	84	0.5	0.5	55	98	5.6	3.0	7.6	2.0
2) B	484	-0.9	0.9	34	77	-0.8	0.6	26	88	0.5	0.6	58	96	8.5	1.6	8.6	1.3
3) C	572	-1.6	0.8	10	37	-1.1	0.4	2	86	0.8	0.5	20	96	9.2	1.9	10.6	1.7
Mean	1,584	-1.3	0.9	22	59	-1.0	0.5	11	86	0.6	0.5	43	97	7.8	2.2	9.0	1.7

S.D.: Standard deviation, N, Nc & C: Frequency of 'Neutral', 'No change' & 'Comfortable' (%), T_{gm} & T_{gmn}: Mean globe temp. when voting & for 'Neutral' vote, ±1 & 0.&1.: Frequency of 'thermal comfort zone'

(1) Thermal sensation

The mean thermal sensation was –1.6 to –0.9 on the 9-point scale. When results from all the spaces are added together, the relative frequency is 22 % for 'neutral' and 59% for 'thermal comfort zone' (Figure 11(a)). The 'cold' sensations are seen in the cold periods of morning and evening, however most sensations are given as 'slightly cool'. When reporting a 'cold' sensation, subjects mentioned cold parts of the body such as soles of the feet, knees, feet, hands and ears.

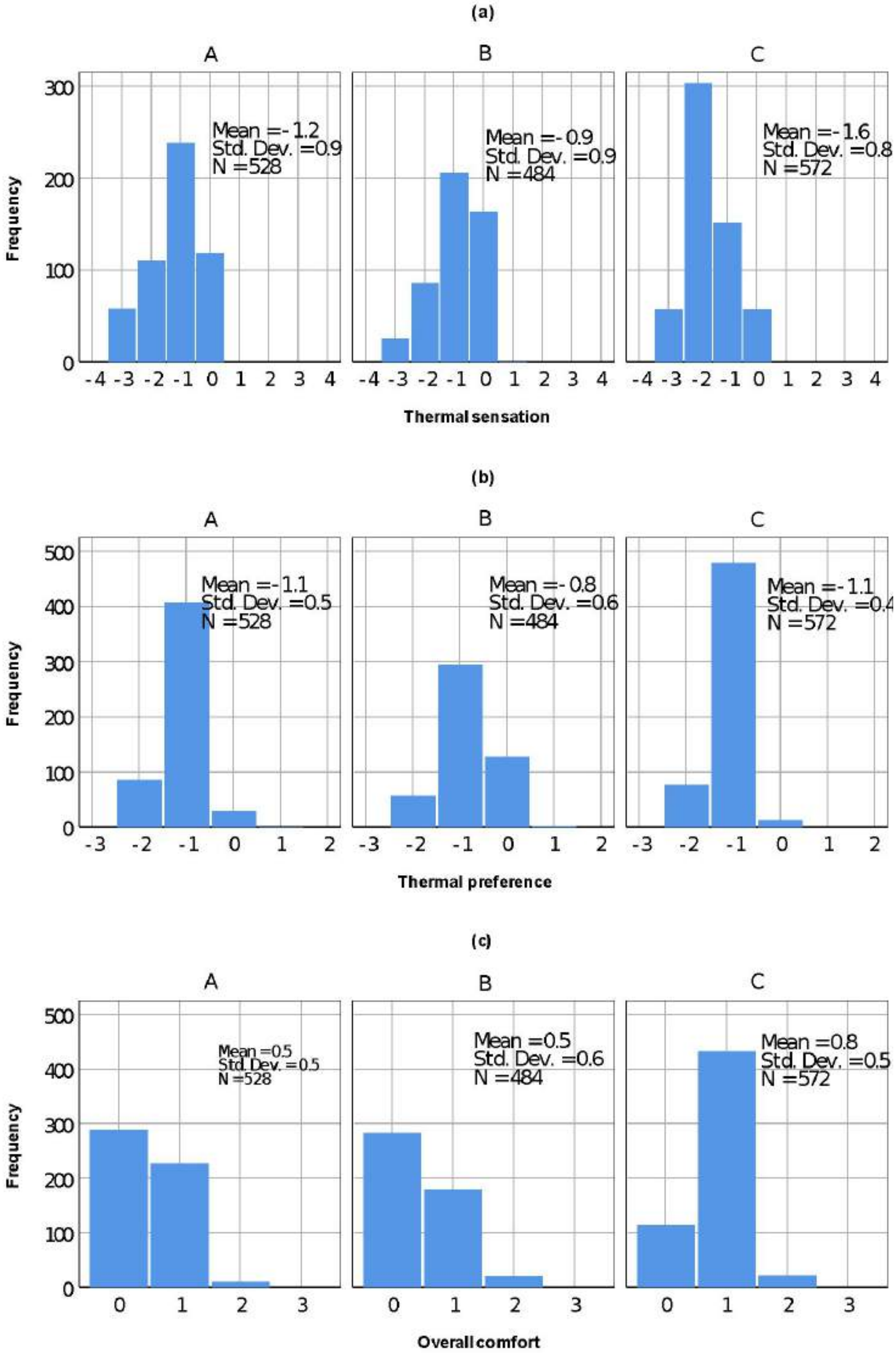


Figure 11. Distribution of thermal responses: (a) Thermal sensation, (b) Thermal preference and (c) Overall comfort.

(2) Thermal preference

The mean thermal preference was –1.1 to –0.8. When the thermal sensation is on the 'cold' side, a 'warmer' vote is reported as a thermal preference (Figure 11(b)). When results from all the spaces were added together, the relative frequency was 11% for 'no change' and 86% for 'thermal comfort zone'.

We have found an interesting relationship between the thermal sensation and thermal preference votes. Even though subjects reported ‘neutral’ in the thermal sensation (n=342), 52% of the votes were for ‘slightly warmer’ in the thermal preference survey. When the subjects were asked the reason for this, they were unable to give one. The reason could be that 1) they would prefer a warmer environment in the winter, 2) they experience a very cold outdoor environment in their everyday life and like to secure a warmer environment, 3) while they are satisfied with the current conditions, they would prefer a warmer environment if possible; a natural desire for most people.

(3) Overall comfort

The mean overall comfort was 0.5 to 0.8. When the results from all the spaces were added together, the relative frequency was 43% for ‘comfortable’ and 97% for ‘thermal comfort zone’ (Figure 11(c)).

(4) Discussion on thermal response

The frequency of ‘thermal comfort zone’ of thermal sensation, thermal preference and overall comfort are high in the evaluated spaces. In all the houses, ‘thermal comfort zone’ of thermal comfort and thermal preference are very similar. While for the ‘thermal comfort zone’ of thermal sensation, house C is lower than the house A and B. It can be said that the thermal satisfaction in traditional houses is considerably high.

4.3. Comfort temperature

(1) Regression method

The correlations between globe temperature and thermal sensation are shown in Figure 12. In determining the mean globe temperature for a certain vote time, temperature readings were taken every five minutes for one hour starting thirty minutes before the vote time and ending thirty minutes afterwards. The following regression equations are obtained:

Group A $TSV=0.19T_g-2.3$ (n=528,117, $R^2=0.37$, S.E.=0.011, $p<0.001$) (1)

Group B $TSV=0.09T_g-1.7$ (n＝484, $R^2=0.03$, S.E.=0.024, $p<0.001$) (2)

Group C $TSV=0.13T_g-2.8$ (n=572, $R^2=0.09$, S.E.=0.017, $p <0.001$) (3)

All $TSV=0.08T_g-1.9$ (n=1584, $R^2=0.07$, S.E.=0.008, $p <0.001$) (4)

TSV is thermal sensation vote, T_g is indoor globe temperature (°C), n is number of sample, R^2 is coefficient of determination, S.E. is standard error of the regression coefficient and p is significance level of regression coefficient.

For example, when the comfort temperature is estimated by substituting ‘0 neutral’ in the equations, it would be 12.1°C for the Group A, 18.9°C for the Group B and 21.5°C in the Group C. This might be due to the problem of applying the regression method in the presence of adaptive behaviour, where it can lead to depressed regression coefficients with consequent effects on the estimate of the comfort temperature if the mean thermal sensation differs much from neutrality, as has been found in previous research (Rijal et al. 2013). To avoid this problem, in the next section the comfort temperature is estimated using the Griffiths’ method.

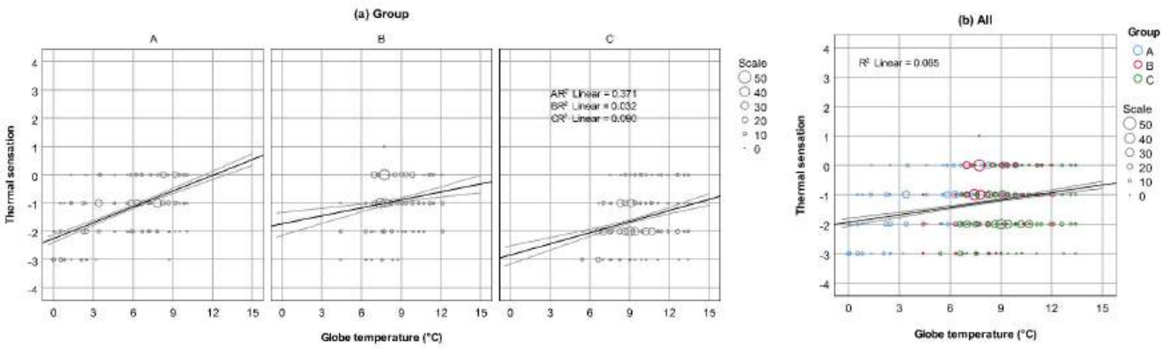


Figure 12. Relation between the thermal sensation and globe temperature.

(2) Griffiths' method

In this section the comfort temperature is estimated by the Griffiths' method (Griffiths 1990, Nicol et al. 1994, Humphreys et al. 2013, Rijal et al. 2017). The calculation method is as follows:

$$T_c = T_g + (0 - \text{TSV}) / a \quad (5)$$

T_c is comfort temperature by Griffiths' method (°C), 0 is 'neutral' thermal sensation vote and 'a' is rate of change of thermal sensation with room temperature.

Nicol et al. (1995) obtained three comfort temperatures by using regression coefficient values (a) of a) 0.19, b) 0.25 and c) 0.33 according to Griffiths' method. a) A coefficient of 0.19 (summer) was obtained by Nicol et al. (1995) in Pakistan. On a 9-point scale, the coefficient obtained in this study is 0.08 from all data (Figure 12 (b)). This value is very small compared with the value of 0.19 (0.25, when converted on the 9-point scale) obtained in Pakistan by Nicol et al. (1995). Nepalese who live in the natural environment may use some methods of 'adaptation', since they always report an almost comfortable thermal response in different environments. b) A coefficient of 0.25 is often obtained in field surveys, according to Nicol et al. (1995). c) A coefficient of 0.33 was obtained by Fanger (1970) in the climate chamber using the probit method. Nicol et al. finally used this value. We have also used this value (0.44: converted to the 9-point scale) to calculate the comfort temperature (Rijal and Yoshida 2006).

(2) Satisfaction with a low comfort temperature

The comfort temperature of the cold climate was determined. When the results from all the spaces are added together, the comfort temperature is 10.7°C, which was lower than the other cold climate (Rijal et al. 2010, Thapa et al. 2018). This may be related to adjustment of the clo value and adaptation in winter. The comfort temperature is 2.7K lower than that of the Solukhumbu district (cold climate). This may be related to the clo value, which was 2.71 clo higher than that of the Solukhumbu district (Rijal et al., 2003, 2010).

(3) Difference in comfort temperature in the same area

To show the differences in comfort temperatures within the same area, the comfort temperatures of houses A, B and C were compared. The comfort temperature of house C is 12.9°C, which is 4.5K and 2.3K higher than those of houses A and B respectively. The mean globe temperature during the investigation period was 5.6°C (house A), 8.5°C (house B) and 9.2°C (house C) (Table 8). In previous research, we also found differences in comfort temperature between the semi-open and indoor spaces (Rijal et al., 2006, 2010). The thermal comfort survey was conducted among residents who were born and grew up in the same investigated area, and if the subjects of house A, B and C were to be changed around and another thermal comfort survey was conducted, a similar kind of comfort temperature could be expected.

Due to the thermal adaptation in each climate, the comfort temperature is related to the indoor temperature (Humphreys 1976, Nicol & Roaf 1996, Rijal et al. 2010, Rijal et al. 2017, Indraganti et al. 2015), and we have therefore compared the indoor globe temperature and the comfort temperature. The correlation between the comfort temperature and indoor globe temperature is quite high (Figures 13 & 14). We have obtained the following equations.

Group A T_c=0.576T_g+5.1 (n=528,117, R^2=0.52, S.E.=0.024, p<0.001) (6)

Group B T_c=0.786T_g+4.0 (n＝484, R^2=0.31, S.E.=0.054, p<0.001) (7)

Group C T_c=0.703T_g+6.4 (n=572, R^2=0.36, S.E.=0.040, p <0.001) (8)

All T_c=0.808T_g+4.4 (n=1584, R^2=0.55, S.E.=0.018, p <0.001) (9)

The results are showing that fundamentally the people had adapted to a large extent to the temperatures that they had.

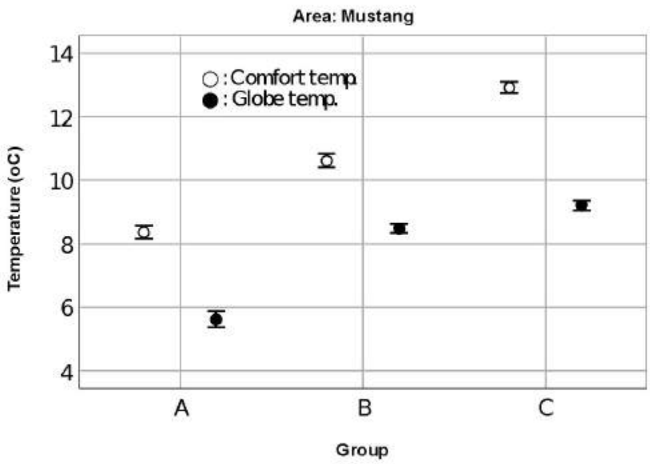


Figure 13. Distribution of thermal responses: (a) Thermal sensation, (b) Thermal preference and (c) Overall comfort.

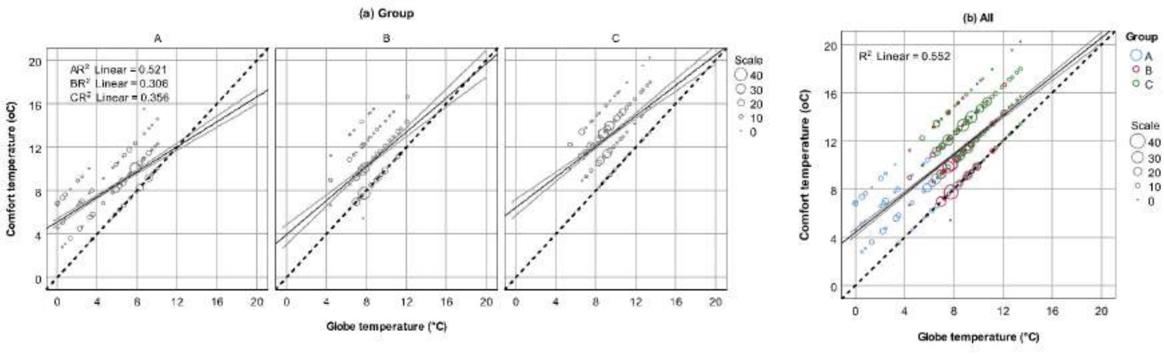


Figure 14. Relation between the thermal sensation and globe temperature.

5. Conclusions

A survey of the thermal environment and thermal comfort was conducted in the winter among residents of traditional houses in the Mustang district in Nepal. The results are:

1. Night time indoor air temperature is 9.6K higher than the outdoor air temperature. Passive heating effects are found in the earthen floors and mud roof, all of which are effective for keeping warm in the winter.

2. The frequency of the ‘thermal comfort zone’ is high in thermal sensation, thermal preference and overall comfort. The residents are satisfied with the thermal condition of the traditional houses.
3. The average comfort temperature was 10.7°C, which is lower than the thermal comfort standard. Due to modifications in clothing and adaptation to winter conditions, the comfort temperature is lower than that of the Solukhumbu district (cold climate).
4. The comfort temperature of ‘House C’ was 12.9 °C, which is 4.5 K and 2.3 K higher than houses ‘A’ and ‘B’ respectively. There are differences in comfort temperatures within the same area. Residents appear to have a certain range of comfort zones, and the comfort temperature could be determined by the degree of exposed air temperature. It means that the comfort temperature is directly related to the thermal environment.

6. Acknowledgments

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Characterization of Passive Cooling Systems for an Extreme Hot Humid Climate

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Abstract: The consumption of energy for air conditioning in buildings has increased exponentially, exacerbated by the effects of Global Warming and Climate Change, this situation is particularly evident in hot climates. A promising alternative to mitigate this problem is the implementation of passive cooling systems, which can contribute to reduce energy consumption and at the same time provide hygrothermal comfort conditions for the building´s occupant. In particular, this situation is more severe in warm humid climates, where the implementation of indirect evaporative cooling systems is a promising approach. This investigation presents the results of a preliminary study conducted in experimental modules with five different systems, integrated on their top cover, compared with a control module. This investigation was carried out in the City of Mérida, Yucatán, Mexico, a climate with typical hot humid conditions. The methodology applied started with a calibration procedure of the equipment and data acquisition systems, followed by a pilot test conducted with a concurrent monitoring process in the six modules for ten days during a typical overheating period. The results indicated that the indoor air temperature in the best module reduced 5K relative to the maximum exterior temperature. This revealed a potential for energy savings by reducing the use of air conditioning, and whilst achieving hygrothermal comfort conditions for the occupants. These experiments will continue during other representative climatic, transitional and underheating periods.

Keywords: Passive cooling, energy savings, hot humid, indirect evaporative cooling, comfort.

1. Introduction. Situation of Temperature Increase on Earth´s Surface Relative to Energy Consumption

With the emergence of the Industrial Revolution in the mid-eighteenth century, when the exploitation and use of coal began, there were various events and changes in society and the environment. From this historical event, the exploitation and burning of the so-called fossil fuels have provoked a severe impact on the environment of the planet and has detonated the effects of Global Warming and Climate Change.

Data updated in real time indicate that the temperature increase from 1880 to 2018 has been evident and constant (NASA, 2018) (Figure 1). These seasonal cycle data clearly show the increase in temperatures globally and that during the typical overheating period, which frequently occurs earlier and extends longer; sometimes the approximate duration on average can be more than six months, depending on the geographical and climatic conditions of each location.

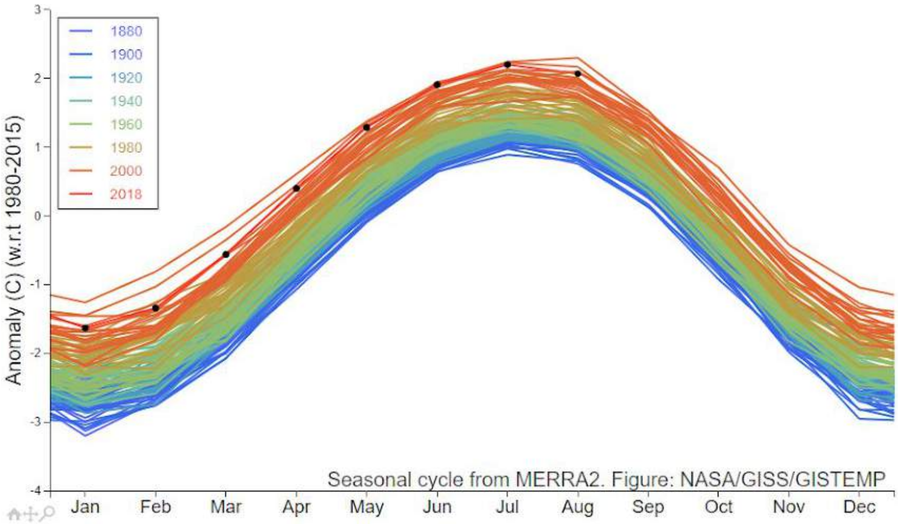

Figure 1. Seasonal cycle of temperature variation in the earth's surface during the Period 1880 to 2018.
Source: NASA 2018. Merra2. NASA / GISSTEMP Oct 9, 2018.

At present, global energy consumption patterns, which mostly come from fossil fuels (coal, oil and natural gas), have increased considerably, causing severe damage to the environment. Historical statistics, of the consumption of energy worldwide since 1830, a little after the emergence of their IR to 2010 (IEA, WEO, 2010), indicate that, in order to supply the goods and services required, anthropogenic activities were carried out with the burning of ten times more energy than in the previous century. Of the total energy consumed in 2010, 80% came from fossil fuels, 11.3% from bioenergy, mainly from the combustion of wood and firewood, 5.5% from nuclear energy, 2.2% from hydraulic energy and only 0.4% of other renewable energy sources.

The intensive use and burning of these three fossil fuels due to anthropogenic activities, have affected intensively and extensively various ecosystems of the planet, including Man. Updated data in real time indicate that the temperature increase from 1880 to 2018 has been evident and constant (NASA, 2018) (Figure 2).

Currently, the statistics report a global annual energy consumption in 2017 of 13,511.20 million tons of oil equivalent (mtoe). (BP, 2018), and that undoubtedly indicates that the predominant energy comes mainly from fossil fuels.

In the case of Mexico, per capita electricity consumption has increased considerably, from 501,445 kWh in 1971 to 2,090,176 kWh in 2017 (IEA and World Bank, 2018), which represents an increase of more than 400% (4.17 times greater) during this period. In the case of total energy consumption per capita, the value is 1.4 tons of oil equivalent (toe). Factors attributed to this situation are the population increase and the economic rise, among others.

In an analysis of electricity consumption by sectors in Mexico, the company that supplies electricity, CFE, (SENER, 2018) reports that in 2015, on average, the 88.8% of consumers come from the residential sector; the commercial one, represents approximately 10%; the industrial 0.8%; services 0.5%; and the agricultural 0.3%. The residential sector has the highest increase since 2007 (Figure 3).

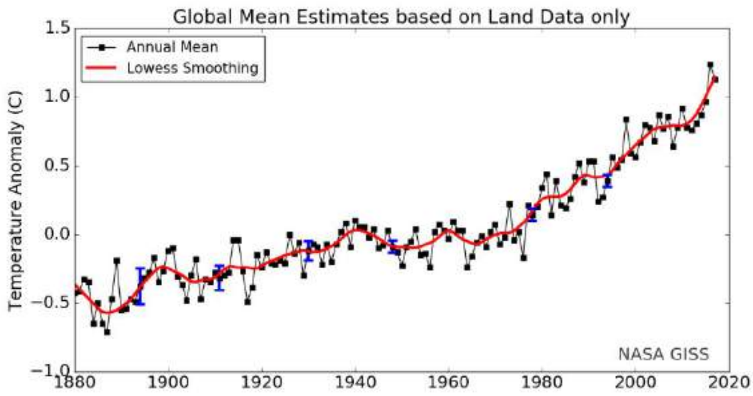

Figure 2. Increase in global average surface temperature and projection to the year 2020. Global Mean Land Surface Temperature
Source: National Aeronautics and Space Administration NASA (2018).

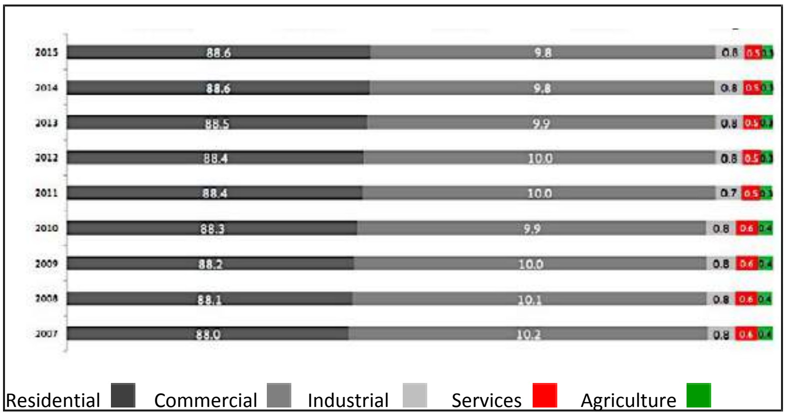

Figure 3. Annual electricity consumption by sectors from 2007 to 2015
Fuente: SENER, 2018. Prospects for the Energy Sector 2016-2030.
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2. Situation of Energy Consumption for HVAC in Buildings

The growth of Global Warming and the intensification Climate Change at global level is directly related to the exponential progression in the use of air conditioning systems in buildings and shows a fast increase, particularly in urban locations. Another important aspect is the amount of energy used, as more than 80% comes from the highly polluting fossil fuels (Figure 4).

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 economic and population growth and will be observed with greater evidence in hot regions as well as in mild climates during the overheating season. Therefore, the use of 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 to the atmosphere and the eventual climate deterioration.

For example 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 necessary to apply actions to solve the problem provoked by the intense and growing use of air conditioning, and one of the most important is to improve its energy efficiency aimed at 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.

Within the utilization of air conditioning systems, the fastest-growing use of energy in buildings is for space cooling, mainly in both hot humid regions where incomes 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

3. Consequences of Environmental Deterioration in the Planet

At present, the world is facing a severe environmental problem provoked by the GW due to the increase of greenhouse gasses, mainly carbon dioxide (CO_2), methane (CH_4) and nitrogen oxides (NxOy), produced by human influence (IPCC, 2016). Some of the consequences of GW include the continuous retreat of glaciers, permafrost, the layer of floating sea ice that forms in the Polar Regions, more extreme and frequent meteorological phenomena, ocean acidification and the increase in surface temperature in the land and in the oceans, among others factors.

The projections of the climate models (Figure 5) indicate that the temperature will increase between 0.3 and 1.7 K, in the case of the more moderate emission scenario (NASA, 2018). Considering the situation of current energy consumption and the consequences of the severe environmental deterioration globally, including Mexico, it is urgent to implement alternative solutions to solve this problem.

A promising alternative to mitigate this situation in hot humid climates is to improve the efficiency of the air conditioning systems, as well as with the application of passive cooling systems, particularly using Indirect Evaporative strategies. 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 greenhouse gasses whilst mitigating the Climate Change and thus contribute to the preservation and improvement of the environment.

4. Case Study. Indirect Evaporative Passive Cooling Systems. Location: Merida, Yucatan, Mexico. Experimental work

The main objective of this research is to evaluate and characterize different Indirect Evaporative Passive Cooling Systems (IEPCS) in experimental modules in their cover zone, aimed at achieving both thermal comfort conditions in buildings in hot-humid climates of Mexico and energy savings.

The Case Study of this research is located in the City of Merida, Yucatan, Mexico, which has predominant hot-humid conditions. The methodology consisted of the development of experimental tests during a representative overheating period.

The initial process included the calibration of data loggers used in the experiments, and the results obtained indicated a consistency in the recorded values, which validated their use with reliability. Experimental modules were built with five different IEPCS systems, relative to a control or reference module. The experimental modules integrated in their cover different IEPCS (Figures 5 a, b, c).

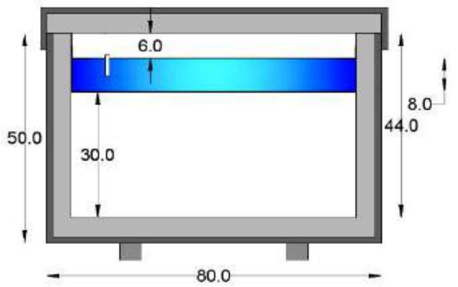


Figure 5a. Geometry and characteristics of control module (section)

Figure 5b. Control module (isometric)

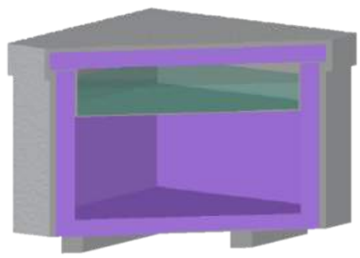


Figure 5c. Control module (section, component view)

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.

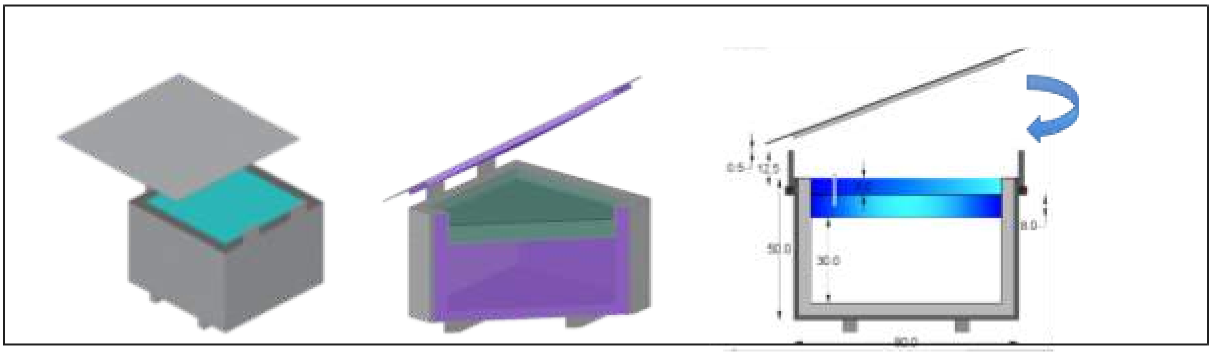
This material is a thermal insulation made of rigid polystyrene foam with a thermal conductivity value (K) for an average external temperature of 24 °C, its value is: 0.0288 W/mK; for an average outdoor temperature of 4.4 °C, its value is: 0.0259 W/mK. It was selected for its high resistance to humidity 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 is provided with a layer of sealer for wood, to prevent weathering of the material exposed to the sun and rain; and finally 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 6 and 7).

Figure 6. View of module with data logger on centre for monitoring of DBT and relative humidity

Figure 7. View of the experimental modules in process of data recording

The main objective of this research was to evaluate and characterize different Passive Cooling Systems (PCS) systems aimed at providing thermal comfort in buildings of hot-humid climates using experimental modules, which included the following systems: Thermal mass (TM), thermal insulation (TI), night radiative cooling (NRC), indirect evaporative cooling (IEC) and solar control (SC). The configurations were distributed as follows: Module 1: TM + TI; Module 2: NRC + TM; Module 3: IEC + TM + SC and Module 4: NRC + IEC + TM + SC. In the procedure of modules M2 and M4, where the NRC system was implemented, to consider the night radiant cooling, a variant was included, with respect to the other modules, which consisted of removing the top cover at 18:00 hrs , and place it again at 6:00 am period (Figures 8 a, b and c).



Figures 8a, b and c. M4 experimental module with the implementation of bioclimatic systems NRC + IEC + TM + SC
Night mode: Remove cover from 6:00 p.m. to 6:00 p.m. the next day
Day mode: Place lid from 6:00 a.m. to 6:00 p.m. on the same day

After the calibration and the climate analysis of the location, a simultaneous monitoring of indoor Dry Bulb Temperatures (DBT) was carried out in the modules for ten days in a typical overheating period. During the monitoring, the climatic values of the exterior were obtained concurrently, through the nearest EMA (Automated Meteorological Station).

5. Analysis and Interpretation of Results

During the monitoring period, values of DBT and relative humidity were recorded at every 10 minutes interval. The values obtained were ordered and averaged over a 24-hour cycle. The results indicated that the average temperatures inside the modules decreased with respect to the maximum external temperatures of the EMA.

The average temperature in the M1 module, between 14 and 16 hrs, when the maximum temperature was recorded outside, is the one that showed the best performance, with a reduction of 5 K. Also, during the periods of higher temperatures outside, the maximum temperatures in modules M1 and M4, (Figure 9). As regards the M3 and M4 modules, they also showed a reduction of DBT.

Therefore, the values obtained showed that it is feasible to achieve a temperature reduction with the cooling systems investigated and consequently, an important saving in energy consumption.

At this stage of the research, the results revealed a potential for energy savings in the systems investigated, which can be applied with the integration of other cooling systems in real buildings in hot humid climates, and at the same time achieve occupants thermal comfort conditions the. These experiments will continue during other climatic periods of transition and underheating.

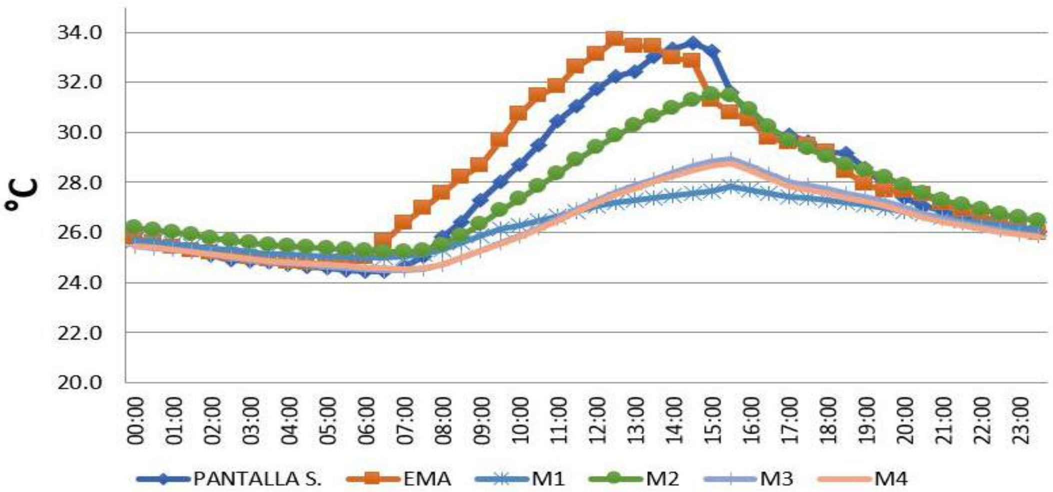


Figure 9. Average hourly temperature behaviour in the modules during monitoring

6. Conclusions

The envelope of the buildings, consisting of roofs, windows, floors, exterior walls, doors and foundations plays a very important role in the thermal behaviour and has a huge impact on the AC requirements of the spaces and the choice of materials is of great importance. In particular, the thermal mass is essential for the reduction of thermal swings. The use of thermal mass, such as the confined M4, applicable in this work, is important for the cooling of spaces, as well as the other integrated bioclimatic strategies: thermal insulation, solar control system, convective cooling, nocturnal radiative and indirect evaporative cooling. The implementation of these passive cooling systems in buildings and homes, where people cannot afford the acquisition of air conditioning equipment and the payment of electricity, is a viable alternative to achieve thermal comfort conditions as well as energy savings. The implementation of these bioclimatic strategies has also a significant social-economic value as are associated with a reduction of energy consumption, directly related to energy savings and the improvement of the economy. On the other hand, the resultant reduction of GHG emissions can provide an improvement of the environment as well as on the quality of living and, most importantly, on the health of people, favouring the reduction of Global Warming and the mitigation of global Climate Change to benefit the present and future generations.

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Identity through Efficiency. (Re-)Discovering Passive Cooling Strategies as an Architectural Idiom for the Gulf Region

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Abstract: The current architectural discourse in the Gulf runs in parallel streams. One is about creating identity through architecture and is focused on the appearance of buildings, as can be seen in many recently built public buildings that are designed with metaphoric images as expressive conveyors of a certain message. The other is about energy-efficiency and aims at enhancing the performance of buildings in the extreme local climate, which is demonstrated in the growing number of large commercial buildings that are audited and certified in energy-rating systems but are otherwise generic designs. While in the one discourse architectural form has a purely symbolic function it is negated in the other and overridden by technology. The problem is that these two discourses are disconnected. The scope of this paper is to show how efficiency and identity of buildings are connected through the issue of passive design strategies that can achieve both aims through architectural form. In order to analyse and communicate "proven solutions to recurring problems" about passive design strategies from the modern Gulf architecture, Alexander's Pattern Language method is applied. The result is a first collection of patterns that lays the basis for an architectural idiom that is place-specific and therefore energy-efficient and identity-generating at the same time.

Keywords: Gulf, modern architecture, passive design strategies, pattern language, identity

1. Introduction

Through the discovery and exploitation of fossil fuels resources in the 1960s, the societies of the Gulf entered into a phase of modernisation that led to a radical transformation of previously traditional cultures. These shifts are demonstrated, for example, in the fundamental changes of the architectural forms and urban settlement patterns of the region over the past two generations. The emergence of larger cities was driven by the abundant availability of energy for transport and cooling at very low costs as well as the almost endless availability of land for settlements due to the absence of agricultural hinterlands. Both factors led to unrestricted urban expansion with scattered, generic building designs and expansive traffic infrastructure. These particular settlement structures and architectures are neither a successful response to the extreme climate of the region nor do they create a regionally specific sense of place for its inhabitants. The problem of a lack of energy-efficiency as well as of identity of buildings seems to stem from the same source: an ignorance of the conditions of the extreme local climate and the lack of architectural responses to this.

1.1. Climate Conditions

The main settlements in the Gulf region are coastal cities, for example, Kuwait, Manama, Doha, Abu Dhabi, Dubai or Muscat, with the exception of Mecca and Riyadh, which are inland settlements. Jeddah is also a coastal city, but located on the Red Sea. In the Koeppen-Geiger classification of climate zones, the Gulf region is defined as an arid, hot desert climate (BWh) (Wikipedia, 2018). However, there are significant differences between the coastal desert climate of the Gulf region and the inland desert climate of the Arab peninsula. In both areas, summer is uncomfortably hot with temperature peaks between 40°-50°C, while winter is pleasantly cool with temperatures between 20°-30°. Also precipitation in both regions is not more than 100mm per year. However, the coastal climate has a much higher humidity and much lower diurnal temperature range than the inland climate, which means that the architectural and technological responses to these conditions are necessarily different.

1.2 Active and Passive Strategies

Creating comfortable conditions within buildings or open spaces can be achieved through two sets of strategies. On the one hand, the so-called passive strategies encompass all measures from urban design to architectural form to building construction that - in a hot climate like in the Gulf region - help to minimize the heat gains in buildings or in open spaces, for example through orientation, ventilation, shading and insulation. The active strategies, on the other hand, consist of all technological and operational measures that are necessary to cool buildings or open spaces beyond the level that can be achieved through passive means, for example air-conditioning, appliances and building management systems.

Both strategies, when successfully applied, lead to energy-efficiency, but only the built expression of architecture as form can contribute to creating an identity of a place. Or, as one of the pioneers of climate adapted architecture, Edward Mazria, said, "a building (...) is the passive system" (Mazria, 1980). Thus the simultaneous search for energy-efficiency and identity of buildings leads to a focus on passive design strategies. While active strategies work everywhere and are placeless, passive strategies are place-specific and thus can be a source of regionally specific form and identity. The question is which passive design strategies were effectively applied in the Gulf's extreme climate and how can these formal responses to the climate be conducive to the formation of an architectural idiom that is specific to the region?

2. Method

The aim of this study is to identify successful passive design strategies for the extreme climate of the Gulf region and to articulate them in such a way that they can be understood and applied by architects as well as non-architects, i.e. anybody who is involved in planning processes. An appropriate method to achieve this aim seems to be the "Pattern Language" that was developed by the architect Christopher Alexander in the 1970s (Alexander, 1977) and was since used for similar purposes of identifying and communicating successful practices in architecture, but also - actually predominantly so - in various disciplines beyond the realm of architecture (Knebel, 2015).

2.1. Patterns as a Method

The Pattern Language method was developed as a means to collect and present "proven solutions to recurring problems" (Alexander, 1977) in urban planning, architecture and building construction. Alexander and his team of architects argued that common-sense knowledge about quality in the built environment was lost during the period of modernism and thus had to be retrieved and made accessible again to all stakeholders involved in planning processes. The methodical approach to achieve this was to conceptually decompose existing, complex spatial and social situations of the built environment, that were deemed to create quality environments, into their constituent parts - the "patterns" - and then recompose these parts through applying a grammar-like structure of combining the single parts into a coherent whole - the "pattern language". The Pattern Language method is thus not about creating new knowledge, but about rediscovering and describing existing knowledge of successful solutions to problems so that ever new combinations of patterns can be generated with them. In order to manage this potentially endless amount of knowledge in an applicable way, Alexander introduced a standardized format for describing patterns. In the so-called Alexandrian format every pattern consists of (Wellhausen & Fießner, 2011):

- a distinct *name*
- an atmospheric description of the *context* or the circumstances in which the pattern takes places (followed by three asterisks)
- a clear *problem* statement (in bold font)
- a reflective overview of the *forces* that create the problem
- a presentation of the *solution* with focus on the recommended action to solve the problem (introduced by the word "Therefore:", and presented in bold font)
- a description of the *consequences* that follow when the solution is applied
- and a list of *links* to other patterns that either preceded or succeeded the described pattern in the process of design and embed the single pattern in the overall construct of the pattern language for the selected realm or discipline.

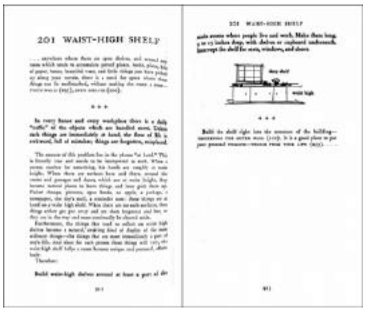
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Figure 1. A page from the Pattern Language book by Christopher Alexander

While Alexander's Pattern Language was received very critically in the discipline of architecture (Dovey, 1990), the pattern language method was very enthusiastically applied in other disciplines, such as e.g. software programming, management theory, pedagogics and many others (Cunningham, 2013). The reason for this surprisingly divisive echo lies in the question of whether the application of the pattern Language is focussed on the content that it tries to generate or on the method of how it describes a given topic. Alexander focussed on content and used the Pattern Language for promoting a very conservative, some would even say reactionary approach to architecture, which led to a wholesale rejection of the method among contemporary architects (Alexander & Eisenmann, 1983). Others, like the software programmer Ward Cunningham, who was also the initiator of the first Wiki, found the Pattern Language a brilliant method for collectively describing and sharing knowledge about problem-solving strategies in digestible portions (Cunningham, 2013). Thus the Pattern Language evolved as a method outside of its initial discipline in fields where the content to which the method was applied was less burdened with ideological debates, like e.g. the conflict between modern vs. traditional architecture. Consequently, the most well-known and long-lived application of the Pattern Language until today is in the realm of software programming (Gamma et al., 1994). However, there are two successful utilizations of the Pattern Language in the original realm of architecture that show the applicability of this method for the above-stated purpose.

2.2. Examples for the Application of the Method

Only two years after the publication of Christopher Alexander's "A Pattern Language", the American architect Edward Mazria published "The Passive Solar Energy Book" (Mazria, 1979), which presents twenty-seven basic rules of thumb for the application of passive design strategies for buildings. "We call these rules of thumb 'patterns'", wrote Mazria, (Mazria, 1979), and, without explicitly mentioning Alexander, applied the Pattern Language method as a means to communicate existing knowledge of the design of energy-efficient buildings in such a way that laymen as well as experts can understand, discuss, apply and, finally, expand this knowledge in practice. Interestingly, Mazria sees patterns not only as a tool to design, but as a means "to analyze or critique existing buildings or proposed designs" (Mazria, 1979). Further, he emphasizes the potential of the Pattern Language as a "flexible" method to not only store but also to develop knowledge so that patterns can "evolve over time" (Mazria, 1979).

Another, more recent application of the Pattern Language method in the field of architecture and climate adapted passive design is the web application "2030 Palette: A resource for the design of zero net carbon, adaptable and resilient built environments world wide" that was launched in 2011 by the Mexican-American architect Alfredo Fernández-González (Fernández-González, 2013). This online platform consists of more than 60 so-called "swatches or sustainable design strategies" that - like Mazria's "rules of thumb" - are put "at the fingertips of designers, planners, and builders" to provide inspiration and information during the process of designing buildings with passive strategies. While Mazria's rules of thumb were communicated analogue, Fernández-González's swatches are digital and provide the designer with a real-time feedback on the effect of applying a passive design strategy in a project due to the conjunction of the platform with energy analysis software tools. Like Mazria, Fernández-González does not explicitly mention Christopher Alexander's Pattern Language as a reference, but directly uses the method and terms. Fernández-González initially titled his research on swatches "Five Passive Cooling Patterns for Architecture 2030" (Fernández-González, 2011) and - like Alexander - categorizes them according to the scale of the planning problem from regional planning to building construction. Further, the way in which the swatches are described as solutions to problems and how the consequences of the content and links of the swatches to related swatches are presented are clear indications that Alexander's pattern format stood precedent.

These two examples show that the Pattern Language method can be successfully applied to the task of gathering and disseminating knowledge of passive design strategies in architecture. However, both applications use the method as a means to communicate information about architecture rather than to generate architecture itself. As shown in the examples above and also in further research by the author on this topic (Knebel, 2017) it can be argued that, while Alexander intended to use the Pattern Language as a design method, it is actually most successfully applied as a content management system. The great achievement of this method lies in establishing a format for extracting and articulating knowledge from a large case base and making it available for a process of case-based reasoning (Kolodner, 1992); a process that, in the end, comes closest to the way designers think up their projects (Knebel, 2018).

The knowledge about passive design strategies for the architecture in the Gulf region already exists in the projects of the past and present, however, until today, it is not retrieved in a coherent manner that builds up a case base on this topic that is accessible and applicable for designers in practice. With the above presented analysis of the use of the pattern language method for building up a case base, it seems appropriate to apply this method to the given research question.

2.3. Sources for Retrieving Patterns

The material for this research into the typological consequences of applying passive design strategies to buildings in the Gulf region is scattered over many different sources.

For the cases of traditional buildings from before the oil-boom (-1960) the research into passive design strategies is quite well-documented and, currently, attempts being made to coordinate the documentation of these findings centrally (Qatar National Library, 2018). For the cases of modern buildings from the first generation (1960-1990) the sources are spread across many different sources. For example, Koolhaas explored the stories of architecture and planning in the whole Gulf region in mixed formats and published an almanac (Bouman, Khoubrou, Koolhaas, 2007); Menoret gathered material on modernist architecture of Abu Dhabi as an e-book (Menoret, 2014); Fabri et al. discovered the first generation of modern building and planning in Kuwait through interviews with the protagonists and individual project documentations (Fabri et al, 2015, 2018); Arbid edited a compilation of modernist projects from the region as part of Bahrain's contribution to the architecture biennale in Venice (Arbid, 2014) and Elsheshtawy presented a documentation of early modern housing projects from Abu Dhabi at the same event two years later (Elsheshtawy, 2016). For the cases of the second generation (1990 - 2020), the contemporary architecture of the region, documentation is available in project compilations like, for example, Schöneberg's book about German architects in Arabia (e.g. Schöneberg, 2008); monographies of individual buildings like the Louvre Abu Dhabi (Global Architecture, 2018); or websites of individual architects and online periodicals (e.g. archdaily). However, until today, there is no systematic and comprehensive publication on the use of passive design strategies in modern and contemporary buildings in the Gulf region, yet. This study is a first step towards this goal.

In order to provide patterns that inspire, the examples were not only taken from the Gulf region but from locations that are roughly between the 20th and 30th degree latitude. Even though the temperature and humidity conditions might vary to a certain degree, at least the daylight situation is similar, and thus, some of the passive design strategies applied to buildings in these locations can be projected back onto cases of architecture in the Gulf region.

2.4. Criteria for Retrieving Patterns

Following Alexander's definition of patterns as "proven solutions to recurring problems" the question is how to covert this definition into concrete criteria for identifying patterns within the given material. For the scope of this research the range of "recurring problems" can be limited to the ones that are caused by the extreme climate, such as, for example, intense solar irradiance, high outdoor temperatures, high relative humidity, or lack of vegetation. Further, the criterion of a "proven solution" is interpreted as a qualitative judgement about the effectiveness of a passive design strategy, for example, the effect of an external shading device for cooling a facade. Further, the validity of a patterns is proven by presenting more than one example of its application. In this early stage of the study the effectiveness of the patterns is based on a qualitative judgement based on the professional and regional experience of the author rather than on a quantitative calculation. It should be mentioned that such retroactive quantitative assessments of passive design strategies on the energy-efficiency of buildings from the modernist period were recently undertaken by researchers for cases from other regions (Gonçalves et al, 2018) (Abraham & Saba, 2018) and led to very relevant comparisons of the assumed and actual effectiveness of passive design strategies from before the age when digital simulations began to guide designs. While such retroactive, quantitative proof of concept is beyond the scope of this paper, it is seen as a relevant next research step of this study project.

3. Patterns

The following seven patterns are a starting point of this study and will be extended over time. In order to familiarize the reader with the format of patterns the focus of each paragraphs are indicated in italics *(context, problem, (forces), solution, (consequences), examples)*, but only in the first example

3.1. ROOF OVER

... *(Context)* in traditional cities of the Gulf region, the urban fabric was often very dense, leaving only narrow alleys between buildings, which then mutually shaded each other as well as the public spaces in-between. Highly frequented public spaces, like e.g. souks, were even roofed-over to provide comfort through shaded outdoor spaces. But in modernist city structures, the distances between buildings are often much larger due to a car-oriented city planning. This results in wide open spaces between buildings that are fully exposed to the sun and heat up beyond comfortable conditions and become uninhabitable at times. As a consequence, most public spaces have become indoor spaces, and are actually no longer truly public, because access is socially exclusive instead of inclusive.

* * *

(Problem) **In the region between 20°-30° degrees latitude most of the solar irradiance is on horizontal surfaces. Open spaces between buildings are most affected. Unless the open spaces provide comfortable conditions they will not be usable as public spaces, which are a fundamental necessity for an inclusive urban society as well as for a healthy living in a walkable city.**

Therefore:

(Solution) **Look for cover. Roof over public outdoor spaces. Despite the harsh climate of the region - open public spaces can be turned into comfortable places through all kinds of horizontal layers that passively moderate sun, light and wind.**

* * *

(Examples) An early example of a shaded outdoor space that is integrated with a building or, as in this case, rather an ensemble of buildings is the Kuwait National Museum by Michel Ecochard that was designed in 1960 and finally opened in 1983 (Fabri, Saragoca, Camacho, 2015). The building consists of four free-standing, two-storey high volumes that are arranged in a wind-mill shape around a large central courtyard covered by a wide space-frame structure, which is upheld higher than the surrounding buildings by four expressively sculpted columns. The large, semi-transparent roof over the courtyard is a passive device that creates a pleasantly mediated climate for a publicly accessible green outdoor space in the city.

 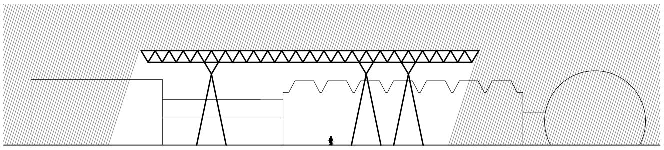

Figure 2. Kuwait National Museum, Michel Ecochard (1960). 29.4°N, 48.0°E

Further, a series of umbrella projects by the German architect Mahmoud Bodo Rasch demonstrate how the construction of efficient passive cooling devices enhances the comfort as well as the identity of public places in the harsh climate of the region. The works built in front of the Prophet's Mosque in Medina (1992, 2011) are a continuous improvement of the mechanisms of light-weight, large-span and retractable umbrellas each covering an area of up to 300sq.m (Rasch, 2016). The "forest" of umbrellas convert the previously open-to-sky public spaces into softly- and evenly lit, naturally ventilated and shaded outdoor spaces with a memorable and comfortable atmosphere.

 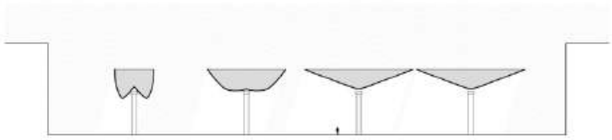

Figure 3. Bodo Rasch / SL Rasch: Umbrellas in Medina. 24.5°N, 39.6°E

The yet unbuilt Al Fayah Park in Abu Dhabi presented by heatherwickstudio takes the idea of shading public outdoor spaces one step further. Instead of exposing visitors and vegetation to the sun, the whole park is entrenched and the cave-like underground spaces are lit and ventilated through large "cracks" in the surface (Studio Heatherwick, 2010). With plenty of shade-tolerant plants and water-bodies dispersed under the heavy "roof", passive cooling of the outdoor space seems efficient (yet, additional cooling of the surfaces through a hydronic radiant cooling system were discussed in the planning process).

 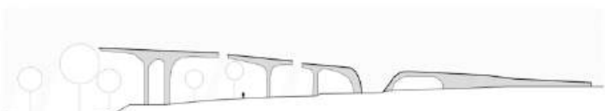

Figure 5. heatherwickstudio: Al Fayah Park. 24.5°N, 54.4°E

3.2. DOUBLE UP

... most traditional architecture of the region is dominated by thick walls. The roof as an architectural element has played a minor role. This is a consequence of the historically limited availability of construction materials for roofs that could span larger dimensions. Today, such materials are available, but the image of a traditionalist wall-oriented architecture remains dominant and modern means of construction are, unfortunately, not used to create a more roof-oriented architecture.

* * *

With the mid-day sun angle at an altitude between 90° in summer and 45° in winter, the main impact of solar radiation on a building is not on the walls, but on the roof. Thus, buildings mainly need protection on their "fifth facade".

Therefore:

Open an umbrella. Give buildings shelter under a double roof. The most effective protection against the sun is a double-roof that shields the building from radiation and instigates a cooling effect through natural ventilation in the gap between the building and the raised roof.

While the traditional images of regional Gulf architecture are wall-dominated forms, the most appropriate shapes are actually roof-dominated buildings. Strengthening the roof as an architectural element not only has a positive effect on the performance of the building, the comfort of its users, but also creates architectural forms that are distinct for the region.

* * *

The building for the US Embassy by Jose Luis Sert from 1955-61 marks a turning point in this modern architect's oeuvre from being a protagonist of the early modern movement of the international style to advocating a regionalist, climate-adaptive approach to design (Lefaivre & Tzonis, 2012). As a consequence, the buildings for the embassy's chancery as well as the residence are constructed with a double roof that is elevated above the actual volume of the building to shield off the radiation of the sun as well as to allow for natural ventilation between the two roof layers.

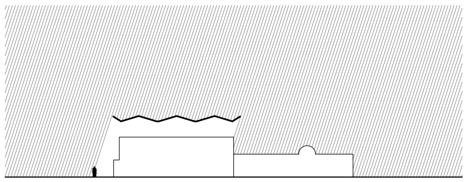

Figure 6. Jose Luis Sert: US Embassy in Baghdad. 31.9°N, 36.0°E

A double roof approach is also employed in the building for the Bahrain National Theatre by architecturestudio from 2015 (architecturestudio, 2018). The large protruding roof shades the openings of the fully glazed foyer and the public spaces in front of the building. In the rear part of the complex it becomes a double roof that floats over the lower volumes of the backstage part of the theatre thus providing a passive cooling effect.

 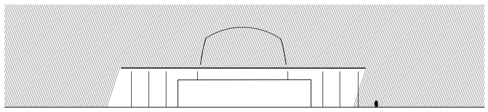

Figure 7. Architecturestudio: National Theatre of Bahrain. 26.2° N, 50.6° E

The motive of small building volumes tucked under a large roof is poignantly expressed in the new Louvre museum in Abu Dhabi by Jean Nouvel from 2017 (Global Architecture, 2018). The exhibition is spread over a series of house-like volumes surrounded by (semi-)public open space with most parts of this ensemble covered by a large roof. The intricately perforated roof creates moderate daylight conditions without glare and the water bodies that partially extend under the roof precool the breeze that constantly flows through the open spaces between the volumes that contain the exhibition spaces.

 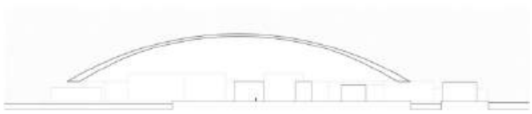

Figure 8. Atelier Jean Nouvel: Louvre Abu Dhabi. 24.5°N, 54.4°E

3.3. LIFT OFF

... most Gulf cities lack spatial constraints that hinder the horizontal growth of the urban fabric over large areas of land. As a result, the cities are not very dense. Rather, they are scattered settlements in which buildings are dispersedly arranged, free-standing objects.

* * *

Isolated buildings do not shade each other and hardly have any effect on cooling the public space around them. In this situation using passively cooled outdoor spaces as an extension of living space from indoors to outdoors is not very likely. Furthermore, the transition from outside to inside spaces is experienced by the user as very abrupt and uncomfortable.

Therefore:

Hover over the ground. Lift the buildings up and create shaded space beneath. While architecture in moderate climate zones is built as a solid object with open space around it, the hot climate of the Gulf region requires an approach where the building's volume floats above the ground and the open space is provided not in front, but under the building.

Lifting buildings off the ground leads to a different access situation. The entrance(s) need not be from the front, but can be from any point from beneath the building. This leads to a new dimension of typological possibilities and can significantly differentiate buildings built in a hot climate from those built under other conditions.

* * *

The Siemens Headquarters in Masdar City by Sheppard Robson Architects built in 2014 is a square-shaped four-storey volume that is elevated over an open ground floor with steps and terraces for public use (SheppardRobson, 2018). The volume of the building is perforated by nine small courtyards placed in a regular grid that provide daylight and - possibly - natural ventilation for the open-plan office space as well as the shaded open space below.

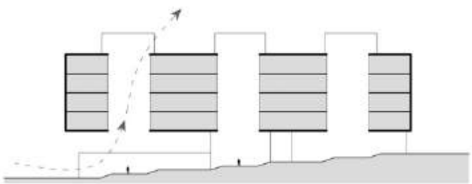

Figure 10. Sheppard Robson Architects: Siemens HQ in Masdar. 24.5°N, 54.4°E

The yet unbuilt Opportunity Pavilion for the EXPO 2020 in Dubai by BIG architects shows another version of how public space is drawn under a building to provide passive cooling for public outdoor spaces (worldarchitecture, 2016). The volume of the building is defined by the trapezoid shape of the flat roof with a small square opening roughly in its centre, as well as three small areas where the building rests on the ground; arches span between these "feet". The double curvature of the surface of the building results from linear connections between these four elements of the building. The entrance to the exhibition spaces is from the central garden-like yard with a water pond that is covered by a cave-like vault and is lit from the small opening in the roof. The form of the building provides a shaded public space under it.

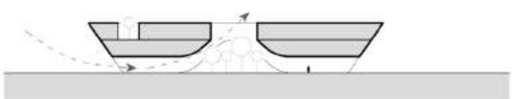

Figure 11. BIG: Opportunity Pavilion in Dubai. 25.2°N, 55.3°E

3.4. BREEZE THROUGH

... when buildings are designed for an optimal technically-driven active cooling mode the best form is a compact volume with a low surface-to-volume ratio.

* * *

But such building forms decrease the availability of natural daylight for interior spaces and also the opportunity to provide cross-ventilation as a means of passive cooling during the winter months in which the climate is pleasant enough to forgo energy-intense active cooling modes.

Therefore:

Breeze through. Inhale and exhale. Make passive cooling through cross-ventilation effective by providing floor plans that are less deep and in which all rooms are connected to exterior facades that can be opened. This leads to interiors in which - at least for some part of the year - the user can feel comfortably connected to the exterior not only by views but also by direct air-exchange.

A traditional passive cooling device are the wind towers that were used to condition interior spaces in low-rise vernacular buildings around the Gulf region. The towers are higher than the house and their tops heat up more than the bottom and thus a draft is caused by the stack effect.

*   *   *

The National Commercial Bank building in Jeddah by SOM from 1983 is an example for a high-rise building working as a wind tower (SOM, 2018,1). The 27-storey high tower is an upright equilateral triangular prism. The typical floor plan is V-shaped with an open-plan office covering two sides of the triangle while leaving the third side open for a multi-storey sky garden. This arrangement is rotated three times with the lowest and highest sky gardens facing NW and the middle one to the SW. The centre of the triangle remains void connecting all three sky gardens and thus providing a continuous air flow from the bottom to the top of the building.


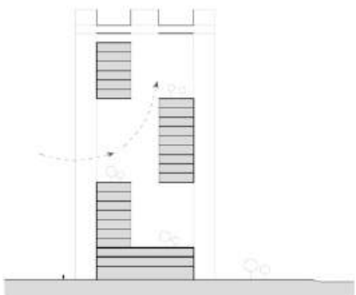

Figure 13. SOM: National Commercial Bank. 21.3°N, 39.2°E

In the same way, the so-called Wind Tower building in Kuwait by AGi architects from 2016 functions as the name suggests (archdaily, 2017). Instead the usual plan layout, in which a service core occupies the middle of a tower, the centre is kept as a vertical void around which the duplex-apartments are grouped. In this way all units can easily be cross-ventilated with air that is precooled over a pool at the bottom of the tower and brought into motion through the stack effect within the shaft.

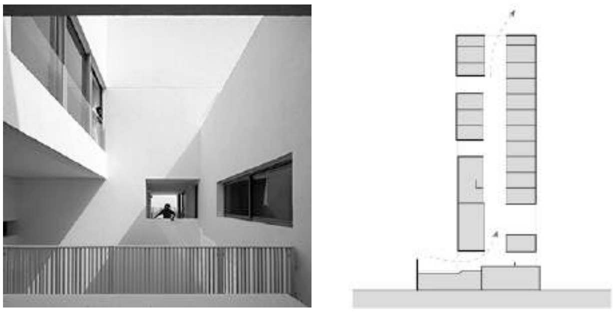

Figure 14. AGi Architects: Wind Tower in Kuwait. 29.3° N, 47.4° E

3.5. WRAP AROUND

... in many Gulf cities, high-rises are built with considerable distances between them, which exposes the facades to intense solar radiation.

* * *

The surfaces of the walls can heat up to temperature levels far beyond the ambient air temperature, but to achieve more energy-efficient buildings the surface temperature of the external walls needs to be reduced.

Therefore:

Wrap it. Shade the building with a double facade; the form of which can be derived from the distinct requirements of providing shelter from the sun.

* * *

The Al Bahr Towers built in Abu Dhabi by AECOM shows a very specific approach to shading the facade of a high-rise (archdaily, 2012). The shading layer is designed according to the sun path at this specific location and is only applied to the East, South and West sides, while the North remains uncovered. Furthermore, the textile shading structure is not static but dynamic, it opens and closes according to the path of the sun. Thus, an optimal balance between protection from the sun and views to the outside is achieved.

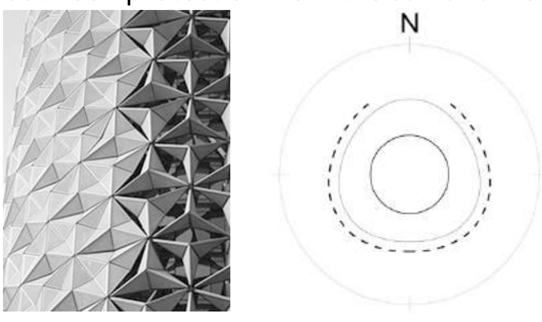

Figure 16. AECOM: Al Bahr Towers. 24.5°N, 54.4°E

The O14 Tower in Dubai by Reiser & Umemoto is an interesting contribution to the wrapping of a building (Reiser & Umemoto, 2018). While in many projects the sequence of layers of a facade from outside to inside is: shading, sealing (opaque or glazed) and structure, the O14 tower reverses this order. The tower has an exoskeleton, a solid shell of concrete that serves as a structural element, and through its perforations also provides filtered light to the fully glazed layer behind it. Through a reversed order of layers the interior spaces are free from columns and highly flexible while the skin of the building is sufficiently protected from the sun.

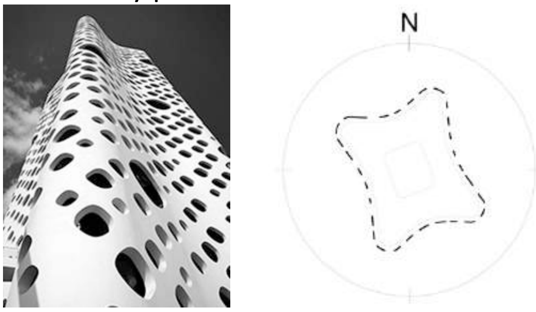

Figure 17. Reiser & Umemoto: O14 Tower in Dubai. 25.2°N, 55.3°E

3.6. LEAN OUT

... when thinking about the design of street profiles and building volumes, the established approach in cities with a temperate climate is to work with setbacks in order to achieve a gradual widening of the street space from narrow on the ground and wider at the top so that a maximum intensity of light is on the horizontal and vertical surfaces of the built environment.

* * *

But in hot climates the aim is to prevent the sun from hitting the ground and walls.

Therefore:

Lean out. Reverse the setbacks and create cantilevers and protruding volumes. Shift the upper levels of the building out and move the lower levels in.

The resulting geometry is effective in creating shaded areas on street level and self-shading facades, but it challenges the common the understanding of a clear border between street and building, which has legal implications, too.

* * *

The Kuwait Funds Building, designed by Walter Gropius' office, The Architect's Collaborative, is an example of an early modern building in the Gulf region that demonstrates the shading effects of overhanging upper floors and recessed ground floors.

Figure 22. TAC: Kuwait Funds Building. 29.4°N, 48.0°E

The Khalifeiya Library in Manama is a small community facility that has an expressive volume of three floor, each shifting further out to provide a shaded street space in front of the building.


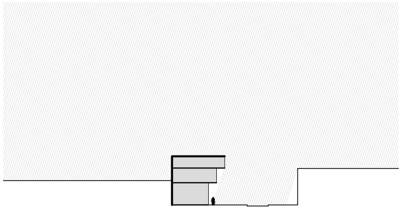

Figure 22. SeARCH: Khalifeyah Library in Manama, Bahrain. 26.2° N, 50.6° E

Similarly, Zaha Hadid's Issam Fares Institute in Beirut is a simple rectangle in plan, but an expressive L-shaped volume in section, creating a shaded outdoor space on ground floor under the protruding volume of the upper floors.


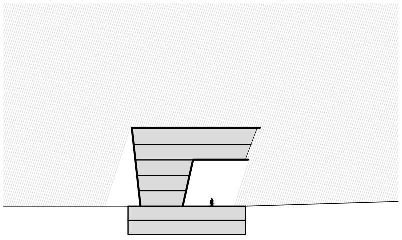

Figure 22. Zaha Hadid: Issam Fares Institute in Beirut, Lebanon. 33.8° N, 35.5° E

3.7. TAKE IN

... a double layer of space beneath, around, or on top of the building is not always possible to achieve.

* * *

When buildings cannot open up to the outside, due to the harsh climate, then other options for openings need to found.

Therefore:

Split up the building. Take outside space inside. Rejig the logic of outside and inside such that buildings contain exterior as well as interior spaces.

The blurred distinction between these two categories of space - inside and outside - can lead to new typological formations and give buildings and their incorporated open spaces their own distinct character.

* * *

The Dubai Municipality building from 1978-9 by Pacific Consultants International - based on an initial design by Kenzo Tange - goes a step further (Kolhatkar, 2018). Here, the roof is merged with the one part of the building that accommodates the administrative functions to form a hollowed out cube while the other part of the building that houses the representative functions is a playful arrangement of primary forms that are tucked under the roof. In between these two parts of the building is a public space that is shaded by a semi-transparent space-frame roof and is cooled by a water pond that flows around the free forms.

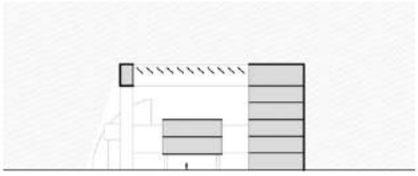

Figure 18. Kenzo Tange: Dubai Municipality Building. 25.2°N, 55.3°E

The headquarters of the Qatar Foundation in Doha, designed by Rem Koolhaas/OMA, looks like a solid cube perforated with many very small openings behind which a complex composition of glazed volumes is accommodated (dezeen, 2017). Outdoor spaces are incorporated into what appears to be an interior at first sight. These exterior spaces in the interior of the building are well-tempered, comfortable extensions of the office and exhibition areas.

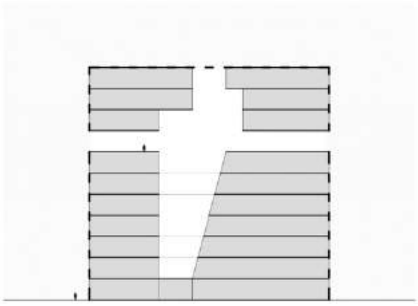

Figure 20. Rem Koolhaas/OMA: Qatar Foundation HQ in Doha. 25.3°N, 51.5°E

3.8 SHIFT OUT

... in climates with less daylight hours and intensity the most valuable areas are along the periphery of a building. Thus the circulation and service core is placed in darkest part of the plan, the centre.

* * *

But in climate zones with intense daylight and solar irradiance, this logic of the core in the centre and usable area at the periphery is inverted.

Therefore:

Move the cores to the edges. Cores are almost always closed elements of a building. When they are shifted from the centre to the periphery of a plan they can be used as a protective layer on facades that are most exposed to solar radiation and need to be kept closed anyways.

* * *

In design of the Tower of the Four Seasons Hotel in Bahrain by SOM the circulation and service shafts are moved from the core to the sides of the plan. Between these solid, opaque towers are stacks of horizontal floors with the hotel and conference rooms. The building looks like a diagrammatic translation the principle of this pattern (SOM, 2018,2) and develops a sculptural strength from this radical approach, even though the orientation is not yet fully optimal to the sun path.

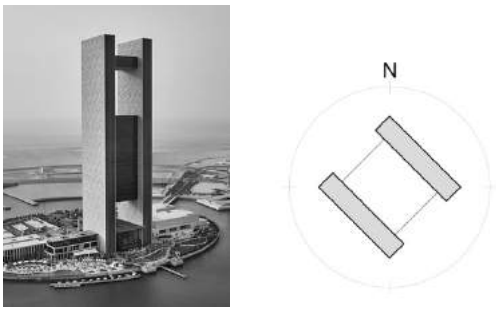

Figure 21. SOM: Four Seasons Hotel in Manama, Bahrain. 26.2° N, 50.6° E

The new headquarters of the King Abdullah City for Science and Technology in Riyadh by Lava architects is a large cubic volume. The circulation and service cores are shifted to the four corners, creating rather opaque east and west facades and quite open north and south sides. The core of the building is hollowed out and serves a large communicative atrium for the users.

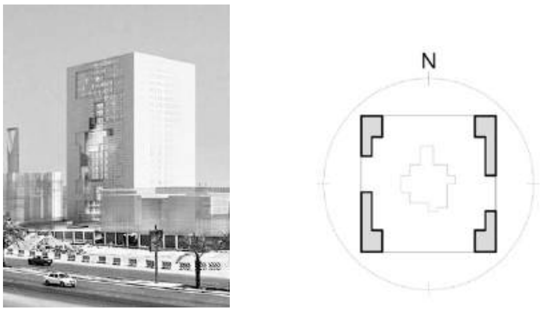

Figure 22. Lava: King Abdullah City for Science and Technology in Riyadh, KSA. 24.7° N, 46.6° E

With this methodical approach, both, the number of patterns and of case studies will be extended to gain more width and depth in the further course of this study. Also, the qualitative judgment of the energy-efficiency of the passive design strategies will be re-evaluated by a quantitative analysis through simulation in a next phase of this study.

4. Conclusion

The examples presented here through the application of Alexander's Pattern Language method show how the application of passive design strategies lead to typological changes of the spatial structure of buildings and open spaces that are distinct responses to the climatic conditions of the Gulf region. In the consequence of these patterns, climate adapted buildings in the Gulf region are no longer objects with binary opposites of exterior and interior but rather have blurred boundaries. The application of double-roofs (ROOF OVER, DOUBLE UP) and second skins (WRAP AROUND) and deep facades (BREEZE THROUGH); lifting buildings off the ground to provide shaded outdoor space (LIFT OFF); incorporating outdoor spaces within the interior volume (TAKE IN, SHIFT OUT) or using the upper levels of a building as a canopy for the lower parts (LEAN OUT) lead to architectural forms that are energy-efficient and place-specific at the same time. These "proven solutions to recurring problems" can be the basis for the development of modern forms that are, in the end, not another generic international style but a distinct regional architectural idiom. Thus it is demonstrated that when passive design strategies are consequently applied architectural identity can be achieved through efficiency.

Of course, identity and efficiency are both more complex topics in architecture than can be demonstrated here in this study - identity is not only derived from form and efficiency is not only a result of passive means. But this study, at least, shows how these two discourses can be tied together so that architectural identity in the Gulf region no longer needs to be construed but rather can be constructed.

In the bigger picture it is noteworthy that the intertwining of the two discourses on energy-efficiency and identity of architecture that is presented here puts the paradigms of functionalism, universalism and regionalism in a new relation. While throughout the history of modern architecture, functionalism was seen as a universally applicable "International Style", today's functionalism driven by climate adaption, is per se a regionalist discourse. A hundred years after the foundation of the modern movement epitomized in the foundation of the Bauhaus in 1919, this is a remarkable paradigm shift in architecture.

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Regular passive exposure to heat induces beneficial effects on cardio-metabolic health

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Abstract: Regular exposure to elevated temperature has previously been suggested to have positive implications for metabolic and cardiovascular health. Two passive heat acclimation studies have been performed to assess the effect of repeated passive heat exposure on physiological parameters, cardiovascular and glucose metabolism, thermal comfort (TC) and sensation (TS).

Eleven young healthy men (YH, 24.6±2.7y, BMI:22.6±2.9kg/m2) and eleven middle-aged overweight men (MO, 65.7±4.9y, BMI:30.4±3.2kg/m2) participated in two separate studies. Both populations were acclimated to heat (YH:7d, ~33˚C and MO:10d, ~34˚C) for 4-6h/d. Before and after acclimation, core and skin temperatures (Tcore and Tskin), heart rate, blood pressure, TC and TS were measured. Fasting plasma glucose (FPG) and insulin (FPI) samples were taken to indicate glucose metabolism and insulin response in MO only.

Tcore decreased in both groups post-PHA (YH:∆-0.14±0.15˚C, p=0.026; MO:∆-0.19±0.26˚C, p=0.036). Blood pressure decreased in both populations after heat acclimation, to a variable extent. Preliminary data suggests that FPG and FPI were lower post-acclimation. TS/TC remained unchanged. In conclusion, despite the relatively mild heat stimulus, passive heat acclimation induces distinct thermophysiological and cardiovascular adaptations in both populations, leading to increased resilience to heat. Glucose metabolism might improve in the middle-aged overweight population. Despite the physiological adaptations to heat, TS and TC remained unchanged.

Keywords: Heat acclimation, thermophysiology, metabolic health, cardiovascular health, resilience.

1. Introduction

Cardiovascular disease (CVD) and Type 2 Diabetes Mellitus (T2DM) are global diseases, being amongst the top 10 causes of death worldwide in 2016 (World Health Organisation, 2016). In recent years, the question has arisen, if uniform and thermally comfortable environments, as recommended by indoor environmental standards, affect human health. A thermally comfortable environment, the establishment whereof is the central goal of aforementioned standards, has been suggested to not necessarily be equal to a healthy environment (Moellering & Smith, 2012; W.D. van Marken Lichtenbelt et al., 2017; W. D. van Marken Lichtenbelt et al., 2018).

In past times, the human thermoregulatory system used to be regularly stimulated by exposure to varying outdoor conditions. In order to maintain a stable core temperature, the body expends energy to warm up and dissipates heat to cool down. However, today, fewer calories might be used to this end due to the lack of temperature variation indoors, which might contribute to a tipping of the fragile energy balance (Johnson et al., 2011; McAllister et al., 2009; Moellering & Smith, 2012; W. van Marken Lichtenbelt et al., 2014; W.D. van

Marken Lichtenbelt et al., 2017). It has therefore been hypothesized that the tightly controlled thermal indoor environment, alongside with oversupply of food and sedentary behaviour, is one of the reasons for the global 'diabesity epidemic'.

There has been a lot of scientific interest in studying extreme temperature conditions and the impact thereof on human physiology and health. A vast amount of studies previously investigated the effect of intense, mostly exercise-induced heat acclimation programs on a variety of health-related outcomes and performance parameters (examples include (Buono et al., 1998; Cheung & McLellan, 1998; Nadel et al., 1974; Nielsen et al., 1993; Regan et al., 1996; Roberts et al., 1977; Sawka et al., 1983). In contrast to exercise-induced heat acclimation, only few studies evaluate the influence of passive exposure to heat (Beaudin et al., 2009; Brazaitis et al., 2009; Fox et al., 1963; Henane & Bittel, 1975; Hessemer et al., 1986; Shvartz et al., 1973). Some studies used very high ambient temperatures between 45-55˚C (Beaudin et al., 2009; Henane & Bittel, 1975; Hessemer et al., 1986), sometimes also combined with high relative humidity, whereas others applied hot water immersion (Brazaitis et al., 2009) or vapour-barrier suits (Fox et al., 1963) in their methods. Recently, two papers with respect to passive heat therapy were added, showing that repeated hot water immersion improves cardiovascular functioning (Brunt et al., 2016a; Brunt et al., 2016b).

In addition to laboratory studies, human field studies in naturally-acclimatised Pima Indians reported that the naturally habituated population has a lower sleeping core temperature than matched Caucasians, but the Caucasians exhibited the same change, namely a lower Tcore, following heat acclimation (Rising et al., 1995).

Together, this shows the great plasticity of the thermophysiological system, which not only functions in genetically predisposed populations but also in those usually not residing in warm climates.

Although the studies enumerated in the above used an external heat stimulus, they do not resemble temperature challenges as encountered by, for example, a (sedentary) person in an overheated office space or dwelling. Due to their methodological nature, it is therefore difficult to draw direct conclusions with respect to a prolonged, repeated stay in an environment of, for example, only 35˚C and moderate relative humidity (under 50%).

However, in the context of climate change and global warming, the frequent overheating of buildings and more severe and frequent summer heat waves, it is crucial to investigate the available coping mechanisms of the human body. Therefore, it is of particular interest to study the effect of *passive* heat acclimation on thermophysiology, and also on aspects of cardiovascular and metabolic health in humans. In the scope of this paper, two passive heat acclimation studies assessing the effect of repeated passive heat exposure on physiological parameters, cardiovascular and glucose metabolism as well as thermal comfort (TC) and thermal sensation (TS) in two separate populations (young healthy and middle-aged overweight) are juxtaposed.

2. Methods

Eleven young, healthy men (YH, 24.6±2.7y, BMI:22.6±2.9kg/m2) and eleven middle-aged, overweight (MO, 65.7±4.9y, BMI:30.4±3.2kg/m2) men participated in the two separate studies. The first study was conducted in the period of December 2014 till August 2015, and the second between October 2016 and May 2017. The Medical Ethics Committee of Maastricht University approved both studies, and both were conducted in conformity with the Declaration of Helsinki (Fortaleza, Brazil, 2013).

Table 1. Participant characteristics of the two separate studies

	YH	MO
	Mean ±SD	Mean ± SD
Age [years]	24.6 ± 2.7	65.7 ± 4.9
Height [m]	1.79 ± 0.07	1.80 ± 0.1
Weight [kg]	72.2 ± 8.9	95.5 ± 15.3
BMI [kg/m2]	22.6 ± 2.9	30.4 ± 3.2
Fat percentage [%]	19.7 ± 3.0	28.5 ± 4.6
Fat mass [kg]	14.5 ± 3.3	27.9 ± 9.0
Fasting glucose [mmol/L]	n/a	6.0 ± 0.5
2-h Glucose [mmol/L]	n/a	7.6 ± 1.9

N=11 for both studies. YH = study with young healthy group, MO = study with middle-aged overweight group

2.1. Study design

Participants were exposed to 7 days at ~33˚C (YH) respectively 10 days at ~34˚C (MO) of passive heat acclimation (PHA) (Figure 1). To study the physiological response to high temperatures, participants underwent an incremental temperature ramp before and after PHA. Fasting plasma glucose and insulin was assessed before and after PHA in MO only.

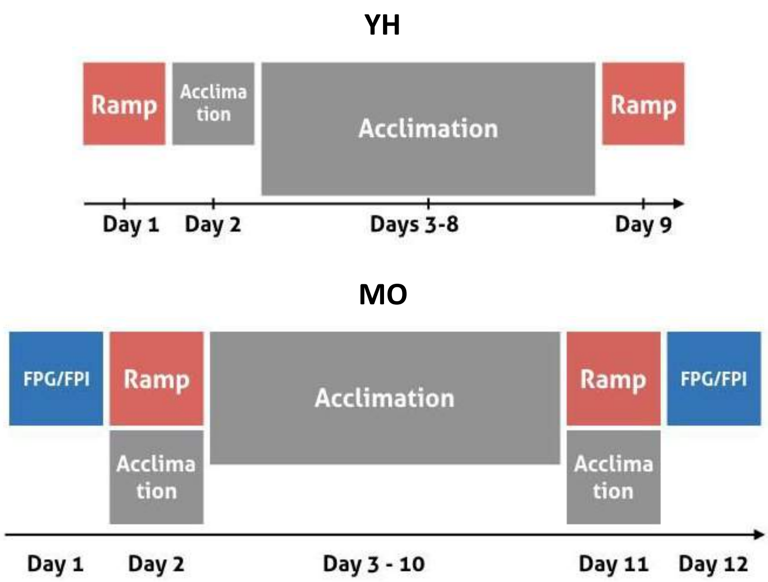

Figure 1. Study procedures for study YH (young healthy participants) and MO (middle-aged overweight participants). *Ramp* = temperature ramp protocol. *FPG/FPI* = blood sampling for analysis of fasting plasma glucose/fasting plasma insulin.

2.2. Temperature ramp protocol

In both studies (YH and MO), the procedures for the temperature ramp protocol were the same. Participants arrived at the laboratory in the morning after an overnight fast (as of 22:00h the evening before). Upon arrival at the laboratory, participants ingested a telemetric pill (Vital Sense, Philips Healthcare, NL) to measure core temperature, which was monitored using an Equivital apparatus mounted to the participant with a chest strap (Equivital Hidalgo, UK). Heart rate was measured with the same Equivital device. To measure mean skin temperature, wireless skin temperature sensors (iButtons, Maxim Integrated Products, California, USA) were attached to 14 ISO-defined body sites (ISO, 2004) with semi-adhesive tape (Fixomull stretch, BDN medical GmbH, GER).

When preparations were finished, participants took place on a stretcher with air-permeable fabric. The ramp protocol started with a baseline period of 60 min followed by an increase of the ambient temperature over the course of 120 min (Figure 2). The baseline temperature (YH: 28.8±0.3˚C, MO: 28.8±0.15˚C) was assumed to be neutral for a resting semi-nude person, based on the literature review of Kingma *et al.* (Kingma et al., 2012) and it was corrected for the isolation of the stretcher that participants rested on during the testing. For YH, the ambient temperature increased to 37.5±0.6˚C during the ramp over the course of 90 min. For the last 6 study participants, an additional 30 min of ramp was added subsequently to the ramp protocol to cover an even wider temperature range. On average, the final temperature that was reached for these six participants during the ramp was 41.6±1.0˚C (averaged over the final 10 min). For MO, the ramp continued for 120 min for all 11 participants and reached 41.3±0.33˚C (averaged over the final 10 minutes).

Relative humidity was allowed to drift freely with the changes in temperature during the test, resulting in an average relative humidity of 25.8±7.2% for study YH and 23.2±3.3% for study MO.

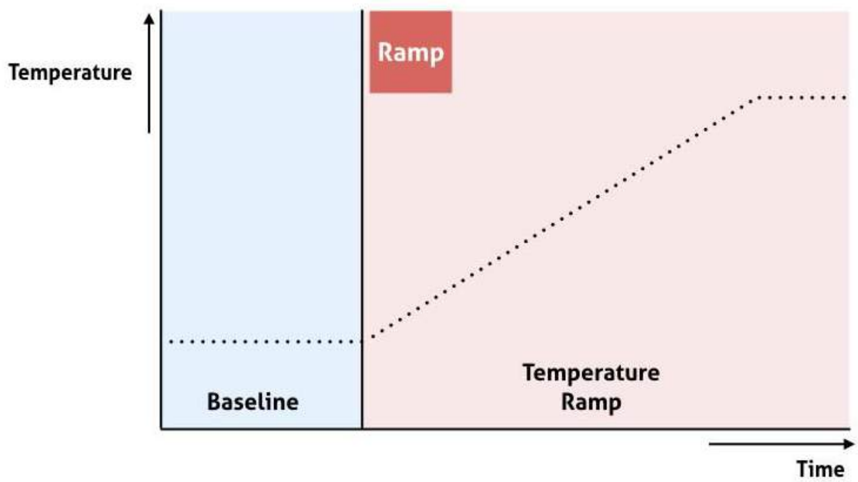

Figure 2. The temperature ramp protocol

2.3. Passive heat acclimation

PHA started in the afternoon of study day two for both studies (Figure 1). During the first and last sequence of PHA, participants stayed in the climate chamber for 4h, and for the other 5 (YH) respectively 8 (MO) days of PHA, participants acclimatised for 6h per day.

Ambient temperature in the climate chamber was kept constant at 33.3±1.6˚C (YH) respectively 34.4±0.2˚C (MO); and relative humidity was 22.3±6.6% (YH) respectively 22.8±2.7% (MO), which classifies the ambient air as dry. All participants successfully completed PHA.

During their stay in the acclimation chamber, participants remained seated at a desk and were allowed to perform regular office work (1.2METs). Participants wore standardised clothing composed of underwear, T-shirt, shorts and socks/slippers. The total thermal resistance of the clothing ensemble plus the desk chair added up to approximately 0.41clo (McCullough et al., 1989; McCullough et al., 1994). Participants had unlimited access to water; and food was provided upon request, in order to not influence habitual diet. They were allowed to leave the chamber for toilet breaks.

2.4. Data analysis

The first 30 min of the ramp protocol were regarded as familiarisation period, and therefore excluded from the data analysis. During the ramp protocol, core temperature, heart rate and skin temperatures were recorded at 1-min intervals. Upper arm blood pressure was recorded at three time points during the temperature ramp protocol (YU: t=55, t=105, t=130 and MO: t=55. t=135, t=165).

In both studies YH and MO, time intervals during the ramp protocol were defined, at which the parameters measured during the ramp (core temperature, skin temperature, heart rate, blood pressure and thermal sensation/thermal comfort for YH) were compared before and after PHA. For YH, the time intervals were at baseline (t=30-55 minutes, 28.81±0.40˚C), T1 (t=105-115, 34.81±0.50˚C) and T2 (t=130-140, 37.53±0.58˚C). For MO, the time intervals were at baseline (minutes 25-55: 28.8±0.15˚C), T1 (minutes 110-120: 35.4±0.40˚C), T2 (minutes 135-145: 38.9±0.49˚C) and T3 (minutes 165-175: 41.3±0.33˚C).

For YH, thermal sensation and thermal comfort were assessed on 6min intervals during the temperature ramp protocols, but due to practical restrictions, the MO group rated thermal sensation and thermal comfort only during the acclimation days, on an hourly basis. In both studies, thermal sensation was assessed using the continuous 7-point ASHRAE thermal sensation scale (ASHRAE, 2013) and a two-part continuous thermal comfort scale, which has previously been used at our laboratory (Pallubinsky et al., 2017; Pallubinsky et al., 2016).

The software packages Microsoft Office 2011 Excel (Microsoft) and SPSS 23 for Mac (SPSS Inc.) were used for data analyses. Paired-sample t-tests were used to compare the measured parameters before and after PHA. Statistical significance was considered for $P \leq 0.05$ and a statistical trend was considered if $0.05 < P < 0.10$. Data is presented as mean±SD.

3. Results

In the following, results for both studies YH and MO will be presented separately.

3.1. Core temperature

In study YH, core temperature was significantly lower after PHA during the ramp protocol at T1 (-0.13±0.13˚C, P=0.011) and T2 (-0.14±0.15˚C, P=0.026), but not at baseline (-0.12±0.23˚C, P=0.115).

For MO, core temperature was significantly decreased by 0.13±0.18°C at baseline (P=0.035), T1 (-0.19±0.26˚C, P=0.036) and T2 (-0.18±0.25˚C, P=0.041) and tended towards a decrease at T3 (-0.10±0.52˚C, P=0.073) after PHA.

3.2. Skin temperatures

For YH, mean skin temperature was not significantly different from the pre-measurement at any time point. Proximal skin temperature was significantly decreased after PHA only at T1 (∆-0.22±0.29˚C, P=0.029). Distal skin temperature increased at baseline (∆+0.74±0.77˚C, P=0.009), and T2 (∆+0.51±0.63˚C, P=0.022) and tended to be higher at T1 (∆+0.49±0.76˚C, P=0.057) upon PHA. Moreover, the gradient between core temperature and distal skin temperature was significantly decreased at baseline (∆-0.86±0.84˚C, P=0.007), T1 (∆-0.61±0.74˚C, P=0.021) and T2 (∆-0.56±0.54˚C, P=0.009).

For MO, mean, proximal and distal skin temperature remained unchanged after PHA, but core-distal skin temperature gradient decreased significantly at T1 (P=0.008) and tended to decrease at T2 (P=0.076) compared with the core-distal skin temperature gradient before PHA.

3.3. Heart rate

In YH, heart was not significantly affected post PHA.

In MO, heart rate was unchanged at baseline, T1 and T3 (HR baseline: ∆-1±4bpm, P=0.356; T1: ∆-2±3bpm, P=0.107; T3: ∆-2±5bpm, P=0.160) but significantly decreased at T2 (∆-4±4bpm, P=0.011).

3.4. Blood pressure

For YH, both systolic and diastolic blood pressure were significantly lower at baseline after PHA (systolic: ∆-8±8mmHg, P=.015; diastolic: ∆-4±5mmHg, P=0.001). At T2 of the ramp, systolic blood pressure was significantly lower after PHA (∆-5±1mmHg, P=0.003), but diastolic blood pressure was no longer significantly different from the pre-measurements (∆-3±3mmHg, P=0.235).

For MO, systolic blood pressure tended to decrease post PHA at T2 (∆-3±4mmHg, P=0.052), but was not significantly lower at any other time point. Diastolic blood pressure was significantly lower after PHA at baseline (∆-4±4, P=0.006), at T2 (∆-4±3, P=0.001), but not at T3 (∆-2±5, P=0.152).

3.5. Glucose metabolism in MO

Fasting plasma glucose (FPG) and fasting plasma insulin (FPI) values before and after PHA were assessed in MO only. Preliminary data suggests that both FPG and FPI were lower post PHA, but further analysis is needed to confirm this result.

3.6. Thermal sensation and thermal comfort

For YH, thermal sensation and thermal comfort were assessed during the ramp protocol (Figure 3A) and statistically tested for differences pre vs. post PHA at baseline, T1 and T2 only. Thermal sensation was significantly lower after PHA at T2 (Δ-0.56±0.15, P=0.04, t=130-140), but the other timepoints were not significantly affected by PHA. Thermal comfort was not significantly changed after PHA.

Other than in YH, in study MO, thermal sensation and thermal comfort were assessed during the acclimation days (Figure 3B). Thermal sensation as well as thermal comfort were not significantly changed by PHA.

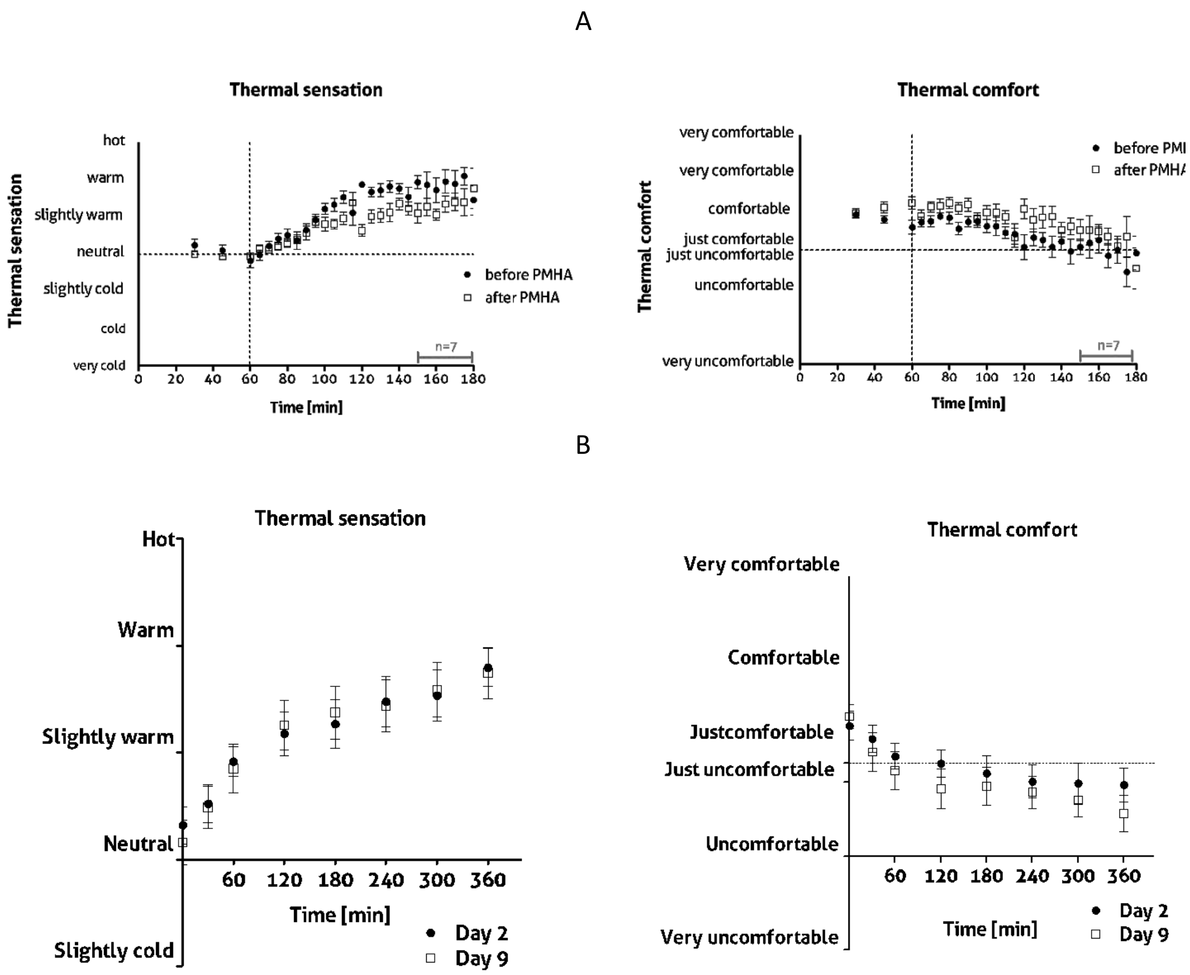

Figure 3. ***A*** Thermal sensation and thermal comfort during the temperature ramp before and after PHA in study YH. ***B*** Thermal sensation and thermal comfort at acclimation day 2 compared with acclimation day 9 before and after PHA in study MO. N=11 if not indicated otherwise. Bars indicate standard error of the mean.

4. Discussion and conclusion

This study evaluated the effects of passive heat acclimation (PHA), i.e. without exercise, on human thermophysiology. PHA is of particular interest, as it represents temperature challenges encountered in everyday life.

In the first study with young healthy participants, we show that PHA consisting of exposure to ~33˚C at 7 consecutive days indeed elicited a decrease of core temperature and a redistribution of skin temperature (towards warmer extremities and a cooler torso) in warm ambient temperatures. Blood pressure, both systolic and diastolic, was generally decreased post acclimation.

In the second study with middle-aged overweight participants, we confirm findings of the first study, showing that the applied acclimation model evoked significant changes of core temperature, which is an important indicator for successful acclimation. Moreover, blood pressure, particularly diastolic blood pressure, and heart rate decreased significantly after PHA. Importantly, preliminary results suggest that fasting plasma glucose and fasting plasma insulin decreased after PHA, hinting towards an improved balance between glucose output of the liver and insulin secretion of the pancreas in a basal situation.

4.1. Thermophysiological parameters

In the first study in a young healthy population, we found that a 7-day PHA protocol elicited significant thermophysiological and cardiovascular changes, which were similar to those typically reported after more intense (often exercise-induced) heat acclimation studies. The second study confirms the effectiveness of PHA also in a middle-aged overweight population. An average overall decrease of core temperature of approximately -0.17˚C in the MO study is even more pronounced than in the healthy participants (YH), where core temperature decreased by approximately -0.14˚C post-PHA, which might, amongst other things, be due to the longer duration of acclimation (10 days vs. 7 days) and the slightly higher acclimation temperature (~34.5˚C vs. 33˚C).

Moreover, in both studies, core-distal skin temperature gradient decreased, suggesting a redistribution of the blood pool towards the extremities, which helps losing heat to the environment. This redistribution was more pronounced in the YH study, denoted by a significant increase of distal skin temperature. A possible explanation might lie in the difference of body composition between the two populations: whereas the YH population had an average BMI of 22.6±2.9kg/m^2 and respectively 19.7±3.0% body fat, the average BMI of the MO group was as much as 30.4±3.2kg/m^2 with respectively 28.5±4.6% body fat. Moreover, age has been shown to be a crucial factor in reduced cutaneous circulatory response to heat (Minson et al., 1998; Richardson, 1989). Together, a thicker subcutaneous fat layer and reduced capacity for vasodilation might have attenuated or blunted the increase of blood flow, and thereby the dissipation of heat, to the distal body parts of the overweight elderly group.

4.2. Cardiovascular parameters

In both studies, we observed a significant decrease of blood pressure. Especially in the MO study, the reduced blood pressure during warming is a highly favourable result, as hypertension represents a frequent medical issue in overweight and elderly individuals. Prolonged and more frequent exposure to warm thermal environments might help to alleviate hypertension and potentially even facilitate a reduced need for medication.

4.3. Glucose metabolism

In the MO study, blood samples were taken before and after PHA to assess the impact of PHA on metabolic health. Preliminary data suggests that both fasting plasma glucose as well as fasting plasma insulin decreased after PHA. This means that PHA might positively affect the balance between hepatic glucose output and insulin secretion of the pancreas in a basal state.

4.4. Thermal comfort and thermal sensation

In study YH, thermal sensation and thermal comfort measured during the temperature ramp protocol was only partially changed upon 7 days of PHA. In study MO, thermal sensation and thermal comfort measured the acclimation days was not changed upon 10 days of PHA.

Importantly, at no point in time, participants voted to feel either 'very uncomfortable' or 'very hot' during the ramp or the acclimation days. In YH, even though the temperature ramp reached final values of ~41˚C, participants never rated thermal sensation higher than 'warm' and comfort values remained around 'just uncomfortable' and 'uncomfortable'.

In MO, on average, thermal comfort ranged between 'just comfortable' and 'just uncomfortable' to 'uncomfortable' during the average acclimation day. Thermal sensation increased from 'neutral' to 'warm' over the course of the 6h of PHA during both day 2 and day 9.

Although an improvement of thermal comfort and a decrease of thermal sensation was anticipated previous to the study, no significant change occurred post-PHA. Interestingly, thermal comfort even decreased a little bit at day 9 of PHA at most time-points, but this decrease was not significant when compared with the voting of day 2. Although physiological changes were observed post-PHA in both studies, after 7 respectively 10 days of acclimation, subjective perception did not change. Possibly even longer adaptation or habituation periods are needed to affect the subjective perception of the thermal environment. Further research is needed to investigate underlying mechanisms.

4.5. Limitations

This study provides information on the effect of PHA on thermophysiological and cardiovascular parameters, thermal perception as well as glucose metabolism. However, with respect to the general interpretation of the study results, a few limitations need to be considered. Firstly, the study population was limited to men only, which is why more information on the effect of PHA in women is needed. Secondly, although participants were asked to not deviate from their normal lifestyle and habitual physical activity, we did not record any information with respect to diet and exercise during the study period. Therefore, future studies should include measurements of dietary intake and physical activity.

4.6. Conclusion

In both the young healthy as well as the middle-aged overweight population, core temperature was lowered after PHA, both in a thermoneutral condition and during warming. Blood pressure was lowered after PHA. Preliminary results indicate that fasting plasma glucose and fasting plasma insulin were reduced by PHA n the middle-aged overweight group. Together, these results indicate increased resilience to heat as well as beneficial health effects due to regular exposure to heat.

Thermal sensation and thermal comfort did not improve after PHA. Generally, sensation and comfort votes remained within reasonable limits during the ramp protocol and PHA.

More research is needed to further investigate the effect of passive heat exposure on glucose metabolism, as the underlying mechanisms are not yet fully understood. A better understanding of the relationship between passive heat exposure and glucose metabolism can help with the design of healthier indoor environments, alongside with the development of tailor-made anti-obesity and insulin-sensitizing temperature interventions.

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Stress indexes and thermal comfort in structural timber school buildings during cold and warm seasons

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Abstract: This study evaluates occupants' comfort and stress indexes in structural timber (CLT) school buildings in the North-eastern region of the USA during cold and warm seasons. The survey was considered from June-September 2017 and October 2017-February 2018 for the warm and cold seasons respectively. The buildings are rated and certified by the Leadership in Energy and Environmental Design (LEED), and they have won different sustainability awards due to their low carbon footprint. The study explored the monitoring of variables and occupants' comfort was assessed using the thermal comfort standards (CIBSE, BSEN15251, ASHRAE) for comparison. The mathematical models were applied to evaluate the stress indexes in the cold and warm seasons. The study showed the average outdoor temperatures of 4.8°C and 21.0°C in the cold and warm seasons in that order. The mean indoor temperatures of 20.2°C and 22.5°C were reported during the cold and warm seasons respectively. The average RH of 43.7% and 58.3% were measured in the cold and warm seasons. The average air velocity was within 0.1-0.2m/s. The overall mean CO_2 level was below 1000ppm, and it was within the acceptable range (350-1000ppm) for healthy and comfortable thermal environment. The classrooms and offices were warmer than the hall in the cold and warm seasons. The location of the hall, its orientation, large volume, frequent use of the doors and windows, as well as different activities carried out in the hall may contribute to the lower temperatures recorded in the space than the classrooms and offices. The outcomes of the mathematical models to evaluate the stress indexes show the WBGTs of 15.4°C and 19.1°C in the cold and warm seasons respectively. The UTCIs of 19.4°C and 22.6°C were computed for the cold and warm seasons. The study shows that building occupants are likely to be susceptible to cold stress and heat stress if external temperatures decrease or increase. The study recommends that further adaptive measures should be considered by the users to improve their comfort; thereby reducing their vulnerability to cold stress and warm stress in different seasons.

Keywords: Thermal comfort, stress indexes, field survey, structural timber (CLT), school buildings, cold and warm seasons

1. Introduction

This paper discusses stress indexes and thermal comfort of occupants in structural timber (CLT) school buildings during cold and warm seasons. The study evaluates occupants' comfort by considering the field survey of the case study building in both seasons. The study also explored the thermal comfort models and mathematical equations to evaluate the comfort and heat stress thresholds for the case study building users. This study also evaluates and discusses both cold stress and heat stress in CLT school buildings in cold and warm seasons respectively. The study aims to add to the body of knowledge by providing the first set of published work that examines cold stress and heat stress at the same time in CLT school buildings in both seasons. The study also aims to add to the existing research (Adekunle 2018a, 2018b) on the performance, thermal comfort of occupants, and stress indexes in CLT school buildings. The study intends to provide additional information on the summer (Adekunle and Nikolopoulou, 2016) and winter (Adekunle and Nikolopoulou, 2019) performance of buildings built with engineered timber materials discussed in the existing papers.

2. Literature review

A documented research project in the field has explained that engineered timber materials like cross-laminated timber (CLT) panels are commonly considered for the construction of buildings (Adekunle, 2014). Published papers on thermal comfort of people in timber buildings maintained that buildings built with timber products are subject to increasing temperatures in summer (Adekunle and Nikolopoulou, 2014, 2016). While the possibility of decreasing temperatures in winter is also reported in such buildings (Adekunle and Nikolopoulou, 2019). A thorough literature review on thermal comfort in educational buildings over the last fifty years has been considered and presented in the recent publication (Zomorodian et al., 2016). The study (Zomorodian et al., 2016) noted that ventilation is a crucial determinant of indoor air quality and occupants' comfort in buildings. Zomorodian et al. (2016) concluded that there is a significant discrepancy in thermal neutralities which revealed the need for micro-level thermal comfort investigations in educational buildings. Similar findings are also found by a study that examined thermal comfort perception of 384 students through the class period during the cold season in a learning space of a university (Mishra et al., 2017). The study (Mishra et al., 2017) showed that thermal sensation votes varied considerably through class time while perception varies depending on the outdoor temperature, operative temperature, gender, and the geographical background of the respondent.

Thermal comfort of occupants and the influence of age groups are examined in past investigations (Hussein and Rahman, 2009; Teli et al., 2013). An existing study examined occupants' comfort in free-running school buildings in hot, humid region (Hussein and Rahman, 2009), as well as tropical climate (Nematchoua et al. 2018), and found out that the thermal environment was acceptable to more than 80% of the people (Hussein and Rahman, 2009; Nematchoua et al. 2018). Also, the people mentioned that the thermal environment was acceptable, even when they indicated 'warm' or 'no change' on the scale (Adekunle and Nikolopoulou, 2016). The mean thermal sensation votes also exceeded the ASHRAE 55 recommended baseline (ASHRAE, 2017). Hussein and Rahman (2009) explained that people are likely to adjust to elevated temperatures in school buildings in the hot and humid region. The usability of the adaptive comfort model in free-running school buildings is also discussed in the existing papers (Hwang et al., 2009; Teli, 2013; Adekunle, 2018a; Jindal, 2018; Nematchoua et al. 2018). A broader range concerning the acceptability rate is reported while a smaller range is noted for the comfort zone when assessed with the adaptive model (Hwang et al., 2009). Also, Nematchoua et al. (2018) evaluated the adaptive thermal comfort approach and correlation between experimental data and mathematical expression in some free-running schools and traditional buildings in the tropical island of the Indian Ocean. The research (Nematchoua et al. 2018) highlighted that comfort temperatures varied from one season to another while the school buildings are less comfortable than the traditional buildings.

Physical measurements of parameters were considered within the thermal environment of school buildings during various seasons (Jindal, 2018; Adekunle 2018b; Nematchoua et al. 2018), and it was observed that the people prefer lower temperatures at a lower rate. Relationships between classroom features and health and comfort for the participants were studied in 54 classrooms of 21 Dutch school buildings (Bluyssen et al., 2018). The study (Bluyssen et al., 2018) measured environmental variables such as temperature, humidity, CO_2 concentration and found out that the users were bothered by smells, noise, sunlight, and low or elevated temperatures. In a separate study, it was reported that the users tend to accept and adapt to temperatures that exceed the comfort threshold (Pereira et al., 2014). Based on findings from current studies in the field, additional updates are proposed to the existing overheating guidelines developed for school buildings (Montazami and Nicol, 2013). Also, the building envelope energy regulation is observed to have a considerable impact on the people's comfort in educational buildings (Liang et al., 2012). A link is reported between the energy efficiency of buildings and indoor air quality (Katafygiotou and Serghides, 2014); while humidity has a less considerable effect on the sensation of users in educational buildings. Zhang et al. (2013) argued that the school buildings' users in the hot, humid region tend to adapt to increasing temperatures and humidity better than the users in the temperate climate. Zhang et al., (2013) explained that people in the temperate region might be prone to increasing heat and temperatures because they are less tolerant of excessive temperatures and humidity. As a result, additional studies are required to assess the vulnerability of users to increasing and decreasing temperatures in school buildings.

Comparing thermal comfort of occupants in free-running (that is, naturally ventilated) and non-free-running (non-naturally ventilated) buildings, Zhang et al. (2013) explained that people in non-free-running buildings make necessary adjustments to make the thermal environment more comfortable than people in free-running buildings. The study (Zhang et al., 2013) also mentioned that people make adjustments at the early phase to regulate the thermal environment while the people in non-free-running buildings are likely to perceive the thermal environment better than the people in free-running buildings. Katafygiotou and Serghides (2014) reported the excessive usage of energy for cooling and heating in various seasons in school buildings. This observation of excessive use of energy in school buildings implies that the uncontrolled utilisation of energy could lead to warm and cold discomfort in the buildings.

NIOSH (2015) examined environmental parameters through monitoring to determine the variables that affect the comfort perception within the thermal environment and found out that the comfort perception is closely linked to physiological modifications, the body heat flow to the immediate environment, and the temperature of the body. The study (NIOSH, 2015) mentioned that environmental parameters, personal variables including clothing insulation influence the body heat flow to the surrounding. The operative temperatures that varied from 19.5°C-27.8°C and 20.3°C-23.9°C are recommended by ASHRAE 55 for warm and cold seasons respectively (ASHRAE, 2017). ASHRAE 55 also mentioned that both environmental, personal, and other variables influence the comfort temperatures limit within the thermal environment. Humidity range of 30%-60% is specified for the indoor environment to avoid the development of mold (EPA, 2012); while humidity level that exceeds 65% could cause microbial development (ASHRAE, 2013).

Generally, buildings are expected to be free-running in summer and non-free-running in winter while heating and cooling systems could come on and off depending on the outside temperatures (Nicol and Humphreys, 2007). Buildings should provide a thermal environment that is comfortable for users even during the period of excessive heat (NHS, 2011). To maintain a comfortable indoor thermal environment, HVAC systems are provided in buildings to adjust the environment (DOE, 2015). As a result, this paper assessed the performance and people's comfort in the buildings. The study considers the thermal comfort standards (BSEN15251, 2008; CIBSE, 2015; ASHRAE 2017) to assess thermal comfort of occupants in the school buildings in different seasons.

On the evaluation of stress indexes in the spaces, the study considered the Wet Bulb Globe Temperature Heat (WBGT) index and the Universal Thermal Climate Index (UTCI) mathematical equations to compute the indexes. The study also utilised the models for a comparative analysis of the stress indexes. The research compares the results with the current studies in the field to determine if the temperatures exceed the thermal comfort standard limits and make possible recommendations to improve occupants' comfort in school buildings.

3. Research Methodology

The study considered a combination of field measurements and mathematical equations as the research methodology. The research also considered the usability and limits of different thermal comfort models (BSEN15251, 2008; CIBSE, 2015; and ASHRAE 2017) to assess the thermal behaviour and people's comfort in the case study. The usability, limits, and features of these thermal comfort standards and applicable parameters for determining the thermal environment have been evaluated and discussed in the published work in the field (Adekunle 2018a).

About the comfort models, the CIBSE (2015) specifies the applicable building category considered for assessing maximum acceptable temperature (T_{max}). The CIBSE model highlights that buildings should be designed with the intention to be within the Category II (recommended acceptable band is 3K) thresholds. The CIBSE TM52 maintains that the Category II upper limit should be determined by applying Equation 1. The equation specifies the maximum acceptable temperature for the Category II TM52. Equation 1 also considers the running mean temperature (T_{rm}).

$$T_{max} = 0.33\ T_{rm} + 21.8 \qquad \text{Equation 1}$$

For the BSEN15251 comfort model, the standard applies to a naturally-ventilated thermal environment with manually controlled windows and mechanical ventilation. However, the thermal environment should not be provided with air-conditioning systems. For the BSEN1525 Category II, the standard applies to the thermal environment occupied by people with 'normal level of expectations.' The thermal environment includes office spaces, laboratories, learning spaces such as classrooms, lecture halls, etc. The standard also takes into consideration the computation of the running mean temperature. Regarding the ASHRAE comfort model (ASHRAE, 2017), the standard follows the similar models discussed in this paper for assessing the performance and occupants' comfort in buildings.

Concerning the field measurements, the environmental monitoring of the variables (temperature, dew-point, air velocity, humidity, and CO_2 concentration) at every 1 hour was considered within the spaces of the school buildings. The data loggers were installed at 1.1 m height above the floor level to measure the variables. The data logged were analysed and discussed in this paper. For the field investigation during the warm season, the field measurements were considered from June to September 2017; while for the cold season, the physical measurements were carried out from October 2017 to February 2018.

Two of the sensors installed in the spaces did not measure relative humidity. However, the data loggers measured temperature and dew-point and other parameters throughout the field measurements. To determine relative humidity for the spaces, the equation (Equation 2) discussed in the existing study (Wanielista et al., 1997) was considered for the calculation of the humidity on hourly bases. In Equation 2, f is defined as relative humidity, T_D is dew-point temperature, and T is temperature. Likewise, the study (Wanielista et al., 1997) explained that dew-point temperature could be computed using Equation 3.

$$f = 100\left(\frac{112 - 0.1T + T_D}{112 + 0.9T}\right)^8$$ Equation 2

$$T_D = \left(\frac{f}{100}\right)^{1/8}(112 + 0.9T) + 0.1T - 112$$ Equation 3

This study also evaluated the Wet Bulb Globe Temperature (WBGT) index and the Universal Thermal Climate Index (UTCI) by considering the appropriate mathematical equations to compute the stress indexes in different seasons. The models have been used for assessment of heat stress and cold stress in various functional spaces of office buildings (NEHC, 2007), school buildings (Adekunle 2018a, 2018b), and residential buildings (Adekunle and Nikolopoulou, 2019; Adekunle, 2019). The detailed account of the WBGT has been provided in the published work (Stull, 2011; Lemke and Kjellstrom, 2012). Also, the detailed information about the UTCI, as well as its general overview have been discussed in the existing papers (Lemke and Kjellstrom, 2012; Adekunle 2018a). Table 1 and Table 2 present the temperature limits and classifications of thermal stresses for the WBGT and the UTCI.

Table 1. Temperature limits and categories of thermal stress for the WBGT.

The WBGT stress index category	**Duration**
Temperature less than 28.6°C	Less than 60 minutes/hour
Temperature at 29.3°C	Less than 45 minutes/hour
Temperature at 30.6°C	Less than 30 minutes/hour
Temperature at 31.8°C	Less than 15 minutes/hour
Temperature more than 38°C	Less than 0 minute/hour

Table 2. UTCI Assessment Rating to categorise thermal stress within the thermal environment (Glossary of Terms for Thermal Physiology, 2003).

Range of UTCI (°C)	UTCI Stress Classification
Temperature above +46°C	Extreme heat stress
Temperature from +38°C to +46°C	Very strong heat stress
Temperature from +32°C to +38°C	Strong heat stress
Temperature from +26°C to +32°C	Moderate heat stress
Temperature from +9°C to +26°C	No thermal stress
Temperature from +9°C to 0°C	Slight cold stress
Temperature from 0°C to -13°C	Moderate cold stress
Temperature from -13°C to -27°C	Strong cold stress
Temperature from -27°C to -40°C	Very strong cold stress
Temperature less than -40°C	Extreme cold stress

To compute the WBGT, Stull (2011) explained that the psychrometric wet bulb temperature could be determined by using the equation propounded in the paper. The study (Stull, 2011) proposed that the psychrometric wet bulb temperature (T_{pwp}°C) can also be described as the wet bulb temperature (T_w) expressed in Equation 4. Stull (2011) explained that the arctangent (atan) function in Equation 4 uses the values that are expressed in radians. The equation defines T_w as the function of T_a (°C) and RH (%) at a mean atmospheric pressure of about 101.325 kPa.

$$T_w = T_a \text{atan}[0.151977(RH\% + 8.313659)^{1/2}] + \text{atan}(T_a + RH\%) – \text{atan}(RH\% - 1.676331) + 0.00391838(RH\%)^{3/2} \text{atan}(0.023101 \times RH\%) – 4.686035 \quad \text{Equation 4}$$

The UTCI model is developed based on the proposition of the same temperature with a reference thermal environment of approximately 50% RH, elevated temperature more than 29°C, and a vapour pressure not greater than 2 kPa (Blazejckzy et al., 2013). Osczevski and Bluestein (2005) explained that a wind velocity above 3m/s would have a considerable impact on UTCI in the cold season when outside temperatures exceed 38°C; while people could be subject to extreme heat stress within the thermal environment (Adekunle, 2018a). To compute the UTCI, the mathematical equation (Equation 5) discussed in the existing research (Błażejczyk, 2011; Adekunle and Nikolopoulou, 2019) can be applied. For Equation 5, T is described as temperature, T_{mrt} is mean radiant temperature, RH is relative humidity, and V is wind speed at about 10m above the ground level. Both the WBGT and the UTCI indexes have been considered for wider applications in many projects (Climate Chip, 2016); while the UTCI considered in this paper is calculated using the strategy outlined in the published work (http://www.utci.org/utci_doku.php).

$$UTCI = 3.21 + 0.872T + 0.2459T_{mrt} + (-2.5078V) – 0.0176RH \quad \text{Equation 5}$$

4. Case Study

The case study is constructed with engineered timber products, in particular, cross-laminated timber (CLT) panels. The case study site is located on approximately 20 acres of urban park land at the base of one of the State Parks in the North-eastern part of the United States (Figure 1). The case study is designed and developed as a mixed-use. It consists of a high school, an inner-city farm land, and a resource centre for communal, recreational, and educational purposes. The CLT school building is one of the first school buildings in the United States to use engineered timber materials for the construction. In terms of the floor area, the case study has an area of approximately 1300sqm. The school development comprises of various functional and operational spaces such as offices, art/drawing studio, classrooms, hall for multipurpose events such as performance, indoor sports, educational, and communal activities.

Figure **1**. The map showing the Northeast of the United States

Regarding the design and layout of the spaces, the hall, general and administrative offices, storage spaces, restrooms, are arranged and located on the first floor. The classrooms, staff rooms, art/drawing studio, are arranged and located on the second floor. The CLT panels are explored for the tension surface, ceiling finishes while vertical CLT panels are utilised for the construction of bearing and shear walls. Glued laminated timber (Glulam) panels are used for the construction of the rafters and to span the hall. Regarding recognition, the case study has received many accolades and won numerous green-rated awards for its low carbon footprint. The case study has also been certified by the Leadership in Energy and Environmental Design (LEED) based on the energy cost-efficient assessment and other sustainability ratings. The LEED is a green building rating system developed in the United States, and it is one of the most broadly used green building rating systems in the world. Based on the wall thickness, the U-values of the walls varied from about 0.13 W/m^2K to 0.20W/m^2K.

The environmental monitoring of variables was conducted in the general office, and the hall (on the first floor); while the on-site measurements were also done in the classrooms (on the second floor). All the spaces highlighted were monitored in both warm and cold seasons. The spaces are naturally ventilated in the warm season, but they are also provided with mechanical heating, ventilation, and air conditioning (HVAC) systems. The development also uses ground source heat pumps for heating and cooling. In terms of orientation, the spaces are arranged in different orientations which have helped to improve the diversity of the data collected and analysed in this paper.

5. Analysis of Data

5.1. Analysis and Findings on the Outdoor Weather Data

For the period of the survey during the warm season, the mean outside temperature (daily) ranged from 12.0°C-27.0°C. In the cold season, the average outside temperature (daily) varied from -12.0°C-22.0°C. The overall average outside temperature for the warm period was 21.0°C while the overall mean outside temperature for the cold season was 4.8°C. The mean maximum and minimum outside temperatures of 25.9°C and 16.8°C in that order were observed during the field measurements in the warm season. In the cold season, the average maximum and minimum outside temperatures were 9.2°C and 0.7°C respectively. The average outside dew-point temperatures of 15.7°C and -0.6°C were measured during the warm and cold seasons in that order. For the mean outside RH (daily), the mean values ranged from 100%-31% in the warm season, and it varied from 100.0%-18.0% in the cold season. The overall mean outdoor RH in the warm season was 71.3%, and it was 67.2% in the cold season. The mean vapour pressure for the warm season was 1015millibars, while the mean vapour pressure of 1019millibars was measured in the cold season.

For the outdoor stress indexes in the warm season, the mean WBGT of 18.7°C and the mean UTCI of 21.6°C are computed for the study location. Also, in the cold season, the average WBGT of 3.3°C and the mean UTCI of 4.8°C are calculated as the external stress indexes for the location. The summary of the outdoor weather data for the warm and cold seasons is presented in Table 3. The analysis on the outdoor weather data measured at the study location showed high maximum temperatures exceeded the 28.0°C critical comfort threshold, while the mean temperature reported for the warm season did not exceed the limit. However, the mean temperature reported for the cold season is less than the comfort threshold recommended by ASHRAE for the heating season. The analysis also revealed that people are likely to be subject to moderate heat stress in warm season when the outdoor WBGT and UTCI are considered. Also, the analysis showed the possibility of moderate to strong cold stress for outdoor occupants during the cold season.

Table **3**. Summary of the outdoor weather data for the warm and cold seasons at the study location.

Parameters	Warm Season			Cold Season		
	High	Average	Low	High	Average	Low
Max. temp. (°C)	32.0	25.9	13.0	27.0	9.2	-10.0
Min. temp. (°C)	23.0	16.8	8.0	22.0	0.7	-17.0
Mean temp. (°C)	27.0	21.0	12.0	22.0	4.8	-12.0
Max. dew-point (°C)	24.0	18.1	7.0	22.0	3.6	-22.0
Min. dew-point (°C)	21.0	13.0	2.0	21.0	-5.1	-25.0
Mean dew-point (°C)	23.0	15.7	4.0	21.0	-0.6	-23.0
RH (%)	100.0	71.3	31.0	100.0	67.2	18.0
Wind speed (m/s)	17.4	5.0	0	22.4	5.6	0
Vapour pressure (Millibars)	1028	1015	1006	1044	1019	982
Precipitation (mm)	612.1	35.6	0	1948.2	73.7	0
WBGT	25.1	18.7	9.4	21.5	3.3	-13.1
UTCI	29.2	21.6	11.8	24.2	4.8	-14.0

5.2. Relationship Between the Outdoor Environmental Variables

On the relationship between the outdoor variables, the analysis showed strong associations exist between the outdoor temperatures and outdoor dew-point temperatures in the warm and cold seasons (Figure 2). The investigation revealed the dew-point has a significant impact on the outdoor temperatures in the cold season than the warm period of the field measurements. The study showed that, generally, dew-point temperatures could affect stress indexes at a higher rate in cold season than warm season.

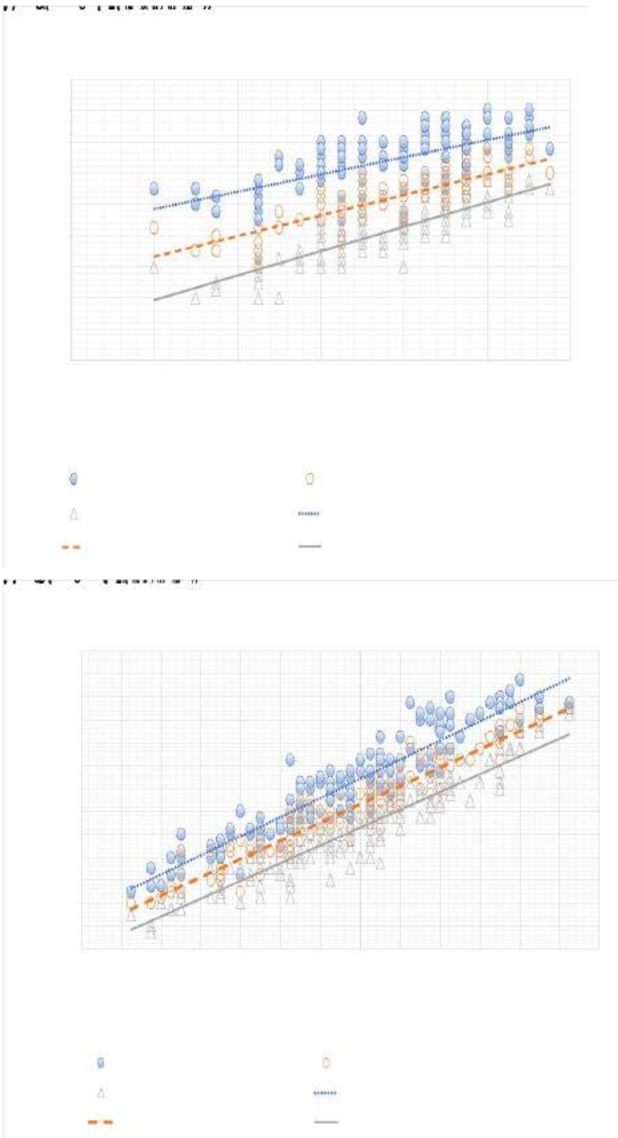


Figure **2**. The relationship between the outdoor temperatures and outdoor dew-point in both seasons

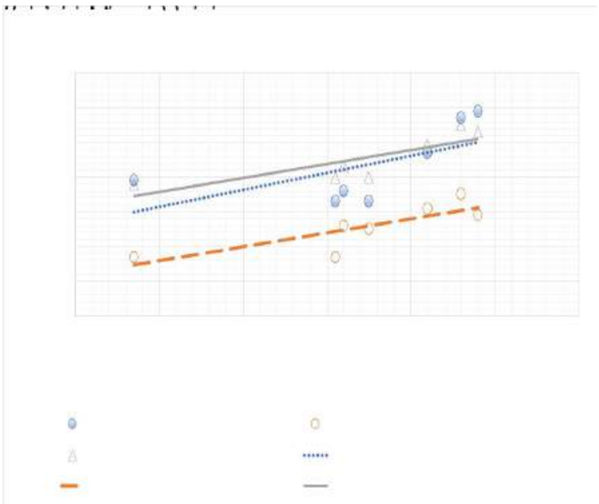
6. Results and Discussions

The findings revealed the mean indoor temperature in the general office on the first floor was 22.6°C in the warm season. In the cold season, the average temperature of 21.0°C was reported in the same space. The mean temperatures of 20.6°C and 19.2°C were measured in the hall on the first floor in the warm and cold seasons respectively. The study revealed lower mean temperatures were measured in the hall than the general office in the warm and cold seasons. The larger floor area of the floor, volume, difference in the space usage and variation in different activities taking place within the spaces, orientation, and regular use of the doors by users may be contributing factors to the lower temperatures reported in the hall than the general office despite the spaces are located on the same floor. The mean temperatures varied from 22.1°C to 24.1°C in the classrooms in the warm season. In the cold season, the average temperatures ranged from 20.3°C to 20.4°C in the classrooms. Classroom 2 (Southeast facing) is the warmest classroom in the warm season. In the cold period, higher maximum and mean temperatures were reported in Classroom 1 (Northwest facing). The orientation, volume, frequent space usage might be contributing factors to higher temperatures reported in Classroom 2 during the warm season.

In the warm season, the average dew-point temperatures of 17.6°C and 15.3°C were observed in the general office and hall respectively. In the cold season, the mean dew-point of 10.9°C and 11.0°C were reported in the office and hall in that order. Across the spaces, mean RH varied from 52.8% to 71.9% in the warm season, and it ranged from 31.8% to 59.6% in the cold season. Higher temperatures were reported in the classrooms than the other spaces in the warm season. The location of the classrooms on the second floor may be a contributing factor to the higher temperatures observed in the classrooms than the general office and hall. A similar trend is also noticed in the spaces during the hours of occupation (8am-5pm). The results showed the possibility of users to be more comfortable in the office spaces and hall than the classrooms during the hours of occupation (8am-5pm) in both seasons. However, further analyses on the occupants' comfort during the non-hours of occupation will not be considered in this study. The overall range of CO_2 level was below 1000ppm (that is, from 48.2-496.3ppm) for most of the time during the field measurements. The mean value of CO_2 concentration was within the acceptable range of 350ppm to 1000ppm recommended for healthy indoor spaces. Table 4 provides the summary of the average, maximum and minimum values of the parameters within the spaces in the warm and cold seasons.

Table **4**. Average, maximum, and minimum values of parameters including the range of CO_2 concentration within the spaces during the warm and cold seasons

Variables	**Warm Season**						**Cold Season**					
	Max temp (°C)	**Min temp (°C)**	**Avg temp (°C)**	**Avg dew-point (°C)**	**Avg RH (%)**	**Range of CO_2 conc. (ppm)**	**Max temp (°C)**	**Min temp (°C)**	**Avg temp (°C)**	**Avg dew-point (°C)**	**Avg RH (%)**	**Range of CO_2 conc. (ppm)**
General office (First floor)	26.6	18.2	22.6	17.6	57.7	48.2 – 496.3	23.0	18.4	21.0	10.9	46.7	56.8 – 400.2
Hall (First floor)	28.2	17.6	20.6	15.3	71.9		26.4	17.6	19.2	11.0	59.6	
Classroom 1 (second floor)	28.1	18.2	22.1	12.5	55.2		30.4	12.4	20.4	1.7	31.8	
Classroom 2 (second floor)	28.9	20.7	24.1	13.8	52.8		23.2	12.3	20.3	6.7	42.9	
Classroom 3 (second floor)	28.5	19.4	23.1	13.1	54.1		26.8	12.2	20.3	4.2	37.4	



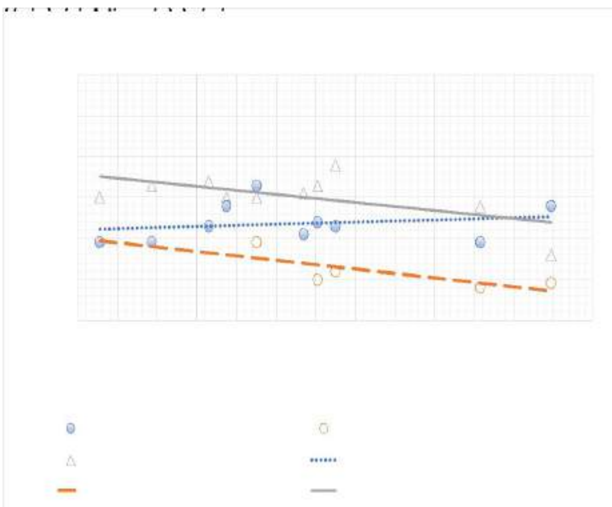


Figure **3**. The relationship between the indoor and outdoor temperatures in the warm and cold seasons

In order to establish the relationship between the indoor and outdoor temperatures in the spaces, the averages for the classrooms were considered for the analysis. The data were plotted to find the association between the variables in both seasons (Figure 3). In the warm season, the associations exist between the parameters in all the spaces with a higher level of relationship found in the hall (R^2 = 0.6653) and the general office (R^2 = 0.6720) than the classrooms (R^2 = 0.3804). The results showed the outdoor and indoor temperatures are strongly related in the two spaces (hall and general office) during the warm season. The temperatures are within a similar range (about 2.0°C) in all the spaces with higher indoor temperatures reported in the classrooms and the general office than the hall. In the cold season, the study showed associations are found between the parameters in the hall (R^2 = 0.5781) and the general office (R^2 = 0.3602), while no link is established between the parameters in the classrooms (Figure 3). The results showed occupants' comfort in the classrooms could be influenced by other parameters such as behavioural actions of occupants, hours of occupation, orientation, use of control, physiological modifications, as well as activities carried out within the spaces, etc.

The air velocity was also measured in the spaces during the field measurements. The mean values of air speed between 0.1m/s and 0.2m/s were observed in the spaces. Based on the parameters measured in both seasons, the mathematical models expressed in Equation 4 and Equation 5 were applied to calculate the mean WBGT and UTCI thresholds within the spaces. The overall mean values of air speed reported in the spaces were used for the computation. The study revealed a higher mean value of the WBGT was computed in the general office than the other spaces in the warm season, while a higher UTCI value was calculated in Classroom 2 (Southeast facing) than the remaining spaces at the case study. In the cold season, higher mean values of the WBGT and UTCI were reported in the general office than the other spaces. Even though the results did not show the occupants are currently subject to heat stress, the study creates an awareness of the possibility of the occupants to be prone to heat stress especially during extreme summertime or heat wave. The study also analysed the number of hours above the critical comfort threshold (28°C) within the spaces. The results showed that the number of hours above the comfort threshold did not exceed 5% of the time.

The overall mean values of the WBGT (19.1°C) and UTCI (22.6°C) were computed in all the spaces in the warm season. In the cold season, the mean values of 15.4°C and 19.4°C were calculated for the WBGT and UTCI respectively. The results showed for the warm season, lower stress indexes are computed in this study than the existing research on heat stress in buildings (Vatani et al., 2016; Adekunle 2018a); while for the cold season, higher stress indexes are calculated in this paper than the existing papers on cold stress in buildings (Adekunle, 2018b; Adekunle and Nikolopoulou, 2019). Table 5 summarises the mean values of the mean temperatures, WBGT, and UTCI within the spaces.

Table **5**. Mean values of the variables within the spaces in both seasons compared with the comfort model, WBGT, and UTCI heat indexes

Variables	**Warm Season**				**Cold Season**			
	Avg temp (°C)	**Mean WBGT (°C)**	**Mean UTCI (°C)**	**No of hours above 28°C**	**Avg temp (°C)**	**Mean WBGT (°C)**	**Mean UTCI (°C)**	**No of hours above 28°C**
General office (First floor)	22.6	20.4	23.5	0	21.0	17.0	20.5	0
Hall (First floor)	20.6	18.3	21.1	0.25	19.2	15.9	19.0	0
Classroom 1 (second floor)	22.1	18.2	21.8	2	20.4	14.1	18.9	1.75
Classroom 2 (second floor)	24.1	19.7	23.8	50.25	20.3	15.3	19.3	0
Classroom 3 (second floor)	23.1	18.9	22.8	25	20.3	14.5	19.1	0

The study conducted further statistical analyses to determine if associations exist between the mean values of the WBGT, the UTCI values, the indoor temperature, relative humidity, and air velocity. The findings revealed that strong associations exist between the parameters especially in the warm season. Stronger associations were also found between the variables in the hall and the general office than the classrooms during the cold season. However, a weak association is found between the mean indoor temperatures and RH within the spaces in the cold season. Figure 4 and Figure 5 show the level of associations that exist between the parameters in the general office in the warm and cold seasons. Similar results were also observed in the other spaces. The research showed that higher values of air velocity at warm temperature do not have a substantial effect on the UTCI values in the cold season (Figure 5).

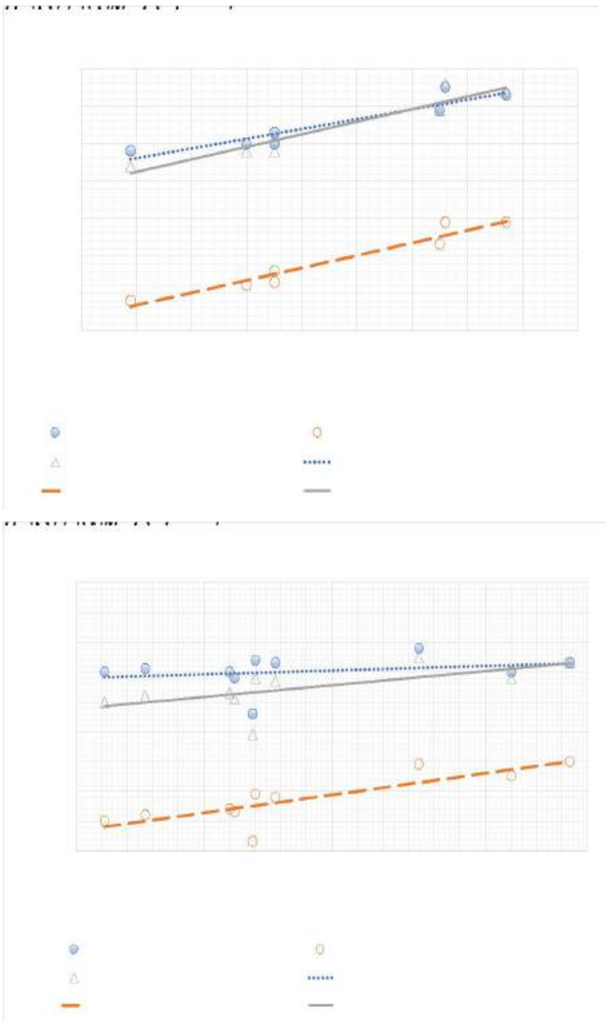


Figure **4**. The relationship between the mean indoor temperature, the stress indexes (WBGT and UTCI) and RH within the general office during the warm and cold seasons

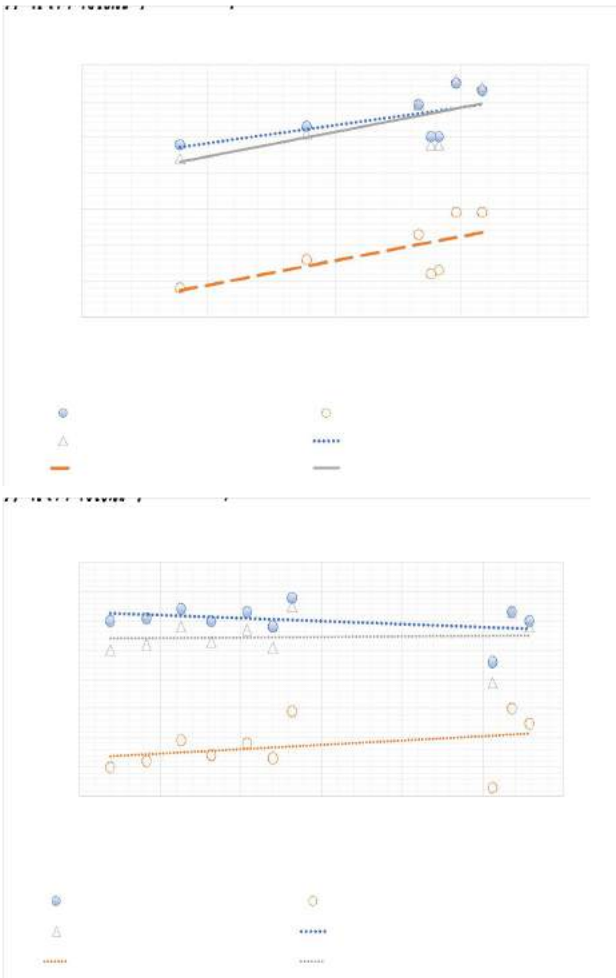


Figure **5**. The relationship between the mean indoor temperature, the stress indexes (WBGT and UTCI) and air velocity within the general office during the warm and cold seasons

Similarly, the outcomes of the research showed that strong associations are found between the WBGT and UTCI values in the warm and cold seasons (Figure 6). The research found out that a combination of different personal and environmental parameters can affect stress indexes within the thermal environment. For examples, behavioural actions of occupants like frequent intake of cold drinks during the heat wave or extreme summertime temperatures or taking hot drinks during the cold season, physiological adjustments, change of clothing insulation can reduce the risk of occupants to heat and cold stresses within the thermal environment in different seasons. Based on the analyses conducted to establish links between the mean values of the WBGT and UTCI, the overall results revealed that a change in the WBGT values has a noticeable impact on the UTCI values. The study also showed the applicability of the mathematical models for evaluation of stress indexes in various thermal environmental conditions.

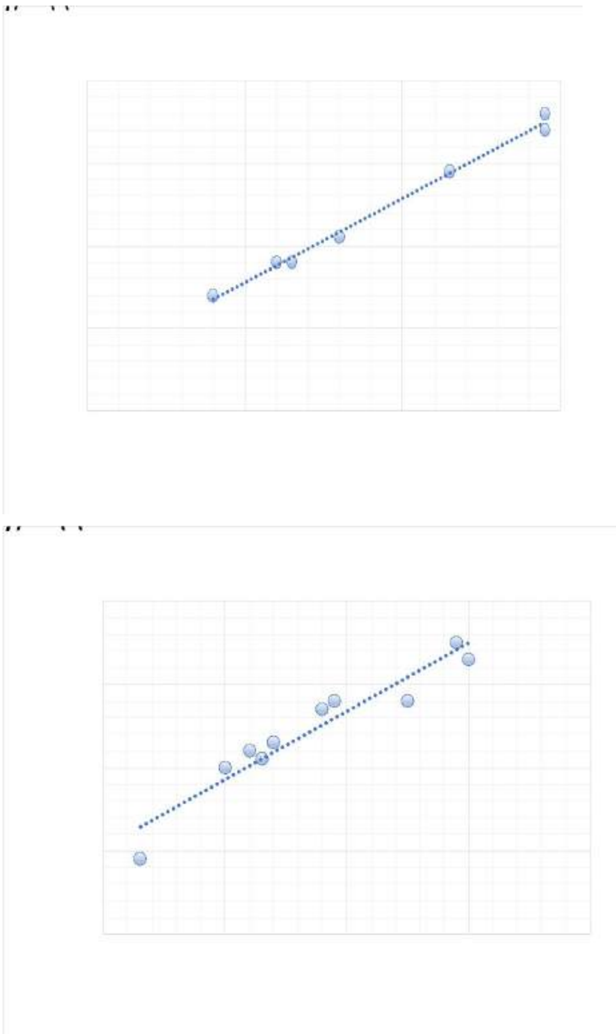


Figure **6**. The relationship between the WBGT and UTCI during the warm and cold seasons

A comparative analysis of the results on the overall average of WBGT and UTCI values with existing studies in the field was considered (Figure 7). The findings showed that higher average temperatures are found in two of the existing studies (Vatani et al., 2016; Adekunle 2018a) than the average temperatures reported in the current study. The results also revealed that higher associations are found between the variables in some of the existing papers than the associations found in the current study in the two seasons. However, higher associations and higher mean temperatures are found in the current study than the study conducted by Lemke and Kjellstrom (2012). The results showed the possibility of occupants to the risk of heat and cold stresses in different seasons.

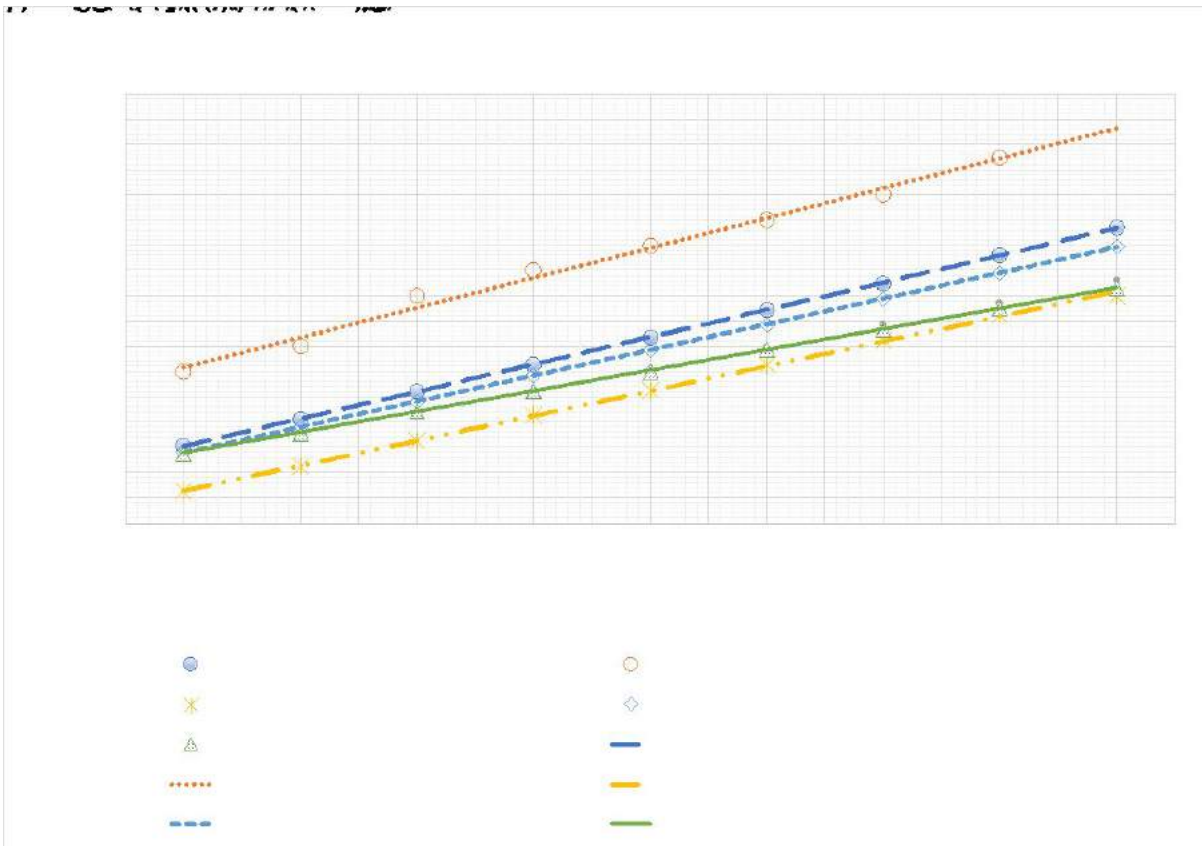


Figure **7.** Comparison of the findings of the current study during the warm and cold seasons with the existing studies on the relationship between the average values of the WBGT and UTCI

The research also compared the indoor temperatures reported in the spaces (general office, hall, and classrooms) with the ASHRAE, the BSEN15251, and the CIBSE thermal comfort categories to evaluate the thermal environment of the case study. Since the case study is expected to be free-running in the warm season but heated in the cold season using the HVAC systems, the comparative analysis of the indoor temperatures with the thermal comfort categories only focused on the data for the warm season. Across the spaces, the research revealed the indoor temperatures are between the applicable Category II upper and Category II lower thermal comfort thresholds for most the time (Figure 8). The temperatures did not surpass the limits for more than 5% the time. Nevertheless, different outcomes may be obtained if the temperatures observed during the hours of occupation (8am-5pm) and non-hours of occupation (6pm-7am) within the spaces are compared with the thermal comfort categories. The study also observed frequent use of control (such as fans, opening of large doors in the hall area), and more extended hours of occupation due to various activities (such as communal, recreational, and educational) at the development may be contributing factors to lower temperatures reported during the field measurements especially in the warm season.

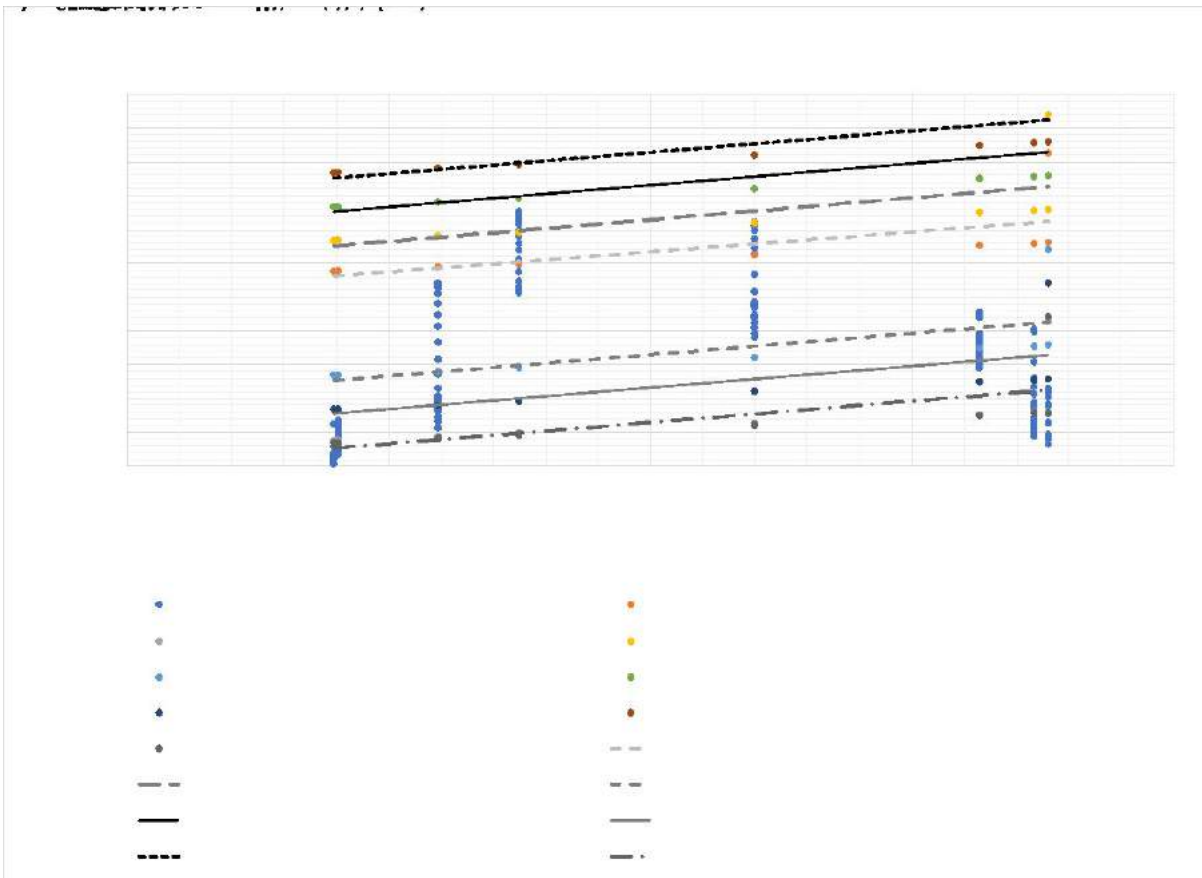


Figure **8**. Internal temperatures observed within the spaces of the case study compared to the ASHRAE, BSEN15251, CIBSE thermal comfort categories.

7. Conclusions

The paper examined stress indexes and thermal comfort in structural timber school buildings built with cross-laminated timber (CLT) panels during cold and warm seasons. The research conducted the field measurements of the parameters on an hourly basis within the spaces in the two seasons. The study revealed the average outdoor temperature of 4.8°C in the cold season and a mean outdoor temperature of 21.0°C in the warm season. The average internal temperatures of 20.2°C and 22.5°C were measured within the spaces of the case study during the cold and warm seasons respectively. The mean RH of 43.7% was observed in the cold season, and a mean RH of 58.3% was measured in the warm season. The average air velocity within the spaces varied from 0.1m/s to about 0.2m/s. The overall mean CO_2 concentration was below 1000ppm, and the mean value was within the acceptable range of 350-1000ppm for healthy and comfortable thermal environment. In the warm season, higher temperatures were observed in the classrooms than in the other spaces. The location of the classrooms on the upper floor may be a contributing factor to the higher temperatures reported in the spaces than the temperatures reported in the general office and hall. In both seasons, the classrooms and offices are found to be much warmer than the hall. The placement of the hall, its orientation, large volume, frequent use of doors and windows, as well as different activities carried out in the hall may contribute to lower temperatures reported in the hall than the classrooms and offices. The study showed that the indoor temperatures observed in the development are within the applicable thermal comfort models (ASHRAE, BSEN15251, and CIBSE) considered in this paper. The applicability of the mathematical equations to assess the stress indexes within the spaces of the case study revealed the mean WBGTs of 15.4°C and 19.1°C in the cold and warm seasons in that order. The mean UTCIs of 19.4°C and 22.6°C were calculated at the case study for the cold and warm seasons respectively. The study highlights that building users are likely to be susceptible to cold and heat stresses as external temperatures increase or decrease in different seasons. The research reveals that higher values of air speed at increasing temperatures do not have a substantial effect on the UTCI values in the cold season but have a noticeable impact on the variable in the warm season. Finally, the study recommends that further adaptive measures should be considered by the users to improve their comfort; thereby reducing their vulnerability to cold stress in the cold season and heat stress in the warm season especially during the extreme heat wave or summertime.

8. Acknowledgement

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The impact of trees on passive survivability during extreme heat events in warm and humid regions

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Abstract: Communities are increasingly affected by excessive heat. The likelihood of extreme heat events is predicted to increase in the Midwest region of the United States. By mid-century (2036–2065), one year out of 10 is projected to have a 5-day period that is 13°F warmer than a comparable earlier period (1976–2005). The frequency of high humidity/dew point days ("extra moist tropical air mass days," MT++ synoptic climate classification system) has also increased significantly during a similar period (1975–2010) and between 2010 and 2014 included 8 of 26 heat events. This impact is exacerbated by the fact that many residences in low-income neighbourhoods in the US do not have central air-conditioning systems (e.g., up to 50% of low-income homes in Polk County, the location of our study in the US Midwest). Modifications to urban landscapes by the addition of trees can modify temperatures in the nearby environment, which is important for reducing summer heat loads on building surfaces. Trees can reduce energy use and improve indoor and outdoor comfort for cooling in summer by casting shade and providing evapotranspirational (ET) cooling. This paper presents a methodology to combine spatially explicit three-dimensional tree morphology and estimates of ET rates with building location and wall characteristic data to test their relative contribution to building energy consumption. Based on a comprehensive tree inventory for our Midwestern study neighbourhood, tree morphology and building data have been integrated in a three-dimensional array in the "Urban Modeling Interface" (*umi*) to estimate cooling due to interception of sunlight. We then perform a series of parametric computational fluid dynamics (CFD) studies to simulate ET cooling for various tree morphologies and relative locations to walls. We resolve conventional mesh generation challenges associated with CFD by introducing a novel, immersed boundary framework based on adaptive octree meshes. This approach can seamlessly include trees and buildings at arbitrary locations with minimal human effort. This model was run with and without trees to quantify the relative impact of that process in the microenvironment. The paper presents first results of CFD modeling for latent heat transfer near urban trees.

Keywords: climate adaptation, passive cooling, urban forest, computational fluid dynamics model, evapotranspirational cooling

1. Introduction

Globally, communities are increasingly affected by excessive heat, which can lead to increased human morbidity and mortality. The likelihood of extreme heat events is predicted to increase markedly in the Midwest region of the United States. By mid-century (2036–2065), one year out of 10 is projected to have a 5-day period that is *13°F warmer* than a comparable earlier period (1976–2005; Melillo et al. 2014). Current average annual 5-day maximum temperatures range from about 87°F along the Canadian border to 97°F in Missouri. The frequency of high humidity/dew point days ("extra moist tropical air mass days," classified as MT++ according to the synoptic climate classification system; Sheridan 2018) has also increased significantly during a similar period (1975–2010) and between 2010 and 2014 included 8 of 26 heat events. Seven out of 12 MT++ days caused a 10% to 30% increase in daily human mortality by the fifth day of extended heat events of 90°F or more (Kalkstein 2014). This impact is exacerbated by the fact that many residences in low-income neighbourhoods in the US do not have central air-conditioning systems (e.g., up to 50% of low-income homes in Polk County; PCHD 2018).

Our research team is developing novel hybrid data-physics models to assimilate weather, building, and near-building microclimate data to integrate with a building energy simulator to forecast building interior temperatures during real-time events or to create scenarios to enhance community preparedness (Hashemi et al. 2018). This approach can combine data across spatio-temporal scales (i.e., satellite, community, home, and individual) with physics-based models of near-building and indoor environments for real-time identification and predictions of locations most affected by extreme heat events.

Members of the project team have conducted relevant research on occupant-building-microclimate relationships and validation of CFD models for urban energy dynamics (Mutti 2014; Deza et al. 2015). They have analyzed multi-phase convective heat transfer in complex geometries (Sharma et al. 2018), symbolic abstraction for optimization of energy efficient buildings (Sarkar et al. 2012, 2013), and human-machine interactions (Lore et al. 2015, 2016). Additional work focused on algorithms for urban heat island modeling and impacts on building energy use (Zhou et al. 2012; Guneralp et al. 2017). In addition, this work has included investigations of the effect of human-building interactions on building energy performance (Kalvelage et al. 2015, 2016), climate change predictions for urban systems (Rabideau et al. 2012), and their integration in the urban modeling interface (umi) to understand impact of weatherization in future climates (Jagani & Passe 2017).

2. Background – Urban Heat and Comfort at the Extreme

The Polk County Health Department (PCHD) (with jurisdiction over Iowa's capital, Des Moines, and adjacent suburban/rural communities) has indicated a critical need for improved knowledge about vulnerability of residents to extreme heat. Preliminary measured data for homes in the Bank neighbourhoods of Des Moines showed that temperatures inside non-shaded, poorly insulated, or non-ventilated homes can be even higher than ambient temperature, conditions that are common in resource-limited neighbourhoods and thus hinder comfort at these extreme conditions. Those uncomfortable conditions are even detrimental to health and wellbeing of occupants, particularly during heat events of extended duration (Lomas & Porritt 2017).

In the US Midwest, events above 90˚F for 3 days or more are considered significant heat events, also called "heat waves." A significant impact of excessive heat is increased human mortality (for example, 670 people died during the 1995 Chicago heat wave). As indicated, increasing frequency of MT++ days have resulted in 10% to 30% increases in daily heat-related mortality (Kalkstein 2014). Peak dew points on the most oppressive days have also increased over time, from 72˚ to 74˚F. The World Meteorological Organization has called for development of HHWS alerts at neighbourhood-specific scales (due to variable characteristics within urban areas and temperature increases caused by heat island effects), for increased knowledge of heat-related indoor conditions (temperature and relative humidity) as they relate to human health, and for improved integration of urban and rural heat alerts (WMO 2015). HHWS should thus be re-designed to focus at finer spatial scales and also better address needs in rural areas. Predicting interior temperature of buildings which lack active mechanical systems is a complex thermo-physical challenge (Lomas & Porritt 2017).

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While it has long been known that vegetation in near-building environments reduces reflected radiation, affects surface heat fluxes, and increases evapotranspiration (e.g., Tabares-Velasco & Srebric 2012 and citations therein), efforts to integrate these effects in combined building-microclimate energy models have only recently been made (Taleghani et al. 2016) and models validated with local data remain rare (TNC 2016). In fact, little empirical research has focused on near-building environments using a comprehensive approach to assess the role of urban trees for building energy consumption. Nowak and co-workers (2008, 2017) studied avoided energy use for cooling and highlighted the need for additional research relating specific tree characteristics (such as dimensions, distance/direction from buildings, and evapotranspiration rates) on those dynamics. Other studies have demonstrated that tree placement (affecting radiation intensity and interception of sunlight) and tree morphology (tree size, canopy size and shape, leaf area, and leaf density) are important determinants of building energy use for cooling (Holmes 2015; Hwang et al. 2017). Others have called for additional research to incorporate such investigations with studies of building heat balances in non-air-conditioned structures (e.g., TNC 2016).

The integration of such data into building energy analyses and visualization tools such as the urban modelling interface (*umi*) (Reinhart et al. 2013) could significantly improve model predictions for building thermal performance in existing urban neighbourhoods, that have tree canopy cover but where buildings lack air conditioning. *umi* is a Rhinoceros-based design environment for architects, engineers, and urban planners interested in modeling the performance of neighbourhoods and cities with respect to operational and embodied energy use, walkability and daylighting potential.

3. Methodology

3.1 Study area

The study area is in Polk County, Iowa, within the limits of the City of Des Moines, and includes a portion of a municipally-recognized area known as the Capital East neighbourhood, relatively close to the city's downtown. It was chosen as a test case because of specific social and economic characteristics that limit residents' ability to control the temperatures within their homes. We developed empirical databases describing both the characteristics of the buildings (340) and the trees (1142) in a portion of this neighbourhood (Hashemi et al. 2018).

3.2 Assessment of tree location and morphology

Tree data were collected in an inventory of a portion of the neighbourhood during summer 2017: 1,142 neighbourhood trees were catalogued using a Trimble Geo 7X Handheld GNSS receiver. Data collected include tree species, trunk diameter, tree height, canopy shape/height, canopy width in two dimensions, and latitude/longitude coordinates.

3.3 Assessment of buildings

We developed a Geographic Information Systems (GIS) shapefile integrating parcels, building footprints, and elevation data for an area within the neighbourhood. Grasshopper 3-D, the Meerkat plug-in, and GIS shapefiles were used to create a 3-D model of the buildings. We used GIS files for building footprints, elevations, and parcels, which were obtained from records maintained by City of Des Moines' Assessor's office. After preparing the shapefiles for buildings and trees, which contained required information to create the model, we imported them into Rhinoceros 3-D. To do so, we used Meerkat (a GIS data-parsing plug-in) to import shapefile data into Rhinoceros 3-D. This plug-in allows selection and cropping of shapefile layers for a specific area of interest. The result is a layered collection of 2-D linework that can then be further manipulated in Grasshopper or Rhino. These steps led to a similar base map for all necessary geometries (buildings and trees). A shadow range analysis of the whole neighbourhood including tree geometries and location for May-September was simulated by Hashemi et al. 2018 (Figure 1). The hours of direct sunlight received by buildings increases from dark to light colours; buildings indicated in blue had more than 5% reduction in cooling demand for the scenario with trees based solely on shading.

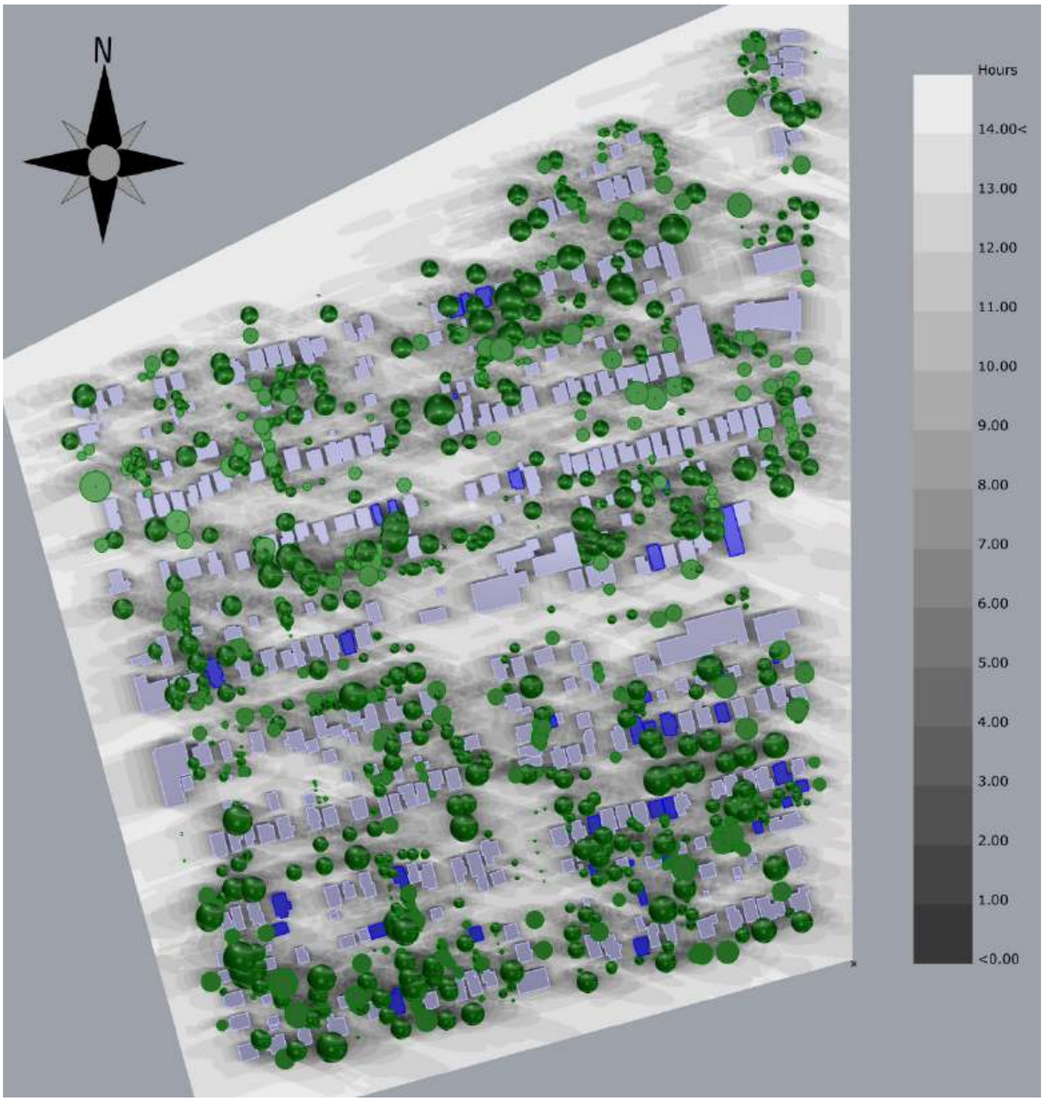

Figure 1. Shadow range analysis of neighbourhood including tree geometries and location (May-September) (Hashemi et al 2018). Hours of direct sunlight received by buildings increases from dark to light colours; buildings indicated in blue are those with more than 5% reduction in cooling demand for the scenario with trees.

3.4 CFD using Immersed Boundary Method

To understand the impact of position of trees relative to position of the built environment requires a parametric study consisting of multiple tree configurations that must be reliably simulated. A major burden of such parametric studies is the need to manually construct high resolution body-fitted meshes that include complex objects. Studies have shown that such manual mesh generation of analysis suitable geometries takes up 80% of time and effort thus precludes detailed parametric analysis (Cottrell et al. 2009). We circumvent this bottleneck by relying on an Immersed Boundary Method (IBM) for Computational Fluid Dynamics (CFD) modeling. The IBM embeds the solid geometry (e.g., trees, buildings) into a background

Cartesian mesh without conforming the background mesh to the objects, and the effect of the immersed boundary on the fluid field is accounted for by distributing the boundary conditions of the immersed geometry on the background Cartesian mesh. Since the IBM does not require a conforming mesh, it becomes computationally convenient to simulate different kinds of configurations while avoiding a cumbersome boundary-fitted meshing process. In addition to the background Cartesian mesh, each discrete object (tree, building) is represented as a Computer-Aided Design (CAD) object. This enables seamless integration into downstream analysis and visualization tools (like the urban modeling interface, *umi*). The B-rep surface defined by the CAD model is triangulated to a stereolithography (STL) format, with the size of the triangle (refinement level) pre-determined to match the resolved scale of numerical simulation (the size of the Cartesian mesh). Each discrete object is completely independent and can be placed anywhere in the Cartesian mesh, which is dynamically refined (see next section). This leads to ease of constructing meshes for a whole neighbourhood, with and without the presence of trees (Figure 2). This mesh construction is fully automatic and requires no manual intervention.

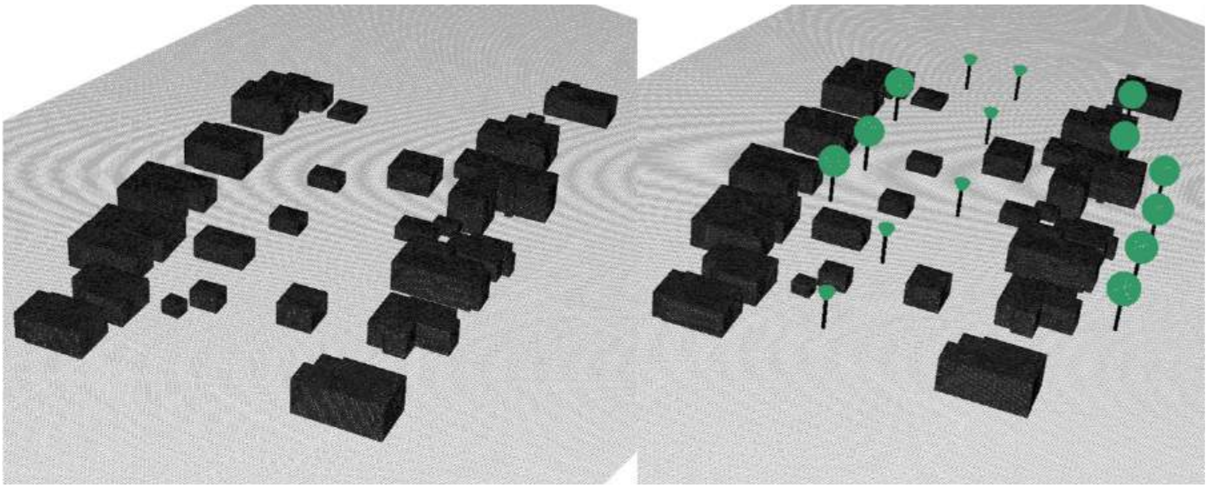

Figure 2: Neighbourhood without trees on the left and the same neighbourhood with trees on the right.

3.5 Incorporation of trees into the urban Computational Fluid Dynamics (CFD) model

Depending on thermal conditions, buoyancy driven thermal plumes exist due to evapotranspiration from trees. The accurate modelling of this phenomenon is critical to evaluating impact on the near- building environment and requires a refined mesh near the tree surface to capture the heat transfer and boundary-related physics. Similarly, accurately capturing the boundary layers on the walls requires a refined mesh close to those boundaries. We used an octree-based Cartesian meshing scheme that enables efficient, parallel and fast mesh generation and refinement. Starting from a coarse uniform mesh, each cell in the mesh was refined if an STL surface (tree or house) passed through it. Here, refinement means sub-division of a cell into its eight constituent octants. Since the refinement happens in a cell-local fashion, this step is parallel and instantaneous. The refinement is repeated until a preselected level of accuracy is achieved. To ensure numerical accuracy and stability, it has been shown that the refinement level between neighbouring cells cannot be drastically different (i.e., a very coarse cell next to a fine cell will cause numerical instabilities). This is ensured by using

2:1 balancing so that no two neighbouring octants differ in size by more than a factor of two. The complete mesh is represented as a graph, which enables easy domain decomposition and parallel distribution (shown for a representative tree-building configuration in Figure 3). More details of this framework are available at DENDRO (Sundar et al. 2008).

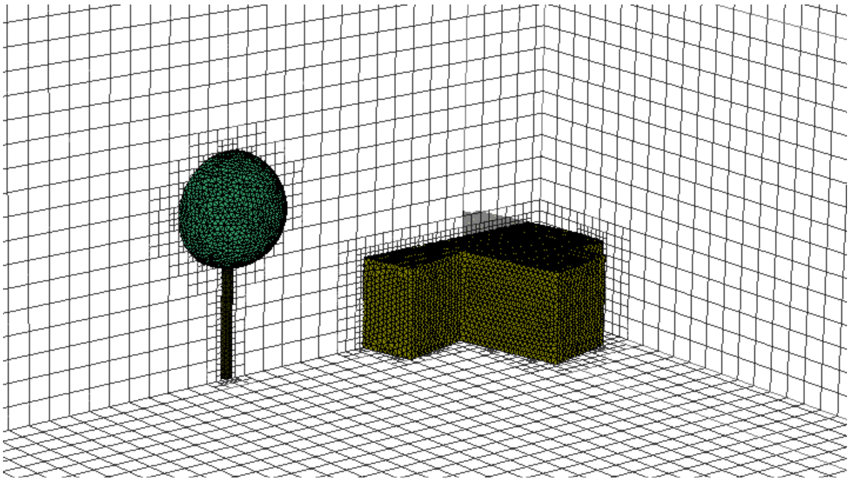

Figure 3. Mesh with adaptive refinement around the interfaces of immersed geometries with enforced 2:1 balancing

3.6 Simulation of tree surface temperature and evapotranspiration

We reviewed the literature to make determinations of surface temperatures for tree leaves and trunks. In hot and humid climates, leaf surface temperatures are generally above ambient temperatures due to absorbed solar radiation. Leaves reduce the effects of solar heating via re-radiation, convection and conduction with the air, and through transpiration and evaporation (Gates 1962). Leaf temperature, in turn, influences rates of respiration, photosynthesis, and transpiration, although the exact numerical influence on each is unknown (Leuning et al. 1995; Blonder & Michaletz 2018). Leaves in hot and dry conditions are generally closer to ambient temperature than leaves in hot and wet conditions because ambient humidity slows the escape of water from leaf surfaces (Lin et al, 2008, Blonder and Michaletz, 2018). Wind speeds have significant effects on leaf temperatures, reducing surface temperatures compared to ambient temperatures by up to 50% (Gates, 1962; Ansari 1959; Vogel, 2009). Further, leaves in direct sunlight have been reported to be from 2 to 20 °C above ambient temperatures, while leaves in shade may be as much as 1.5 °C below ambient (Gates, 1964; Gates, 1962; Pincebourde and Woods, 2012; Vogel 2009; Smith and Carter, 1988; Lin et al, 2008). Based on these general observations we determined that leaf surface temperatures for the tree species found in the Capitol East neighbourhood would be approximately 10 °C above ambient temperature at noon on a typical sunny June day with average wind speeds of 5 mph. The temperatures of the tree's trunk would be very similar to the ambient temperature.

We then created a 3 x 3 matrix of estimated evapotranspiration (ET) values for a representative small, medium, and large tree across three seasons (spring, summer, and fall). We used the 'K_c-ET_o' method of estimating ET (Allen 1998; FAO ET calculator) and published crop coefficients (K_c) for select tree species using the following equation:

$$ET = K_c ET_{ref}$$

where ET is evapotranspiration (for a tree), K_c is the crop coefficient, and ET_{ref} is the reference evapotranspiration (also known as ET_o).

We chose three species to serve as "proxies" for the small, medium, and large trees that occur in the neighbourhood to estimate the crop coefficient for each (Johnson et al 2000, Irmak et al 2012). The species and K_c values we used (Table 1) were selected from the limited literature on ET for trees and reflect similarity in tree form, leaf morphology, and degree of maturity compared to the trees for which they serve as proxies.

Table 1: Kc values for small, medium, and large trees for representative monthly conditions in spring, summer, and fall. Kc is a unitless coefficient.

	K_c values by tree species and size		
Season	Small	Medium	Large
Spring (April)	0.4	0.5	1.1
Summer (July)	1.0	1.2	0.9
Fall (September)	0.9	1.6	1.1

We determined reference evapotranspiration (ET_{ref}) based on estimated ET from a field of uniform grass under normal and non-stressed conditions calculated according to the FAO Penman-Monteith equation (Allen 1998) using the FAO ET calculator. Historical weather data were obtained from Weather Underground data for a nearby neighbourhood. Then ET_{ref} was calculated for three dates, representing typical conditions in spring (April 22, 2017; cool and low humidity), summer (July 17, 2017; hot and high humidity), and fall (September 15, 2017; warm and moderate humidity; Table 2).

Table 2: Reference ET for spring, summer, and fall based on historical Weather Underground station data.

	Season		
Parameter	Spring	Summer	Fall
Representative date	April 22, 2017	July 21, 2017	September 15, 2017
Reference ET (mm/day)	3.9	6.5	4.7

Tree ET was then estimated for each season as a flux for each representative tree selected from the Capitol East tree inventory (Table 3). These ET values can be used to estimate the total daily volume of evapotranspiration by a single tree using the tree's canopy area.

Table 3: Estimated ET flux for small, medium, and large trees for spring, summer, and fall.

	ET (mm/day) by representative tree species/ size		
Season	Small	Medium	Large
Spring	1.6	2.0	4.3
Summer	6.5	7.8	5.9
Fall	4.2	7.5	5.2

3.7 Simulation details and boundary conditions

A total of 18 + 1 configurations are simulated for this study. A house was selected from the neighbourhood by identifying a building with average size and moderate complexity. The height of the house was normalized to 1 (dimensionless height). The tree was generalized as a cylinder-shaped trunk and a spherically-shaped canopy. The trees in our simulations are parametrized into three different sizes and three different placements (Table 4).

Table 4: Size and placement of tree (H is height of house).

Size of tree (trunk height/canopy diameter)		
Small	Medium	Large
1.25/1	1.5/1.25	1.75/1.5
Placement of tree (distance from front of house)		
1.5	2.5	5

We placed the tree and house within a computational domain of size 20*20*5, with the house at the bottom center (10, 10, 0) (Figure 4). We chose such a large computational domain to ensure that there are no boundary-induced effects, and to ensure that any wakes developed behind the structures are accurately captured.

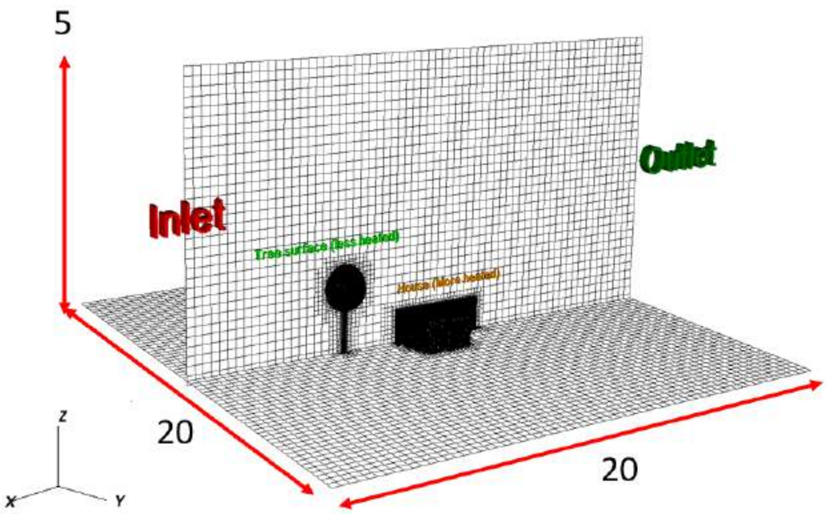

Figure 4. Domain of the simulation (not to scale).

The boundary conditions include a velocity inlet condition of 0.25 (a dimensionless velocity), at a direction normal to the boundary with the temperature of the incoming flow at ambient temperature. The pressure outlet for outflow boundary (a dimensionless pressure) is 0. A no-slip wall was created for the ground at ambient temperature. A zero-gradient, adiabatic wall was created for the top, front and back boundary of the building. The internal house temperature was set at 30°C above ambient temperature. For the simulations without evapotranspiration cooling trees consisted of two parts, the trunk at ambient temperature, and the canopy at 10°C above ambient temperature. We solve all equations in their non-dimensional form. Consequently, the flow physics determining parameter for this geometry is the Rayleigh number, which is of the order of 1e7.

4. Results

All simulations were performed on a high performance computing system (TACC Stampede). The simulations were run on 24 Skylake nodes. The average x (Figure 5) and z (Figure 6) air movement velocity for the house and tree were calculated for four cases: a house only, a small tree close to the house, a medium tree close to the house, and a large tree close to the house. Incoming air flow from the left is obstructed and deflected by the tree. For the z velocity comparison the medium-sized tree has a larger influence on air flow than the large tree, possibly because the canopy of the large tree is further away from the house and has less effect on air movement close to it. Temperature iso-surfaces were also developed for same comparisons (Figure 7). The effect of the buoyancy-driven wake is clear in the house-only configuration as the temperature iso-surface shows an upward movement in the z-direction. With a tree in front of the house, the temperature surface is changed dramatically, and as the size of the tree increases, the temperature iso-surface increases in length in the x-direction (Figure 7).

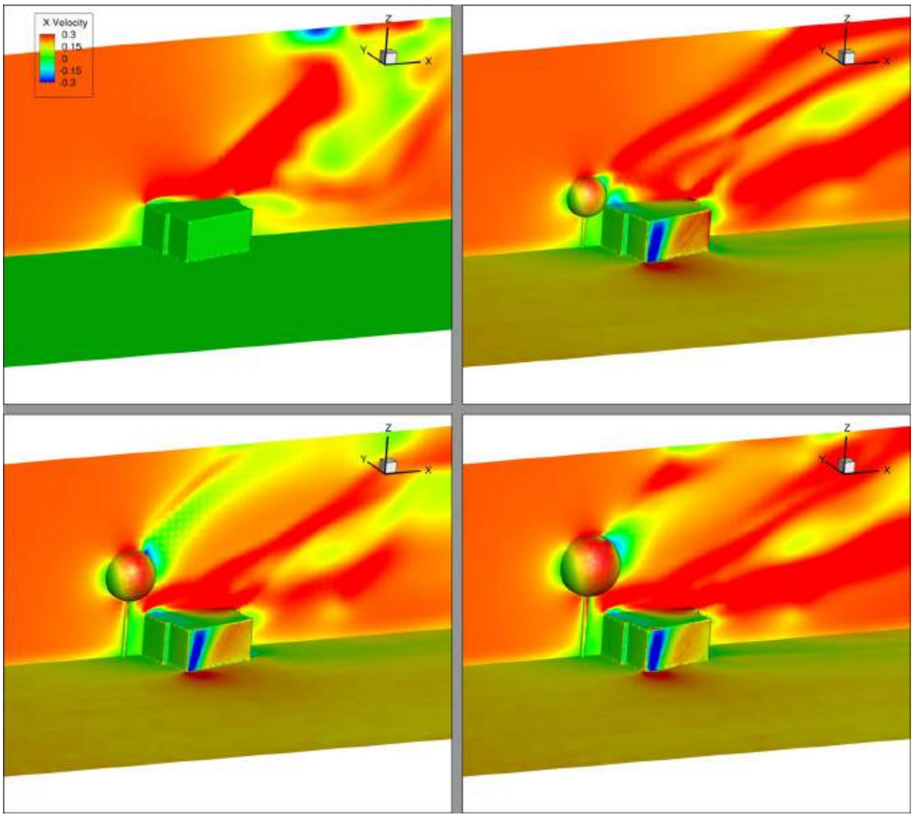

Figure 5. Comparison of x-velocity of house only (top left) and three different size trees close to the house

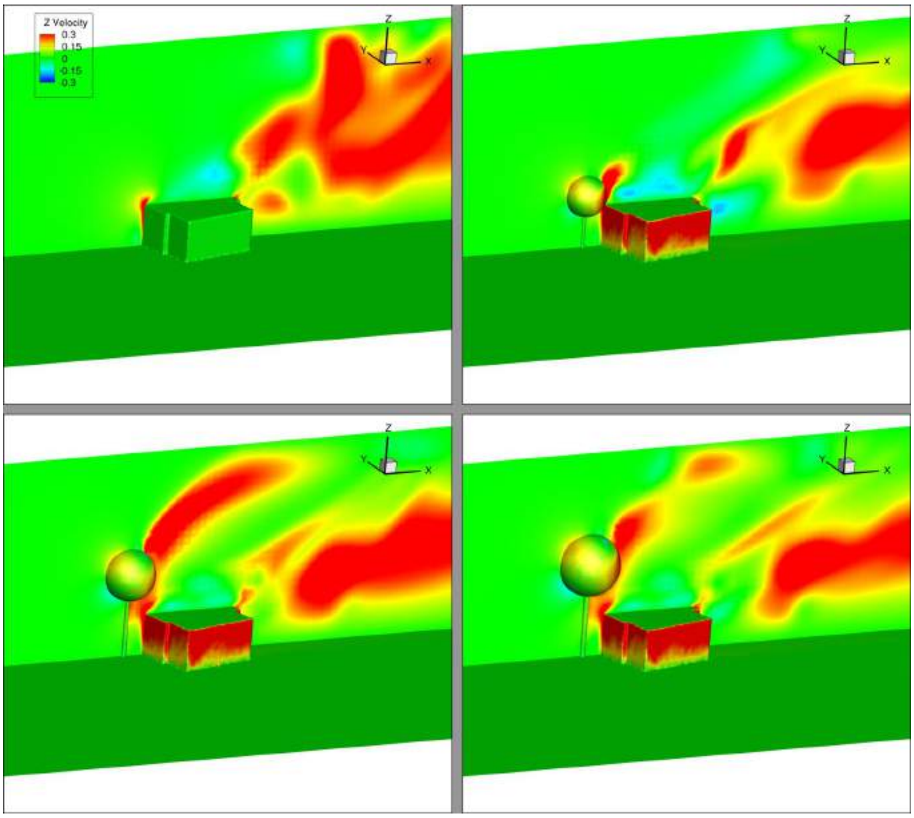

Figure 6. Comparison of z-velocity of house only (top left) and three different size trees close to the house

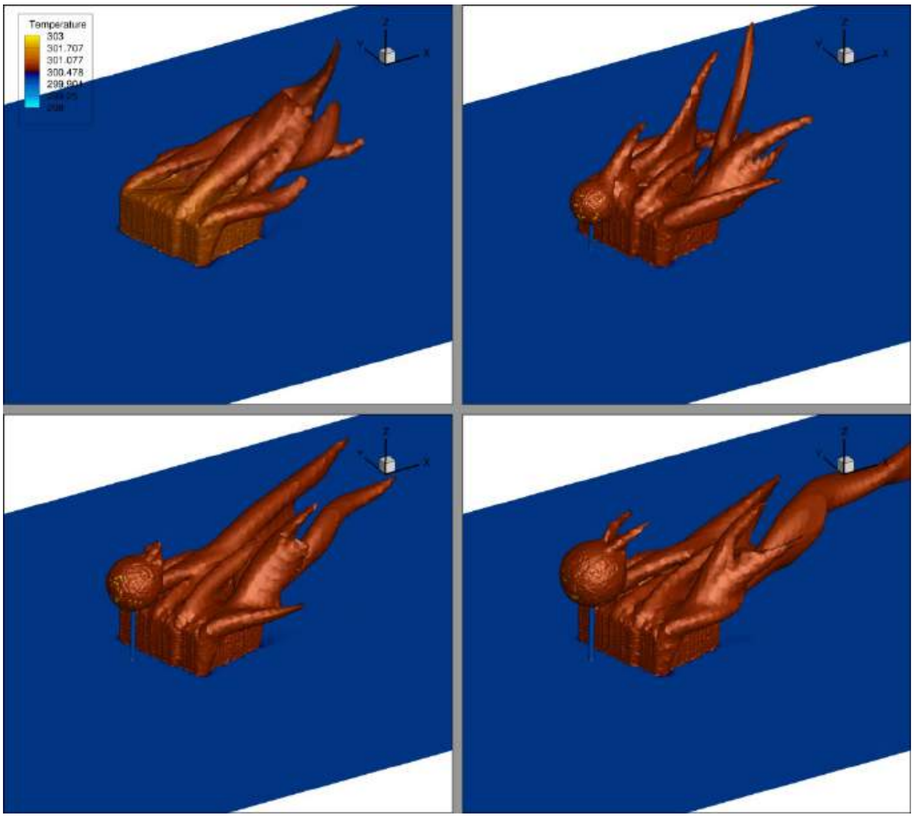

Figure 7. Comparison of temperature iso-surface of house only (top left) and three different size trees close to the house

We also compared effects of the same-sized tree at different distances from the building by examining the z-velocity for a small tree at three different locations (Figure 8). The upward movement of air flow due to warming of the canopy can be seen clearly in the moderate and far configurations, while air flow past the canopy in the closest configuration is mixed with upward-moving flow from the house itself, generating a very different flow configuration. The temperature contour of the same comparison indicates that the closest distance configuration has the biggest impact on the temperature contour above the house (Figure 8). The upward moving boundary layer above the house shows an earlier separation with the presence of a tree at moderate and more distant locations compared to the house- only configuration.

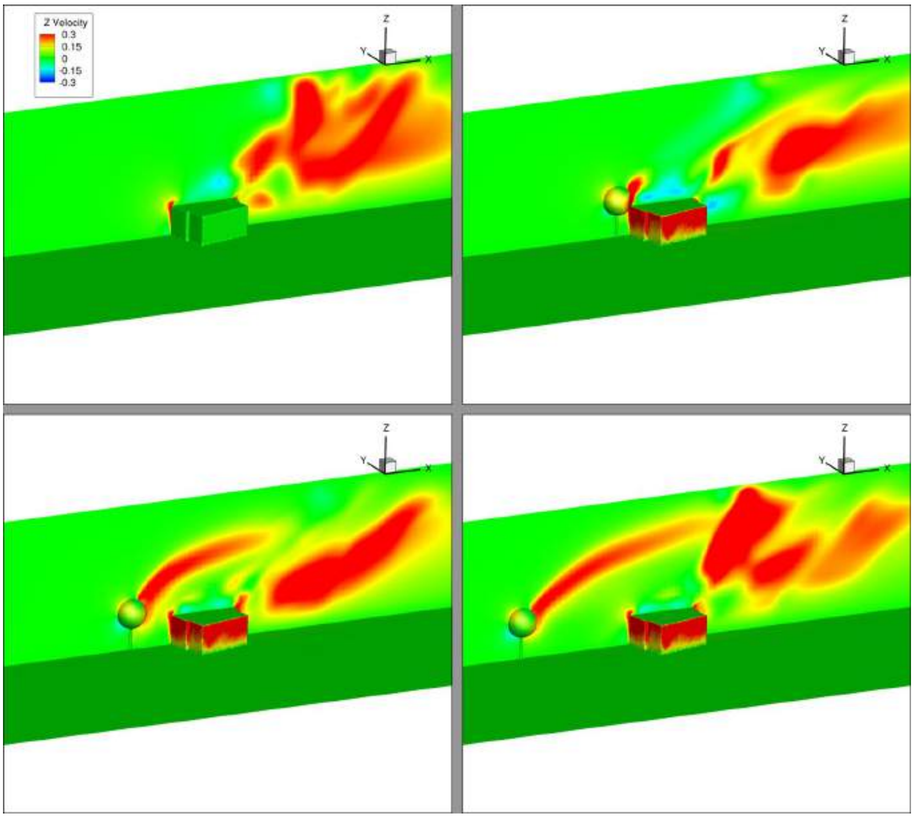

Figure 8. Comparison of temperature iso-surface of house only (top left) and three different size trees close to the house

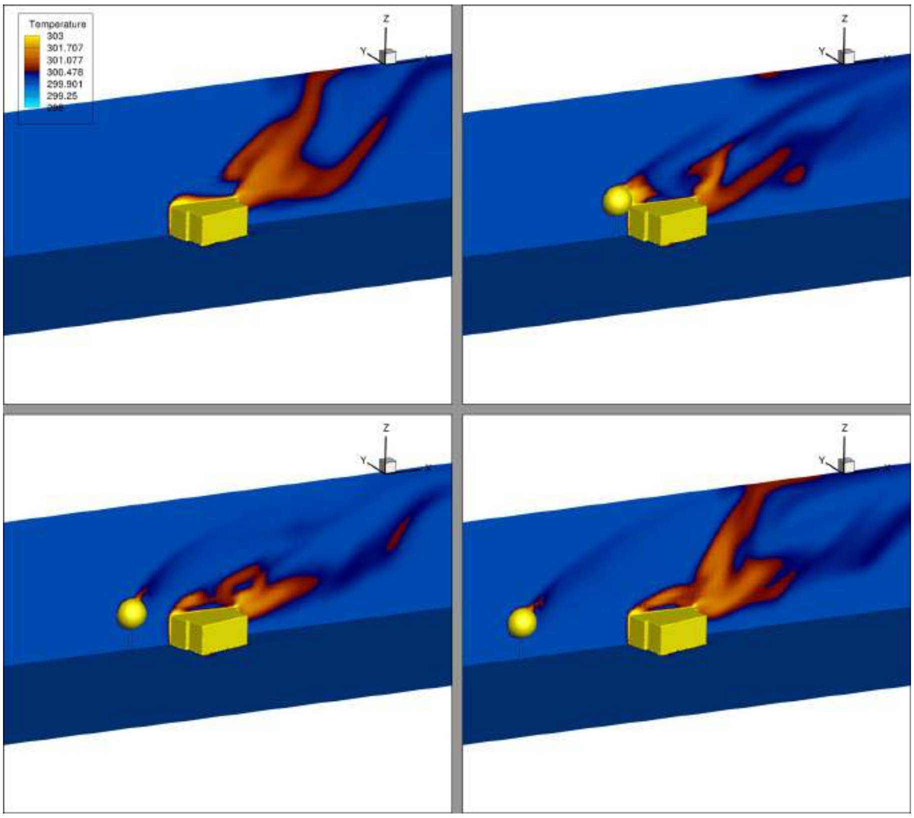

Figure 9. Comparison of temperature iso-surface of house only (top left) and three different size trees close to the house

5. Discussion and Conclusion

This paper reports first results of a simulation framework to integrate the impact of trees in an urban context in energy performance evaluation for buildings and neighbourhoods. Trees can reduce energy use and improve indoor and outdoor comfort for cooling in summer by casting shade and providing evapotranspirational (ET) cooling. This paper presents a methodology to combine spatially explicit three-dimensional tree morphology and estimates of ET rates with building location and wall characteristic data to test their relative contribution to building energy consumption. Based on a comprehensive tree inventory for our Midwestern study neighbourhood, tree morphology and building data have been integrated in a three-dimensional array in the urban modelling interface" (umi) to estimate cooling due to interception of sunlight. We then performed a series of parametric computational fluid dynamics (CFD) studies to simulate ET cooling for various tree sizes and and different distances to walls. We resolved conventional mesh generation challenges associated with CFD by introducing a novel, immersed boundary framework based on adaptive octree meshes. The preliminary results shown in this paper highlight the important fact that trees provide improvement in situations of extreme heat via two mechanisms (a) shading and radiation blockage, (b) ET-based local cooling. The preliminary results also indicate the dynamic nature of the tree-building interaction, which will influence window placement on walls and roof to enhance natural ventilation strategies in a warming climate. The ET cooling potential related to roof openings seem particularly noteworthy as it could reduce overheating specifically in upper residential floors. The dynamic nature of these current results also indicate to the need to conduct further simulations. Therefore, a seasonal matrix will be simulated next.

The models we have developed allow us to discern the relative impact of tree shading in relation to building characteristics and according to tree size and distance from the home, as well as the potential effect of evapotranspiration for the same scenarios. We observed distinct patterns for air movement and temperature profiles that are likely to influence building energy dynamics and suggest landscape configurations for trees and buildings that could contribute to more effective passive temperature control within dwellings in this neighbourhood. The potential to integrate these specifics into design configurations for this and similar neighbourhoods can provide significant benefit to reduce building interior temperature conditions in situations of extreme heat events. Thus future work in our team will now combine radiation blockage as complement to the CFD simulations.

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Upgrading the Outdoor Comfort of Suburban Residential Neighbourhoods in the Gulf Region

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Abstract: Many cities in the GCC states have experienced a rapid and highly unsustainable urban expansion. Supported by the low price of energy, until recently there has not been any serious economic need to implement energy efficient urban planning principles in regard to enhance the outdoor comfort within the suburban residential neighbourhoods. Car dependency is prevailing and exterior spaces are not appropriately responding to the population's needs. Large parts of the outdoor areas have been sealed; the absorbtion of heat has increased. Together with motorised traffic, the badly insulated buildings create further waste heat. These factors have caused urban heat islands. Since the GCC cities consist in very large parts of suburban residential neighbourhoods, the enhancement potential is very high. Within this research, typical neighbourhoods will be analysed regarding their outdoor spaces and urban heat islands. For a case study in Muscat/Oman various enhancement proposals will be formulated by integrating green into public and private spaces, urban agriculture, shading, reduction of sealed areas, reduction of street width, raise of albedo, improved energy efficiency of buildings, water recycling for irrigation, creating walkability and bikability. As result a toolbox will be presented, containing general improvement options, which thereafter will be evaluated and prioritised.

Keywords: Climate change adaptation, green building, outdoor comfort, sustainable urban design, urban heat islands

1. Introduction

Urban heat islands in the Gulf region constitute a severe threat to the outdoor comfort of urban areas, especially during the hot summer months, when the conditions are extreme due to the high temperatures. This research aims to find strategies of how the outdoor comfort of suburban residential neighbourhoods in the GCC states could significantly be enhanced. Feasible and effective solutions will be presented which demonstrate how urban heat islands in existing suburban residential neighbourhoods can be significantly reduced. With the research results and especially the priorisation of the suggested enhancement options, there is the intention to promote the necessity to transform the existing suburban residential neighbourhoods into more sustainable and more lively urban environments and also to show ways of how this sophisticated goal can be achieved. Environmental performance analysis software has served to provide support during the urban analysis and evaluation phase. The main focus is set on improving the outdoor environment for the residents of the neighbourhoods and on reducing the urban heat island effect. Therefore some general urban improvement measures like redensification, implementation of new building typologies, and development of new means of public transport are not treated in detail within this study.

2. Research background and challenge

Many cities in the GCC states have experienced a rapid population growth and a significant urban expansion with a high consumption of land for the new settlements. Until today, the fast urban expansion with its rapid consumption of land is continuing in a fast pace. As we can see in the following images with the examples of Riad, Dubai/Sharjah and Muscat, large parts of the urbanised areas consist of suburban residential neighbourhoods with detached or semi-detached villas.

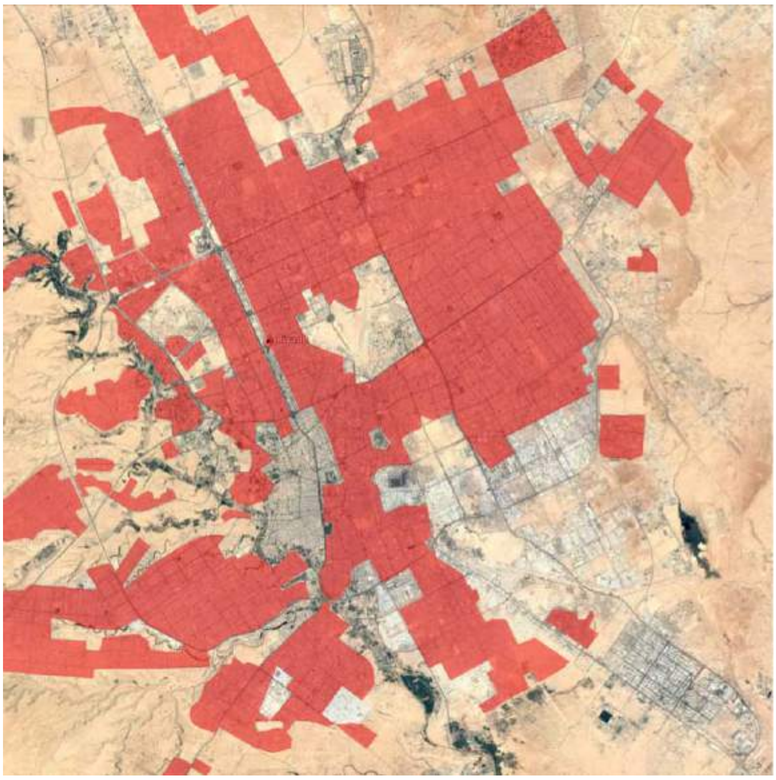

Figure 1. Satellite image of Riad with suburban residential neighbourhoods indicated in red (Source: Map data © 2018 Google, Digital Globe, red indications by author)

Figure 2. Satellite image of Dubai and Sharjah / UAE with suburban residential neighbourhoods indicated in red (Source: Map data © 2018 Google, Digital Globe, red indications by author)

Figure 3. Satellite image of Muscat / Oman with suburban residential neighbourhoods indicated in red (Source: Map data © 2018 Google, Digital Globe, red indications by author)

So far, these developments have been highly unsustainable and until recently – supported by the low price of energy – there has not been any serious economic need to implement energy efficient urban planning principles in regard to enhance the outdoor comfort of the mainly monofunctional suburban residential neighbourhoods. However, the threat of climate change is constantly increasing. Therefore, also in regard to the development of suburban residential areas a paradigm shift will be necessary (Kader, 2015). An additional factor is that the current suburban residential neighbourhoods have only a low standard of social qualities (von Richthofen, 2016). Thus an enhancement of the liveability of the neighbourhoods appears to be necessary, too.

3. Rationale, research aim

The Gulf countries' urban development of the past forty years has been very fast and unsustainable. This is based upon the economic progress and the societal as well as political conditions since the countries' increase in wealth due to their export of fossile fuels (Diener et al, 2015). Because the energy costs to maintain buildings have been very low, there was no serious need for energy efficient development neither on urban nor on architectural scale. This has also been the case especially for the development of buildings in suburban residential neighbourhoods. The choice of the detached or semi-detached villa as prevailing building type has lead to a high consumption of land and a low population density (St Clair, 2009). Only relatively few studies set their focus on the elaboration of improvement strategies for the deficits of these existing neighbourhoods. But, as illustrated in the figures 1, 2 and 3, large parts of the GCC cities consist of suburban residential neighbourhoods. Thus the enhancement potential is very high. For the reasons mentioned above, this research area appears to be very relevant, since in future it will be of major importance to increase the sustainability of the residential neighbourhoods on ecological, economical and social level. There is an urgent need to for improved and more lively neighbourhoods by a more integrated planning (Nebel et von Richthofen, 2016).

The aim of this research is to create more lively and more healthy neighbourhoods by upgrading the outdoor comfort. This goes hand in hand with additional enhancement strategies, such as re-densification with mixed-use building structures as well as improving the energy efficiency of the existing building stock (Kader, 2018) and the implementation of urban and suburban agriculture, horticulture, gardening, e.g. in backyard plots, on terraces, roofs with micro-gardens (Czechowski et al, 2014). Furthermore, the liveability of the neighbourhoods is to be enhanced by establishing recreation space for residents in walkable distance from their homes, especially for youth and elderly people. Also social aspects are to be integrated: for example reduction of stress or improvement of social ties by the creation of adequate spaces for gatherings, communication, recreation or relaxation. Additionally it is expected that the new public spaces will have a positive influence on the mental and physical health of the residents.

4. Suburban residential neighbourhoods today

Today's suburban neighbourhoods, in Oman as well as in the other Gulf countries, consist of monofunctional developments and a very low population density. Car dependency is prevailing because the exterior spaces are not appropriately designed to respond to the population's needs and social functions are lacking. In comparison to the social structures of traditional settlements, there is a strong de-socialisation trend (Nebel et von Richthofen, 2016).

Of big influence for the outdoor temperatures stands the fact that a large amount of exterior surfaces has been sealed (e.g. with roads, parking areas, buildings) and the absorbtion of heat thus has increased. Furthermore, most of the buildings are badly insulated and – together with motorised traffic – generate further waste heat. Especially these factors have lead to the formation of urban heat islands.

The hot and mostly arid climate of the Gulf countries during the summer month is among the hottest in the world. These extreme conditions even increase by the urban heat island effect created by the unsustainable development of the residential neighbourhoods. As a consequence, the rising discomfort in summer makes the outdoor areas unbearable for pedestrians. Interventions to reduce the urban heat islands are not sufficiently implemented, improvement strategies are missing. The building codes for constructions needs to be improved (Jaheen and Abu-Hijleh, 2016). An enhancement of the outdoor comfort with the application of climate adapted design is overdue (Gehl and Gagner, 2011). The impact of further global warming is a severe threat for the neighbourhoods' future.

5. Case study analysis of a residential area in Muscat, Oman

Several typical suburban residential neighbourhoods have been analysed during urban and architectural design studios conducted by the author at the German University of Technology in Oman between 2014 and 2019. The area of Al Mawalih as indicated in figure 4 served as a basis for the case study analysis discussed in this paper. Monofunctionality and low density are two main characteristics of the neighbourhoods. Another major deficit is the lack of greenery. The main focus is set on the outdoor spaces, on the urban heat island effect in order to find enhancement options on a design level. Sealed and unsealed surfaces, street and building layout, car parking, shading, solar reflectance index (SRI) of materials, vegetation, building density, waste heat from buildings and traffic as well as the relevant climate data are considered (Kader, 2015).

Figure 4. Satellite image of an exemplary residential neighbourhood of 1 km^2 in Al Mawalih, Capital Area of Muscat / Oman, GPS 23.6026 58.2282 (Source: Map data © 2018 Google, Digital Globe)

6. Identification of various improvement methods

As illustrated in figure 5, a series of enhancement proposals will be formulated in a systematic way for a case study area in the Capital Area of Muscat by integrating strategies with increased trees and green surfaces at public and private open spaces (including green roofs and façades), urban agriculture, extensive shading concepts, reduction of sealed areas, reduction of street width, raising of albedo by an increased use of bright and less smooth surfaces, improved energy efficiency of buildings, water recycling for irrigation of green, establishment of walkability and bicycle lanes to reduce motorised traffic.

Figure 5. Enhancement proposal for the analysed residential area of 1 km^2 in Al Mawalih. Orange = pedestrian and bike network, black = existing buildings, blue = new public and commercial services, red = redensification with multistorey houses, green = recreational public spaces. (Source: Alexander Kader, 2018, based on design studios conducted with students from the German University of Technology in Oman)

The urban greening program consists in adding trees and other green, a network of trees especially along walkways, house gardens and rooftop gardens as well as green façades. Furthermore, it contains a people-centered agricultural production with public and private gardening areas to be provided. Currently sealed spaces are planned to be opened for greenery and agriculture. Recycled greywater from all households serves for irrigation of plants (non food plants only). A pedestrian network has been created. Infrastructure for pedestrians contains sidewalks, safe street crossings, shaded pathways, shaded open spaces to stay for pedestrians, green recreational areas. Bikelanes are created next to the pedestrian walkways. Playgrounds that are shaded (e.g. under trees) are offered for kids and their families. In a similar way, also gathering and sitting areas are provided. An increased albedo is reached by a careful selection of adequate materials, surfaces and colours as well as by a reduction of sealed areas and an increase of green with the use of local plants. Shadings reduce the gain of solar heat in buildings. Buildings are shading themselves mutually as well as by trees. Ventilation corridors serve for a natural ventilation of the neighbourhoods. A retrofit concept for the existing buildings is planned to reduce the waste heat created by the AC units. Car traffic is reduced, bicycle use and walkability increased. The concept for the transformation of the outdoor areas of the neighbourhoods into lively spaces contains especially a more efficient managing (and reuse) of resources (e.g. water, plants, land). The toolbox of table 1 contains further informations regarding the enhancement measures.

The efficiency and impact of some of the identified improvement methods are planned to be simulated with energy performance software in order to provide more detailed investigation results. A special focus is set on analysing factors like "walkability and bikability" and "solar reflection of outdoor surfaces". Current and idealised future conditions are examined with comparative simulations. Figure 6 illustrates a simulation of the walkability of the case study area in Al Mawalih with the urban modelling software "umi (urban modelling interface) 2.0" from the Sustainable Design Lab of Massachusetts Institute of Technology (MIT) and the 3D-CAD software "Rhinoceros 5.0". Due to the settlement's monofunctionality and thus the lack of services and other amenities, the entire area turns out to be marked red by the software program, which symbolises a very weak walkability factor. The improvement proposal (see figure 5) with its services and amenities distributed within the neighbourhood provides a much better simulation result (see figure 7).

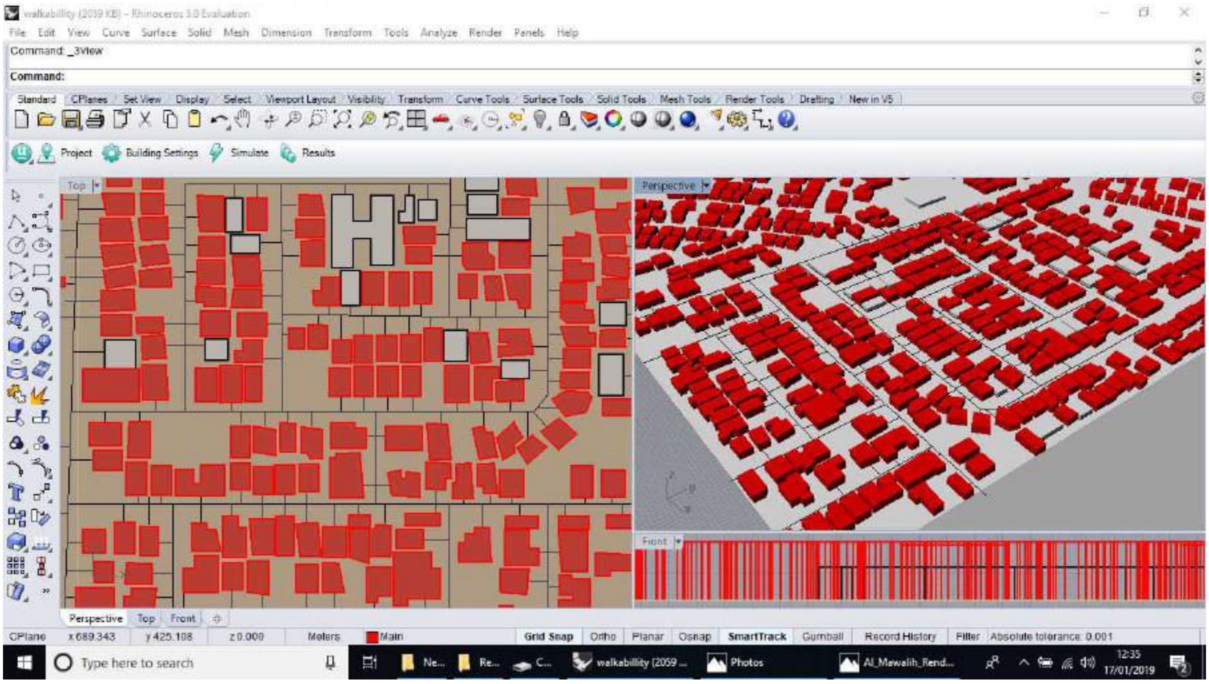

Figure 6. Simulation of walkability of the current situation in the case study area in Al Mawalih with the software umi 2.0 and Rhinoceros 5.0. (Source: author)

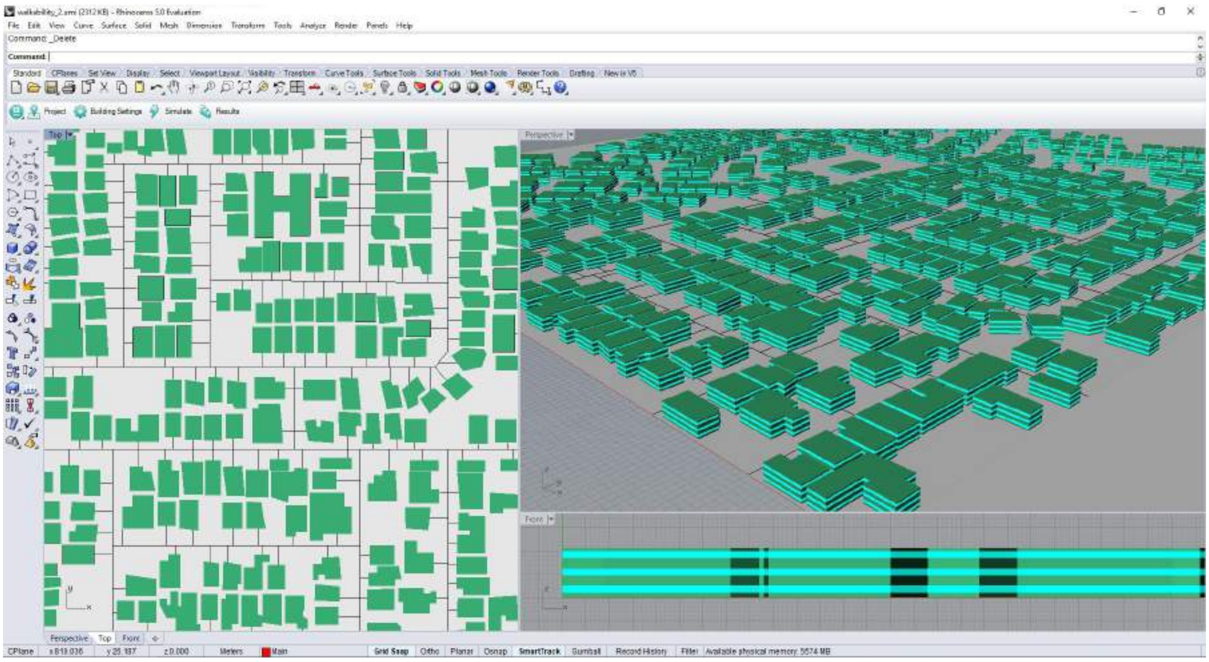

Figure 7. Simulation of walkability of an improved proposal of the case study area in Al Mawalih, with the software umi 2.0 and Rhinoceros 5.0. (Source: author)

7. Toolbox of methods of how to enhance the outdoor comfort and reduce urban overheating

An outcome of the various identified improvement methods is a table in which the different measures are listed in a generalised way. The table can serve as a toolbox with possible improvement options, which can be applied individually, but on the other hand, could be interconnected into strategical recommendations of how to enhance the outdoor comfort of existing residential neighbourhoods. Obviously, there are a multitude of interdependencies between the individual points. The improvement effect is higher if a method is not implemented in isolation, since each of the proposed interventions creates synergy effects which, for the upgraded residential neighbourhoods lead to an even higher enhancement factor.

Table **1**. Toolbox of various improvement methods to enhance the outdoor comfort and reduce urban overheating

	TOPIC	COMMON STANDARD	IMPROVEMENT OPTION
1	**Reducing sun exposure of public spaces <u>with trees</u>**	Public spaces are predominantly exposed to the sun.	**Trees for shading of public space**. Provide shading for public spaces such as pathways and bikelanes by planting trees. The trees can be irrigated with recycled household water.
2	**Reducing sun exposure of buildings <u>with trees</u>**	Buildings are predominantly exposed to the sun.	**Trees for shading of buildings**. Trees can be planted in a way that they partially shade the buildings. They can be irrigated with recycled household water.
3	**Reducing sun exposure of public spaces <u>with horizontal shading structures</u>**	Street space and other public spaces are predominantly exposed to the sun.	**Horizontal shading structures.** Provide shading for public spaces such as pathways and bikelanes by constructing adequate horizontal shading structures.
4	**Reducing sun**	Buildings are predominantly	**Compact arrangement of buildings for**

	exposure of buildings <u>by compact arrangement</u>	exposed to the sun. Heat gain by solar radiation is high.	**mutual shading.** With a compact arrangement, buildings can shade each other mutually. Also shading of exterior spaces can be achieved by a respective arrangement of buildings. *Comment: This measure plays an important role during redensification of existing neighbourhoods.*
5	**Reducing cooling energy demand of buildings <u>by shading</u>**	Buildings are predominantly exposed to the sun. Heat gain by solar radiation is high.	**External shading devices for buildings.** Exposed façade areas and roof areas can be (partially) shaded by covering façades and roof to protect from direct sun light. Especially all windows which are sun exposed are to be shaded. On the roof, water tanks and technical installations are to be shaded as well.
6	**Improving the solar reflectance of surfaces by using <u>more adequate materials</u>**	The existing neighbourhoods have a large amount of sun exposed sealed surfaces, often with materials which have a low solar reflectance index (SRI).	**Solar reflectance improvement of materials.** Use of material with bright coloured and less smooth surfaces, which have a high SRI. Unsealing or partially unsealing of surfaces, e.g. for parking areas.
7	**Improving the solar reflectance of surfaces by implementing <u>more green areas</u>**	Large amount of sun exposed sealed surfaces. There are few green spaces.	**Solar reflectance improvement with plants.** Covering of unsealed areas with shrubs and trees. Green has excellent properties regarding solar reflection. The plants can be irrigated with recycled household water.
8	**Improving the solar reflectance and reducing the cooling energy demand of buildings by installing <u>green roofs</u>**	Buildings are predominantly exposed to the sun. Most plots contain only very little green elements and there are no green roofs.	**Green roofs.** Implementation of green roofs, possibly with intensive vegetation, which can enhance the solar reflection and can serve as well as insulation for the building (besides further benefits). The plants can be irrigated with recycled household water.
9	**Improving the solar reflectance and reducing the cooling energy demand of buildings by installing <u>green façades</u>**	Buildings are predominantly exposed to the sun.	**Green Façades.** Implementation of green façades can further enhance the solar reflection and can serve as well as shading for the building (besides further benefits). The plants can be irrigated with recycled household water.
10	**Improving the air quality and reduction of air pollution by planting <u>trees and shrubs</u>**	Dust and car exhaust fumes are common pollutions within the residential neighbourhoods.	**Green to improve the air quality.** With the implementation of trees, shrubs and other green, air pollution will be significantly reduced; dust will be filtered by leaves of trees and shrubs.
11	**Enhancement of the microclimate with <u>urban agriculture</u> and <u>horticulture</u>**	The residential neighbourhoods only rarely contain urban agriculture.	**Urban agriculture.** Urban agriculture can be established by private households and as well on designated public areas as shared activity. *Comment: besides many further benefits,*

			the agriculture serves for sustainable organic food production.
12	**Creating recreational space by installing <u>public green</u>**	The residential neighbourhoods rarely contain public green spaces for recreational purpose.	**Recreational green public spaces.** Designated public areas within residential neighbourhoods can be transformed into shaded green recreational spaces with urban furniture.
13	**Providing water for irrigation of plants by <u>greywater recycling</u>**	Until today, greywater recycling is rarely applied in the residential neighbourhoods.	**Greywater recycling for irrigation.** Water reuse and water recycling techniques can significantly save fresh water and can be used for irrigation of plants (non food only).
14	**Increase walkability and bikability by creating a <u>network</u> of sidewalks and bike lanes**	There are only few pedestrian pathways. Predominantly they are exposed to the sun.	**Pedestrian and bike lane network.** Create a network of (shaded) pathways and bikelanes, which connect all parts of the neighbourhood. In addition, shaded open spaces to stay for pedestrians can add to improve the comfort for pedestrians.
15	**Increase walkability and bikability by providing <u>service functions for daily needs</u> within the neighbourhood**	Most neighbourhoods are predominantly monofunctional and contain only very few services.	**Providing more services for daily needs.** More services for daily needs in walkable distance are to be added into the residential areas. E.g. by inserting mixed use buildings.
16	**Increase comfort for the residents by adding <u>public spaces for activities</u> and <u>playgrounds</u>**	Usually there are neither public recreational spaces nor playgrounds in the residential neighbourhoods.	**Active public spaces.** Shaded open recreational spaces for various activities invite to stay for pedestrians. Playgrounds and similar amenities as well add to enhance the living quality of the neighbourhoods.
17	**Reduce car use by <u>mobility improvement</u>**	Cars are the major means of transport. There is only little public transport, little use of bicycles and no adequate infrastructure for walking and cycling.	**Mobility improvement.** Offering different means of transport. Besides an enhanced public bus system, infrastructure for walkability and bikability can be established. Reduced street width for cars, increased street width for pedestrian and bike ways. Safe street crossings are to be provided as well.
18	**Reducing urban overheating from waste heat of roof-mounted AC-units by <u>energetically retrofitting the neighbourhoods' existing building stock</u>**	The existing residential buildings are mainly built in a highly unsustainable way and, due to a lack of appropriate insulation of the façade, have a strong demand of cooling energy. The waste heat of roof mounted AC split units is contributing to urban overheating.	**Retrofit of existing building stock.** An energetical retrofit would result in a very high amount of energy saving. Possible measures would be for example the installation of insulated windows, wall and roof insulation, external shading, renewal of doors to exterior and reduction of further thermal bridges.
19	**Rising awareness for urban sustainability by <u>introducing renewable energy generation</u>**	Renewable energy generation is not applied within residential neighbourhoods on broad scale.	**Renewable energy generation.** Photovoltaics, solar warm water heating, and small wind generators can be installed at private house roofs and public areas of the neighbourhoods. For example, the pathways could be shaded by constructions with photovoltaic roof elements.

20	**Reducing urban overheating by establishing wind corridors**	The prevailing wind directions usually have not been integrated into the design of the existing residential neighbourhoods.	**Ventilation with wind corridors.** When the residential neighbourhoods will be redensified and when green will be added, the prevailing wind directions have to be studied in order to create wind corridors to naturally ventilate the areas. Urban overheating can be significantly reduced.
21	**Enhancing the social qualities of residential neighbourhoods by implementing social activities on public spaces**	The existing residential neighbourhoods do not have many public spaces, which are used by the inhabitants.	**Social activities.** Spaces for gatherings and communication within the residential neighbourhoods can be used to enhance and re-socialise the residents with each other. Various activities can be provided (related e.g. to markets, sport, crafts, play, performance, food)
22	**Quality enhancement by a more efficient use of resources**	Resource management of existing residential neighbourhoods usually is not very efficient or sustainable. For example, in the GCC countries, water consumption per capita is among the highest in the world. Land consumption for residential neighbourhoods is very high. Plants are often used only for embellishment of highways.	**Resource efficiency increasement.** Recourses like water, land and plants have to be used much more efficient. Household water can be re-used and recycled, rainwater can be collected. Neighbourhoods can become more lively and more efficient by redensification and implementation of mixed use buildings with public services on the ground level. With an efficient use of trees and other plants, the outdoor spaces can become better usable for pedestrians and bicyclists due to shaded areas, better air quality, lower temperatures etc.

8. Result: Evaluation and priorisation of the improvement methods for existing suburban residential neighbourhoods, conclusive remarks

While the improvement measures have been listed and explained above, figure 8 contains an estimated comparison of the environmental impact of the improvement suggestions in relation to the effort of its realisation. The illustration intends to demonstrate clearly which methods are to by applied first in order to achieve the best enhancement results if budget or time are limited for the implementation of a neighbourhood enhancement strategy. Improvement suggestions considered as most effective are indicated in dark green. The suggestions “Solar Reflectance Improvements with Plants” and “Trees for Shading of Public” space are the first of the priority list, since they require less effort than the other suggestions which are indicated in dark green. Further enhancements can built upon these suggestions for a better outdoor comfort, for example retrofit proposals for the existing houses, or strategies for a significant redensification.

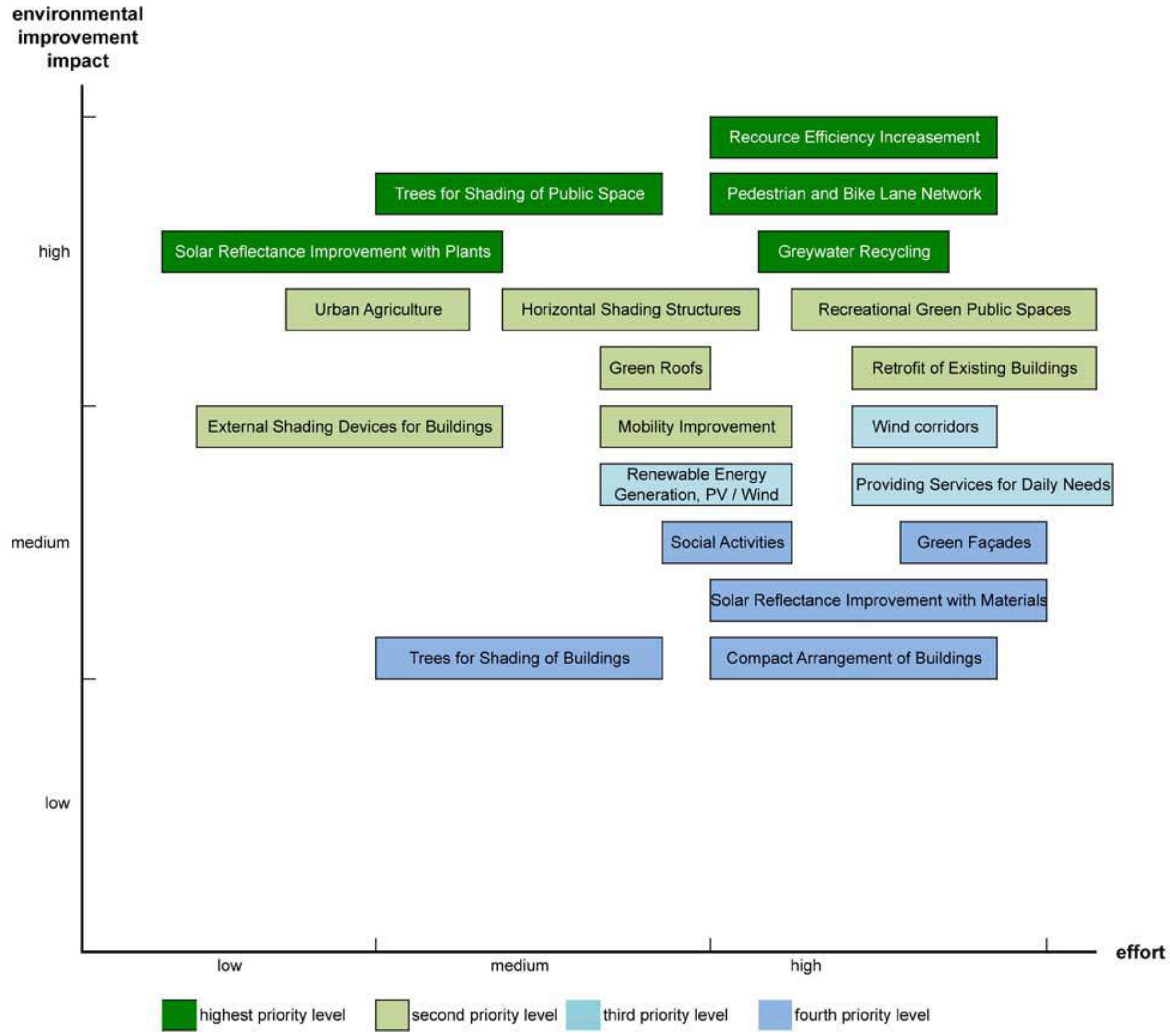

Figure 8. Estimation Environmental Impact of the Improvement Suggestions for Existing Suburban Residential Neighbourhoods in Relation to Effort.

The elaborated toolbox and prioritised enhancement recommendations could serve as a support for planners as well as authorities to establish appropriate environments with enhanced outdoor comfort. From an economic perspective, an efficient value chain might be reached by establishing public-private partnerships for the transformation of the suburban residential neighbourhoods.

9. Further studies

Within further studies, the suburban residential neighbourhoods are to be analysed more in detail regarding all factors mentioned in the toolbox table (see table 1). Different examples of neighbourhoods in all Gulf countries are to be compared between each other in order to better see their similarities and differences. In addition, further studies will contain more performance simulations of the neighbourhoods on urban and architectural level with the aim to elaborate more detailed results in regard of the enhancement methods listed in the toolbox table. They can also focus on comparisons of different (simulated) neighbourhood improvement scenarios in order to find out which solution could be the most effective in regard to reducing the urban heat island and increasing the outdoor comfort. The simulation studies of the neighbourhoods, for example of the walkability, are to be deepened and extended to other factors such as solar reflection of all outdoor surfaces, solar incidence on building surfaces, shading of public space.

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Influence of perceived environmental quality on outdoor thermal comfort during hot summer days in sub-tropical high-density cities

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Abstract: This study investigates the inter-relationships between urban microclimate, thermal sensation, perceived environmental quality during hot summer days in sub-tropical high-density cities. A questionnaire surveys with 1,917 respondents and micrometeorological measurements was conducted in 17 sites on 15 hot summer days. Subjective assessment of sensation of meteorological variables and perceived environmental qualities was obtained in order to determine the influential factors affecting outdoor thermal comfort. The study sites, which were categorized into three types of urban settings (residential areas, streets, urban parks/waterfront), showed considerable differences in meteorological conditions. Air temperature (T_a), mean radiant temperature (T_{mrt}) and universal thermal climate index (UTCI) were found to be higher in street environment while there are no significant differences in wind speed (v). Logistic regression analysis was used to identify significant variables that affect overall thermal comfort. Measured meteorological variables were not significantly associated with overall thermal comfort while subjective sensation of meteorological variables was all significant at α = 0.001. Among perceived environmental qualities, aesthetic satisfaction showed the largest effect size at α = 0.001. This study offers new insights to urban design practices to consider different environmental qualities for improving outdoor thermal comfort.

Keywords: outdoor thermal comfort, perceived environmental qualities, logistic regression, urban design

1. Introduction

Outdoor thermal comfort is widely regarded as an important component in urban planning and design. Climate-sensitive design of outdoor spaces improves outdoor thermal comfort by providing shading through urban structures (Thorsson et al., 2011; Lau et al., 2015; 2016), regulating microclimate through vegetation (Bowler et al., 2010; Shashua-Bar et al., 2010), reducing the thermal load (Emmanuel et al., 2007; Lin et al., 2011) and enhancing ventilation which promote convective heat exchange (Pearlmutter et al., 2007; Krüger et al., 2011; Saneinejad et al., 2014). It also promotes physical and mental health of urban inhabitants by encouraging more frequent use of outdoor spaces for physical activity and social interactions (Sanches et al., 2016; Kabisch et al., 2017). As urbanization is expected to increase at unprecedented rate, living quality in cities are increasingly concerned and enhancing the quality of outdoor spaces becomes important to urban planning and design.

In sub-tropical or tropical high-density cities, outdoor thermal comfort is considerably affected by the rapid urban development in this region and hence urban heat island effect (Arnfield, 2003). It results in deteriorating quality of outdoor spaces which are often perceived as the extended living spaces (Ahmed, 2003). More importantly, outdoor thermal comfort is associated with the perception of environmental quality such as aesthetics (de Castro Fontes et al., 2008), acoustics (Venot and Sémidor, 2006), air quality (Pantavou et al., 2017), and perceived control of the environment (Nikolopoulou and Lykoudis, 2006). Understanding the effect of perceived environmental quality on outdoor thermal comfort is necessary for better design practices. Most of the studies emphasize the relationship between subjective thermal sensation and the physical environment such as micrometeorology and urban geometry but do not consider the environmental stimuli of such outdoor spaces. It results in a lack of understanding of how the subjective assessment of thermal comfort is influenced by people's perceived environmental quality. It is therefore important for scientists to quantify these inter-relationships for enhancing outdoor thermal comfort and hence the use of outdoor spaces in high-density cities.

The present study aims examine how perceived environmental quality affects subjective thermal perception and identify influential factors that are associated with outdoor thermal comfort in sub-tropical high-density cities. In high-density cities, there are constraints in the physical environment that may restrict the potential of mitigating thermal discomfort. Findings of the present study also provides new insights to urban design practices to consider different environmental qualities for improving outdoor thermal comfort.

2. Methodology

2.1. Study Areas

Hong Kong is situated in the southern part of China with a latitude of 22°15'N. It has a sub-tropical monsoon climate and is typically hot and humid in summer. Summer mean air temperature is approximately 28°C and, in particular, air temperature in the afternoon often exceeds 31°C. Relative humidity ranges from 60-70% during daytime in summer.

Hong Kong has a population of 7.4 million in 2017 and the population density in urban areas is approximately 6,700 persons per km^2 (Census and Statistics Department, 2018). In order to accommodate such a large population, it is characterised by high-density and high-rise urban morphology in built-up areas with an average building height of 60m. The compact urban settings result in intense urban heat island effect and insufficient air ventilation in the urban areas.

Three types of urban settings were selected for conducting questionnaire surveys and micrometeorological measurements, including residential areas, urban parks, and streets (Figure 1). There are large variations in environmental conditions due to the urban form, land use, pedestrian activities, and traffic conditions.

2.2. Micrometeorological Measurements

A mobile meteorological station, containing a TESTO 480 data logger for measuring air temperature (T_a), relative humidity (RH) and wind speed (v) and a globe thermometer for measuring globe temperature (T_g), was used in micrometeorological measurements in the resent study. The globe thermometer is composed of a thermocouple wire (TESTO flexible Teflon type K) placed inside a black painted plastic ball with a diameter (D) of 38mm and emissivity (ε) of 0.95. Mean radiant temperature (T_{mrt}) was then calculated according to the following equation from Thorsson et al. (2007):

$$T_{mrt} = \left[(T_g + 273.15)^4 + \frac{1.10*10^8*v^{0.6}}{\varepsilon*D^{0.4}}(T_g - T_a)\right]^{\frac{1}{4}} - 273.15 \qquad (1)$$

With the meteorological parameters collected and the respondent's metabolic rate and clothing level, Universal Thermal Climate Index (UTCI) was calculated to represent the objective thermal comfort index. UTCI is commonly used in thermal comfort studies conducted in different climate regions (Krüger et al., 2011; Chan et al., 2017) and sufficiently represents the thermal comfort conditions in objective means.

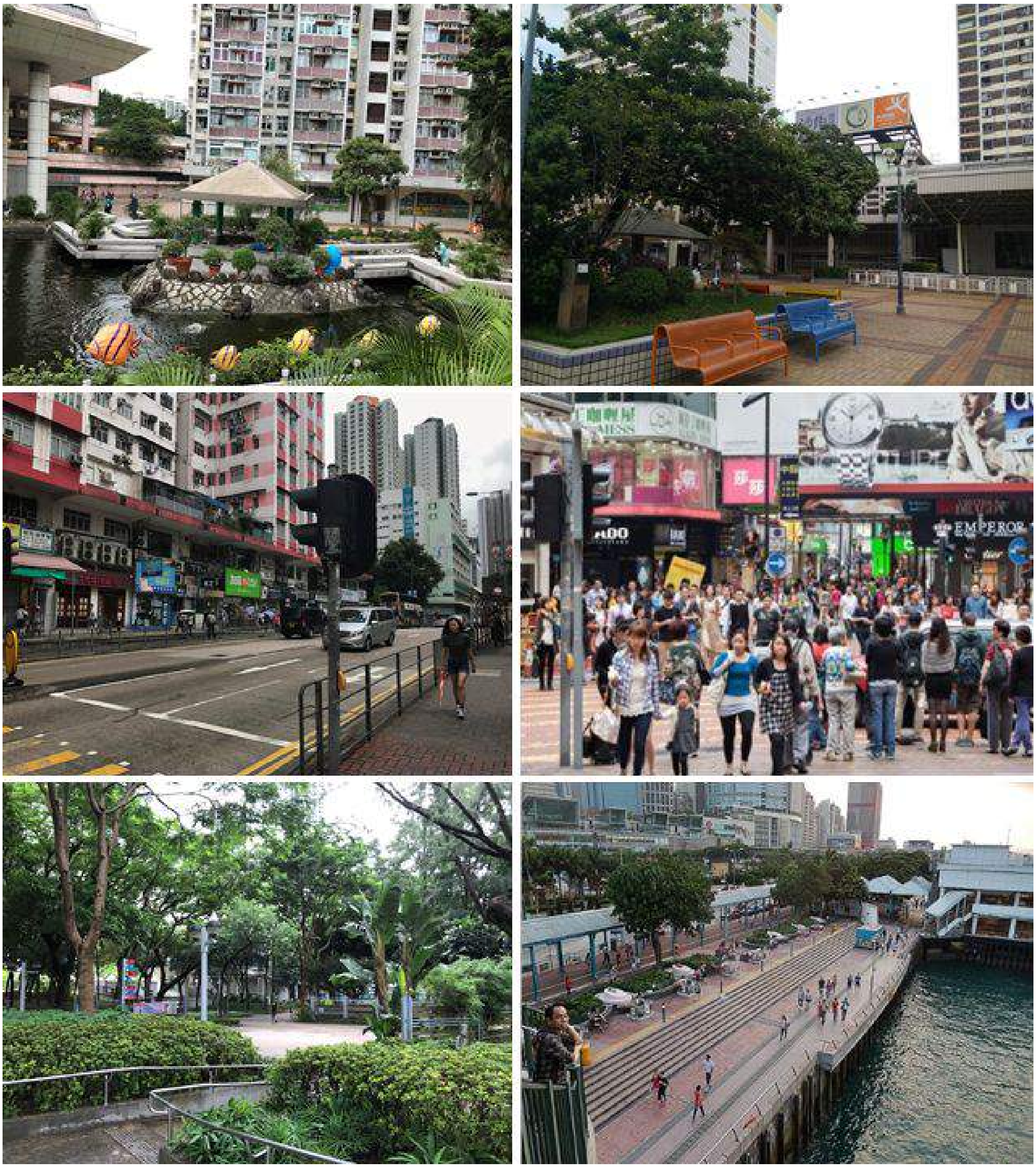

Figure 2. Boxplots of the meteorological variables measured during the survey campaign.

2.3. Questionnaire Surveys

Based on previous outdoor thermal comfort studies (Johansson et al., 2015), a questionnaire survey was developed to obtain respondents' subjective sensation of meteorological variables and perception of environmental qualities. It was carried out between June and September 2018 and it took place between 10:00 and 16:00 on weekdays to minimize variations in weather conditions and pedestrian activities. The questionnaire is composed of questions on sensation regarding temperature (TSV), humidity (HSV), wind speed (WSV) and solar radiation (SSV) based on seven-point ASHRAE scale (ASHRAE, 2010) such that thermal sensations were reported from cold (-3) to hot (3), with neutral sensation as 0. Overall state of thermal comfort was rated on a four-point Likert scale from very uncomfortable (-2) to very comfortable (2) without any option for the neutral state. Perceived environmental qualities, including aesthetic, acoustic, air quality, safety and convenience, were rated using a five-point Likert scale from very satisfactory (+2) to very unsatisfactory (-2) with a neutral option (0). Demographic background of the participants was also obtained while the activity level of the participants was also recorded to represent the metabolic rate. The clothing level was observed by the interviewer using the checklists from ANSI/ASHRAE Standard 55 (ASHRAE, 2010).

2.4. Statistical Analysis

Logistic regression analysis has been widely used in studies of thermal comfort for understanding how environmental conditions influence thermal perception (Kim et al., 2013; Kumar et al., 2018). The logistic regression equation between the probability of perceiving thermal comfort (p) and perceived environmental quality (T) is defined as:

$$logit\, p = \log log\ \left[\frac{p}{1-p}\right]\ = bT + c \qquad (2)$$

The probability of respondents perceiving thermal comfort can therefore be determined by the odds ratios (ORs) of the significant variables.

3. Results and Discussion

3.1. Respondent Characteristics

Table 1 presents the characteristics of respondents. Male and female respondents account for 45.0% and 55.0% respectively while young (<18) and old (>55) respondents account for about half of the respondents in the present study. Approximately one-third of the respondents were under air-conditioned conditions 15 minutes before the survey as air-conditioning is relatively common in Hong Kong. The majority of the respondents (53.5%) were walking in the last 15 minutes and respondents who were standing and sitting 15 minutes before the survey account for 33.2% and 12.4% respectively. Only 0.9% of the respondents were doing exercise before conducting the survey since the survey was conducted mostly in street environment during weekdays.

Table 1. The characteristics of the respondents in the present study.

Sex	**n**	**%**	**15-min AC environment**	**n**	**%**
Male	863	45.0%	Yes	682	35.6%
Female	1054	55.0%	No	1235	64.4%
Age	**n**	**%**	**15-min activity**	**n**	**%**
<18	480	25.0%	Sitting	237	12.4%
18-24	363	18.9%	Standing	637	33.2%
25-34	212	11.1%	Walking	1026	53.5%
35-44	175	9.1%	Doing exercise	17	0.9%
45-54	186	9.7%			
>55	491	25.6%	**Total no. of respondents**	1917	
Prefer not revealed	10	0.5%			

3.2. Micrometeorological Measurements

Figure 2 shows that boxplots of the meteorological variables measured in different urban settings. Mean T_a was generally higher in street sites (34.0°C) due to the high level of pedestrian activities and traffic conditions. Maximum and minimum T_a were also the highest in street sites (38.9°C and 30.4°C respectively). In urban parks or the waterfront, T_a was generally lower, and the temperature range was also smaller, predominantly due to the cooling effect of vegetation and water bodies. As such, *RH* measured in these sites was also higher in urban parks and the waterfront. Wind speed was relatively consistent across three types of urban settings in the present study, with mean *v* values of approximately 1 m/s. Maximum *v* measured was slightly higher than 2 m/s with a few outliers reaching up to 3.21 m/s observed in street environment. It is primarily due to the effect of heavy traffic flow during the survey.

Mean T_{mrt} was lower in residential areas and urban parks or the waterfront (35.4°C and 36.5°C respectively), which is due to the presence of extensive vegetation in the areas. The outlier values were observed in the waterfront and open spaces in the housing estates. In street environment, the complex street geometry resulted in a wide range of radiative environment with a relatively higher average of T_{mrt} (43.9°C). Due to the predominant influence of T_{mrt}, similar pattern was observed in UTCI values with the highest mean UTCI values observed in street environment (38.3°C). The results showed that the urban settings have an influence on the micrometeorological conditions and hence potentially affect subjective thermal perception.

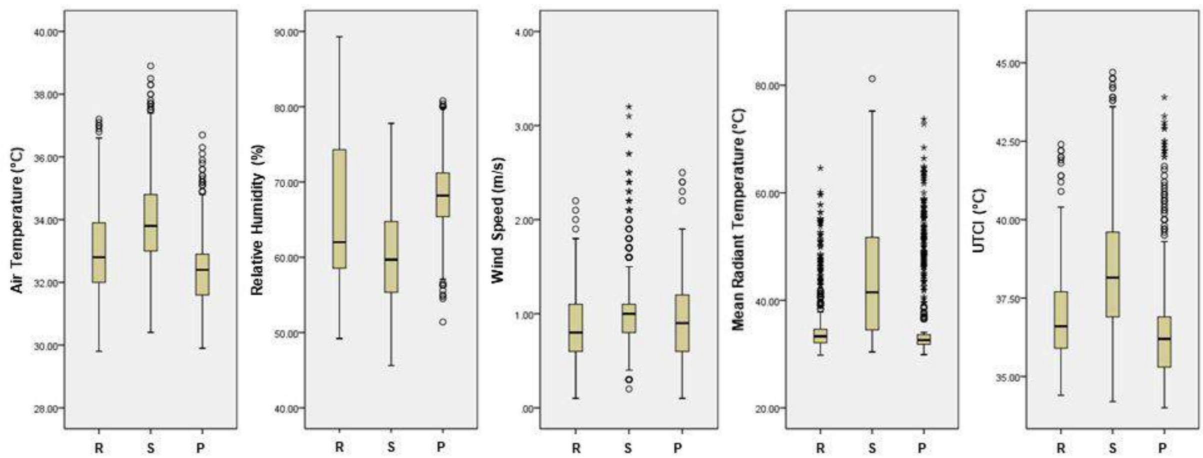

Figure 2. Boxplots of the meteorological variables measured during the survey campaign.

3.3. Overall Thermal Comfort

Overall level of thermal comfort was investigated by logistic regression analysis using three sets of variables obtained from the questionnaire surveys and micrometeorological measurements, namely measured meteorological variables, sensation of meteorological conditions, and perceived environmental quality. The odds ratios (OR) were presented in Table 2. Crude ORs and ORs adjusted for the three sets of variables were calculated for the entire samples (N = 1,971). Respondents who reported uncomfortable votes were set as the reference (OR = 1) in the analyses such that the ORs reported in Table 2 represent the probability that the respondents express thermal comfort relative to their counterparts. For instance, OR = 2.938 for WSV can be interpreted as respondents who reported comfortable votes being 2.938 times more likely to feel that the air movement is strong (+2) or very strong (+3) than respondents who reported uncomfortable votes.

Table 2. Crude and adjusted odds ratios (OR) and 95% Confidence Intervals (CI) for three sets of variables with respect to respondents reported comfortable votes.

	Crude OR	Adjusted OR
Measured meteorological variables		
Wind speed (v)	1.102 [0.889,1.368]	1.178 [0.875,1.586]
Relative humidity (RH)	**1.013 [1.005,1.021]	*1.017 [1.000,1.034]
Air temperature (T_a)	1.002 [0.987,1.017]	1.122 [0.929,1.355]
Mean radiant temperature (T_{mrt})	1.001 [0.993,1.009]	1.019 [0.992,1.047]
UTCI	1.003 [0.989,1.016]	0.876 [0.713,1.075]
Subjective sensation		
Thermal sensation (TSV)	***0.246 [0.199,0.305]	***0.291 [0.226,0.375]
Solar radiation sensation (SSV)	***2.637 [2.152,3.231]	***0.537 [0.418,0.690]
Wind speed (WSV)	***2.938 [2.034,4.242]	***3.414 [2.262,5.154]
Humidity sensation (HSV)	***0.490 [0.376,0.637]	***0.547 [0.409,0.730]
Perceived environmental qualities		
Convenience	***1.730 [1.336,2.239]	**1.462 [1.093,1.956]
Aesthetic	***2.283 [1.867,2.791]	***1.565 [1.209,2.025]
Acoustic	***2.063 [1.686,2.525]	*1.383 [1.073,1.784]
Air Quality	***2.439 [1.981,3.001]	**1.521 [1.159,1.996]
Safety	***1.773 [1.380,2.277]	*1.337 [1.001,1.785]

Table 2 shows that respondents expressing thermal comfort are not significantly associated with measured meteorological variables except relative humidity. It indicates that thermal comfort in outdoor environment is not necessarily determined by objective means. However, the crude ORs indicate that subjective sensation of meteorological variables and perceived environmental qualities were significantly associated with respondent's thermal comfort. Wind sensation, solar radiation sensation, and perception of air quality show the strongest relationship with thermal comfort. In the adjusted model which takes into account all the three sets of variables, similar pattern was observed but most of the effect size was reduced after adjusting for the other variables. This suggests that the interactions between different perceptions of environmental qualities in perceiving comfort in outdoor environment are highly complex and may offset each other in perceiving overall comfort in outdoor spaces.

Among the sensation of meteorological variables, respondents feeling hot (TSV = +2 or +3) were 70.9% less likely to report comfortable votes than the counterparts while respondents feeling strong solar radiation and humid were, respectively, 46.3% and 45.3% less likely to feel comfortable. However, respondents feeling strong winds were 3.414 times more likely to feel comfortable. It suggests that air movement in dense urban areas are important to outdoor thermal comfort under hot summer conditions. Moreover, satisfaction with aesthetic quality of the outdoor spaces shows the largest effect size among the perceived environmental quality (OR = 1.565, p = 0.001). It is closely followed by satisfaction with air quality and convenience with ORs = 1.521 and 1.462 respectively (p = 0.01).

4. Implications on Urban Geometry Design

Previous studies suggested that the most relevant factors to outdoor thermal comfort are T_a and T_{mrt}, which are closely associated with urban geometry, since it is particularly important to provide shading opportunities in urban outdoor spaces. Our results showed that perceived environmental qualities are significantly associated with outdoor thermal comfort. The relationship between outdoor thermal comfort and the degree of positive feeling towards different aspects of perceived environmental qualities was evaluated. The probability of respondents' reporting comfort votes was significantly associated with aesthetic, acoustic, air quality, convenience and safety of the outdoor spaces.

In high-density cities, the limited land resources caused a lot of constraints in the design of urban geometry, which determines the thermal environment. Design strategies can therefore consider environmental qualities that influence outdoor thermal comfort and increase the adaptive capacity. Further studies are required to investigate how these environmental qualities influence the physiological and psychological pathways of outdoor thermal comfort.

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Retrofit of an existing mosque in the UAE to achieve comfort in a nearly zero energy building

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Abstract: With climate change and global warming as the key challenges of the 21st century, there is an immediate need to ensure that our built environment is sustainable and able to adapt to the extreme future weather events. This research study investigates the energy use and thermal comfort conditions in an existing mosque in Dubai, designed to achieve UAE's nearly zero energy building target of 90 kWh/m^2/year. Due to the hot desert climate of UAE, mosques consume a considerable amount of electricity to provide thermal comfort to their occupants. To investigate retrofit measures for such buildings, the energy demand and thermal comfort conditions of an existing mosque are evaluated using on-site measurements and operational data to inform design decisions. Numerical analysis was used to model the mosque's energy usage in a 3D simulation software, IESVE. The calibrated model output was then used to estimate overall reduction in energy use due to different passive and active retrofit measures. These solutions are in line with Dubai Green Building Regulations and Passive House Standards. On-site solar systems are also explored, to offset the high energy use intensity (EUI) of the mosque and to enable it to become a nearly zero energy building.

Keywords: Retrofit, Hot Climate, Dubai Green Building Regulations, Passive House Standards, Thermal Comfort

1. Introduction

The energy use in buildings is increasing globally year on year. Increasing of population, along with the higher powering demand of modern living have led to an almost doubling of the global energy consumption (Eia.gov, 2016). According to predictions (Bp.com, 2017; Eia.gov, 2016), the average annual percentage increase of energy is about 1.4%, if extrapolated, meaning that by 2035 the global energy demand will grow by about 30%. Building energy use accounts for 36% of global final energy use and almost 40% of the total CO2 emissions (Iea.org, 2018). It is thus a significant percentage and this point of concern has been addressed by the Paris climate change agreement COP21. In December 2015, 175 countries signed the agreement and have pledged to reduce their prudent use of natural resources by establishing and following rigorous sustainability targets (Unfccc.int, 2015). In the United Arab Emirates several initiatives have been launched including the UAE vision 2021, Dubai integrated energy strategy 2030, and UAE 2050 energy goals, to promote the use of clean energy and ensure sustainable development within the country (Vision2021.ae, 2017). The country is comprehensively targeting energy use and carbon emissions from its building sector, which accounts for 80% of the total energy consumed annually (EMS, 2017).

In the light of these goals, the concept of Nearly Zero Energy Buildings (nZEBs) was introduced to provide a stepping-stone to the realization of a net positive built environment and a decarbonized global economy. According to an Emirates Green Building Council Report, a nZEB is defined as 'a highly energy efficient building which has an annual energy use intensity (EUI) of 90 kWh/m²/year and supplies most of its electricity demand through renewable energy sources produced on-site or off-site' (Emirates Green Building Council, 2017). According to Dubai Supreme Council of Energy (DSCE), 25% of the existing building stock in Dubai is inefficient with high electricity consumption, but presents significant energy saving potential (Gregorio and Zahr, 2015). This energy saving potential can be realized by introducing a retrofit program for existing buildings, which focuses on targeting the main consumption drivers such as cooling, lighting and building envelope performance.

Currently, the Etihad ESCO is leading the building energy retrofit program by addressing 2,250 buildings and targeting 69 GWh and 200 MIG per year of savings (Gregorio and Zahr, 2015). However, these projects consider public buildings like offices, industrial buildings and villas. There is another building typology which is quite unique in its architecture and operation, and which is rarely assessed. It is the mosque, a place of worship and the religious building for Muslims.

There are about 6,747 mosques in the UAE today (Iacad.gov.ae, 2017). Existing mosques can be retrofitted to become more sustainable and low-energy in order to contribute to the UAE energy goals. In this context, retrofitting is defined as substantial physical changes made to a building, in order to provide it with a component or feature that enhances its performance, operational cost or sustainability (Dixon et al., 2014).

1.1. Mosque building typology

Generally, a typical mosque consists of a large rectangular prayer hall, oriented towards the direction of the Great Mosque of Mecca. This direction is known as the Qibla, and it is indicated by a recess in the centre of the qibla wall, as shown in Figure 1. Mosques also consist of segregated prayer halls; the large main prayer hall is designated for the male worshippers while a comparatively smaller prayer hall is used by female worshippers. They are operated five times a day throughout the year. Overall, the intermittent operation of a mosque is based on prayer times which vary according to the local solar time instead of a fixed schedule.

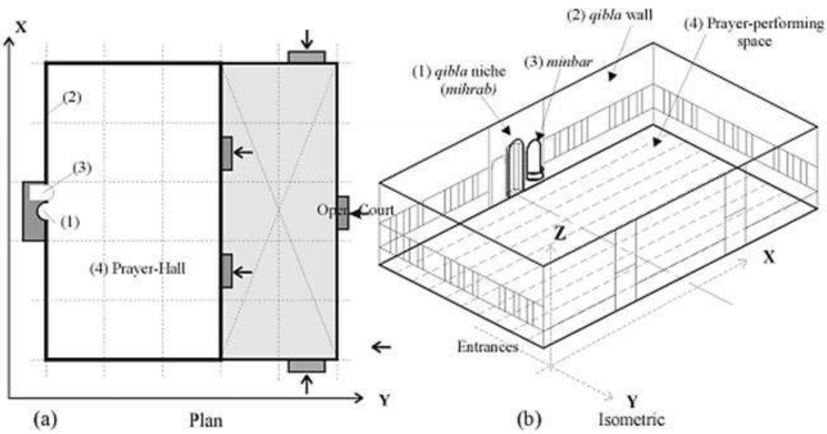


Figure 1. Layout of a typical mosque (Abdou, 2003) (a) Plan view (b) Isometric view

Through centuries, the function of the mosque has remained unchanged. However, with time, its architectural form, construction method, building materials and environment control systems have evolved considerably, to fulfil the needs of the changing climatic conditions and occupant thermal comfort requirements. In the gulf region, mosques are large volume air-conditioned public buildings encased in a heavy building envelope. Their interior surfaces are mostly finished with reflecting materials such as plaster and marble, and the floor is covered with thick carpets (Budaiwi, Abdou and Al-Homoud, 2012).

As mosques are a public place of worship, it is vital to maintain adequate internal room temperatures, humidity levels and good indoor air quality within the prayer halls, as their imbalance can cause the occupants discomfort in the form of headaches, sweating, shivering or allergies (Schiller Brager, 2001). Considering mosques in extreme hot climates, an air conditioning system is essential in providing a suitable indoor environment. However, it consumes a significant amount of electricity. Therefore, in order to reduce the overall energy demand effectively, the HVAC, as well as the artificial lighting systems should be made efficient in their operation and energy consumption, leading to a reduction in the overall cooling load of the building (Aste and Del Pero, 2012).

1.2. Literature review

Sufficient research has been conducted on the energy consumption trends, building retrofits techniques and thermal comfort conditions of mosques located in hot desert climates. Through assessment of monitored energy use of a numbers of mosques located in Riyadh, it was found that high energy consumption by a mosque HVAC system does not mean that the mosque offers optimum internal thermal comfort conditions. On the contrary, the mosque envelope thermal insulation provides lower cooler loads and adequate internal comfort temperatures. Also, in mosques where the main prayer hall has a large volume and a high ceiling, an upper warm zone is created due to air stagnation warm periods. To avoid such air distribution and to ensure thermal uniformity within a space, it is recommended that an air supply diffuser should be placed at a height of 2 m above ground level and close to the occupied zone of the mosque (Al-Homoud, Abdou and Budaiwi, 2009).

54 mosques were investigated in Sharjah, United Arab Emirates, to identify the impact of the building form on overall thermal performance and internal thermal comfort conditions. First, it was found that the geometry of the mosque has little effect on internal thermal comfort and energy loads, when compared to other factors like building envelope design or HVAC properties. However, it is concluded that the performance for octagonal shaped mosques is better as compared to square or rectangle shaped. This is because the octagonal mosque has the smallest surface area for the same inner room volume and this results in lower building fabric heat gains (Mushtaha and Helmy, 2016).

Energy simulation tools like Visual DOE are also used to assess the performance of a mosque, in terms of its construction materials and annual energy consumption. A similar study carried out in the hot eastern region of Saudi Arabia concluded that significant reduction in cooling loads can be achieved when the building envelope is properly designed. Also, depending on the volume of the mosque, improvement in room air infiltration rates can result in 10% lower cooling loads (Budaiwi, 2011).

Another study uses Visual DOE to simulate the energy performance of an existing mosque. It combines the benefits of building envelope retrofit and A/C operational strategies. The results of the study suggest that to maintain optimum thermal comfort conditions within the mosque while consuming the least amount of energy, it is important that the building envelope has low thermal transmittance values and low air infiltration rates. Also, the A/C system should be operated on intermittent one-hour bases, according to the occupancy schedule, on the condition that the A/C equipment is sufficiently oversized. Efficient energy system controls should be present in the mosque, that allow lights and cooling systems to turn on one by one, and not all at once. This ensures that at a given time, only the systems required are functioning (Budaiwi, Abdou and Al-Homoud, 2012).

Expanding on the experience and results from previous research, this research study carries out a thermal comfort assessment and evaluates the building envelope performance of an existing mosque located in Dubai, United Arab Emirates. Retrofit solutions to improve the overall energy profile with a view to reduce the EUI and achieve the local nZEB targets are proposed. This paper is developed in the following sections: section a presents the methodology and data collection process of the building details and energy patterns. Section b discussed the thermal comfort analysis, and section c presents the IESVE energy model development and investigation of passive and active energy saving strategies as retrofit solutions. The results of this research can have a broad application, as the retrofit solutions can be effectively applied to mosques in other gulf regions and similar climates.

2. Research Methodology

2.1. Case study mosque

The Abdul Rahman Siddique Mosque (Fig.2) located in Palm Jumeirah, Dubai, has been selected as the case study building. It was constructed in 2007 and has the capacity to accommodate approximately 843 worshippers.

Figure 2. Abdul Rahman Siddique Mosque, Palm Jumeirah

The total mosque built area is roughly 1,530 m², including the Imam and Muezzin residences. The mosque consists of two prayer halls, the main court (sahen al majid), female and male restrooms and ablution areas. The male prayer hall has a height of 10 meters and features a glass dome at its centre. On the other hand, the female prayer hall is located at the mezzanine floor and it is much smaller as compared to the main prayer hall.

2.2. Research approach

This research study has evolved through four stages, as stated below:

Stage 1 - Collecting operational energy data for the mosque and estimating the current building energy performance levels;

Stage 2 - Carrying out a thermal comfort study based on occupant feedback surveys and on-site measurements;

Stage 3 - Numerical simulation in IESVE software for the creation of a validated baseline energy model;

Stage 4 - Evaluation of passive and active retrofit strategies following national and international standards to propose an optimised retrofit scenario.

The following table shows data sets collected and measured for this research project and the equipment used:

Table 1. Date sets collected and their source

	Source	Data	Equipment
1	Data collected by mosque developer	Location and capacity of the mosque Operational data (annual electricity and water bills) Architectural floorplans, sections and elevations Lighting, HVAC, power and water supply layouts Building material details, finishes schedule	-
2	On-site measurements	Physical measurements of air temperatures, relative humidity and air velocity Thermal imaging Carbon concentration levels Occupancy patterns	MISOL temperature & humidity data loggers FLIR Thermal imaging camera Hot wire thermo-anemometer (C.A 1052 - Chauvin Arnoux) Heat Stress Wet Bulb Globe (Extech HT30) Measuring tape CO_2 Analyzer (Extech EasyView 80)
3	Occupant feedback surveys	Thermal comfort satisfaction End user feedback regarding existing services	
4	IESVE Energy model outputs	Annual energy use Impact of passive and active energy saving measures	IESVE software IBM SPSS 24 software Sketchup software

2.3. Methods of analysis

The architectural plans, operational data, materials and building services systems details are used for design evaluation of the existing mosque and to create a baseline model in IESVE. The base model shows the baseline annual energy use of the mosque.

Through the on-site physical measurements of air temperatures, relative humidity and, air velocity, the internal thermal comfort conditions are estimated and the Iso-PMV maps are generated within a particular space. Through predicted mean vote (PMV) and percentage people dissatisfied (PPD) values, the corresponding 7-point ASHRAE comfort scale value is estimated and occupant thermal perception within a particular space is gauged.

Furthermore, by conducting a thermal comfort survey, data representing user satisfaction and their thermal comfort perception of a particular space are obtained. This data are compared to the above mentioned calculations, to determine how the current system design and end user perception compare against each other.

After evaluating the first two data sets, the mosque is simulated in 3D energy modelling software IESVE. It considers occupancy patterns, building material details, thermal mass and local weather files to simulate external and internal conditions, which lead to an accurate estimation of the building's annual energy consumption. These results are then compared against real-time operational data of the mosque to calibrate and validate the model.

The next step is to develop strategies to reduce the mosque's EUI. For this, a number of active and passive energy saving measures are employed and simulated in IESVE to determine their impact. For evaluating passive strategies, four design cases are formed, based on Dubai Green Building Regulations, The Passive House Standards, and shading strategies. After multiple iterations, the best performing scenario is considered for applying active energy saving strategies.

To achieve nZEB target, on-site energy generation through solar panels is explored. The panels are simulated in the IESVE software and the annual power output is determined. The retrofit solutions proposed at the end combine the optimum combination of passive and active strategies.

3. Thermal Comfort Study

For the thermal comfort study, on-site measurements and surveys were taken during the months of December and January, during the Friday afternoon congregational prayer when the mosque occupancy is at its highest.

3.1. Occupant feedback surveys

For the occupant feedback survey, the questions were designed in English and Arabic and trialled to ensure that they are easy to understand and ethically sound. The survey included the worshippers present in the main prayer hall and female prayer hall. Worshippers were selected at random, and a total of 102 surveys were collected. 77.5% of the respondents were male while 22.5% were female. For an ideal survey setting, the sample must contain equal number of male and female respondents. However, this was not achieved by the study and the collected data is skewed and might affect certain findings.

From the bar chart shown in figure 3, it is seen that the mosque occupants are mostly wearing kandura and abaya, which is the traditional attire of UAE. From figure 4, it can be

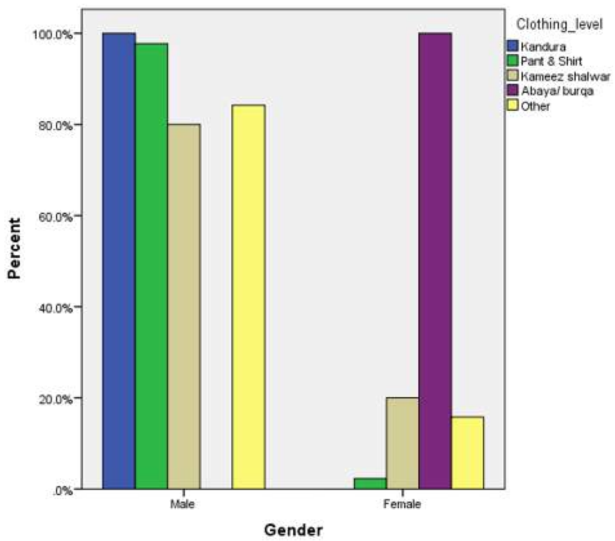


Figure 3. Clothing preference of worshipers in Main and Female Prayer Hall

observed that typically people come to the mosque for Friday's congregational prayers and the main prayer hall has the highest occupancy levels.

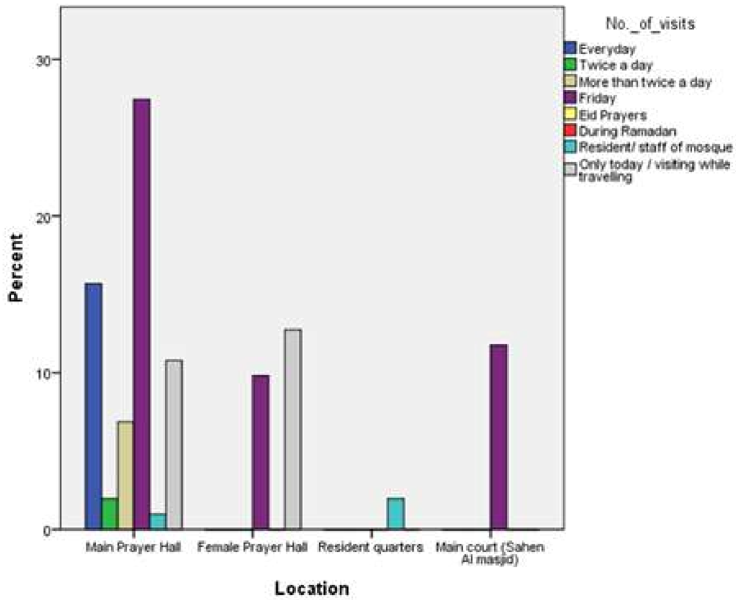


Figure 5. Mosque occupants for different spaces and their frequency of use

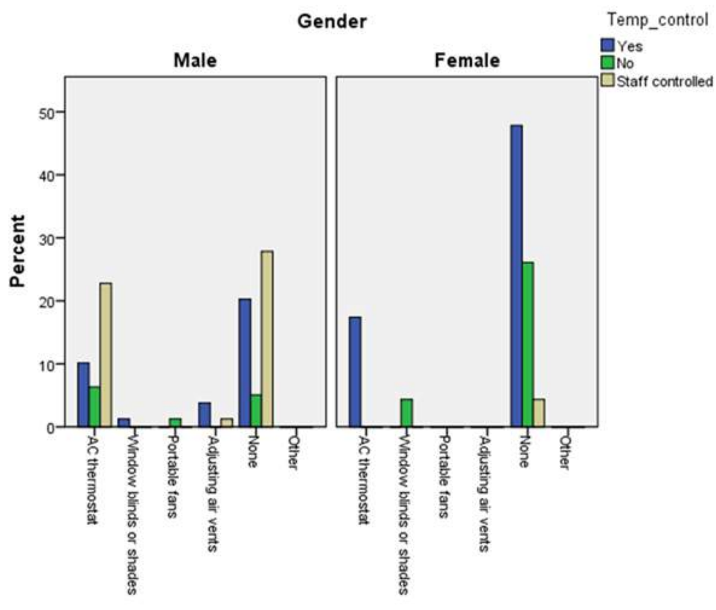


Figure 4. Use of lighting and HVAC controls in the main prayer hall and female prayer hall

Through the surveys it was found that 14.6% of the respondents are daily users of the mosque and 46% of the mosque occupants prefer to sit in the first rows. During summer, people in the main prayer hall tend to sit near the pillars, as the pillars are cool and its more comfortable sitting under the light coming through the dome.

Overall, 58.82% of the mosque occupants do not use any type of controls to change the internal temperature setting while 34.3% use the AC thermostat when required. User perception of controls can be seen in the figure 5. As the thermostat is locked in the main prayer hall, a considerable number of people accounted for this fact by stating that AC thermostat is controlled by the mosque staff. On the other hand, the thermostat in the female prayer hall is accessible by all, however, a majority of people opt not to change the temperature settings.

84% of the mosque users said that they are satisfied with the mosque's internal temperatures. When asked about thermal comfort during summer and winter seasons, the response was majorly neutral. Figure 6 shows the rating of thermal sensation on the 7-point ASHRAE scale. It can be seen that the majority of mosque occupants were comfortable with the thermal conditions. However, 44% of them felt slightly cool and cool.

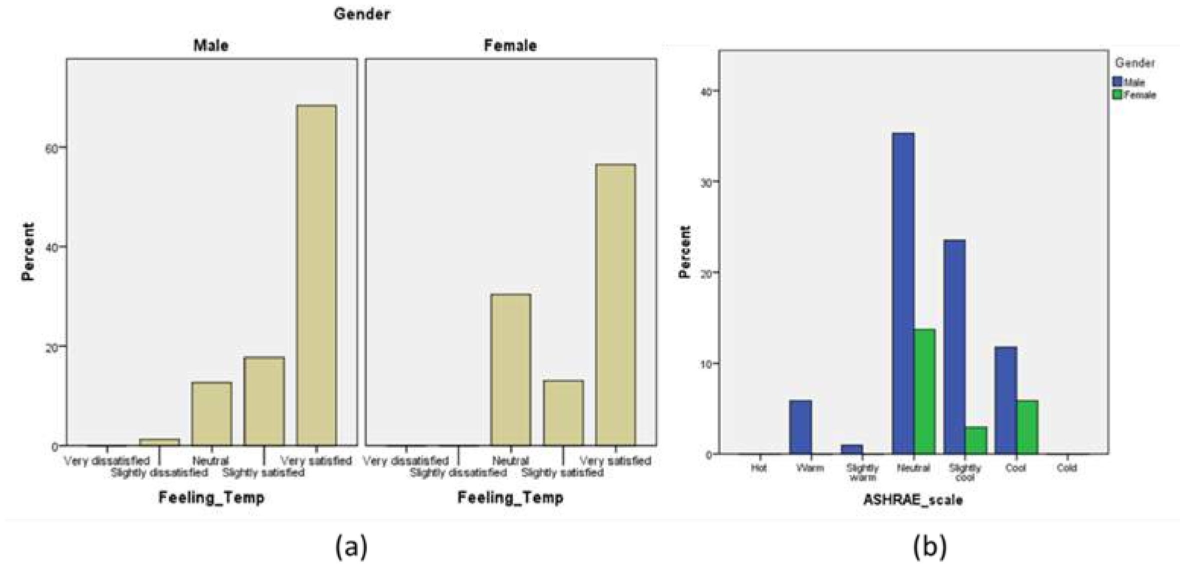


Figure 6. Occupant thermal comfort perception (a) Bar chart showing thermal satisfaction in the male and female prayer hall, (b) Bar chart showing respondent ratings on the 7 point ashrae scale

3.2. Thermal comfort measurements

Thermal comfort conditions in the mosque prayer halls were assessed by measuring air velocity, average air temperature and globe temperature at different points in the halls, through the equipment mentioned in Table 1, section 2.2. Figure 7 shows the positions in the mosque where measurements were taken at different heights of 0.5m, 1 m and 1.5 m. These three different positions cover the points of interest for praying posture. As seen in Figure 7, the measurement positions (red dots) selected are closer to windows, doors, corners, and below duct grills.

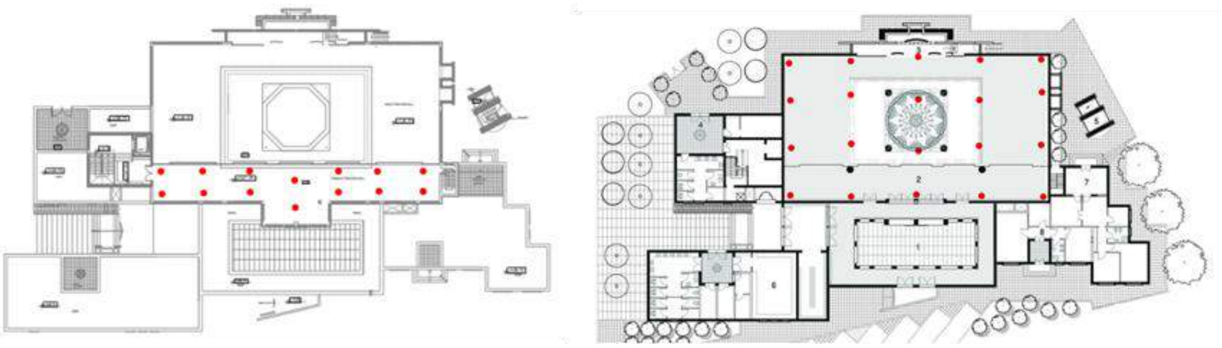


Figure 7. Left to Right – Measurement positions for the female prayer hall and main prayer hall.

Average operative temperature was calculated using the collected data. In the context of thermal comfort, operative temperature is defined as the temperature at which the average person feels thermally neutral (Oxizidis and Papadopoulos, 2013). It is calculated using the following formulas:

1. $T_{op} = H \times T_a + ((1-H) \times T_r)$
2. $T_{op} = (T_a \sqrt{10v} + T_r)/(1+ \sqrt{10v})$
3. $T_{op} = \frac{1}{2} Ta + \frac{1}{2} Tr$, for $v < 0.1$ m/s

Where

H = Heat transfer coefficient

v = Air velocity

T_{op} = Operative temperature

T_a = Ambient temperature

T_r = Radiant temperature

T_G = Globe temperature

The operative temperature calculated from these three formulas is averaged to arrive at a single value. This value was used to determine Predicted Mean Vote (PMV) values from the PMV chart. On the other hand, Percentage People Dissatisfied (PPD) values were calculated from Fanger's PMV model

The following table shows a summary of the measurements taken in the main prayer hall and ladies prayer hall. The calculated operative temperature and PMV and PPD values associated with each prayer hall have also been indicated.

Table 2. Summary of measurements and results

	Main Prayer Hall			Female Prayer Hall		
No. of measurement points	16			14		
No. of observation at each point	3			3		
	Average	Min	Max	Average	Min	Max
Humidity (%)	47.9	44.1	53.3	54.9	51.2	58.2
Wet Bulb Globe Temperature	19.4	18.8	20.5	17.6	16.5	19.1
Ambient temperature - Ta (°C)	24.6	23.95	25.5	21.4	20.4	22.5
Globe temperature - Tg (°C)	24.3	23	28	21.9	20.4	24.3
Air velocity (m/s)	0.0	0	0.21	0.1	0	0.39
Operative temperature – Top (°C)	24	24	27	22	21	23
Predicted Mean Vote (PMV)	0.4	0.20	1.08	-0.45	-0.96	-0.02
Percentage People Dissatisfied (PPD) %	8.4	5	29	9.86	5	19

3.3. Discussion

Both prayer halls are mechanically ventilated and have air tight windows. As the average operative temperature defines both ambient air temperatures and radiant temperatures, it is used as an indicator of internal thermal comfort conditions. According to ASHRAE standard 55 (ANSI/ASHRAE standard 55, 2013), the ideal operative temperature lies between 21.5°C to 25.1°C, for a Clo value of 1.0 and relative humidity of 50%. For the main prayer hall and female prayer hall, average Top is 24°C and 22°C respectively. The average clo value for the male prayer hall is 0.89 and for the female is 1.04, and the average relative humidity for the male prayer hall is 47.9% and for the female is 54.9%. This means that the HVAC system provides satisfactory thermal comfort conditions to these halls.

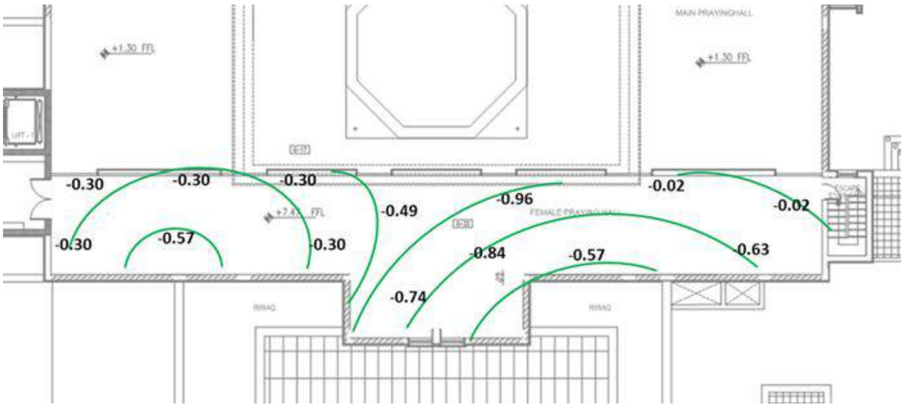


Figure 8. Iso-PMV map of the female prayer hall

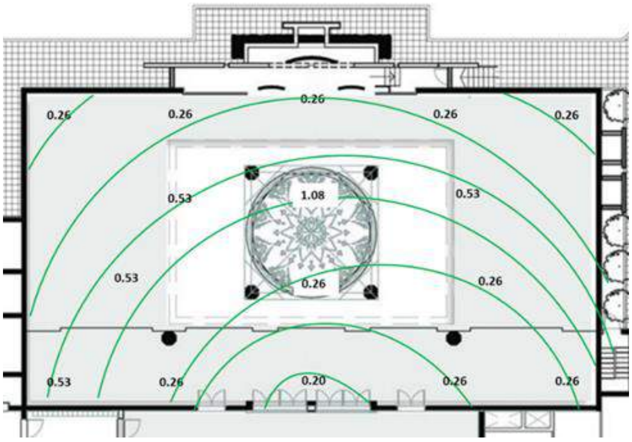


Figure 9. Iso-PMV map of the main prayer hall

The PMV values show an occupant's perception of their thermal environment. From table 2, it can be seen that PMV values for both halls are quite low and indicate '0 Neutral' on the ASHRAE comfort scale. Figure 8 and 9 show the Iso-PMV maps of both prayer halls, with contours that join similar PMVs to some extent. A thermal uniformity can be observed in the pattern. According to Fanger, the greater the thermal uniformity within a space, the lesser will be the number of people thermally dissatisfied (Fabbri, 2015).

However, not every user of the mosque feels satisfied with the internal environment. The surveys and the measured data, both point to areas where the occupants feels slightly warm or slightly cool. For the main prayer hall, it is the area beneath the dome where the PMV is nearing slightly warm with an average value of 1.08, and for female prayer hall, it is near the large internal windows where the PMV is nearing slightly cool, with values of -0.57 to -0.84. With reference to figure 6, the above PMV values can be correlated with the survey results, which show 8.9% of the worshippers in the main prayer hall felt warm while 39.1% of the female worshippers felt slightly cool.

4. Mosque Energy Consumption

The mosque annual energy consumption for 2016 and 2017 is presented in Figure 10. Overall an increase of 12.17% is noted between the two years. This increased the mosque's initial EUI from 212 kWh/m²/year to 237 kWh/m²/year. However, Figure 10 shows that the energy consumption trend remains consistent between the two years. The energy use of the mosque is due to the cooling, lighting systems and small power.

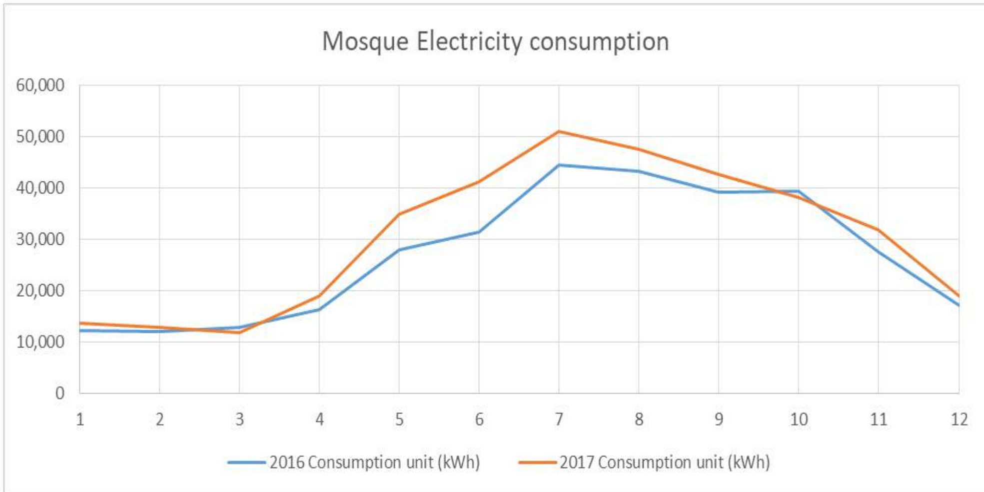
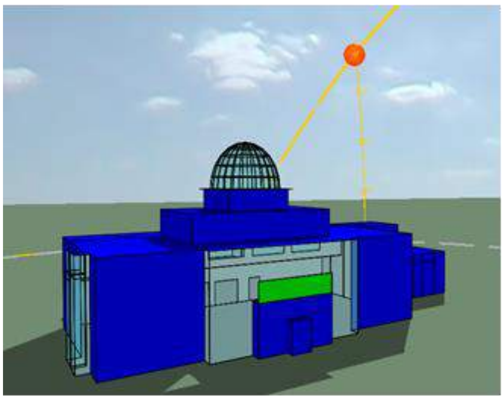


Figure 10. Mosque actual energy consumption for the year 2016 and 2017

From Figure 10, it can be seen that there is a substantial increase in electricity consumption in May and June, which peaks in July and starts dropping in August, with an annual low in March. As the function of the mosque didn't change during 2016 and 2017, the increase in energy consumption can be attributed to an increase in the number of occupants, an increase in external summer temperatures or lower operational efficiency of the cooling systems.

5. IESVE Baseline Model

In order to perform a comprehensive energy assessment, the IESVE software is used as a simulation tool. It provides a dynamic simulation of the modelled building, as shown in Figure 11, and gives an accurate estimation of the building's annual energy consumption and carbon emissions.



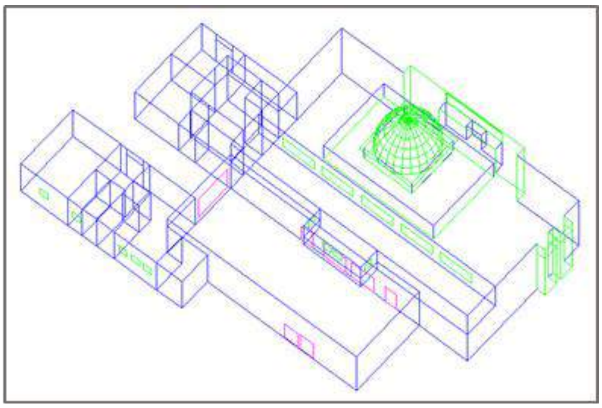


Figure 11. IESVE model of Abdul Rahman Siddique Mosque. Left image: 3D model with sun path and shadows. Right image: Axonometric view of the model geometry

For accurate energy simulation results, the mosque floor plans and construction materials were used to create the baseline IES model, as presented in Table 3:

Table 3. Construction materials and thicknesses used in the Baseline IES model

Construction Element	Thickness (mm)	Type	ASHRAE U-Value

Internal partition	250	Internal Partition 250 mm	1.0711
External Wall	320	Insulated concrete wall with marble tiles	1.7606
External stone wall	600	Mosque external stone wall	1.7611
Roof	400	Uninsulated Flat roof	1.5647
Internal ceiling / floor	300	300mm insulated Concrete ceiling	1.0139
Ground	400	Un-Insulated Solid-Ground Floor	1.3902
Internal glazing	8.5	NCM notional internal window; SC=0.47	1.8044
External glazing	4,12,4	NCM notional window (E/SE/W/SW), SC=0.6	2.4644
Dome	6,12,6	NCM 2010 Notional Rooflight, SC=0.5	1.8086
Glass curtain wall	4,6,6	NCM notional glass curtain wall	2.3026
Door	100	Wooden Door	1.1574
Shade	100	Local shade (cast concrete - Lightweight)	2.0920

Table 4 gives a summary of thermal and operational characteristics of the mosque that are used as inputs in the baseline IESVE model:

Table 4. Summary of thermal and operational characteristics of the modelled mosque

Component / Characteristic	IES Baseline mosque model	
Location	Palm Jumeirah, Dubai, UAE	
Orientation	'Qiblah' wall is oriented west	
Weather file	Dubai Intl Airport, United Arab Emirates (AbuDhabiIWEC.fwt)	
Frequency of use	5 times a day, daily	
Total mosque conditioned floor area (m^2)	1530	
Capacity (persons)	843	
	Main Prayer Hall	Female Prayer Hall
Dimensions L x W x H in m, (area in m^2)	34.3 x 19.3 x 10 (698 m^2)	34.3 x 4.9 x 4.2 (191.6 m^2)
Window to wall ratio (WWR) %	42.16	4.25
Lighting power density (LPD) W/m^2	12.51	21.875
Air infiltration rate (ACH)	0.167	0.167
Estimated occupancy (m^2/person)	2.8	4.8
Set point temperature (°C)	23	23
HVAC system	3 Precision Air Conditioning Units (PACU)	
HVAC operation	Intermittent HVAC operation Summer: March to Sept ~10 operating hours Winter: October to February ~8 operating hours	

Total cooling capacity (kW)	37.5
Type of fan	Constant flow
Heating capacity	None
Outdoor air quantity	None
Hot water system	Local electric water heaters

The numerical model has been calibrated against the electrical energy data of 2016 and 2017. The simulated model's annual electricity consumption follows the actual energy trends. The performance gap between the modelled and the actual values for 2017 is about 3.29%. According to the baseline IESVE model, the annual energy consumption is 375,313 kWh and annual carbon emissions are 194,787 kgCO_2.

The following table shows thermal comfort parameters recorded from IES for 22nd of December, for the main prayer hall and female prayer hall.

Table 5. Internal thermal comfort values as predicted by the IES Baseline model, for 22nd December

	Main Prayer Hall	Female Prayer Hall
PPD %	8.89	9.28
PMV	0.43	0.45
Average Air temperature (°C)	23.84	22.73
Average Humidity (%)	57.85	60.88

By comparing the above given values with Table 2, outlined in section 3.2, it can be seen that average internal air temperatures predicted by the IESVE model fall within the range of those measured on site. The PMV and PPD values also show similarity with the values calculated by the thermal comfort study. However, the PMV for the female prayer hall is slightly higher. On the other hand, the average humidity levels are also slightly overestimated by the IESVE model. This variance in data can be due to the properties of the chosen weather file, used for carrying out the IESVE energy simulations. Overall, the IESVE baseline model can be used in a confident way to represent the actual mosque energy profile and energy retrofit scenarios.

6. Retrofit Solutions

6.1. Passive design cases

The Dubai Green Building Regulations and Specification (GBRS) and the Passive House Standards provide guidelines to improve the building envelope performance. These guidelines are used to develop the passive energy saving strategies for the mosque. The IES baseline mosque model was run separately for four cases, which are described as follows:

Case 1a: Building external fabric U-values, shading coefficients and infiltration rates as per the Dubai GBRS

Case 1b: Enhancing case 1a with the use of strategic shading

Case 2a: Building external fabric U-values, shading coefficients and infiltration as per the Passive House standards

Case 2b: Enhancing case 2a with the use of strategic shading

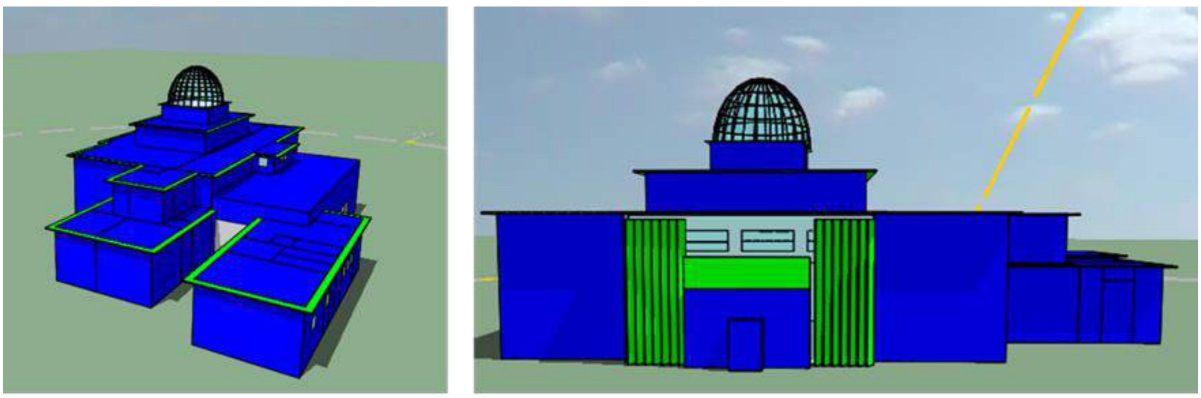
The following table sets out the design criteria followed by the above given passive design cases:

Table 6. Dubai GBRS and Passive House standards

		Dubai Green Building regulations and specifications	Passive House Standards
Thermal transmittance U-values (W/m²K)	Roof	0.3	0.15
	Walls	0.57	0.15
	Windows	1.9	≤ 0.8
Glazed Element	Shading coefficient (SC)	0.32	0.57
Air infiltration		< 10 $m^3/h/m^2$	< 0.6 x room volume per hour
		~ < 0.167 ach	0.042 ach

For design cases 1b and 2b, two different shading methods were used consecutively. From previous research conducted on shading configurations (El Bakkush, 2015; Freewan, 2014), it is concluded that overhangs are most suitable for shading the south face of the building, while diagonal fins were suitable for shading the west façade of the building. As the mosque is located in the northern hemisphere, roof overhangs and diagonal shading fins were designed according to the solar angles of the site, as shown in Figure 12.

The typical roof overhangs size for this type of building is 700 x 700 x 100 mm (El Bakkush, 2015), while the diagonal shading fins have the following dimensions: 600 x 100 x 9500 mm. As shown in figure 13 (b), shading fins are inclined at an angle of 45° facing north, and have 570 mm spacing between the total 14 fins designed for the west glazed façade of the mosque.



(a) (b)

Figure 12. IES baseline model of the mosque with added shading devices (a) South face of the face showing roof overhangs (b) West façade of the building showing diagonal shading fins

6.2. Active strategies

The following active strategies are applied to the best performing passive design case, as presented in Table 7. These strategies also consider general energy conservation tips issued by Dubai Electricity & Water Authority (Dewa.gov.ae, 2017).

Table 7. Active energy saving strategies

Active strategy	Method

1	Replacing existing lights with LEDs	The existing mosque lighting fixtures are replaced with LEDs, which have a much lower power consumption
2	Motion sensors and dimmers	To model the effect of motion sensors and dimmers in IES, the Lighting power density (W/m²) is reduced by 10%.
3	Cooling set point temperature	The cooling set point for every room, except for the plant room, is increased by 1°C to 24°C in the IES model. This temperature setting is kept for both summer and winter variation profiles.
4	Programmable thermostat	With the application of a programmable thermostat, the HVAC system is only operational during prayer times, when the mosque is occupied. Previously air conditioning systems were running between prayers as well, to keep the mosque cool.

6.3. Results

Table 8 shows the results of using passive and active strategies on the IESVE baseline mosque model:

Table 8. Summary of results after applying the passive retrofit solutions

		Annual energy consumption of the mosque (kWh)	EUI (kWh/m²)	Percentage reduction from base case model
Electricity bills from DEWA	2016	323,912	212	-
	2017	363,347	237	-
IES Mosque baseline model		375,313	245	-
Passive design strategies	Case 1a	323,074	211	13.92%
	Case 1b	316,077	207	15.78%
	Case 2a	295,483	193	21.27%
	Case 2b	289,036	189	22.99%

Table 9. Summary of results after applying the active retrofit solutions

		Annual energy consumption of the mosque (kWh)	EUI (kWh/m²)	Percentage reduction from base case model
Active strategies	Replacing lights with LEDs	350,602	229	6.58%
	Motion sensors & dimmers	374,862	245	0.12%
	Set point temp. at 24	352,554	230	6.06%
	Programmable thermostat	365,251	239	2.68%
Best Passive design strategy (Case 2b) + all active strategies		231,053	151	38.44%

Case 1a provides a reduction in energy consumption by 13.92%, while case 2a provides energy reductions of 21.3%. As the shading approach for cases 1b and 2b is kept the same, both cases provided 2.2% of energy reductions due to shading. As seen in table 6 in section 6.1, the passive house standards are more stringent as compared to Dubai green building regulations. Hence, the results for case 2a show far greater energy saving potential than case 1a. Therefore, the most efficient passive energy saving method is the one presented by case 2b, which is applying the concept of the Passive House standards to the existing mosque, adding external shading devices like overhangs and diagonal shading fins.

Active energy saving strategies are applied to passive design case 2b. From table 9, it can be observed that using LEDs as the mosque's lighting system results in 6.58% in energy savings. Motion sensors and dimmers have a low impact, as they only decrease the lighting load by 0.12%. On the other hand, setting the air conditioning at 24°C results in the highest energy savings of 6.06%. By using a programmable thermostat, the cooling loads decrease by 2.68%.

It can be observed that the overall thermal comfort is not compromised by increasing the set-point temperature and introducing the programmable thermostat as shown in Table 10, when compared to the values mentioned in Table 5, section 5.

Table 10. Thermal comfort results from IESVE model, after passive and active retrofit measures

	Main Prayer Hall	Female Prayer Hall
PPD %	9.89	11.7
PMV	0.48	0.57
Average air temperature (°C)	22.78	23.25
Average humidity (%)	67.09	67.98

Overall, by applying all four active strategies to passive design case 2b, the annual electricity consumption of the mosque decreases by 38.44% of the baseline value. However, the mosque's EUI is 151 kWh/m² and it is still higher than the one required to achieve the UAE nearly zero energy target, which is 90 kWh/m²/year.

Figure 13 shows the mosque's EUI at different stages. After applying both active and passive measures, there's still a need to reduce the mosque's energy consumption by approximately 40%, which corresponds to 92,500 kWh annually. This value can be off-set by using onsite renewable energy generation.

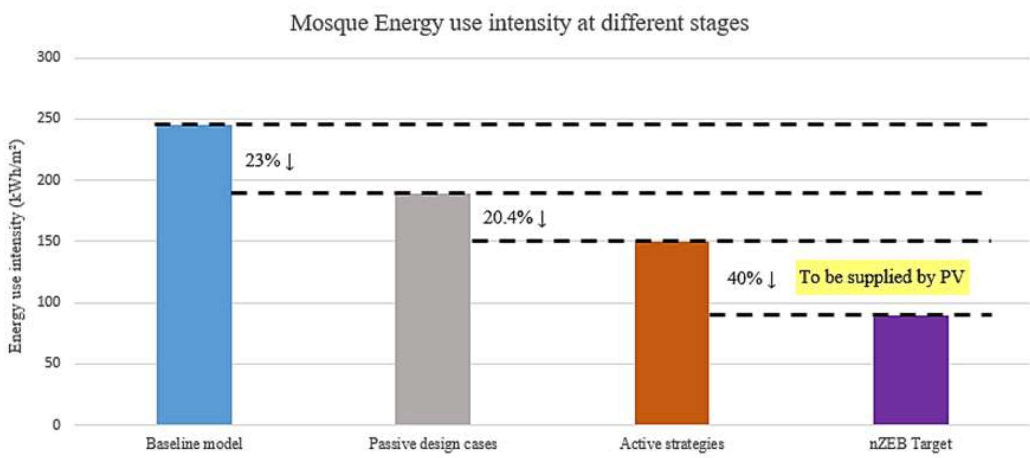


Figure 13. IES mosque's EUI at different stages of retrofit solutions. Reductions in energy consumption due to each stage is also shown in percentages.

7. On-site Solar System

The entire mosque building provides a roof area of approximately 1,227.5 m². Through the mosque's IESVE model and the software's solar analysis capabilities, the power generated from the solar panels can be estimated accurately. Monocrystalline solar PV panels (Power output 330 W, Module efficiency 17.03%) are installed on the flat roof of the main prayer hall, men restrooms and the staircase the roof. Furthermore, placing the solar panels on the roof contributes to blocking direct heat radiation and lowers the cooling load of the associated rooms.

Through the IESVE model, the exact number of solar panels required to achieve a 40% reduction in the energy consumption was calculated. It is concluded that by placing 179 solar panels, the mosque's total energy demand from the national grid reduces to 137,568 kWh. This results to an EUI of 89.91 kWh/m². Therefore, with the help of on-site solar power generation, the mosque can become a nearly zero energy building.

Furthermore, the solar panels contribute by reducing the heat gains through the roof, a factor that contributes to the cooling demand and overall energy use reduction. Moreover, the thermal conditions improve slightly as well, as shown in Table 11.

Table 11. IESVE results for thermal comfort parameters, after applying retrofit strategies and Solar PV system

	Main Prayer Hall	Female Prayer Hall
PPD %	9.85	11.31
PMV	0.48	0.55
Average air temperature (°C)	22.77	23.16
Average humidity (%)	67.11	68.42

8. Conclusions and Recommendations

Through careful analysis, this research considered the real time constraints faced by an operational mosque in Dubai, and has shown that similar existing mosques may be able to be retrofitted to achieve nearly zero energy building (nZEB) targets. Based on the results obtained from IESVE energy model simulations, approximately 21.3% and 2.2% savings in annual energy consumption can be achieved by following Passive House standards guidelines and suitable shading techniques respectively. A further reduction of 15.45% can be ensured by strategically incorporating energy conservation measures, as advised by local electricity authority DEWA. To reach the nZEB target of 90 kWh/m²/year, 179 monocrystalline solar PV panels (330 W) were proposed to be installed to offset 40% of the mosque's annual energy demand and the resulting EUI of 89.9 kWh/m²/year may enable it to become an exemplary nearly zero energy building.

While targeting low energy demand, internal thermal comfort conditions of the mosque are also kept in mind. It is found that by using passive and active retrofit strategies, and rooftop solar PV systems, the thermal comfort conditions of the mosque do not change drastically and remain acceptable. However, it should be noted that the thermal comfort parameters obtained from IESVE simulations can be slightly over-estimated, based on the accuracy of the weather file used.

The design and operation retrofit strategies proposed in this study may be applied to similar buildings in hot humid climates. A primary recommendation is to improve the existing building envelope with wall and roof insulation, with minimum thermal transmittance value of 0.15 W/m²K. For mosques with large window areas, high performing façade glazing elements should be used, having minimum thermal insulation of 0.8 W/m²K. As lighting and air conditioning systems are major contributors to energy usage in a mosque, adjusting their operational profiles to intermittent rather than continuous operation can lead to significant energy saving of 15.45%. This combined effect can be achieved given that all existing luminaires are replaced with LEDs and HVAC equipment is suitably oversized, with the A/C being operated only during prayer hours i.e. when the mosque is occupied. It is recommended to have regular maintenance of the overall HVAC system for it to perform to its nominal capacity. This also ensures that adequate thermal comfort conditions are maintained within the retrofitted mosque.

To contribute to UAE future energy goals, retrofitted nearly zero energy mosques can provide a high profile example on how to conserve energy in public buildings. Based on the results of this study, it is observed that the local Dubai Green Building Regulations have the capacity to improve further and consider a better building envelope performance criteria, as seen in Passive House guidelines, but these need to be enhanced with additional hot climate solutions such as external shading. Although the building envelope retrofit is the major contributor to energy savings, shading the envelope has a significant effect on the overall cooling demand and is typically a cost-effective measure.

In addition to the above, proposed retrofit measures can be used to set formal retrofit guidelines for mosques and similar public buildings in the region. This will promote both energy conversation and public awareness on the issue for governments and private landlords.

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Australian energy efficiency policy is killing passive low energy earth building

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Abstract: I would rather be presenting, "Earth the ultimate green building material that, when combined with passive low energy design principles, provides safe, healthy, comfortable, desirable, energy efficient and sustainable buildings for the world's people into the future." Buildings that are climate change resilient and address all of the problems we face today. Buildings that meet 2050 targets for zero LCD carbon buildings, immediately.

Unfortunately, I am here to explain how earth homes can provide adaptive thermal comfort and GHG emission reductions more effectively through other means than modern "thermal shell" efficiency. To question our Australian governments' short-sightedness and ineffectiveness in reducing GHG emissions in a meaningful way. To criticise a blinkered and narrow focus set into legislation and the rating scheme used to verify compliance. The Nationwide House Energy Rating Scheme (NatHERS) is using a methodology that is erroneous, not thoroughly benchmarked against reality and without reference to a suitable metric. An approach that protects and encourages business as usual and denies best practice passive low energy architecture a reasonable compliance pathway.

Australian regulation needs to focus on promoting best practice first and mitigating worst practice second. We need recognition for Passive Low Energy Architecture and an appropriate assessment pathway.

Keywords: Earth building, natural conditioning, mass-linked ventilation, NatHERS, "thermal shell"

1. Philosophy that drives my work and passion for change - the big picture

My philosophy, in regards architecture, has evolved over my working life. My current position on sustainable building is a holistic view that considers all challenges and opportunities and arrives at full LCD net zero carbon outcomes without sacrificing health, safety or comfort as quickly as possible.

The OECD advised wealthy developed countries they need to reduce their energy and resource flows by 80%. When we consider around 40% of energy and resources is related to buildings, I question whether we are going about it diligently.

The world needs a solution that is equitable and sustainable to all. Developed and developing economies can learn from each other. To me best practice efficiency and energy conservation is achieved through striving to emulate nature and natural processes and through learning from vernacular architecture.

I question the true worth of some technological solutions like air conditioners and mechanical ventilation heat exchangers and reverse cycle heat pump hot water systems. To me we are often creating a problem to solve with technology rather than resolving problems from first principles and as simply as is possible.

We need to constantly re-consider what is best practice. Why create poorly designed buildings that are reliant on air conditioning when there are appropriate climate responsive principles that work for any climate? Can thermal mass do the job of RCAC with better outcomes? Why seal buildings and install MVHR units when mass-linked ventilation can condition fresh air in naturally ventilated buildings? Why encourage a design paradigm where homes with poor design and good "thermal shell" efficiency become dependent on RCAC and MVHR units? Why was this the vision for Australia in 2030 presented within the recent National Energy Productivity Policy process? This is not a vision of more sustainable homes. It is business as usual.

All refrigerants, used in RCACs are harmful. Today's best refrigerant is the next least harmful and the next to be banned. RCACs are noisy, add to the heat island effect and they are less reliable than natural conditioning. Why develop policy, regulation and a scheme that supports all of this technology and at the same time, hinder simple and more reliable proven technology and design through not providing a pathway to approval?

Sir Richard Branson touched on the problem of Comfort at the Extremes recently as he launched the Global Cooling Challenge (GCC). How do poor people from Africa, India, Asia etc. afford to buy and run air conditioners in a world that is warming? According to the GCC the impact of RCAC alone will be a 0.5C rise in global temperatures. The GCC offers a $3m prize for a super-efficient RCAC. Such a piece of technology may or may not be feasible. This is a first world problem we are spreading worldwide. The best solution avoids the need for air conditioners using mass-linked ventilation and appropriate design for climate.

I am a champion of the big picture. How do 7.7 billion people plus coexist harmoniously and achieve some form of equitable sustainable future with the resources and energy of one planet without completely destroying what is wonderful about it, just to satisfy our own interests for the short time we are here?

2. Remember the purpose of the exercise - small change - no cigar – only collateral damage!

I prefer a Life Cycle Design (LCD) tool for building assessment because it considers every aspect of a building and reports in the common carbon metric - designed to measure GHG emissions. To deliver low carbon buildings by 2030 and a zero carbon economy by 2050 we need to be addressing all operational and embodied energies. We need to ensure savings in thermal comfort are not adding as much to embodied energy. We need to reduce all energies and carbon impact to a point where renewable energy can reduce energy to carbon zero. To be mindful of carbon intensity and that energy conservation comes from reducing need first and energy efficiency second.

Whilst the purpose of energy efficiency worldwide is GHG emission reductions, since 2003 all attention in Australia has concerned gradual reductions in predicted space heating/cooling energy (MJ/M2/year) in new buildings. Prior to the introduction of NatHERS average Australian houses had predicted thermal performance of 2.5-Star. Regulation started with 4-Star performance in 2003, moved to 5-Star in 2005 and 6 -Star in 2011. The conversation is now around 7-Star.

For 15 years NatHERS has focused on space heating/cooling energy or perhaps 20% of operational energy. NatHERS applies to new homes and large renovations which represent roughly 2% of the building stock. NatHERS 6-Star aims to achieve a predicted saving of 60% of heating and cooling energy. NatHERS is addressing 60% of 20% of 2% of energy or 0.0024% of operational energy in homes each year. So, after 15 years, we should see a 0.036% improvement in Australia's building stock due to "thermal shell" improvements. Nothing!

Regulation is allowing GHG emissions to grow and has created problems related to public health, safety and productivity, energy security and energy cost. Policy has hindered rather than prepared Australian homes for climate change resilience. It has made the inevitable move towards a renewable energy economy and a zero carbon economy more difficult. I have always questioned the efficacy of the assumption of air-conditioning as a starting point and also the use of unverified predictive modelling.

Until recently the NCC was dealing specifically with space heating/cooling, but not hot water or any other operational energy. Operational energy has been the responsibility of individual states and then mostly limited to hot water. Embodied energy is ignored. If we compare NatHERS with eTool Life Cycle Design we can see both the big picture and the small focus (Figure 1).

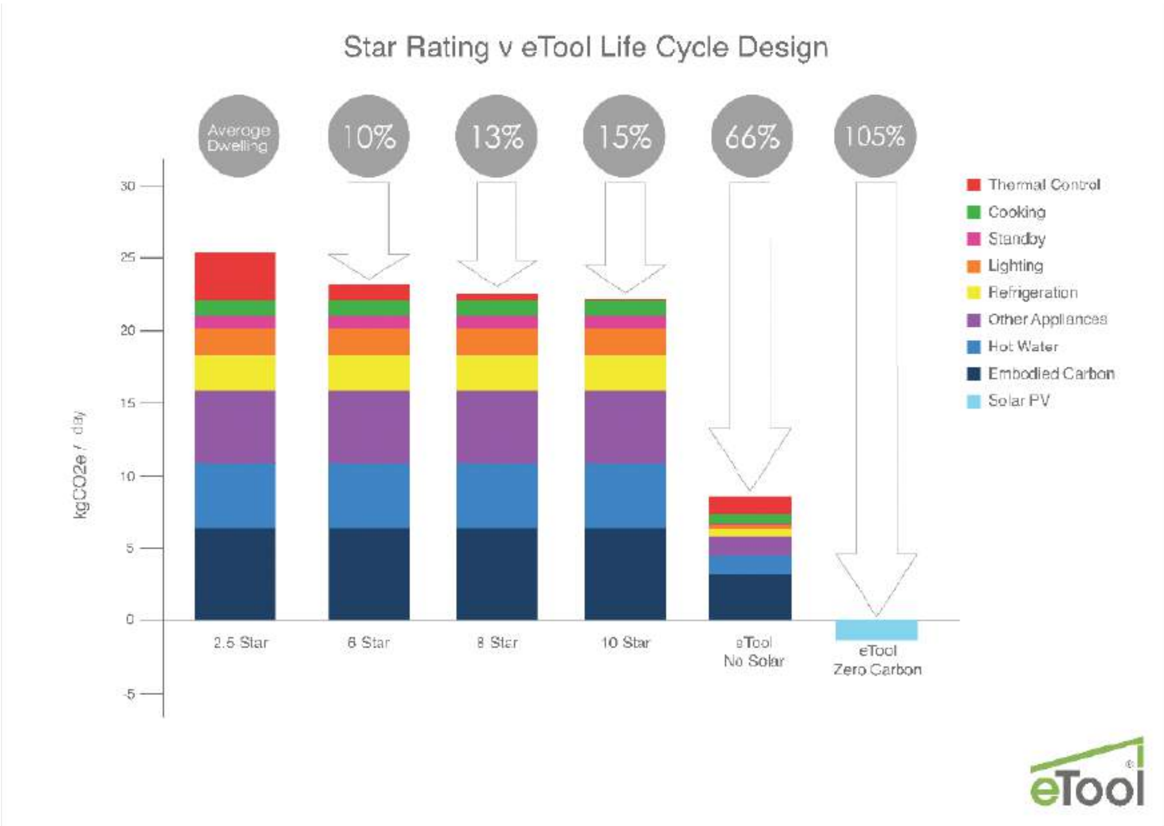

Figure 1. NatHERS Star Rating verses eTool LCD

A scheme that is achieving so little is locking earth out as a sustainable building solution. What is worse, not because we are poor performers. In reality we are good performers in terms of thermal comfort, cost, carbon and health. Audits and monitoring shows we perform better than predicted in NatHERS. NatHERS can't assess the thermal performance of naturally ventilated and naturally conditioned buildings. It is not designed to do so. We have become "nice guys but collateral damage", as a representative from the Victorian government said to an earth brick manufacturer who has been forced into bankruptcy.

My 27-year old mudbrick home was retrospectively rated 3.2-Star in 2013. Every earth home I have constructed in the past 37 years doesn't require cooling and uses carbon neutral heating - so carbon zero thermal comfort. In terms of kgCO2e/day they are 10-Star performers though they don't have 10-Star "thermal shells" in NatHERS. My 3.2-Star home is rated 113% Zero Carbon in eTool LCD. Several local earth homes are zero carbon LCD also. My home performs 6/6 Stars in NABERS actual performance tool.

3. The short history of Energy Efficiency Policy in Australia – a modern tragedy

In the 1980s the Australian government introduced a voluntary Five Star Design Rating. It was supported and promoted by Federal, State and Local governments. It suggested Glass, Mass and Insulation could be used with Passive Solar Design to achieve; "high efficiency through excellence in design and construction". Some people embraced it. This advice shaped my PSD mudbrick home and my career. It helped every one of my buildings to achieve zero carbon thermal comfort. To provide adaptive comfort without sacrificing health or safety, whilst containing cost and LCD.

Industry ignored the opportunity so by early 2000 the government was forced to act on global concerns regarding GHG emissions. It needed regulation to force a change towards reducing GHG Emissions in buildings. The aim was worthy, though I believe, the wording of the new proposed Energy Efficiency Provisions set Australian energy efficiency in the wrong direction (Excerpt 1).

> Part 2.6 Energy Efficiency - Original wording for Building Code of Australia
>
> "The Objective of this Part is to reduce greenhouse gas emissions by efficiently using energy."
>
> The Functional statement reads,
>
> **"To reduce greenhouse gas emissions, a building, including its services, is to be capable of efficiently using energy"**

Excerpt 1. RD RIS 2001-2 Proposed introduction of Energy Efficiency Provisions

My submission to the Australian Greenhouse Office in 2001 questioned the wording and predicted failure in reducing GHG emissions as effectively as possible. Imagine if the wording of Part 2.6 somehow required buildings to be designed to capture store and release naturally occurring conditions to perhaps negate the need for space heating and cooling. Imagine if a two-tiered approach was initiated to assess naturally conditioned and air-conditioned buildings differently. This is what we still need.

EBAA has made countless submissions since the introduction of Residential Energy Performance Assessment Tools which became NatHERS. On EBAA's behalf I have visited state energy departments in WA and NSW, written submissions to investigations of the Scheme and submissions to proposed changes in the NCC. We have liaised and visited the advisors to Energy ministers and NatHERS Administrators, The Head of the Residential Team in the Department of Environment and Energy and leading thermal modelling academics. I have also raised the problems regarding Australia's Energy Efficiency Policy at Earth Building Conferences and in online magazine articles.

We called an industry summit in 2017 and invited every government entity and politician responsible. Dong Chen (CSIRO), to his credit, was the only attendee. I recently participated as a stakeholder in the National Energy Productivity Plan (NEPP), Trajectory towards low energy homes for 2030. Last year I presented at the CSIRO's Australian Residential Energy Rating conference.

Regulation is being prepared for the step up to 2030 targets where most operational energies in buildings will be required to be low energy and low carbon. This broader view of energy efficiency is welcome though we are concerned about airtightness being introduced into the NCC and higher star ratings in NatHERS. If NatHERS moves to 7-Star without being able to assess naturally ventilated and conditioned buildings fairly things could become impossible.

The great irony and tragedy is that buildings that have completely negated the need for RCAC can not be modelled and assessed fairly and the huge advantage of this attribute goes unrewarded when it so relevant and capable in addressing GHG emission reductions more effectively and immediately without the negatives. We can achieve so much more though we are disqualified at the first hurdle.

A building that is thermally comfortable without needing energy may not meet the objectives through not being able to “efficiently use energy”. As silly as it seems this happens in reality. NatHERS can model in Free Running Mode and Regulation Mode, though only Regulation Mode can be used for rating purposes. Regulation Mode is designed to assess “thermal shell” efficiency. Buildings can have excellent thermal performance and very poor “thermal shell” efficiency if modelled and assessed with the wrong criteria. Regulation mode is not designed to model and assess naturally conditioned and ventilated buildings due to parameters in the Protocol that governs the CHENATH engine. If you ask the wrong questions of a powerful simulation tool you will get the wrong answers.

It is frustrating when the government’s solution is continuing failure and missed opportunity when passive low energy building is disallowed through an inability to recognise its greater advantages in the regulatory process.

4. Yet to be achieved in NCC, NatHERS, Your Home Technical Manual – viva la resistance

The objectives of the Energy Efficiency Provisions are relatively unchanged from 2003. Excerpt 2. from our submission to proposed changes for 2019 is included. We recommend the NCC moves the focus towards highlighting a clear hierarchy of best practice before adequate practice. The focus has been on insulating and sealing the building envelope rather than advocating appropriate climate responsive design and this is the missed opportunity of the Energy Efficiency Provisions to date. If regulated, NatHERS would need to respond with a suitable assessment of thermal comfort performance of naturally ventilated/conditioned buildings.

NCC Volume(s): ☐ One ☒ Two ☐ Three

Clause/Figure/Table: F2.6

Recommended change to draft:

FUNCTIONAL STATEMENTS

F2.6

To reduce greenhouse gas emissions, to the degree necessary—

(a) a building should be designed and constructed to negate or minimise the need for heating, cooling, lighting and mechanical ventilation; or

(a) **(b)** a building, including its domestic services, is to be capable of efficiently using energy; and

(b) **(c)** a building's domestic services for heating are to obtain their energy from—

(i) a carbon neutral energy source; or

~~(i)~~ **(ii)** a low greenhouse gas intensity source; or

~~(ii)~~ **(iii)** an on-site renewable energy source; or

~~(iii)~~ **(iv)** another process as reclaimed energy.

Explanatory information:

1. Carbon neutral energy sources include fire wood, wood pellets, other biomass and biogas.

~~1.~~ 2. The greenhouse gas intensity of energy sources vary. For example, natural gas has a low greenhouse gas intensity compared with electricity generated from coal.

~~2.~~ 3. For the purposes of F2.6, the renewable energy source must be on-site

Comment/reason for change:

Reason for change
In order to move in the direction of the government's trajectory for zero carbon homes it is essential that the focus moves towards highlighting a clear hierarchy of best practice before adequate practice. The focus has been on insulating and sealing the building envelope rather than advocating appropriate climate responsive design and this is the missed opportunity of the Energy Efficiency Provision to date. Public education should start within the NCC.

Excerpt 2. EBAA submission to NCC Draft Changes 2019 – Part 2.6

Until it is recognised that buildings can negate the need for heating and/or cooling through design for climate and this is best practice, everyone from regulators and politicians to clients will continue to believe energy efficiency is simply about "thermal shell" efficiency. To date regulation around energy efficiency in Australian buildings is "the tail wagging the dog". The mainstream building industry is predominately light-weight prefabricated construction, mostly timber framed and clad with a single skin of fired-clay brick and designed without regard for climate. The majority of new homes are being fitted with RCAC. To make an air conditioned, effectively lightweight, building more energy efficient, the government and industry agreed on a course of action. All that could be done was to introduce insulation and sealing.

NatHERS Regulation Mode was designed to model how well buildings "efficiently use energy". A number of modelling parameters such as the unusual thermostat set points, out dated climate files and Star bands are more suited to buildings that are easy to heat and difficult to cool. It uses a simple ventilation logic that may not optimise performance in naturally conditioned buildings. The climate files are averaged to remove anomalies like heat waves and cold snaps. The ESKY paradigm is further favoured by not modelling with min ACH, rather it uses assumed air leakage. Blower door testing for verification of airtightness is a proposed change to the NCC this year. We are concerned that dangerously airtight buildings may improve efficiency though create even worse issues concerning health and safety. The NCC needs to quote minimum healthy ACH and mandate inclusion of MVHR for buildings with airtightness beyond healthy air leakage. Provisions around health and amenity and ventilation standards have been continually sacrificed for energy efficiency.

5. NatHERS Star bands - not for musical legends more for BAU thermal laggards
Star bands are energy allowances per climate used for rating purposes. Why is 6-Star performance awarded to buildings in Darwin with predicted 349MJ/m2/year energy use when in Hobart 6-Star means 155MJ/m2/year and in my climate, 6-Star energy allowance is 81MJ/m2/year? This counters my thinking around passive low energy building and sustainable best practice. Resolve the challenge with appropriate climate design principles, provide adaptive comfort as effectively as possible and meet the global imperative using the least possible GHG emissions. Avoid the need for RCAC if possible. Avoid the need for heating or use the lowest carbon intensive solution.

The Star band approach acknowledges that inside an adequate "thermal shell" more energy is required for RCAC to deal with Darwin's climate. Isn't it giving an inappropriate design paradigm a larger licence to pollute and an excuse to exist in that climate? Maybe the building is still "efficiently using energy" if it is doing the best it can, within the context of the modern paradigm? It is certainly a very poor outcome in terms of GHG emissions especially in Darwin where it will be consuming 349MJ/m2/year of cooling energy supplied by gas-powered generators. It is not best practice when 1-Star tropical homes can provide comfort without energy.

In my climate a 6-Star project home will consume 81MJ/M2/year - roughly equal energy for heating and cooling with RCAC. An earth home would have no cooling load and the heating could be met through design or through burning 1T carbon neutral biofuel (hardwood). A pellet heater is a cleaner alternative for towns. The scheme doesn't consider holistic best practice so is failing to achieve zero carbon performance easily.

Not everyone has been happy with NatHERS. Thermal modelling academics have been critical since the beginning. Terence Williamson believes thermal modelling is a useful tool for optimising design though it should not be used as a regulatory tool. Some early software problems have been resolved though how effectively has NatHERS been reducing GHG emissions? The Board of the Australian Building Sustainability Assessors (ABSA) split over the efficacy of NatHERS. The NCC and NatHERS have been increasing stringency – better insulation, better sealing and higher Star bands. The redress to continuing failure has been to increase stringency rather than questioning the paradigm. Occupants behaviour and poor building practice are the usual scapegoats when actual performance falls short of predicted performance.

The CSIRO conducted the only evaluation of NatHERS comparing the actual and predicted performance of lower rated homes with 5-Star homes in Brisbane, Melbourne and

Adelaide. Heating energy was found to have reduced in higher rated homes though the report explained this may have been due to simpler floor plans and more efficient appliances in newer homes. Although, despite the simpler plans and efficient appliances, actual cooling energy was greater in higher rated homes in all three cities and cooling loads were higher than predicted in all three cities. Although 5-Star was a failure we moved to 6-Star and 7-Star is proposed. Regulatory Impact Statements concentrate too heavily on cost of meeting stringency verses payback periods and predicted GHG emission reductions and not on impacts on health, safety and energy supply etc.

6. Thermostat set points, the 2.5C leeway – PMV or Adaptive Comfort?

Are thermostat set points relevant to naturally conditioned buildings without thermostats? NatHERS uses PMV like heating set points and Adaptive Comfort like cooling set points for modelling conditioned buildings. Then there is a 2.5C leeway on top of the cooling set point. This advantages modern conditioned Eskies that are easy to heat and difficult to cool. It may be why NatHERS is under predicting cooling energy in conditioned buildings. In my climate 24.5C is the cooling set point though NatHERS doesn't accrue cooling loads until 24.5+2.5 = 28C. I believe someone with RCAC in a modern home will start conditioning at lower temperatures. In my climate NatHERS will accrue heating loads to the living area of a naturally conditioned home at <20C. This may be true of a conditioned home however the point at which we feel the need to light a fire is 16.5C and more in line with Comfort Clouds. Surely when modelling conditioned buildings, PMV applies to both set points? Only in naturally conditioned buildings do we find more relaxed Adaptive Comfort expectations. Assessment needs to be measuring thermal performance based on hours of discomfort related to time of day, space within the building and prevailing weather conditions.

7. Australian's love eskies - what could possibly go wrong?

Deaths in heatwaves have become the biggest killer in Australia, and in this context we hear from the NSW Energy Minister that generation and infrastructure will never be able to meet peak load demand in heat waves. The impact of energy efficiency measures to date are bad to potentially catastrophic including the following: Overheating in modern thermal shell homes dependent on air conditioners for cooling; recorded deaths and hospitalisations from carbon monoxide poisoning in well-sealed buildings; ignition of bushfires and more deaths and destruction as a direct result of failure in "poles and wires" due to the peak load demand of RCAC during heat waves; spiralling energy infrastructure costs (every time a $1,400 RCAC is installed, the cost to electrical infrastructure is $7,500); loss of energy security, discomfort, hospitalisation and deaths during heatwaves; increased blackouts from load-shedding activities and failure in most Australian capital cities and in regional areas; and shut down of high electricity use industries to power RCACs; the long-term health, productivity and safety impacts of sealing buildings for efficiency; electricity costs have also risen due to peak load and emergency generation.

A debate exists between those defending coal-fired power stations that are being phased out through age, reliability and economics and those proposing renewables. The failure of the electrical system and ever increasing costs of power has been blamed on the move towards renewables. Politics! Power generation and distribution are almost fully privatised and there is an economic pull and an ecological push to renewables. The problem is peak load demand. The cause is reliance on RCAC for cooling. Surely the best solution is to minimise peak demand through time-shifting demand and negating the need for RCAC? Mass achieves this.

The greenest Watt is the one that does not need to be generated. The cheapest Watt is the one you don't need to buy. The safest Watt is the one you don't need, in a heatwave or bushfire, when your life depends on it. The impact of policy has been far worse than failing to reduce GHG emissions.

8. Watts that - the "thermal shell" has an ACHilles Heel?
Peak load demand can be avoided with the alternative energy efficiency paradigm – passive low energy buildings. The modern "esky" energy efficiency paradigm is supported by industry, government legislation, thermal assessment and advice. "Eskies" store nothing but air conditioned according to a thermostat. An esky in the sun is useless without ice. It becomes overheated easily so is designed to resist flow of heat through solid surfaces and reflect it from translucent surfaces. The "thermal shell" of a home is a weakened esky because it has windows and doors and people inside who need fresh air.

Healthy air changes per hour or ACH are the ACHilles Heel of the lightweight, well-insulated, well-sealed paradigm. The inconvenient truth. Modelling with assumed air leakage rather than assured min healthy air changes, is cheating - a bit like "VW Diesel-gate".

Comfort and efficiency is lost with infiltration in modern thermally lightweight homes. If 1-2 ACH or good healthy recommended air changes for homes were mandated such buildings would be overwhelmed very quickly by external conditions and energy efficiency would be impacted by 40% according to a source inside NatHERS. Without minimum ACH there are serious long-term health implications for occupants of modern buildings. What about safety in a heat wave or bushfire? There is no buffering, no store, no refuge in a lightweight building. A typical modern building will fail more slowly if unhealthily-airtight and quickly when healthy air changes are allowed. Modern lightweight buildings are easily unsettled thermally with solar gain, open windows, heaters and coolers. They may need to be heated and cooled in the same day and this is the absolute opposite of how mass buildings perform. Lack of mass creates energy waste and discomfort.

9. Mass-linked ventilation - safe, adaptive comfort and fresh air – simultaneously
Due to inappropriate ventilation logic used in simulation the predictions about cooling loads are pessimistic though it is still clear heavyweight buildings can avoid RCAC. In reality predicted cooling loads are often nil. If thermal mass was added to effective thermal lightweight buildings it would help in two ways. Building would have capacity to store coolth both natural conditions and from RCAC operating by day when the PVs are working best and before the usual peak load demand as working families return home. At this time RCAC peak load is also impacted by loss of solar production. Thermal mass is as valid as new battery technology and is as valuable as newer forms of energy storage in the transition to renewable energy. The NCC should define and promote thermal mass.

I know from living in my home for 27 years that it provides a good level of adaptive comfort all year with heating in winter. It copes extremely well in summer and even better than the excellent cooling energy results NatHERS gives it (11.3MJ/m2/year). A typical project home in Nowra with 6-Star thermal efficiency may have 4 times this predicted cooling load. In reality I don't have a cooling load because I don't need a RCAC.

My home usually maintains 21C to 24C during summer. In a normal three-day heatwave where temperatures can be into the 40s by day and less often in the 20sC by night my home maintains absolute comfort until the third day where it and has reached as high as 28C before dropping with a cool change.

It stores natural external conditions like coolth of night and warmth of day. It stores the warmth of the heater and moderates the home against overheating. It doesn't lose this heat it stores excess heating energy for later when the fire is out. Mass conditions the incoming air through a mass-air heat exchange process Gary Baverstock calls mass-linked ventilation which balances temperature as well as humidity.

The massive earth walls provide the adaptive comfort that is totally related to the current conditions and those of the past few days giving us the adaptive comfort Fergus Nicol can describe in an equation or a Nicol graph. The massive single skinned walls are responding to the external conditions not opposing them like a modern home does using its "thermal shell". We enjoy adaptive comfort and fresh air simultaneously. Unlike the modern ESKY we can enjoy comfort without sacrificing indoor air quality or efficiency.

10. Climate change – we are ready and safe and healthy

I have been studying CSIRO Climate Analogues for an understanding of what to expect of climate in coming years. Basically my cool temperate climate, will become temperate by 2030, subtropical by 2050 and tropical by 2090. This is the maximum consensus view of CSIRO climate scientists. We are absolutely safe in a heat wave, a bushfire or a cold snap without power and the predictable even "bass note" adaptive comfort and "thermal refuge" Sue Roaf talks about is maintained by the thermal mass.

This summer the weather has been unusual, a preview perhaps. We endured prolonged subtropical weather with high humidity and constant heat into the low 30s by day with nights staying unusually warm dropping only briefly to 24C at dawn before rising again. This is unpleasant weather. By day inside averaged around 25-26C during January. I could sleep by night with home fully ventilated and by day I enjoyed total comfort with a desktop fan and minimum ventilation. I could improve "thermal shell" performance and achieve close to current standards with improved roof/ceiling insulation, sealing and double glazing. This would be expensive and I'm reluctant to give up healthy air changes by sealing. I always have windows open slightly so what is the point. I am beyond carbon zero and I would rather improve design performance.

If the CSIRO Climate Change predictions are accurate I would be better to invest in ceiling fans now and eventually increase ventilation with louvre windows to deal with subtropical weather within 30 years. In reality though, I am comfortable all year with natural ventilation and mass-linked natural conditioning. I have always been carbon neutral in heating because I use firewood for heating. It is low-tech, affordable and sustainable and the quantity I use into the future will diminish with climate change.

To model safety in modern buildings, NatHERS climate files need to be up to date not 10-15 years old and not averaged to remove statistical anomalies like heat waves and cold snaps. Recent record breaking spikes are the killers and the ones that need to be modelled. If climate change resilience is important then modelling these heatwaves would be a starting point. Climate change predicts erratic weather and nothing manages erratic weather as well as thermal mass. Modern buildings may be easier to heat though prone to overheating and higher cooling energy use than predicted in NatHERS. Do we have the best policy settings in place to deal with resilience, health, energy management and survivability?

11. We are better than modelled and can still optimise – not so fast!
Earth has excellent hygrothermal performance characteristics that balance humidity levels. France is looking at humidity values for materials. These are well respected though this feature can't be modelled in NatHERS. A range of earth wall densities are used across the world to optimise thermal characteristics ergo thermal performance for climate. It would be possible to comply with "thermal shell" efficiency in colder climates with reduced earth wall density. However, the NatHERS library of materials doesn't include these other values.

NatHERS won't accept internationally established values. EBAA is raising the funds to undertake the thermal research to support inclusion of three new earth wall densities. Earth is not a proprietary product, research should be conducted by the government for common good. The EU has invested Euro 1m in the Cob-Bauge project.

12. A better way can't be assessed – please give us laws, a tool and an appropriate rule
I designed and constructed a passive low energy rammed earth home three years ago in an attempt to achieve thermal comfort with reduced heating and no cooling. It is a holiday home. The brief was that it needed to be comfortable on arrival any time of year. The rural site has good solar access in my cool temperate climate. It is easy to avoid the need for RCAC in this climate by using thermally massive walls throughout, though heating is required and given the long periods of absence, the mass would settle at an average temperature in winter that would not provide immediate comfort. This was the design challenge.

The design response was to add a sunspace to a reasonable passive solar design. I was curious about predicted performance and so had it modelled in NatHERS. The assessor agreed the building would perform well though it couldn't be assessed in NatHERS. Sunspaces, fly roofs, stack ventilation, natural ventilation, mass-linked ventilation and other passive features are difficult to model in NatHERS.

The building works brilliantly using appropriate seasonal ventilation strategy. The design and mass-linked ventilation achieves thermal comfort. The northern (sunny-side) suntrap is essentially a fully glazed narrow verandah-come-hallway/entry that widens slightly in the middle to create a useful sunroom outside the living dining area. The sunspace is built outside the external thermally massive walls. The sunspace can be an extension of the living areas and main bedroom through three sets of large well-sealed sliding doors. In summer, the entire sunspace can be completely ventilated with banks of louvres and high awning windows and so it becomes a semi-enclosed verandah. A small awning window is also left open to release buoyant air upstairs in the stairwell. During winter, the sunroom is closed to capture warmth and the home proper can co-join or remain isolated. In the milder times of the year, an occupant can partly ventilate, or fully ventilate, to warm or cool the home as they wish. It is very simple to operate. Provision was made for hydronic heating in the floor, though it hasn't been connected nor required in the two winters since being occupied.

The building was designed to provide a high level of adaptive comfort through design, though can be backed up with energy produced with the PV array providing potential hydronic heating and cooling if required, the client has been happy with performance for three summers and two winters without the hydronic heat pump system installed. Building compliance with thermal comfort was obtained based on NSW BASIX, a State operated system with a DIY Thermal Comfort Tool. This is not available in other states. If we didn't have NSW BASIX, earth building would be dead in NSW.

I have discussed two examples of buildings that are providing best practice thermal comfort effectively through design though both fail to comply with the national energy efficiency regulations. Australia's regulations are an attempt to mitigate worst practice in lightweight project homes built without regard for climate and fitted with RCAC. It is not regulation designed to promote best practice. It is failing best practice entirely.

Passive low energy buildings need to be measured in terms of adaptive thermal comfort in respect to place and time given prevailing external conditions. Assessment needs to be of thermal design performance not "thermal shell" efficiency, comfort clouds not set points, naturally conditioned outcomes not energy loads, ventilation not infiltration, mass not simply insulation and opportunity and response to external conditions rather than exclusion of it and RCAC reliance. We need a two-tier approach to assessment. One for naturally conditioned ventilated buildings and one for conditioned buildings.

13. How much energy – are we moving forwards or backwards?

I wonder about the small predicted gains that are being achieved in reality against the embodied energy and resource flows going into all the energy hungry expensive technology and specifications of energy efficient buildings. The rammed earth home achieves greater autonomous thermal comfort though the higher specification insulation, double glazed windows, sunspace and hydronic heating has worsened embedded carbon so the eTool LCD rating amounted to a good 61% carbon reduction not a great carbon zero rating. Australia does not target embodied energy/carbon yet though it is wise to check we are not moving backwards. I wonder why we drifted so far from design for climate using traditional low embodied energy materials like earth.

14. Modern buildings - what are the hazards?

RCAC has become the "technological fix" for poor building design. MVHR may extend the life of this paradigm though at what cost? Though RCAC is useful in providing comfort in some situations, dependence on it and encouragement of it has created huge problems to do with energy security, cost and transition to renewables as well as health, safety and the environment, especially in hot climates. Here is a look at the risks associated with modern buildings I came across recently. It looks at the risks associated with modern buildings according to existing, current and future hazards (Figure 2.)

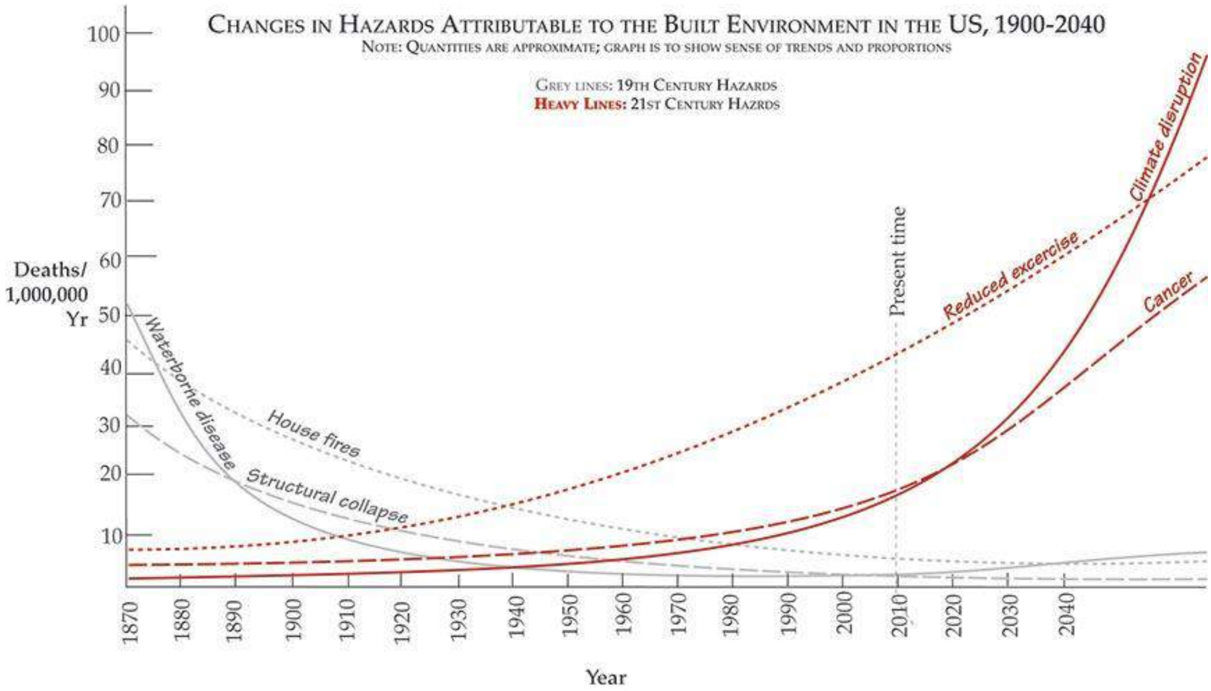

Figure 2. Hazards in the Built Environment – Art Ludwig

14. The sustainable solution – clear as mud

On January 17th, 2012 - The Smithsonian Institute celebrated 40 years as the World's largest Museum and Research Centre, with 40 predictions for the next 40 years. The number one thing you need to know about the next 40 years, according to the Smithsonian is: "Sophisticated Buildings Will Be Made of Mud".

Maybe when earth building is used with passive low energy design we can begin to understand how 7.7 billion people could possibly coexist harmoniously and achieve some form of equitable sustainable future with the resources and energy of one planet.

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Structural Design of a Movable Modular Shelter for Extreme Wind Conditions: A Study in Collins Bay, Antarctica.

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Abstract: This paper describes structural aspects of a movable modular shelter, designed to withstand wind gusts of 200km/h in extreme cold conditions. The shelter was conceived by a mixed team of Architects and Engineers and will be used as accommodation by researchers carrying out field work in the Antarctic Peninsula. Preliminary results confirm its viability and ease of use. Considerations are made on contextual factors, such as local wind characteristics, ease of use, and structural design issues.

Keywords: Structural Design, Extreme Wind Conditions, Modular Shelter.

Introduction

The objective of the Polar Lodge Project was to design and build a sustainable, low-impact, optimized, modular lodge, to facilitate scientific studies in the Antarctic. The Design of the shelter was developed throughout 2018 by the Polar Lodge project team - a mixed team of Architects and Engineers from the Higher Technical Institute (University of Lisbon), Heriot-Watt University (UK) and the University of Bahrain (Kingdom of Bahrain).

Figure 1. The Structure of the Polar Lodge shelter, February 2019, Collins Bay, Antarctica.

An yurt-like tent was produced by July 2018, using an innovative timber and bio-composite structure and an experimental triple-skinned, lightweight envelope which combined with the structure is designed to withstand extreme high winds, and extreme cold.

This new Module, called Polar Lodge 2 (PL2), follows on from a 2016 experimental prototype, being in fact a traditional Mongolian yurt, that collapsed in 200km/h winds in the Antarctic (Guedes, 2016). In 2018 the yurt structure, form, and building materials were overall upgraded, under the supervision of Prof. Sue Roaf (Heriot-Watt University), in response to the severe weather conditions found in Antarctica during 2016.

PL2 presents a new environmental and sustainable approach to creating resilient structures for the extreme cold, combining ancient tent design with leading edge modern technologies and materials. The major drivers for the design not only included the original specification that the structure should be modular; easy to transport and fast to assemble by a small team; resistant to high winds; have minimum impact on the ecosystem; and be comfortable but the associated performance specifications were upgraded in light of experience.

1. Local Wind Characteristics

Antarctica is the coldest continent on Earth, with minimal recorded temperatures ranging from −93.2 °C to −98 °C (Vizcarra, 2018). This Continent also holds the record of the strongest winds: winds can easily reach gale force, between 100 and 200 km/h, and in places where the wind flows through narrow valleys, it can attain a speed of 90 m/s (325 km/h). There are on average 11.6 days per month when the wind exceeds 100 km/h (Bromwich, 1989).

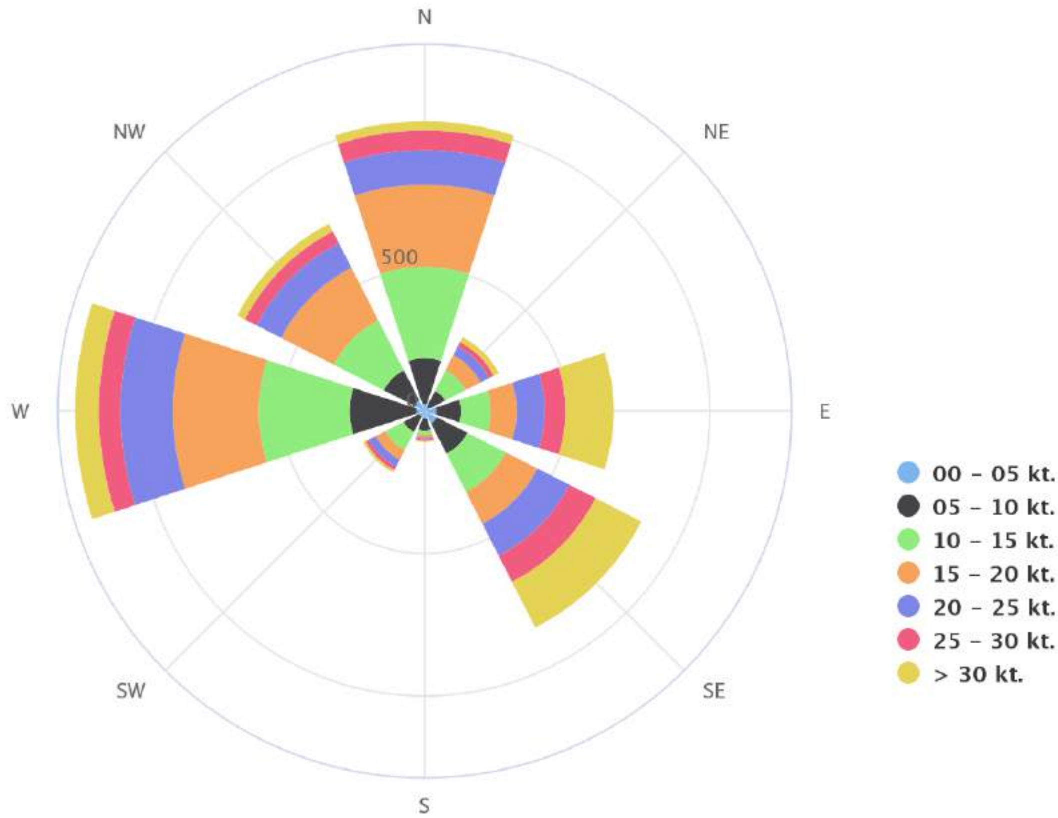

Figure 2. Wind Rose for Bellinghausen, showing the Monthly Mean values for predominant wind directions and intensity (source: Chilean Air Force Airport at King George Island) .

The continent has an EF Köppen classification of ice-cap climate, with very cold, and generally extremely dry weather (it is technically a desert, averaging 166 mm of precipitation per year). Temperatures in inland Antarctica rarely rise to 0°C even in summer.

With the exception of a few seaside areas, snow rarely melts, and, after being compressed, forms the glaciers. The continent is rarely penetrated by weather fronts, due to the effect of the katabatic winds caused by cold air sweeping down from the central plateau toward the ocean, particularly in spring and autumn.

Figures 2 and 3 show the mean values for wind speeds in different stations in the Antarctic. Figure 4 shows the results of a study measuring the frequency of storm force winds, over 180Km/h (Turner et al, 2009).

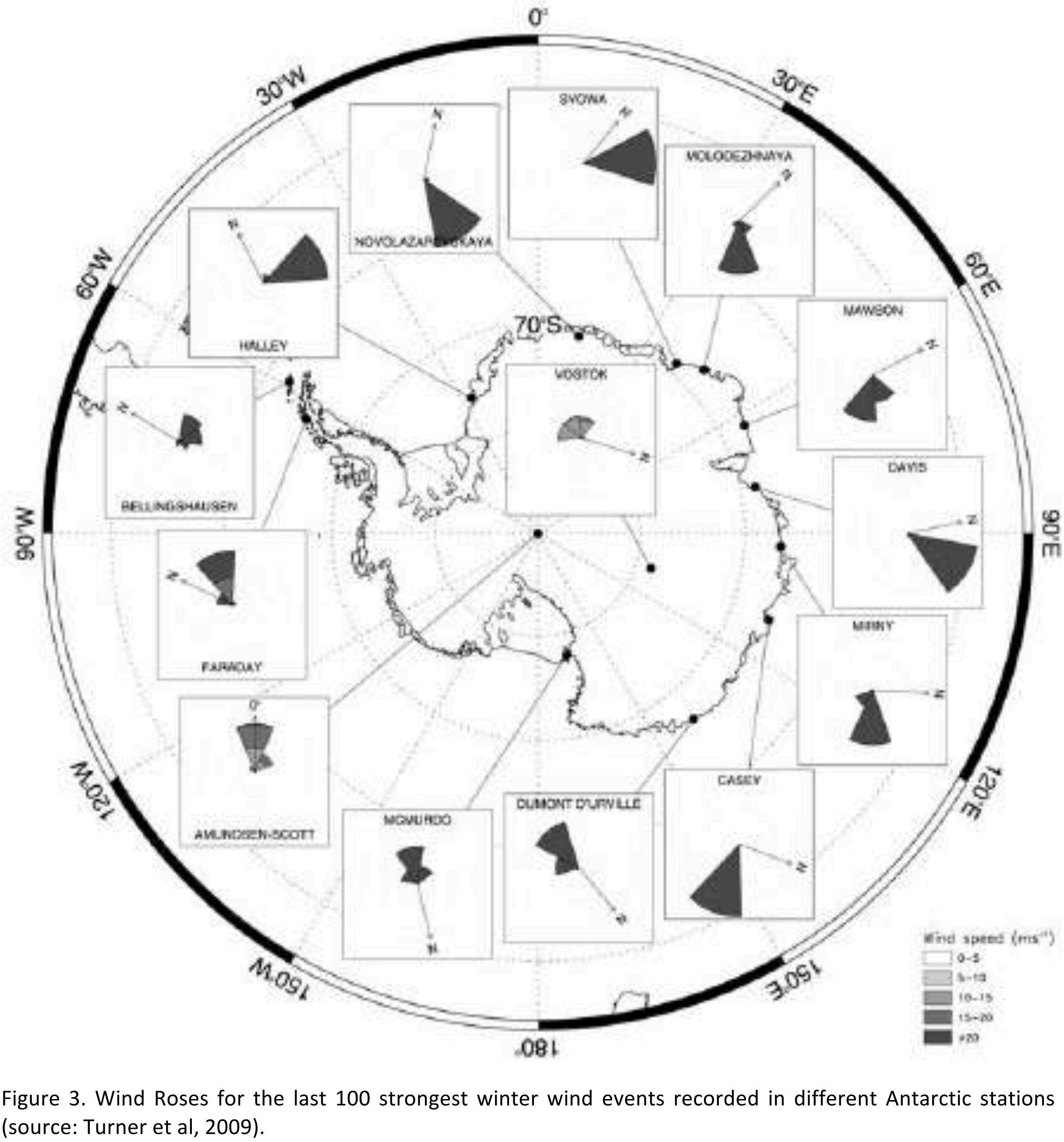

Figure 3. Wind Roses for the last 100 strongest winter wind events recorded in different Antarctic stations (source: Turner et al, 2009).

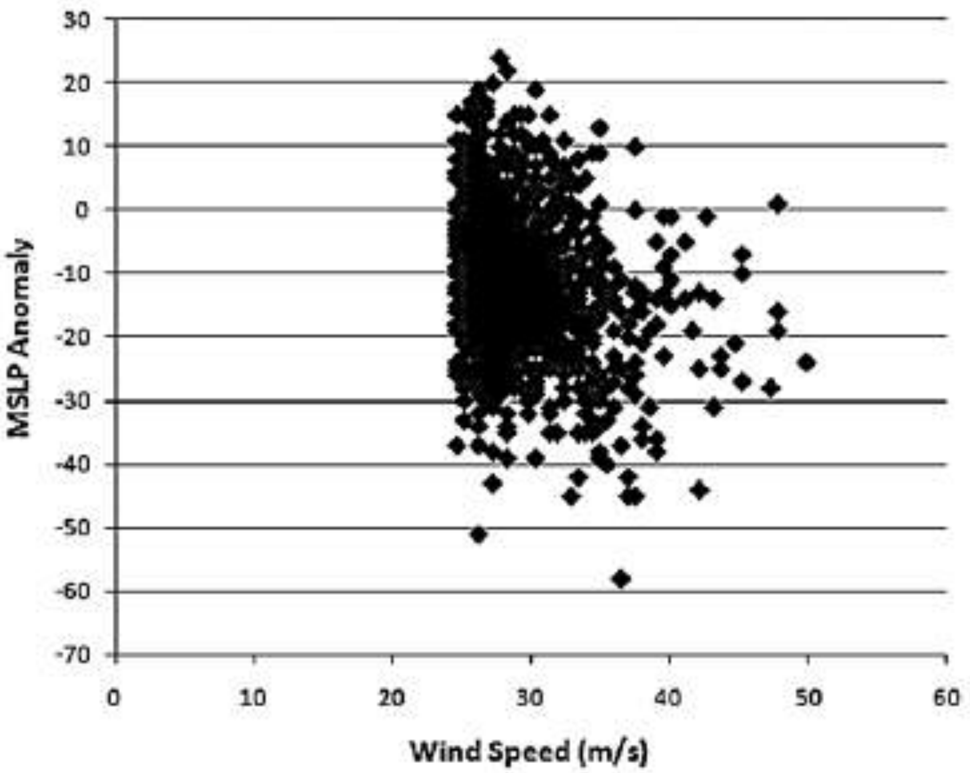

Figure 4. Scatter diagram of winter season wind speeds (m/s) of storm force or above measured at Mawson station in 2008 (source: Turner et al, 2009).

The Lodge was placed in Collins Bay, below the Bellinghausen Dome. Although Bellinhausen is not amongst the stations with the highest frequency of storm force winds (cf. figure 3), storm force winds of over 200km/h occur during winter in this location, making it adequate for this study.

2. Design Considerations

PL2 iteratively developed from the traditional yurt form erected in 2016 and was subject to a number of studies before the field trip to erect it, and considerable modification as it was being raised. Modifications included:

2.1. Structural Resistance

The structure of the Yurt-like lodge was optimised using appropriate software. Through a series of iterations, several components were redesigned in order to increase the overall robustness of the model, namely:

a) The timber ceiling ring, which was made smaller in diameter and thicker, letting the beams go across it by 3 to 5 cm. This is the most sensitive element of the structure: after an analysis of the previous model it was found that it collapsed due to the lack of resistance of the ring, which broke under extreme wind pressure, consequently bringing down the structure.
b) The overall thickness of all beams and trellises.
c) All the joints' attachments' were reinforced (ceiling ring to beams; beams to trellises), including the door's attachments.

The model comprises five parts: a circular trellis, a doorframe, a roof, a top ring and two central columns. The top of the Lodge was fixed in order to, in a simplified manner, model the steel cables that were attached at such location.

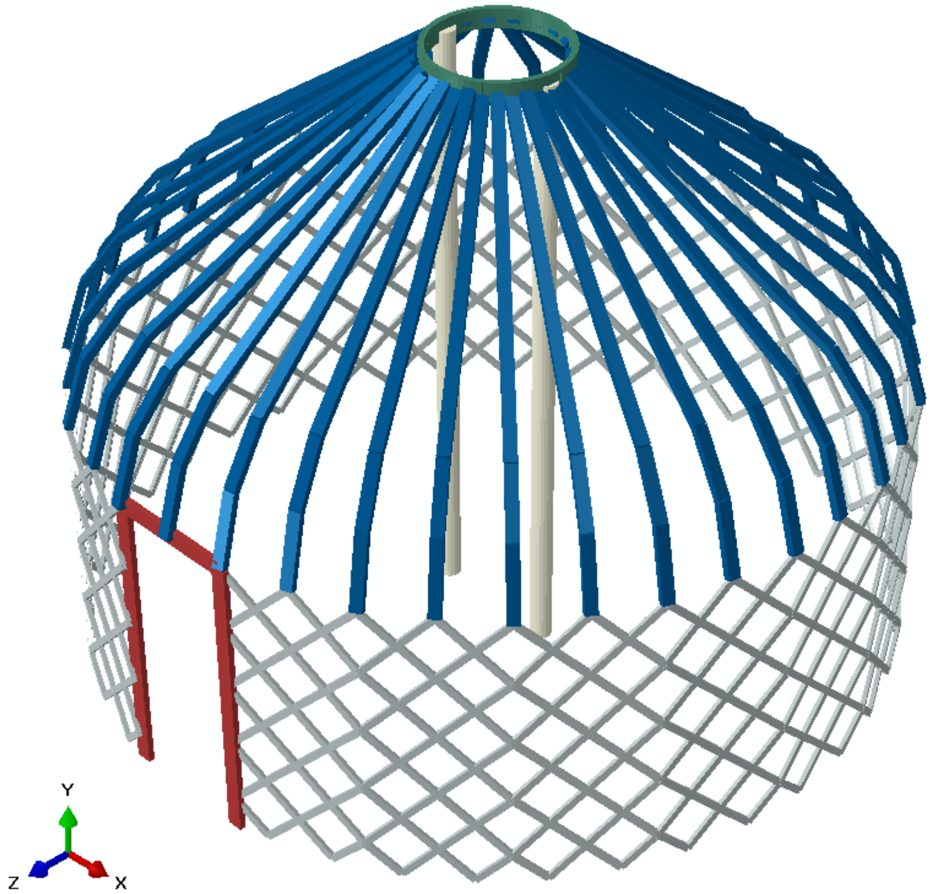

Figure 5. Overview of the numerical model

Figure 5 shows the final built result. Figures 6 to 8 show the behaviour of the final solution under different wind speeds. As the Lodge location is in a particularly wind spot, as the dominant wind is funnelled through a valley of rocks, for safety's sake simulations using a 1.5mx1.5m rock wall facing the dominant wind were also carried out. Bags to fill with rocks were brought to the site, and this wall was put up during one morning (figure 9).

The wind load was applied as equivalent forces, calculated according to EN 1991-1-4 distributed along the negative axis Z direction on the beams of the exposed side. Three wind speed values were considered: 100, 140 and 200 km/h. For these, two situations were modelled, without and with the rock wall serving as a wind breaker. The latter was considered by modeling only the forces due to suctions that arise on the faces that are not exposed to wind, but assumed redistributed by the canvas to the beams of the exposed faces.

In Figure 6 the longitudinal stresses on the Lodge beams respectively, with and without the rock wall, are shown for a wind speed of 100 km/h. The tensile and compressive maximum stresses were limited to 12 (tensile) and 20 MPa (compressive), respectively, in the color mapping. These are typical values for a good construction wood. If the stresses surpass these values, red (tensile) and blue (compressive) colors are shown in the model.

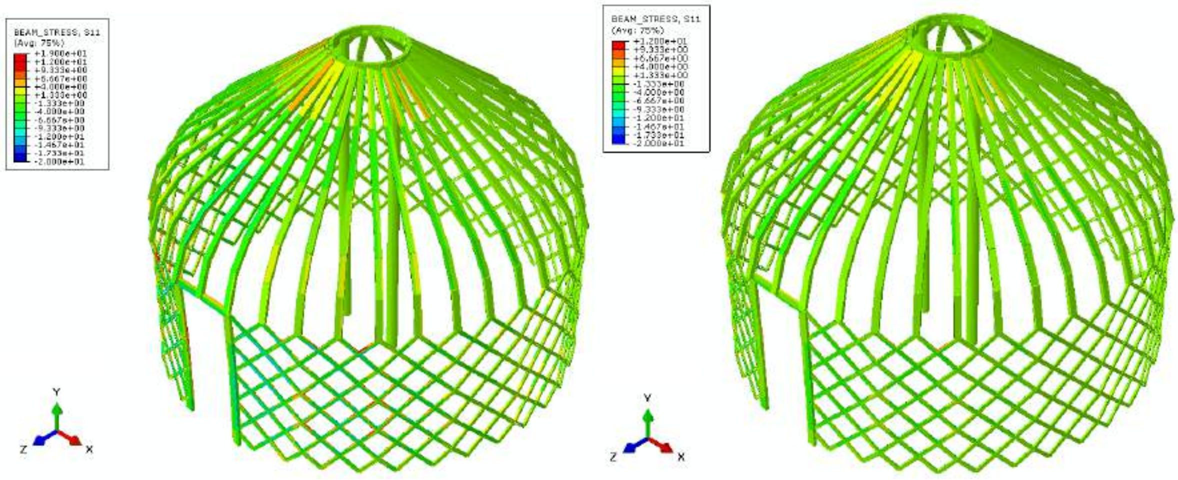

Figure 6. Longitudinal stresses on the Lodge beams - wind speed of 100 km/h. Left: without rock wall; right: with rock wall.

In Figure 7 the longitudinal stresses on the Lodge beams for a wind speed of 140 km/h, which was actually measured on site on the 24th February, and respectively, not considering and considering the rock wall are shown.

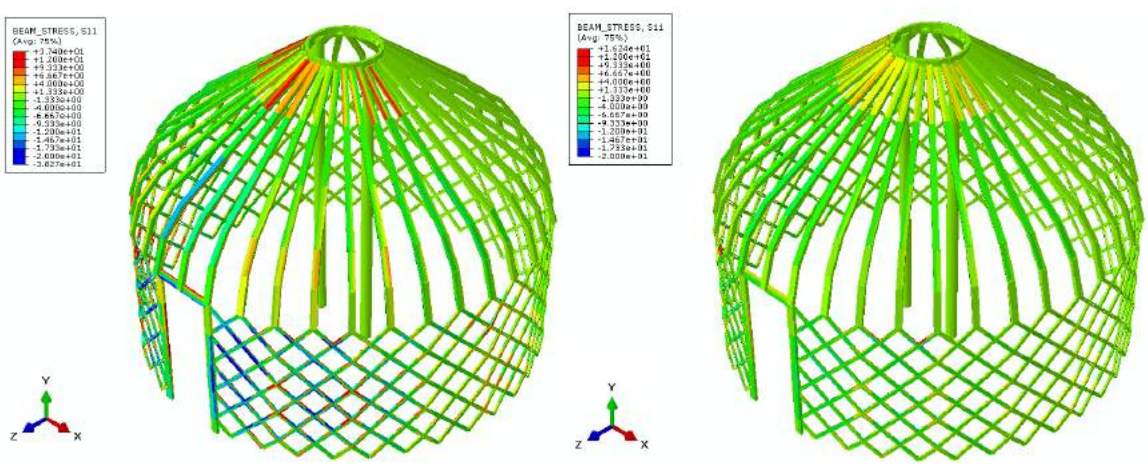

Figure 7. Longitudinal stresses on the Lodge beams - wind speed of 140 km/h, measured on site on the 24th February. Left: without rock wall; right: with rock wall.

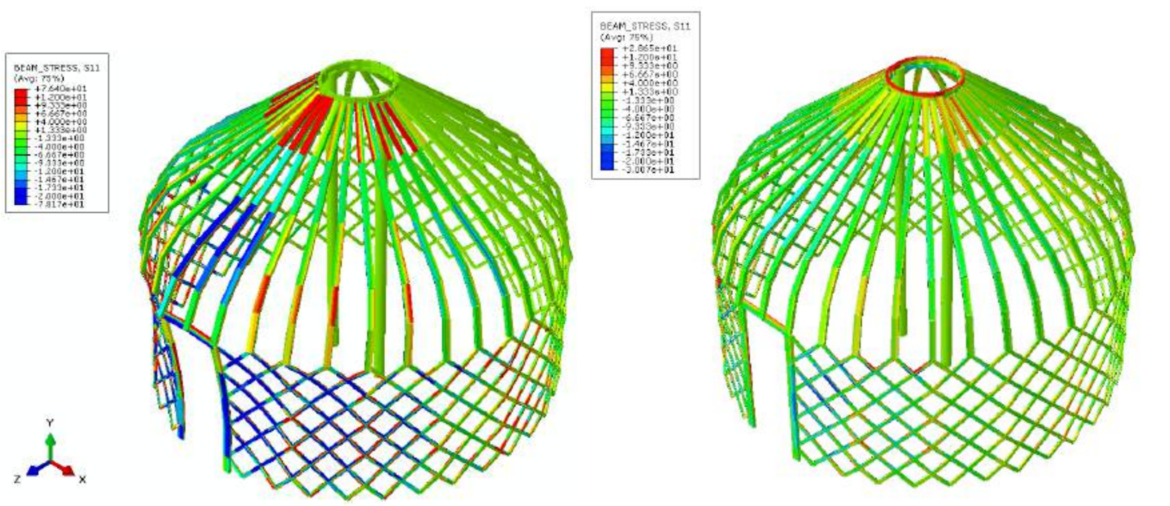

Figure 8. Longitudinal stresses on the Lodge beams - wind speed of 200 km/h. Left: without rock wall; right: with rock wall.

In Figure 8 the longitudinal stress field on the beams for a wind speed of 200 km/h and respectively, considering and not considering the rock wall are shown.

In all the scenarios considered, the main stress concentrations are, as expected, in the exposed faces of the trellis and of the roof. Regarding the former, an increase in the cross section area will increase the resistance of the Lodge trellis and the maximum values of stresses can be reduced bellow the allowable limits. Considering the latter, the placement of intermediate beams/supports connecting the mid-span of the roof beams and the vertical central columns are deemed to be able to reduce the magnitude of the stresses to about 25% of the actual value.

From the previous figures it can be concluded that the Lodge can resist wind speeds of up to circa 140 km/h, as it did in the field. However, for winds up to 200km/h this may only be achieved due to the wind breaker materialized as a rock wall in the exposed face. Bags to fill with rocks were brought to the site, and this wall was put up during one morning. Figure 9 shows the adjacent rock wall.

Figure 9. The adjacent rock wall (covered in black canvas)

Figure 10. The final result, including the 10+10 ties to the ground.

To ensure further stability, 10 ties were also placed vertically from the roof to the ground, and another 10 ties were placed over these, forming a 45º angle with the ground. Figure 10 shows the final result.

2.2. Building Materials

In order to establish future performance comparisons with the previous prototype, wood (Ash wood) was chosen as the material for the structure. Budget considerations also weighed in this decision. The optimised timber structure was made by *Yurtmaker* in Telford.

A survey was also carried out in the UK in early 2018 by Prof. Sue Roaf, in order to identify the best suitable envelope materials, in terms of durability, weather endurance, and thermal insulation capabilities.

The final decision felt upon two innovative materials for the skins: 1) a space blanket type multi-layer double skin from ORVEC of Hull, and 2) re-used Dyneema racing yacht sails for the outer coat from *Northsails* in Palma de Mallorca, Spain. The tent cloths were manufactured by the master tent makers at *Sheerspeed* in Honiton.

2.3. Ease of use

The portability and ease of assembly' objectives were accomplished: The whole Lodge fitted in a single Zodiac boat, and was transported from Escudero to a remote location in Collins Bay, within Collins glacier. It was then mounted in approximately 2 hours. The stone wall took approximately further two hours to be put up and wrapped.

3. Further Work

The lodge will be used until the end of Summer (late March) and again from November 2019 till March 2020. Feedback from users, including questionnaires, will be collected during these periods, and posted online (at extremelodge.com). This will allow a more thorough assessment of the Lodge, leading to its optimisation.

Further issues concerning the performance of the materials, structure and overall comfort will also be assessed in the next campaign.

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Investigating the performance of a ventilated wall system combined with evaporative cooling in an educational building in hot dry climate

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Abstract: The global demand for energy efficient cooling strategies in non-domestic buildings is increasing, especially within African, Asian and Middle-Eastern regions. School buildings often have poor thermal comfort and poor indoor air quality (IAQ), which affect the pupils' health, education and productivity. In this paper the thermal performance of naturally ventilated walls when adding passive cooling to the wall, fabric and looked into passive cooling techniques to enhance thermal comfort and the temperature and ventilation inside the classrooms are investigated. The results demonstrated that the proposed passive cooling, in conjunction with outdoor air, could significantly reduce the temperature and enhance the thermal comfort inside the classrooms. Simulating the system using CFD reveals the system's success in reducing ambient air temperature, achieving thermal comfort, and supplying fresh air. The maximum air temperature decreased from almost 44 °C to around 22 °C under an external shade temperature of 46 °C approximately.

Keywords: Evaporative cooling, Natural ventilation, Building fabric, School Building, Khartoum

1. Introduction

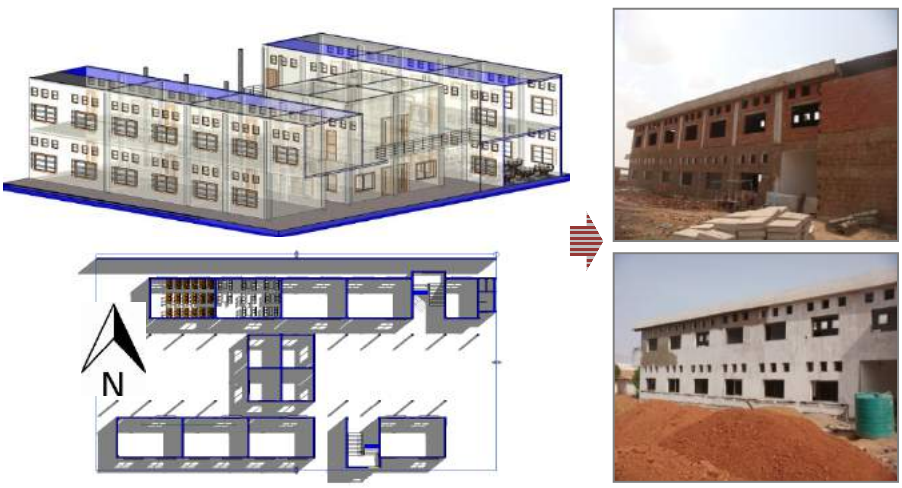
Satisfying its occupants thermally is the main purpose of any building, especially schools. This is due to the obvious influence of thermal comfort conditions on the students' health and productivity(Wyon D, 1979, Kwok AG, 2003). Generally in Sudan, and particularly in Khartoum, factors, such as the local climate of the site, its characteristics, urban planning and density, orientation, architecture design, and ventilation, are usually not given enough thought. This leads to a poor indoor environment, which affects levels of human comfort, health, student productivity and efficiency. Schools buildings are often designed without consideration of the climatic conditions in developing countries like Sudan. For instance, high air temperatures in the range of 37-42 °C were recorded in one Khartoum classroom in the afternoon during summer season. The thermal comfort recommended by the American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) is 22-23 °C, expressed as dry bulb temperature, under a relative humidity of 50% (ASHRAE, 2010).

As it is the interface between the internal and external environment of any building, the envelope requires careful design to achieve energy savings (David W. Bear et al., 2007, Carbonari et al., 2015). This is considered as one of the best available options in retrofitting buildings. This care should be increased for educational buildings because of their specific characteristics that are not limited to the specific nature of their occupants, activities, and occupancy patterns. In this regard, it may worth mentioning that 25% roughly of the students' time is spent inside schools (Calautit & Hughes, 2016). It has been made clear that modifying the school buildings to cope with a hot and harsh climate will not only have an influence on reducing energy consumption, but it will also help to maintain a comfortable indoor condition. Therefore, the pupils will be more satisfied in the classrooms. For example, fluctuation in the temperature will be reduced to a minimum, and they will not need mechanical air conditioning (the government cannot offer such air conditioning (A/C) systems) to achieve thermal comfort. Pupils, in particular, are therefore at risk as they are more vulnerable to poor health than adult. Wyon et al. (1979) stated that increasing the amount of heat ''stress'' can affect the children's mental performance. The paper at hand proposes a wall system as means of passively modifying indoor air temperatures and thus achieving thermal comfort in a school building in a hot dry climate. Computational fluid dynamics (CFD) simulations have been run to examine the behaviour of the cooling wall system in reducing the effect of outside air temperature under different wind velocities in the summer period, utilising weather data for Khartoum. The work concludes that the system was capable of reducing the air temperature by up to 12C°-15 C°. The mechanism of the suggested wall system reduces the air temperature through exploiting its sensible heat as the latent heat required for evaporating the water integrated in the wall system. The cooling effect is achieved by both direct and indirect evaporation. The ability of similar systems to considerably reduce, and sometimes eliminates, the required cooling loads inside buildings has been reposted in previous studies (Carbonari et al. 2015].

2. Methodology

2.1. The site and the selected school

Khartoum city is located at 15.5 °N and 32.6 °E within a hot desert climate (BWh) according to Koppen-Geiger climate classification. For the purpose of this study, a primary school building with H-shape as presented in Figure 1 was selected. The school consists of eight classrooms in addition to administration spaces with an occupation period of around seven hours starting from 7:30 until 3:00. It should be mentioned that the governmental schools in Khartoum depend on natural ventilation as the main passive strategy to modify the internal



Thermal conditions. Considering the unfavourable outer conditions due to high air temperature, it is more efficient to cool the outside air before entering the classrooms.

Using Thermal Analysis Simulation software, a simulation model of the school was developed as presented in Figure 2. Both the climatic conditions of Khartoum city and the local construction system and materials were considered in the developed simulation model. The dry bulb temperature, indoor air temperature, heat conduction, and cooling load of the whole school were obtained. Besides, they were obtained for selected classrooms located on the northern and southern facades of the school in winter and summer seasons.

Figure 1. The real design of the school H shape form and modelled in Revit software

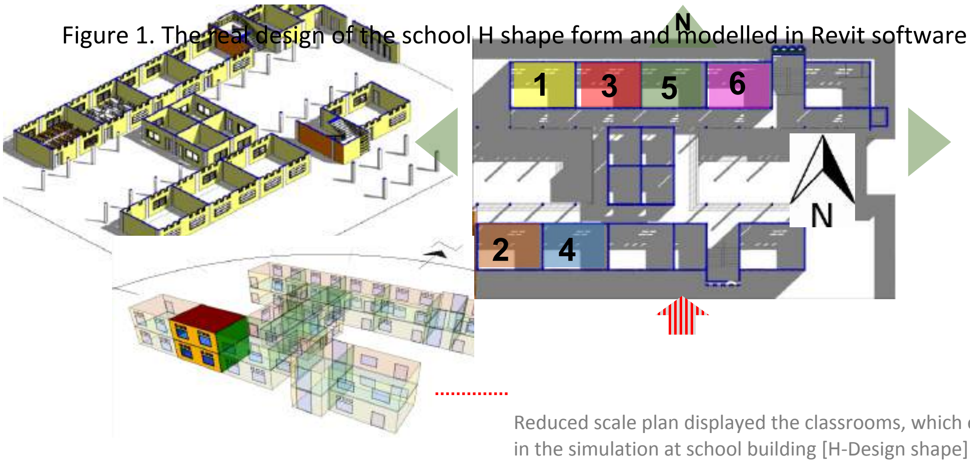
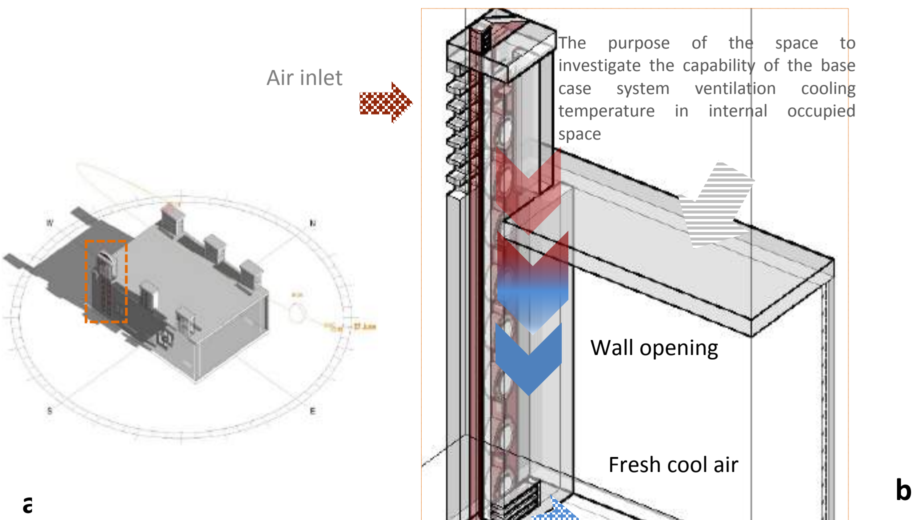


Figure 2. The location of the classrooms in H design shape examined in the TAS simulation

2.2. Description of the suggested wall system

A wall system that depends on evaporative cooling to improve the classrooms' thermal conditions is suggested. As depicted in Figure 3, the suggested design of the wall consists of two layers of brick between which a porous ceramic layer is located. The wall has an overall length of 2.5 m with an extended environmental inlet opening of 1.0 m height and 0.5 m width. This inlet allows outdoor air to enter the wall system where evaporative cooling takes place through contact with the porous ceramic wall. Due to the bouncing influence, the cooled air accumulates at the bottom of the system where it enters the classroom through the outlet opening.



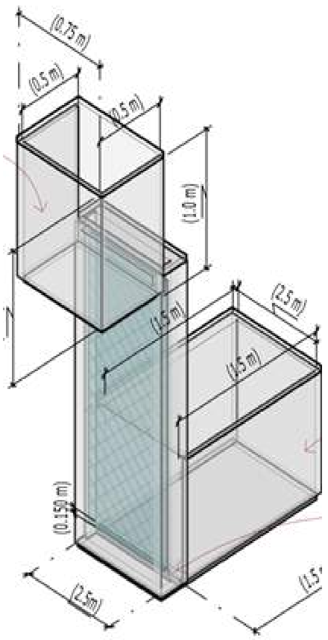


Figure 3. The suggested wall system: (a) schematic geometry, and (b) detailed 3D geometry

2.3. The specifications of the wall system model

With the purpose of investigating the efficiency of the suggested wall system, it was attached to an occupied space of 1.5 m height, 2.5 m width, and 2.5 m depth. Applying the meshing tools of ICEM software, a 3D CFD simulation model was generated with conformal structure mesh of hexahedral cells. The application of the hexahedral mesh ensures a smooth running of the iteration and a considerable reduction in the convergence. The mesh with dimensions of 0.5 cm by 1.0 cm formed the computational grid that was used to calculate the airflow and heat flux within the ventilated cavity. This mesh was applied for the air channels, the passive cooling wall (PCW), the façade's outer layer, the wall's inner space, and the outer classroom. Besides, a 3D simulation model was implemented to determine the flow path and temperature distribution of the natural ventilation in the classroom. Considering the climatic conditions of Khartoum city, the air temperature of the base case was assumed as 36 °C. The investigated air velocities were defined as 0.2 m/s, 0.4 m/s, 0.6 m/s, and 0.8 m/s. As obtained from fluent software, the density, specific heat, and thermal conductivity of the air with 36 °C are displayed in Table 1. It should be mentioned that the porous ceramic wall is considered as the heat flux required by fluent software.

Table 1. Properties of air with 36 °C temperature [citation]

Temperature, [°C]	Density ρ, [kg/m^3]	Specific heat c_p, [kJ/kg K]	Thermal conductivity k, [W/m K]
36	1.127	1.005	0.0271

3. Results and discussion

3.1. Results from Thermal Analysis Simulation

The case study simulation for school building construction (H design) investigates the thermal behaviour of the internal conditions of the classrooms under the climate of Khartoum city. In the simulation, several variables were considered, such as the climate and the construction materials, which had been used in the construction with reference to the local building regulations of Khartoum, and according to the construction system that had been applied.

Under free running conditions, the indoor dry bulb temperature of classrooms (1) and (2) are plotted in Figure 4 and Figure 5 respectively. As observed, the figures display the solar gain, general range of indoor temperatures compared to the external temperatures.

During the school day hours of summer season, the indoor bulb temperatures were in the range of 44.3-53.7 °C, which is higher than that of outdoor by 8 °C approximately. This overheating may be due to the poor thermal performance of the building's envelope besides to the occupants' presence.

Figure 4. Indoor dry bulb temperature of classroom 1 in winter and summer compared with outdoor temperature

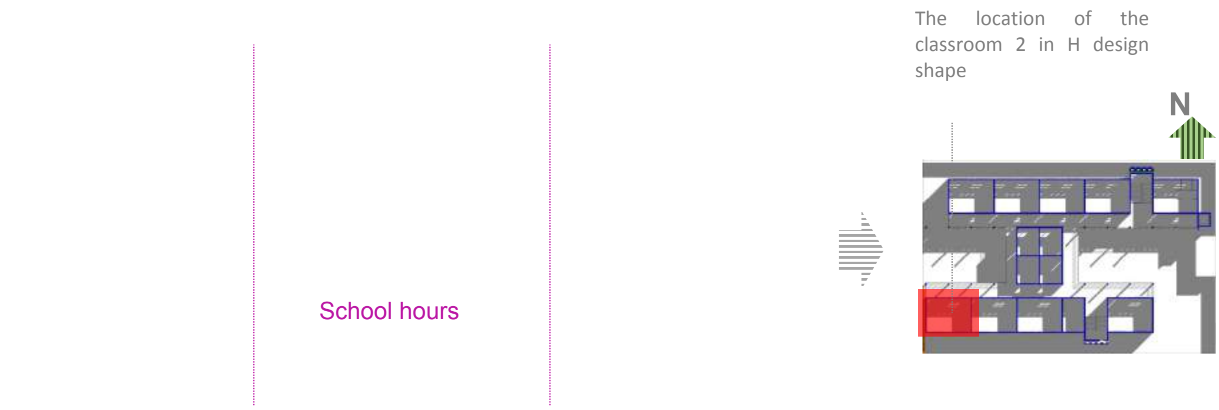


Figure 5. Indoor dry bulb temperature of classroom 2 in winter and summer compared with outdoor

As mentioned earlier, the thermal performance of the school in winter and summer was investigated with special focus on the risk of indoor overheating and the influence of heat conduction, through building envelope, on the required cooling load. For a detailed analysis, classroom (1) that is located on the upper floor at the northern wing of the school was selected. The findings indicated a considerable effect of heat conduction through the roof and the southern wall of classroom (1) in both seasons.

With regard to classroom (1) and classroom (2) in the (H) design shape school, as denoted in the figures above, where classroom (2) is facing south, solar radiation started to heat the class through the openings in the classroom envelope after sunrise. As demonstrated in figure (6) and (7), it started with 1400 W at 7:00 am, which is the time the pupils started their lessons. In summer, the solar radiation exceeded more than 1700 W as it become stronger. Furthermore, in the afternoon period, the solar radiation reached a peak in classrooms (1) and (2), with it being greater than 3200 W and 3400 W at 12:00 pm in winter and summer, respectively. As a result, the increased dry bulb temperature caused overheating inside the classrooms.

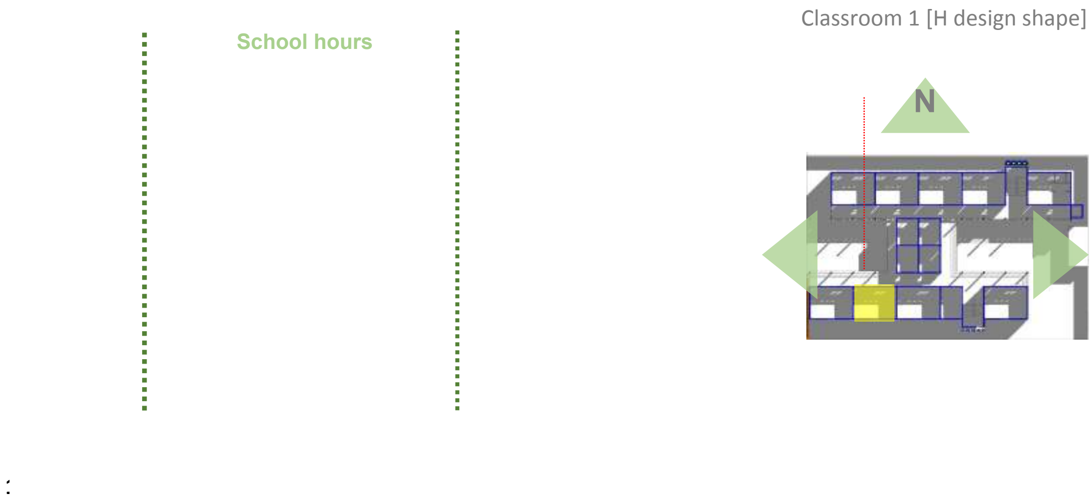


Figure 6. Solar heat gain and dry bulb temperature inside classrooms (1)

Figure 7. Solar heat gain and dry bulb temperature inside classrooms (2).

Considering the northern wall of classroom (3), Figure 8 presents the external surface temperature. As noted, the temperature was around 41 °C during the afternoon period particularly between 16:00 and 17:00. Thus, it is possible to consider this wall as a major contributor to the overheating of this classroom, which emphasises the importance of the wall system suggested by this paper. It is worth mentioning that classroom (3) is adjacent to classroom (1) as observed in Figure 8.

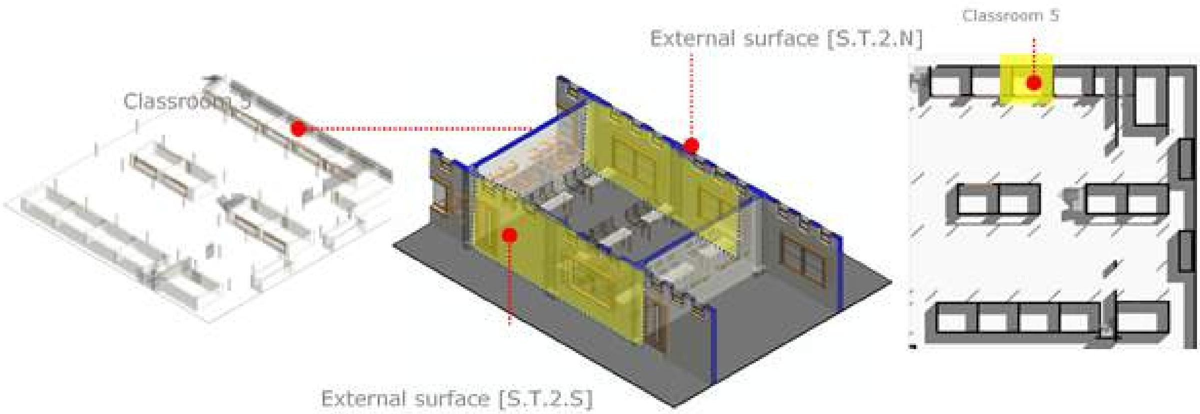


Figure 8. External surface temperature in classroom (3) during winter and summer seasons

3.2. Results from CFD

The change in the temperature of the outdoor air when passes through the suggested passive cooling wall system are presented in Figure 8 and Figure 9 in five horizontal and vertical planes. For both planes, a maximum temperature of almost 39.9 °C was recorded, whereas as minimum temperature of around 22-25°C was recorded.

The figures below illustrate the visualization of temperature distribution obtained by the simulation. The left-hand side of the contour plot shows the scale of air temperature (C°), which is colour coded and related to CFD colour map ranging from 15 °C to 36 °C. At the environment inlet domain, the external hot air (at 36.5 °C) flowed into the ventilated cooling wall to the occupied space. The air temperature was reduced at the immediate downstream at the bottom of the ventilated wall; with calculating temperature reduction of around 12 °C. Based on the air temperature and temperature drop, the cooling effect is higher at low air velocity of 0.2 m/s and 0.4 m/s for the ventilated cooling wall position at -5 W/m2 heat flux and -10 W/m2 heat flux. The airflow was influenced by the effect of the ceramic passive cooling, where natural convection flows occurred. Besides, another factor in providing the modelling of natural passive cooling was the implementation of the gravitational force and the full buoyancy effect of the cool air, which was denser. The achieved temperature drop was almost 12 °C and 14 °C respectively, Figures (9) and(10).

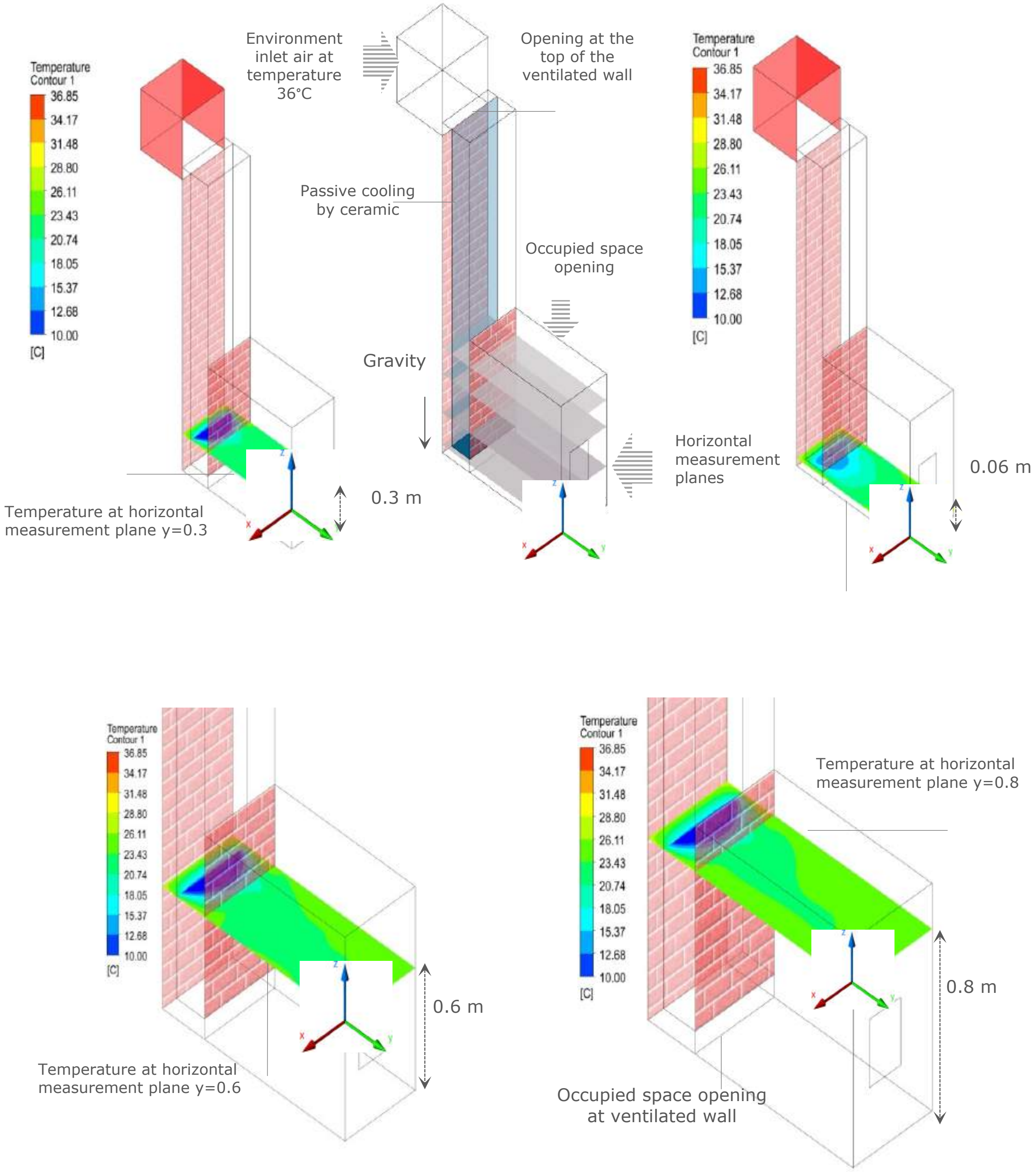


Figure 9. Air temperature change in the horizontal planes

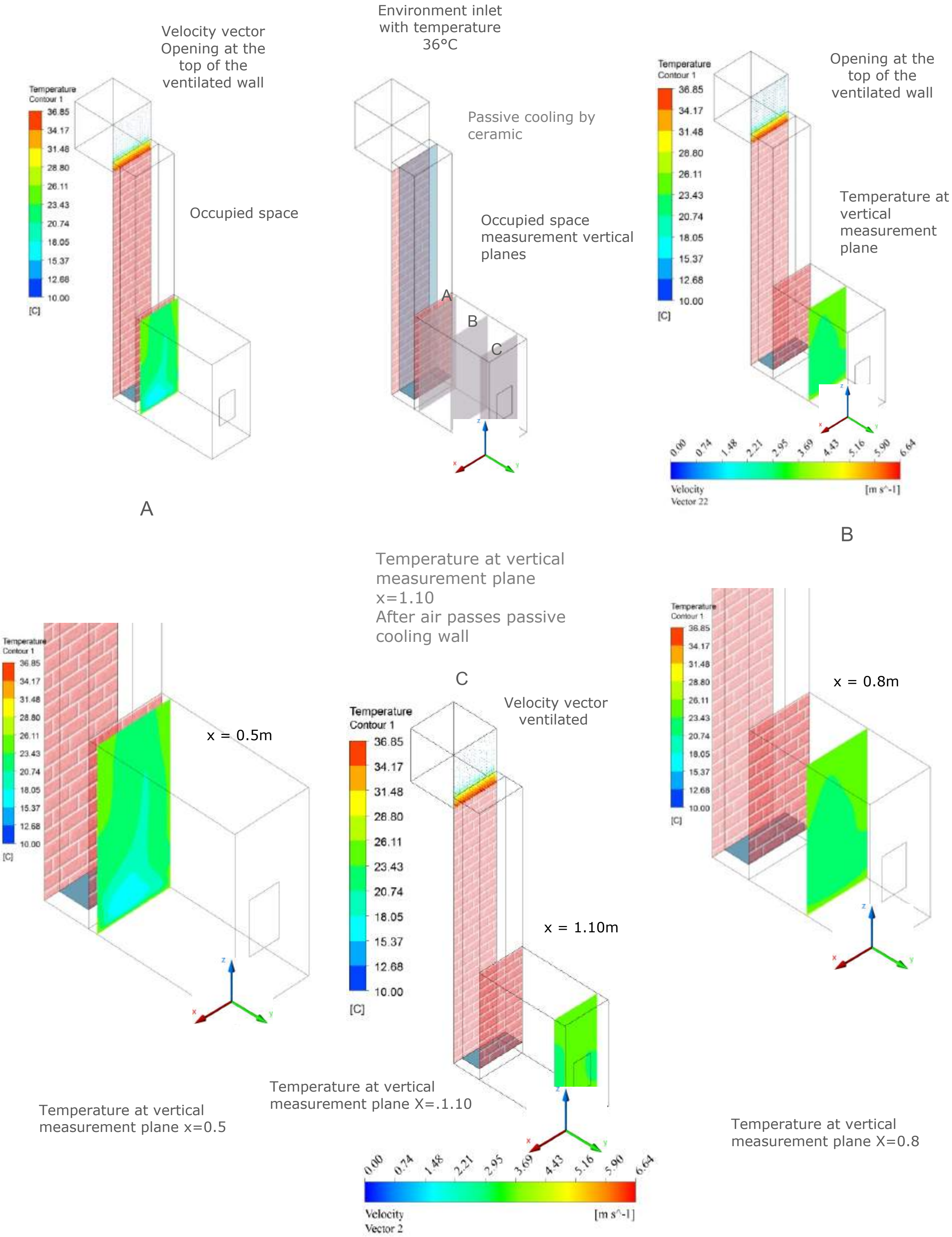


Figure 10. Air temperature change in the vertical planes

4. Conclusions

A passive cooling wall system was suggested and its influence on the cooling load of a governmental school in Khartoum city. Combining natural ventilation and evaporative cooling through a porous ceramic wall, the performance of the system has been investigated under different air velocities.

The air is cooled with PCW so that it enters the room with considerably reduced temperatures between 5°C and 8°C and provides cool fresh air. Since the air is getting cooler and denser, it spreads out through gravity all along the wall, forming a continuous layer of cool air, which then enters the classroom. The cold air rises as the occupants and other heat generating sources heat it. The effect of passing air over a hot object is that the air rises vertically, so each classroom should have its separate supply of outside ventilation air at floor level.

The results indicated a reduction in the indoor air temperature of almost 22-25 °C. Additionally, the reduction in the air temperature inside the classroom is estimated by 49%-61% roughly at measurement plane compared with almost 8%-18% of decrease in temperature distribution at the measurement planes at the occupied space. It should be mentioned that the suggested wall system was not able to cool the indoor air temperature only; it, additionally, was able to shift the thermal wave that occurs in the envelope. Therefore, the suggested wall system can be considered as a promising solution to the extreme thermal conditions of the hot dry climate especially considering that it is environment friendly besides its relatively low cost.

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Towards healthy and energy efficient new homes: current issues and future directions

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Abstract: Modern low energy buildings are design experiments that are only truly verified when energy and environmental performance is monitored and evaluated in practice. In the UK, increasingly stringent energy requirements and fabric performance standards have improved airtightness but with a consequence that there is an increased reliance placed on designed ventilation provision. Concerns about the effectiveness of this have been raised by professionals and researchers alike regarding the risk of inadequate ventilation, poor indoor air quality and overheating in contemporary homes.

Whilst the practice of housebuilding has seen considerable improvements over the last decade, there remains a number of common unintended consequences that need to be addressed. This paper discusses the inherent trade-offs between energy, comfort and health in housing while exploring key challenges of achieving real energy and environmental performance in practice, building on the outcomes of the HEMAC (Health Effects of Modern Airtight Construction) multidisciplinary network. An outline of the network structure and activities is presented, along with a summary of the key outcomes. A research agenda is presented, highlighting key gaps in the knowledge and future directions for research in this field.

Keywords: Health, indoor air, comfort, housing, building performance

1. Introduction

Legislation set out in the European Energy Performance of Buildings Directive (European Parliament, 2010) requiring all new buildings to be nearly zero-energy by the end of 2020 has resulted in considerable efforts among EU Countries to increase the number of nearly zero-energy buildings (NZEBs). Buildings account for approximately 40% of the total energy consumption therefore measures to reduce energy consumption and increase the application of renewable technologies play an important role to help promote energy security and reduce greenhouse gas emissions and reliance on fossil fuels (Department of Environment, Community and Local Government, 2012).

A key prerequisite for the achievement of 'nearly-zero' energy in buildings is exemplary thermal performance of the building fabric. Increasing standards for U-values has significantly reduced these losses, so air infiltration through cracks and other adventitious openings in the building envelope has a major influence on the total energy consumption of a building. Air infiltration is one of the most significant contributors to heat loss in dwellings and can account for more than 30% of total heat energy consumption (Jokisalo et al. 2008; Liddament and Orme, 1998). As homes become more thermally efficient, energy losses associated with ventilation and air infiltration become more significant (Liddament and Orme, 1998).

The rate of infiltration is determined by pressure differences across the building envelope and is typically quantified and compared by determining the building airtightness or air permeability level, defined as, "air leakage rate per envelope area at the test reference pressure differential [usually 50 Pa] across the building envelope" (IS EN 13829:2001, p.4). Airtightness is a major building performance issue and plays a central role in compliance with building regulations and energy performance schemes. In the UK, airtightness regulations are enforced through mandatory testing, which has seen a dramatic improvement of airtightness performance particularly in the residential sector, with new homes achieving average levels of 5 $m^3/hr/m^2$ (Cradden, 2019). In fact, the airtightness test is one of the few mandatory post-completion regulatory tests and this has driven improvements in this area.

Although airtightness standards and regulations have become more stringent, requirements for ventilation provision have not evolved at the same rate and indoor air quality in residential settings remains to a great extent unregulated (Coggins et al. 2008). There is growing concern regarding the potential consequences of poor ventilation on the indoor environment, particularly on exposure to pollutants indoors. Ventilation affects the transport of air contaminants between indoor spaces and between indoor and outdoor spaces, influencing exposure to pollutants of indoor and outdoor origin and from the building fabric, where air is drawn from contaminated areas (Sherman and Chan, 2004). Some studies have shown that airtight homes with low outdoor air exchange rates can result in elevated concentrations of indoor air pollutants and moisture originating from indoors (Offermann, 2010).

At the same time, the residential sector has seen a considerable shift in ventilation practices with whole house heat recovery ventilation now commonplace for airtight dwellings built to higher energy standards (NHBC, 2012; Baborska-Narozny and Stevenson, 2017). Recent research has highlighted poor standards of installation, performance, and operation of these systems in practice and the potential consequences of system failure in airtight homes (McGill, 2015; Sharpe, 2014; NHBC, 2012). As explained by Kukadia et al. (2012, p.5),

> "In principle, increased air-tightness provides scope for improved energy efficiency, both for naturally and mechanically ventilated spaces. However, very airtight buildings need to be fail-safe, i.e. a situation in which the basic ventilation needs for health and safety are met in the event that the ventilation system fails to operate".

The ability of mechanical ventilation systems to be 'fail-safe' is hindered by a number of factors. These include the basic reliance on a continuously running mechanical system, which is affected by the design and specification, quality of installation, commissioning and maintenance, and also a lack of awareness and understanding of the importance of ventilation among homeowners and tenants, particularly in social housing. For example, recent studies have found that mechanical ventilation systems are often deactivated by resident's due to concerns with noise, thermal comfort, draughts or cost of running (McGill, 2014; Sharpe et al. 2016).

The home environment is a dominant exposure for humans since more than half of the body's lifetime intake of air is inhaled in the home (Sundell, 2004). Yet source control in housing has been fundamentally neglected. As explained in the UK Building Regulations (Approved Document F, 2010), while reference has been made to recommended pollution levels, source control is not adequately covered in the guidance due to the limited knowledge on pollutant emissions from construction and consumer products. Indeed, research examining health outcomes associated with exposure to indoor air pollution is also considerably lacking.

Whilst some progress has been made to address concerns regarding indoor air quality in airtight housing, there is a fundamental lack of research in this important field. To effectively determine health outcomes associated with architectural design strategies and exposure to indoor air contaminants requires an essential breakdown of discipline-specific boundaries, particularly between the architectural and health fields. Research has been able to identify presence of pollutants in buildings, and medical studies have established health effects of some exposures (e.g. WHO), but very few studies have been able to identify causal links between a pollutant in a building and a health effect. Moreover, the multi-scale nature of this task requires a fundamental understanding of complex factors and inter-relationships between the environment, architectural design, indoor air quality, non-chemical stressors and human populations.

This was the key focus of the AHRC funded multidisciplinary network, established in 2017 to promote dialogue and encourage interdisciplinary collaborations in order to identify key gaps in knowledge and develop shared research agendas. The primary aim of the 'Health Effects of Modern Airtight Construction' (HEMAC) network was to bridge the gap between the fields of public health and architectural design, to support the design of healthy low energy homes. Through transdisciplinary dialogue, the network encouraged engagement from the architectural community to identify important relationships, risks and opportunities between building design–energy–indoor environment–health nexus.

This paper presents a summary of what is known about the intersection of these fields and describes key research needs to advance our understanding of the impact of energy efficient design strategies on indoor air quality and human health. An outline of the network structure and activities is presented, along with a summary of the key outcomes. Important challenges are identified, with a particular focus on the inherent trade-offs between energy, comfort and health in housing, in light of recent literature. A research agenda is presented, highlighting key gaps in the knowledge and future directions for research in this field.

2. Health Effects of Modern Airtight Construction: an overview of network activities

The HEMAC network is made up of a steering committee of researchers and practitioners from medicine, indoor air science, microbiology, engineering, architecture and ventilation; including participants from the UK, Ireland, the Netherlands, Denmark, Belgium and China. Healthy building design requires knowledge, input and engagement from a wide range of professionals that would typically have minimal interaction (see Figure 1). The network invited participants from a wide range of fields to participate in a series of events aimed to encourage knowledge translation and the development of innovative cross-disciplinary projects.

The network was established through funding received from the Arts and Humanities Research Council (AH/N006607/1) which facilitated a series of initial events, including a symposium (September 2016), a workshop (November 2016) and a sandpit (April 2017) hosted in Glasgow, Scotland. The following section presents an overview of the three networking events, highlighting key outcomes from the various activities and discussions.

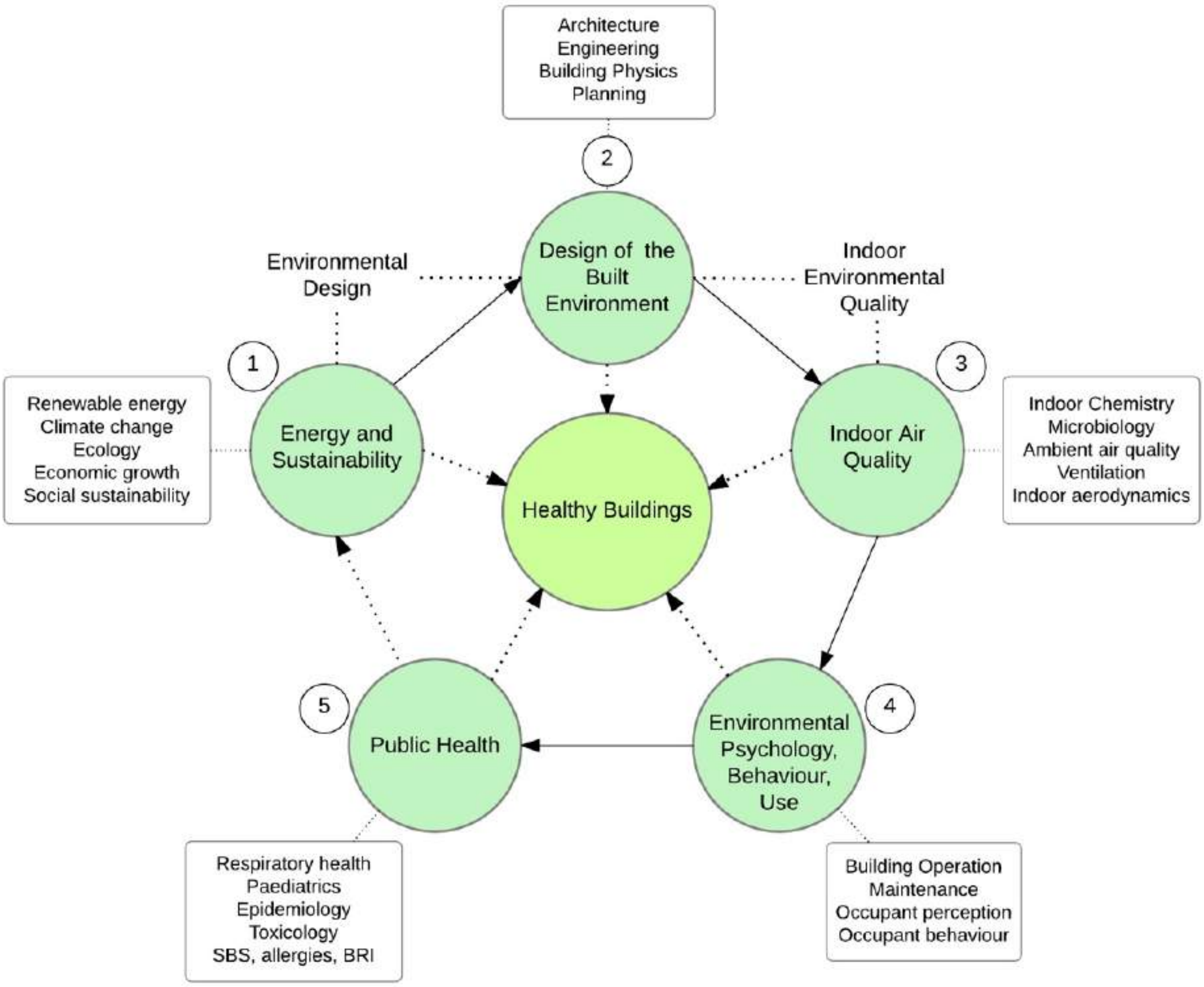

Figure 1. An overview of the transdisciplinary field

2.1. Symposium

The purpose of the symposium was to provide a platform to bring various disciplines together to present recent research findings concerning indoor air quality in airtight housing and to put forward ideas regarding important gaps in the knowledge and future research direction. The event was attended by a cross-disciplinary group of 89 participants from a range of fields including health, architecture, engineering, ventilation, housing and environmental design. Presenters were asked to consider: i) What is known (i.e. key problems and challenges relating to their specific area of expertise), ii) What are the current gaps in knowledge, and iii) What are the solutions? (i.e. how do we move forward). These questions were deliberated further during a discussion session at the end of the day, which was followed by an online survey that collated opinions concerning key problems and challenges in the field.

The symposium event highlighted a number of important gaps in knowledge and areas for future development. Presentations from medical professionals during the morning session provided a background to indoor air pollution and common consequences of inhaling specific pollutants in clinical terms. As highlighted by Seaton (2016) during the opening presentation, the body reacts to all particles inhaled as invading organisms, which can increase the risk of stroke, asthma attacks and heart attacks, when measured across populations. This was further developed by Agius (2016), who highlighted important known health risks associated with specific indoor contaminants, providing evidence of the toxic potential of chemicals commonly found in the home environment.

The discussion that followed emphasised the need for an effective statutory reporting system to gather evidence of unexpected reactions to consumer products and materials. As noted by Seaton (2016), determining the role of contaminant exposure, including bio-accumulative agents, to chronic health conditions is particularly difficult and requires long term studies that can be extremely difficult to acquire funding for. The need for long-term studies is supported by Wargocki et al. (2013, p. 8) who notes, “Traditionally, acute effects on humans are monitored and there is quite limited research data on the chronic comfort and health effects in the built environment including serious effects such as cancer”.

Mawditt (2016) provided an overview of the state of art of ventilation in the UK, emphasising concerns regarding poor measured airflow rates in modern homes. Evidence was presented of recent research in this area, highlighting important policy and strategic needs. In a study examining the performance and use of whole-house Mechanical Ventilation with Heat Recovery (MVHR) systems, a range of shortcomings were identified, including a lack of sufficient airtightness, lack of commissioning and compliance with regulatory standards, poor measured airflow rates, inappropriate duct types and a lack of system balance (Sharpe et al. 2016).

Evidence from the Netherlands presented by Boerstra (2016) emphasised that problems identified with the performance of mechanical ventilation were not limited to the UK, calling for changes to the building code to introduce maximum ventilation noise levels and maintenance requirements for ventilation systems. A survey of 299 homes with MVHR and Mechanical Extract Ventilation (MEV) found problems with inadequate maintenance, high noise levels and inadequate measured airflow rates in practice (Balvers et al. 2012). Similarly, outcomes of a review of ventilation levels in European dwellings suggests homes are often under-ventilated, attributed in part to a lack of occupant understanding of ventilation systems, resulting in increased concentrations of indoor air pollutants (Dimitroulopoulou, 2012).

A Q&A session highlighted some important concerns regarding the ‘circle of blame’ culture between architects, clients, developers, construction professionals and end-users in the UK, and the growing disconnect between ventilation design and performance in practice. Whilst indoor air quality standards are available in the UK, these are voluntary and for guidance purposes only; they are not enforced and are rarely measured. Nevertheless, while there was agreement that increasing ventilation levels will likely reduce indoor air quality related health problems, Wargocki (2016) noted that ventilation is only a modifying factor and should not be used a panacea for all indoor air quality problems. As highlighted by Borsboom et al. (2016, p.64), “In order to design a ventilation or pollutant control strategy based on health, there must be a clear understanding of the pollutants to control, indoor sources and source strengths of those pollutants, and acceptable levels of exposure in the home”. At present, there is currently insufficient data on indoor source concentrations, variability and exposure to develop a health-based ventilation standard (Borsboom et al. 2016).

An overview of key challenges for policymakers was provided, calling for a more co-ordinated approach to built environment policy for the achievement of healthy buildings (Dimitroulopoulou, 2016). As emphasised in a report published by the UKIEG (Myers et al.

2017, p.22), “A government department lead is needed to co-ordinate cross government department work on the issue of the indoor environment, health and wellbeing”. This is supported by Jacobs et al. (2007), who suggests that governmental policy in this area needs a solid scientific foundation, including data on health outcomes relating to particular building characteristics and practical interventions that encourage investment in quality, low-income housing. This is a particular focus of the All-Party Parliamentary Group on Healthy Homes and Buildings, established in 2017 to encourage holistic solutions to address the problem of unhealthy housing. The White Paper published in October 2018 provides the following recommendation: “[to] Grow the research and evidence base, starting with a focus on housing and schools, to develop a clear case for further Government action on standards for new build” (APPG Healthy Homes and Buildings, 2018, p.14).

There was a consensus amongst symposium speakers and participants regarding the importance of involving architects and building designers in the discussions, to ensure that quality of the indoor environment is a key priority during the design process. Sullivan (2016) highlighted that architects need to be better informed through user feedback and post-occupancy evaluation data, to gain a better understanding of what works where. Swainson (2016) suggested that architects have lost the art of design for natural ventilation in dwellings and suggested that more work is needed to change the mind sets of architects and developers from viewing ventilation as an ‘add-on’ or inconvenience. As noted by Fisk (2005, p.10), “Building professionals are often isolated from the consequences of decisions that result in suboptimal indoor environment quality”. He suggests the need to effectively convey the economic benefits of improved indoor environmental practices while providing scientific evidence of the effectiveness of interventions.

2.2. Survey Feedback

After the symposium event, a survey was distributed to speakers and participants online using SurveyMonkey, to gather feedback and collate ideas to help inform future events. The survey asked participants to provide suggestions for topics for the follow-up workshop event, indicate what outcomes they would like to see from the network, and outline what they believe is the key problem that needs to be addressed. The responses are summarised below.

Topic suggestions

- Source control and construction material emissions (in airtight buildings)
- Microorganisms in homes (health impact, trends, monitoring, effect of building design and occupant behaviour)
- Guidance for design and construction professionals
- Impact of end-user interactions on indoor air quality (noise, awareness, control, perception)
- Review of existing evidence of IAQ in modern airtight homes
- Effectiveness of ventilation systems in practice (improving ventilation performance, regulations and guidance, including commissioning of ventilation technologies)
- Metrics and standards for measuring and monitoring indoor air quality

Suggested outcomes

- Guidance / Code of Practice for architects, building services engineers and building users on the key findings, especially common mistakes to avoid

○ Increased public awareness of indoor air quality in homes
○ Large scale, collaborative, interdisciplinary, and international bids to address evidence gap
○ Investigation of the value, effectiveness and enforcement of UK regulations and standards in practice, leading to regulatory change where required
○ A database of material emissions and case studies of current materials used in low-energy buildings
○ Establishment of a calibrated assessment scale and methodology for measuring and reporting IAQ problems
○ Quantification of the cost of poor IAQ to the health service and indirect costs to the UK economy

Key problem that needs addressed
○ Disconnect between academia and practice
○ Lack of evidence linking cause and effect such that regulation can be meaningful
○ Lack of funding, particularly for interdisciplinary research
○ Perceived conflict between energy efficiency and ventilation
○ Poor dialogue between regulatory bodies and real-world stakeholders
○ Need for indoor air quality standards, based on maximum pollutant concentrations
○ Source control
○ Lack of understanding and awareness of ventilation and indoor air quality, particularly among residents
○ Fundamental lack of action – the 'head in the sand' attitude of building professionals

2.3. Workshop event

Feedback acquired from symposium participants along with key research priorities identified from presentations and network discussions were used to identify central topics for the workshop event. Nine workshop sessions were held in total, led by topic experts to help guide the discussions. Participants at each workshop were asked to develop a research question and associated methodology, to be shared with all attendees during an afternoon review and feedback session. The workshop event was attended by 46 people from both academia and practice, and culminated in a series of presentation pitches, where a spokesperson from each group provided an overview of the outcomes of each session. The resulting research questions from each session are summarised in Figure 2. After the event, a feedback survey was distributed among workshop participants where they were asked to provide comments on the outcomes of the workshop sessions and rank each of the project proposals in order, based on those they believed should be given priority. This exercise highlighted agreement among participants regarding the need for a comprehensive evidence review of IAQ and ventilation in modern airtight construction, followed by a need to address the effectiveness of ventilation systems in practice.

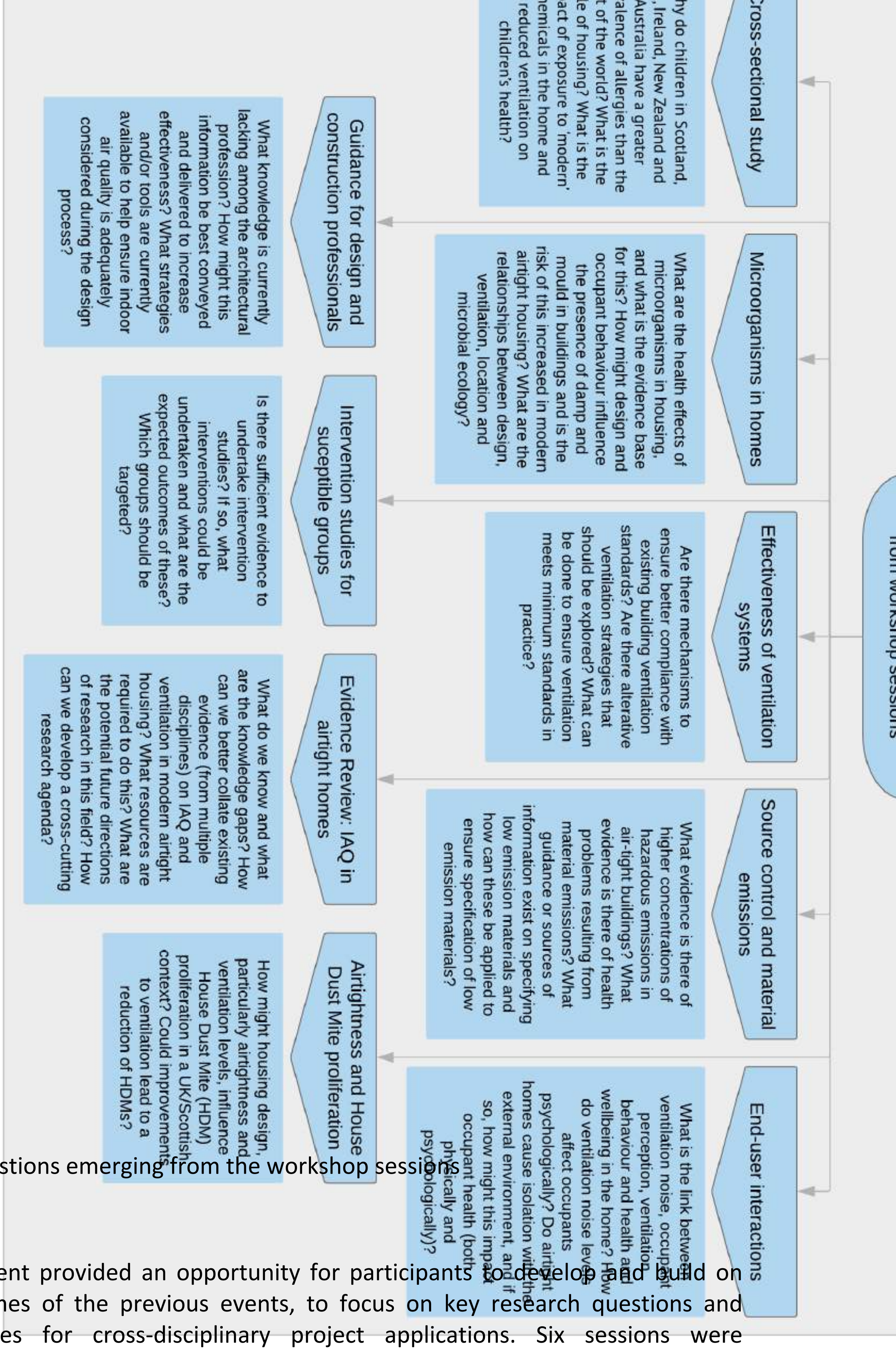

Figure 2. Key questions emerging from the workshop sessions

2.4. Sandpit

The final sandpit event provided an opportunity for participants to develop and build on some of the outcomes of the previous events, to focus on key research questions and identify opportunities for cross-disciplinary project applications. Six sessions were supported in total, developed from previous workshop sessions. The sessions were organised over a full day, with a series of comfort breaks, a networking lunch and a final summary session in the afternoon. The sandpit sessions were semi-structured and interactive in nature, involving participants from a range of different disciplines, predominately from the UK but also included experts from Ireland, China, Denmark, Austria, the Netherlands and Belgium.

The process was broken down into various stages, including: i) Introductions, ii) Defining problem and scope of the study, iii) Generating ideas, iv) Identifying aims and objectives, v) Developing a project proposal, vi) Providing an outline of a research bid, and

vii) Presentation development. The intensive discussion forums were structured to help encourage the development of creative methodologies to address important research challenges.

3. Future directions for research, practice and policy

The series of networking events highlighted important priorities for research, practice and policy in the field, to help identify potential unintended consequences of modern building practices while improving the delivery of healthy, energy efficient new homes. The network brought together a diverse group of participants from various disciplines and backgrounds, providing the opportunity for new perspectives and ideas. The following section outlines research areas that the group identified as urgently requiring attention, many of which are the current focus of ongoing initiatives in the UK.

Participants agreed that there is a fundamental need for sharing and collaboration between disciplines and among the international community at large, highlighting the important role of the network in bridging gaps between these distinct groups. To raise the profile of IAQ in airtight housing, it was stressed that an evidence base is required to establish fundamental associations on which to base informed recommendations. To achieve this will first require a collation of existing knowledge and resources to gain a greater understanding of the problem and raise awareness among the general public of the health risks of pollutant exposure in the home. This is the primary aim of a new working group, led by the Royal College of Paediatrics and Child Health (RCPCH) and the Royal College of Physicians (RCP), with involvement from the HEMAC Committee, which aims to undertake a systematic review of the literature to identify, evaluate and appraise existing evidence regarding the health effects of indoor air pollution on children and young people. The results will help raise awareness of the potential impact on health and associated costs to the NHS, while identifying areas where further research is needed.

At the same time, the Department of Public Health in England has requested the National Institute for Health and Care Excellence (NICE) to develop guidance on indoor air quality at home, with the intention that this will be used in the future to develop a NICE quality standard for indoor air pollution. Two HEMAC Committee members are currently on the NICE Committee as topic experts. The draft scope was released for consultation in February 2017 with the final scope published in September 2017. Draft guidance consultation is expected to take place between May and July 2019, with expected publication of the final guidance document in November 2019. It is anticipated that the guidance will help provide evidence-based recommendations on indoor air quality in the home, to help health and social care professionals, housing providers, building professionals and relevant local authority staff make informed decisions based on the best available evidence.

Progress in this field will require enhanced investment at a government level to increase the availability of funding and accelerate research capacity, through cross-council initiatives. Evidence provided by HEMAC Committee members, through both oral and written submissions to the APPG on Healthy Homes and Buildings, has highlighted the need for greater investment to support funding for multidisciplinary research projects that currently fall between the remits of individual research councils. The White Paper published in 2018 notes, *"There should be an inter-departmental Government Committee involving all Government departments and agencies responsible for construction, the devolved administrations and all those with an interest in creating better homes and buildings including but not limited to; the Department of Health and Social Care, the Department for Education and Public Health England, to ensure that health and wellbeing is a key policy consideration in existing and future housing provision". (APPG Healthy homes and Buildings, 2018, p.4)*

This is supported by the UK Indoor Environments Group, who hosted a joint APPG roundtable event in March 2018 to raise awareness among UK parliamentarians of the health effects of poor indoor environments and identify ways of coordinating activity in this area. As highlighted by MP Tony Lloyd (2018) in his presentation, this will require collective investment and the application of mechanisms to allow government to function in a joined-up way, taking into account that departments each have their own budgets. The UKIEG report (2018, p.3) notes, "An advisory non-departmental expert committee is required to discuss and inform policy makers and MPs about scientific matters relating to health and housing".

While these ongoing initiatives are helping to draw attention to this issue, it is becoming increasingly clear that more research is required in order to improve knowledge on the health effects of poor indoor environments. As suggested by Ucci (2018), there is an urgent need to improve the existing evidence through improved datasets on indoor exposures that can be compared to health data. This, however, is not an easy task. The complexity of measuring health effects of exposure to indoor air pollution is exacerbated in part by the various interactions between physiological and psychological outcomes, chemical interactions and susceptibility. Moreover, from a health perspective, aetiology can be difficult to determine as many symptoms of exposure to airborne substances are non-specific, making differential diagnosis challenging (Colome et al. 2015).

The heterogeneous nature of indoor air pollution means that limited generalisations about its cause and effect can be made (Hoskins, 2003). Exposure assessment techniques must be improved therefore to account for the high degree of exposure variability in the home environment, among individuals, over time and between spaces, to effectively detect exposure associated changes to health outcomes, with sufficient statistical power (Martin et al. 2013), and relate these to building design features. This will require large-scale exposure studies involving multiple disciplines, including medicine, exposure science, air quality, behavioural science and building design; which are considerably lacking in the UK.

As noted by Jacobs et al. (2007, p.979), "Existing research methods remain ill equipped to disentangle specific housing characteristics from a host of confounding variables to discern their effect on disease causation and exacerbation." Greater investment is required to enhance current research methodologies to support and facilitate multi-layered, multidisciplinary approaches. It is hoped the HEMAC network will help to support the development of innovative approaches and advancement of research in this area. The activities have already resulted in an AHRC funded research project to investigate the influence of ventilation design on the prevalence of anti-microbial bacteria in homes. The multidisciplinary pilot study brings together a team of microbiologists, architects, engineers and housing providers to evaluate how architectural design and ventilation performance may influence the presence of antimicrobial resistant microorganisms in homes. This study is currently piloting research methods and protocols to systematically evaluate environmental conditions and microbiological characteristics indoors, including the use of low-cost indoor air quality monitors to facilitate the collection of much larger datasets.

4. Conclusions

The network events provided a forum and meeting place for academics and practitioners with an interest in this field to share ideas and insights on how to improve the quality of the indoor home environment for people. It is hoped that through sharing the outcomes of the network activities, these conversations may be continued to help improve dialogue among practitioners, academics and policy makers, while highlighting important gaps in the knowledge for other researchers interested in undertaking work in this area.

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Are our offices inclusive for women? Gender differences in thermal comfort and satisfaction in offices in Qatar and Asia

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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 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. Several 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, Thermal comfort in offices in India: Behavioral adaptation and the effect of age and gender, 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 GCC have abundantly available fuel leading to extravagant energy consumption patterns. Their unique socio-political obligations compel them to have subsidized and cheap energy tariffs, which further exacerbate the energy use (S., M., & J., 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 Gulf Cooperation Council Countries (GCC) are few and far in between. Indraganti and Boussaa conducted yearlong field studies 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 the first author 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 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 private buildings. 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 data were collected when the buildings were run in naturally ventilated mode and 4310 sets in air-conditioned (AC) mode. About 10% data was collected during power outages when ACs were off and windows were closed. This data is eliminated from analysis.

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) CO2 concentration. These were at a height of 1.1m following ASHERAE 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 38 to 29.6 years. The average age of female sample varied from 40.8 to 29.3 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

Survey	Gender	Sample size	Age (years)		Body surface area (kg/m2)		Clothing insulation (clo)	
		(N)	Mean	SD	Mean	SD	Mean	SD
Doha	Male	2558	36.0	8.286	1.88	0.15	0.75	0.135
	Female	1184	31.3	7.685	1.65	0.14	0.95	0.309
Chennai	Male	2037	29.6	8.61	1.79	0.14	0.67	0.039
	Female	870	31.3	9.527	1.56	0.13	0.81	0.109
Hyderabad	Male	2394	32.5	9.202	1.79	0.14	0.68	0.036
	Female	747	29.3	8.17	1.59	0.13	0.74	0.113
Tokyo	Male	1231	38.0	12.786			0.63	0.061
	Female	1171	40.8	11.555			0.62	0.09

2.2. Measurement of other environmental parameters

Thermal comfort is a multi-dimensional paradigm as it depends on several other environmental variables in addition to the four prime variables. Therefore, measuring the occupant sensation and preferences for other environmental parameters is also important. With this objective 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, thermal preference and thermal acceptability. 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 very cold. Thermal preference was measured with Nicol's 5-point scale as shown in Table 2. Thermal acceptability was measured using a binary scale with 0 being acceptable and 1 being unacceptable.

Table 2. Scales used to measure (a) thermal sensation scales and (b) subjective response to other environmental variables 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		

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	Excellent						
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 consisting of office buildings in Asia (Ličina, Cheung, Zhang, Dear, & et.al., 2018). This data consisted of 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).

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 lesser 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 humidity ratios 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 3. 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).

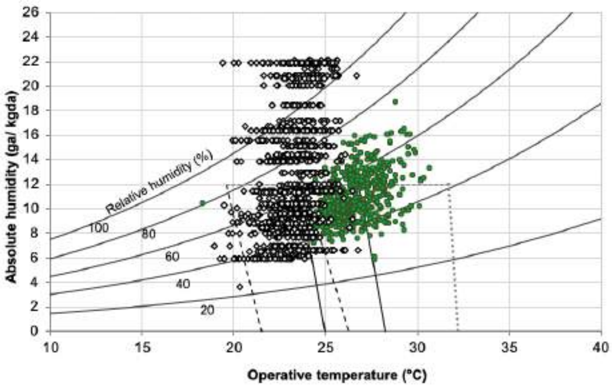

Figure 1. Indoor environmental data of Doha (black diamond) and Chennai-AC (green square) for comparison superimposed over the psychrometric chart.

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 (range: 13.6 – 31.7 °C). The same in AC environments in Chennai, Hyderabad and Tokyo was 26.9 (range: 17 – 34.9 °C) and 25.7 °C (range: 17.1 – 34.8 °C), and 27.4 °C (range: 19.8 – 35.3 °C) respectively. Similarly, the mean comfort temperature in NV environments in Chennai, Hyderabad and Tokyo was 28.6 (range: 21.1 – 33.7 °C) and 27.9 °C (range: 19.9 – 37.7 °C), and 27 °C (range: 18.8 – 38.3 °C) respectively.

Table 3. Descriptive Statistics of outdoor and indoor environmental variables in various cities surveyed (To : Outdoor daily mean temperature (°C); Ti = Indoor air temperature (°C); Tg : Indoor globe temperature (°C); RH: Relative humidity (%); AH = Absolute humidity (ga/ kgda); Va: Air velicoty (m/s); Tc = Comfort temperature (°C); SD: Standard deviation; NV: Natuatlly 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	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
T_o	30.8	6.54	26.9	2.71	28.9	2.77	25.4	2.98	27.544	3.94	25.9	2.16	28.0	1.67
T_i	23.8	1.18	29.7	2.22	26.5	1.52	29.0	1.89	26.110	1.64	29.3	1.43	27.9	1.10
T_g	23.4	1.21	29.5	2.10	26.7	1.40	28.7	1.98	25.607	1.69	29.4	1.54	27.9	1.13
RH	45.4	6.87	59.7	5.51	50.1	7.48	43.1	11.08	45.580	10.82	52.6	6.39	50.9	4.41
AH	8.2	1.28	15.7	2.73	10.8	1.96	10.7	2.66	9.479	2.06	13.4	1.58	11.9	1.24
V_a	0.04	0.06	0.5	0.33	0.2	0.20	0.1	0.21	0.049	0.08	0.2	0.15	0.3	0.16
CO_2 concentration (ppm)	1337.1	332.22	821.0	621.81	1369.8	459.47	859.7	290.51	961.590	310.92	612.7	167.34	1149.1	413.21
Noise level (dB)	57.8	6.73												
Lighting level (lux)	361.3	280.38												
Tc	24.0	2.61	28.5	2.42	26.8	2.91	27.9	2.59	25.735	2.50	27.0	2.53	27.4	2.23

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 4. This reflects some amount of overcooling in the air-conditioned environments. Table 4 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 the other gender felt both cold and heat discomfort (at 95% CI), as they voted on (-3) very cold and (2) hot sensations. 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. This finding is in contrast to the finding of Fanger (Fanger, 1970) who noted no significant gender differences in the thermal feeling in climate chamber experiments with college age subjects.

Table 4: 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.

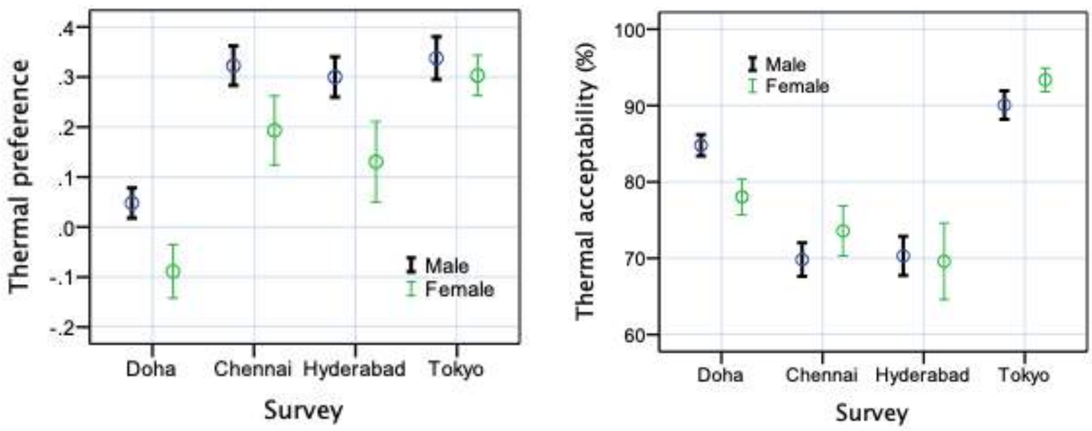

Figure 2: Gender differences in mean thermal preference vote (TP) and thermal acceptability (%) in various surveys in AC mode. Error bars indicate 95% CI around the mean.

Linear regression of TSV with indoor globe temperature in Doha returned two 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. Interestingly, these differences are more pronounced as the subjects moved away from the mean thermal conditions experienced in the offices. In the other three surveys while there are differences in the thermal sensitivity of males and females, they are not statistically significant.

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 of both the genders in Doha. The mean comfort temperature of male and female occupants was 24.1°C (SD = 2.426) and 23.7 °C (SD = 2.963) respectively. On the contrary, we found slightly higher comfort temperature for female subjects in Hyderabad survey (mean = 26.1°C; SD = 2.396) in AC mode. Male subjects in Hyderabad recorded 0.4 K lower comfort temperature compared to their counterparts and the difference is significant at 95% CI. In Chennai and Tokyo, the comfort temperature for both the genders was around 3 K higher than Doha and the gender differences are not significant.

We divided the subjects into two age groups under and over 25 years. Interestingly the mean comfort temperature of female subjects (22.6 °C) in Doha within the younger age group is significantly lower (by 0.9 K) than their male counterparts. On the contrary, an Indian study reported (Indraganti, Ooka, & Rijal, Thermal comfort in offices in India: Behavioral adaptation and the effect of age and gender, 2015) females under 25 years age having significantly higher compared to males. Interestingly, older female subjects in Doha expressed comfort at 1.5 K higher than younger females as shown in Fig.4. This difference is statistically significant at 95% CI. This finding assumes significance in designing appropriate environments mostly used by younger subjects such as academic facilities.

Similarly, older males had significantly higher comfort temperature (by 0.7 K) than younger males. 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. Brager and de Dear (Brager & 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.

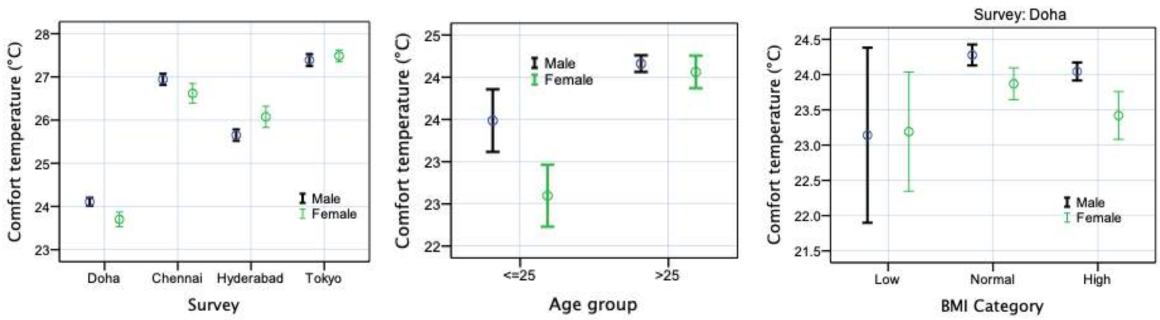

Figure 4: Gender differences in mean comfort temperature in (a) various surveys and (b) age group (c) BMI category in AC mode. Error bars indicate 95% CI around the mean.

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). 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 not 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.

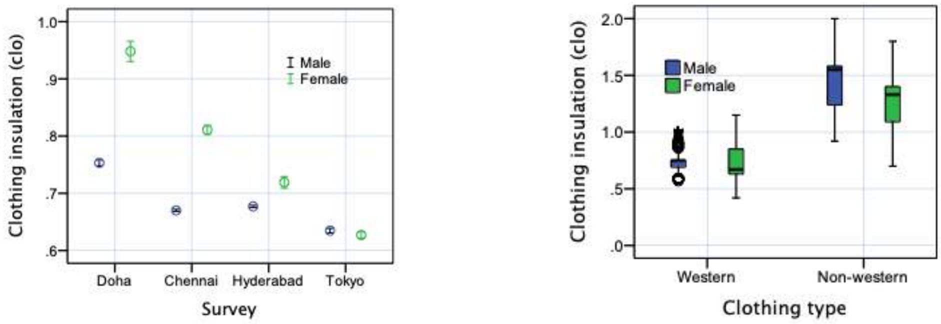

Figure 4: Gender differences in mean clothing insulation (a) various surveys and (b) box plot showing the differences in clothing insulation for Western and non-western ensembles for both the genders in Doha survey. Error bars indicate 95% CI around the mean.

3.5. Comparison with Asian offices: gender variations

We estimated the proportions dissatisfaction in both genders for various proxy environmental satisfaction scales as shown in Fig 5. It can be noted that women are more dissatisfied in all the environmental parameters considered and there are significant differences in thermal comfort, noise level and lighting level satisfaction. We estimated the odds ratio for these satisfaction variables using the binary logistic function in SPSS V22. It was found that women are 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 probable (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).

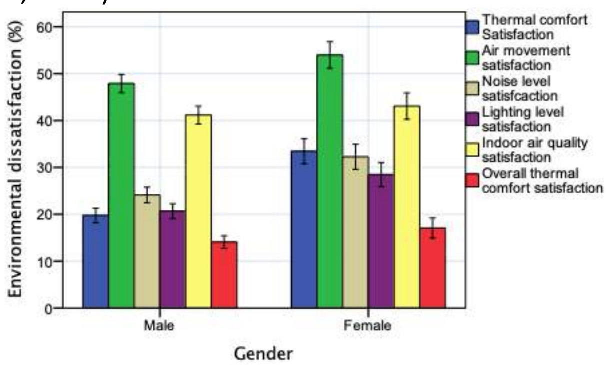

Figure 5: Gender differences in mean dissatisfaction for various environmental parameters in Asian offices. Error bars indicate 95% CI around the mean.

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.

ACKNOWLEDGMENTS

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A Meta-analysis on Gender Thermal Comfort

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Abstract: Various studies of gender differences in thermal requirements have proliferated in recent years. Such investigations are very important in all over the world for building design with thermal comfort approach. Several observational and laboratory thermal comfort studies reported diverse and conflicting results. Therefore, meta-analysis that statistically combines the results of several independent studies is important for synthesizing the findings, thus providing statistical evidence and better answering research questions. In the present article, the association between gender and thermal comfort was addressed using meta-analysis. The RP 884 database was exploited in the analysis. The odds ratio was the selected effect size in predicting subjects' thermal perceptions under neutrality. The random effects model was explained and rigorously justified prior to conducting meta-analysis. The obtained results revealed that gender is not a significant variable in predicting subjects' thermal perception under neutrality. Further research agendas on gender differences in thermal perceptions when feeling hot or cold are recommended.

Keywords: Thermal Comfort; Gender; Meta-analysis; Random effects; RP 884 database.

1. Introduction

Human thermal comfort is a complex topic with several overlapping issues. Human adaptations, expectations, preferences, and indoor and outdoor climates are a few of the factors affecting human thermal perception. Biological differences between males and females add a one-dimensional issue to the complexity of the topic. In this brief introduction, a few studies were randomly selected to briefly address the conflicting conclusions on gender differences in thermal comfort, thus providing a clear perspective on the importance of the present article.

In the pioneering work of Fanger on gender differences in thermal comfort, no significant differences were found between males and females in feeling thermally neutral (Fanger, 1970). Yet Karyono (2000) showed different results in his observational study. The investigator observed that men felt warmer than women in office buildings. A different situation was found in a field study conducted in a residential building in Hyderabad (Indraganti & Rao, 2010). The thermal acceptance of women was higher than that of men. The authors also reported that gender correlated weakly with thermal comfort. A similar observation was made by Indraganti et al Indraganti (2015). The study was carried out in offices in Chennai and Hyderabad. The investigators noticed that women were comfortable at a temperature about 0.7 °C higher compared to men in a naturally ventilated environment. However, they observed that women better accepted the indoor thermal environment.

Kim et al. (2013) examined the findings of laboratory experiments in several published studies. They reported the inconsistency of gender differences toward the indoor thermal environment under neutrality. Their observation was formulated by examining extensive thermal comfort studies. In contrast, they repeatedly noticed that for studies with substantial samples such as 1,000 records, females were more dissatisfied with the indoor thermal environment than males. Earlier, Karjalainen (2011) inferred from a wide-ranging literature study that females were more susceptible to variation from the optimum temperature (Schellen, 2012) . The author reported that a similar observation was made earlier by Fanger (1970), although the result was not significant. Karjalainen (2011) mentioned that investigators should no longer neglect the differences in thermal requirements between genders (Schellen, 2012). This statement was made despite the fact that no meta-analysis was conducted to show evidence for this conclusion. A meta-analysis is crucial to statistically address gender differences in thermal perceptions toward the indoor thermal environment under neutrality. This is the approach adopted in the study. According to Arnqvist and Wooster (1995):

> *'Comparisons of sets of studies are at the heart of science: any single study is worth little if not compared and related to other similar studies. In virtually all fields of science, specific hypotheses have been addressed in multiple studies.'*

2. The Material and Method

In this investigation, a meta-analysis was carried out by using primary data collected from the ASHRAE RP-884 database. This has the advantage of using the most appropriate procedure in the calculation of the effect size. This database has been explored by many thermal comfort investigators (de Dear & Brager, 2002; Toe & Kubota, 2033; Humphreys et al, 2013; Harimi, 2017).

2.1 Characteristics of the Studies in the Meta-analysis

There are 52 Excel files in the RP-884 data which contain data from surveys conducted in naturally ventilated and air-conditioned buildings. In this study, 16 files were extracted and screened, among which nine studies were carried out in air-conditioned buildings and seven in naturally ventilated buildings. The selection of the studies was made according to the initial requirements set in our recent study (Harimi, 2017). Additional criteria were added which will be explained in the next section. Table 1 summarizes some of the characteristics of the selected studies. The study Id. in Table 1 was coded according to the original Excel file named in the ASHRAE RP884 database. The survey years of the selected studies were from 1982 to 1994.

In the present study, if the gender was wrongly coded or omitted from the database, the entire raw in the database was excluded prior to meta-analysis. Only a few cases were excluded at this stage. The number of females or males at each indoor operative temperature was set 25. This is to minimize the effect size bias. The ASHRAE database contains longitudinal and cross-sectional design studies. Studies in Karachi, Quettar, Saidu (Pakistan), Oxford (UK), and Townsville (Australia) are categorized under longitudinal research design. The remaining studies listed in Table 1 are categorized under cross-sectional research design. This probably has an effect when estimating variances from the selected sample. Consequently, the results will be subject to bias. Violating the independence assumption in meta-analysis inflates the true variance (Viswesvaran et al, 1999; Hunter et al, 1990). Humphreys et al (2016) suggested that the subjects' responses in thermal comfort studies should be treated as independent. In thermal comfort studies, within-individual variance is approximately the same as between-individual variance (McIntyre, 1980). This assumption was also adopted in the development of the adaptive thermal comfort models in ASHRAE 55 (2010) and CEN Standard EN15251 (2007) standards. In this investigation, longitudinal studies were all treated as cross-sectional.

The ASHRAE 7-point scale is a discrete scale. In the ASHRAE RP 884 database, some investigators used a continuous scale. Other studies added midpoints to the ASHRAE seven-point scale. The third group, representing the largest number of studies, opted for the discrete ASHRAE scale. In this study, a discrete dichotomous approach was used. The subjects' votes were firstly rounded to zero digits. If the subject voted "neutral", the subject was assumed to be thermally comfortable. The recorded operative temperatures were all rounded to zero digits. The indoor operative temperatures, sample size, and other relevant information are also listed in Table 1.

A total of 4189 responses were considered. There were 3014 responses from air-conditioned buildings and 1175 from naturally ventilated buildings. The screened 16 samples from the ASHRAE database were split into 39 files according to the indoor operative temperatures. For instance, the study coded as Id. 3 was split into five files. Further information is given in section data analysis procedure.

2.1.1. Locations of the Studies

The selected studies were identified via Google Maps (Figure 1). These studies were from thermal comfort surveys carried out in Bangkok (Thailand), Montreal (Canada), Brisbane (Australia), Darwin, Melbourne, Townsville (Australia), Karachi, Quettar, Saidu Sharif (Pakistan), and Oxford (UK).

Figure 1. Study locations

2.1.2. Data Analysis Procedure

For the present meta-analysis, the random effects method was selected. In the random effects method, the true effect is assumed to vary from study to study.

Random effects will not only consider the variability between effect sizes due to sampling error but also the variability in the population of effects (Neyeloff, 2012). The reason for this choice is the diversity of the locations in the database. The variations of the indoor and outdoor climates further justify the choice of method.

Borenstein et al (2007) reported that the selection of the random effects model is appropriate when the collected studies might initially have different purposes. They explained that the random effects model performs well when the effect size varies slightly

Table 1. Characteristics of the initial selected studies

ID	Main Investigator	Location	Conditioning Type	Initial Sample Size	Operative Temperature ^{0}C	Year of the Survey	Sample Size (Male)	Sample Size (Female)
3	Busch J. F.	Bankok Thailand	HVAC	776	22, 23, 24, 25, 26	1988	43, 68, 95, 83, 49	51, 113, 92, 71, 36
4	Busch J. F.	Bankok Thailand	NV	392	32	1988	26	65
9	Donnini, G. et al	Montreal Canada	HVAC	443	23, 24	1994	56, 35	73, 47
10	Donnini, G. et al	Montreal Canada	HVAC	426	22, 23	1995	39, 94	53, 82
11	de Dear and Auliciems	Brisbane Australia	HVAC	564	23, 24, 25	1983/1984	40, 90, 70	47, 84, 50
12	de Dear and Auliciems	Brisbane Australia	NV	611	27, 28, 29, 30	1984	93, 59, 57, 29	63, 40, 60, 32
13	de Dear and Auliciems	Darwin Australia	HVAC/ Dry	493	22, 23, 24, 25	1982	27, 32, 45, 35	35, 65, 61, 32
14	de Dear and Auliciems	Darwin Australia	HVAC/Wet	555	22, 23, 24, 25	1982	31, 48, 43, 37	41, 64, 71, 30
15	de Dear and Auliciems	Melbourne Australia	HVAC	512	22, 23, 24	1982/ 1983	47, 73, 68	29, 42, 38
16	de Dear and Auliciems	Melbourne Australia	NV	555	22, 23	1983	40, 56	31, 43
19	Nicol et al	Karachi Pakistan	NV	470	25	1994	27	71
23	Nicol et al	Quettar Pakistan	NV	492	29	1993	31	29
26	Nicol et al	Saidu Sharif Pakistan	NV	548	12	1993/1994	34	25
2A	Nicol et al	Oxford UK	NV	877	20, 21, 22	1994	30, 35, 29	43, 89, 97
36	de Dear and Fountain	Townsville Australia	HVAC/Dry Season	62A	23, 24	1992	45, 67	65, 72
37	de Dear and Fountain	Townsville Australia	HVAC/Wet Season	606	23, 24	1993	37, 43	57, 73

due to the subjects' age, education, or health or other factors. Interestingly, ISO 7730 (2005) mentioned that demographic characteristics such as race and culture influence subjects' thermal comfort. Therefore, the random effects model is well justified in the present article.

This approach will allow us to make comparisons of thermal comfort between males and females within the selected indoor operative temperature ranges.

Effect sizes are very valuable in cumulative science (Lakens, 2013). An effect size is a measure of the magnitude of an observed relationship, treatment effect, or population parameter (Kelley & Preacher, 2012). It is important for quantifying effects determined on arbitrary scales and for evaluating the relative sizes of effects from various studies (Coe, 2002). For the selection of the effect size, several methods are available in the literature (Nakagawa & Cuthill, 2007). For instance, Lipsey and Wilson (2001) suggested a few methods of estimating effect sizes from different effect statistics. However, some requirements have to be fulfilled according to the test statistic and the hypothesis testing procedure (Lalongo, 2016). Nakagawa & and Cuthill (2007) reported that “r” statistics, “d” statistics, and the odds ratio “OR” meet the requirements of most situations (see Nakagawa *et al.* for more details). Therefore, presenting these effect statistics as explained by the authors eases integration into a meta-analysis. The effect size measure used in the present meta-analysis is the odds ratio. It is developed for a dichotomous dependent variable (i.e., the outcome) when a comparison between two groups is to be made (Polanin & Snilstveit, 2016). It standardizes findings across studies so that comparisons among studies will be possible (Marsh et al, 2008). In the present study, it was not possible to apply the logistic regression procedure due to the limited sample size at various air temperatures for males and females in many studies due to the requirements of logistic regression (Harimi et al, 2015) in predicting comfort temperature. Further, the correlation coefficient was also excluded because the data at various indoor temperatures were limited and due to other known statistical issues (Harimi et al, 2013).

Cohen’s (d) has been employed by Gülay (2014) in exploring the effects of gender on the organizational commitment of teachers. It is defined as the difference between the means over the pooled standard deviation (Marsh, et al, 2008; Lalongo, 2016). Cohen’s d was also excluded because the subjects’ votes on the ASHRAE seven-point scale might not be normally distributed at the selected indoor temperatures, and thus the mean values of subjects' votes may not be representative as the data will be skewed. Additionally, when considering the 39 files, the requirements of Cohen’s (d) were not fully met. The same observation holds for other effect size measures, such as Hedge’s g and other methods reported by lalongo (Lalongo, 2016).

Odds ratios are simple to calculate and interpret (Arnqvist & Wooster, 1995). The outcomes from meta-analysis can be easily explained to help with decision-making. The odds ratio appears to be the most appropriate method for the determination of the effect size when using the present database, thus it was selected. The odds ratio was estimated at each selected operative temperature from each study. In this investigation, the odds ratio refers to the odds of being thermally comfortable for males relative to the odds of being comfortable for females. The odds ratio is well explained with worked examples in Wang (2016). In the present study, Comprehensive Meta-Analysis (CMA) software was used in the analysis. The formulas are similar to those available in RevMan.

3. Results and Discussion

Prior to computation and analysis of effect sizes, the percentage of subjects who were comfortable was estimated at various operative temperatures for males and females. Table 2 ranks the percentages of subjects who voted “neutral” in the studies from highest to lowest. The study coded as S19T25 recorded the highest percentage of 75% with the indoor operative temperature of 25 ^{o}C. The lowest percentage of 11.5% was for the study coded as S12T30 with the indoor temperature of 30 ^{o}C.

3.1. Characteristics of the Studies in the Meta-analysis

Table 2 summarizes the results according to the study Id. at each indoor operative temperature. For instance, study Id. S15T23 refers to the collected data from Excel file 15 of the ASHRAE database at the rounded operative temperature of 23 ^{o}C.

Table 2. Characteristics of the studies in the meta-analysis

Study Id.		Total Comf.	Total Subjects	Subjects Comf. (%)	Rank	Males Comf. (%)	Females Comf. (%)	Conditioning Type
S15T23	23	53	115	46.1	6	42.5	52.4	HVAC
S3T24	24	83	187	44.4	7	45.3	43.5	HVAC
S3T23	23	77	181	42.5	8	52.9	36.3	HVAC
S13T25	25	2A	67	41.8	10	31.4	53.1	HVAC
S10T23	23	73	176	41.5	11	44.7	37.8	HVAC
S3T25	25	61	154	39.6	12	36.1	43.7	HVAC
S36T24	24	51	139	36.7	15	35.8	37.5	HVAC
S11T24	24	62	174	35.6	16	36.7	34.5	HVAC
S3T26	26	30	85	35.3	17	2A.6	44.4	HVAC
S3T22	22	33	94	35.1	18	27.9	41.2	HVAC
S37T23	23	33	94	35.1	18	43.2	29.8	HVAC
S15T24	24	37	106	34.9	20	36.8	31.6	HVAC
S14T25	25	23	67	34.3	21	32.4	36.7	HVAC
S15T22	22	26	76	34.2	22	44.7	17.2	HVAC
S11T23	23	29	87	33.3	23	35.0	31.9	HVAC
S37T24	24	37	116	31.9	24	39.5	27.4	HVAC
S9T24	24	26	82	31.7	25	31.4	31.9	HVAC
S14T24	24	33	114	2A.9	26	18.6	35.2	HVAC
S11T25	25	34	120	2A.3	27	2A.6	2A.0	HVAC
S10T22	22	26	92	2A.3	2A	35.9	22.6	HVAC
S14T22	22	19	72	26.4	29	22.6	29.3	HVAC
S9T23	23	34	129	26.4	30	33.9	20.5	HVAC
S13T22	22	15	62	24.2	31	29.6	20.0	HVAC
S36T23	23	25	110	22.7	32	33.3	15.4	HVAC
S13T23	23	20	97	20.6	33	21.9	20.0	HVAC
S14T23	23	22	112	19.6	35	27.1	14.1	HVAC
S13T24	24	20	106	18.9	36	15.6	21.3	HVAC
S19T25	25	74	98	75.5	1	55.6	83.1	NV
S2AT22	22	68	126	54.0	2	55.2	53.6	NV
S23T29	29	32	60	53.3	3	67.7	37.9	NV
S2AT21	21	62	124	50.0	4	42.9	52.8	NV
S16T23	23	46	99	46.5	5	50.0	41.9	NV
S16T22	22	30	71	42.3	9	47.5	35.5	NV
S12T27	27	59	156	37.8	13	36.6	39.7	NV
S2AT20	20	27	73	37.0	14	23.3	46.5	NV
S12T2A	2A	20	99	20.2	34	16.9	25.0	NV
S12T29	29	15	117	12.8	37	14.0	11.7	NV
S4T32	32	11	91	12.1	38	7.7	13.8	NV
S12T30	30	7	61	11.5	39	17.2	6.3	NV

The abbreviation "Comf." refers to the subjects who voted "neutral" on the ASHRAE seven-point scale. This was made after data screening and completing all of the procedures set out in Section 2. Figure 2 depicts the percentages of subjects who felt thermally comfortable from the combined studies at the selected operative temperatures. The subjects felt more comfortable in naturally ventilated buildings compared to air-conditioned buildings. Surprisingly, the difference reached up to 41.4% at 24 °C. Thus, the relationship between operative temperature and feeling of comfort is stronger in naturally ventilated buildings. This also supports the selection of the random effects method for the assessment of gender differences in thermal comfort.

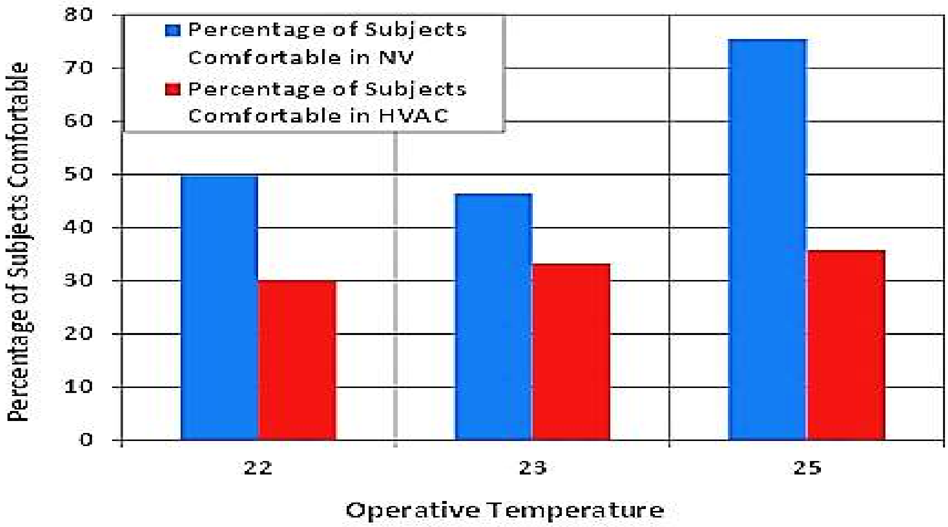

Figure 2. Percentages of subjects who felt thermally comfortable from the combined studies

3.2. Computation and Analysis of Effect Sizes

In this study, the variation in thermal comfort studies in a meta-analysis is assumed to vary randomly. The initial obtained results were reorganized for the purpose of interpretation. Table 3 lists the odds ratios with their corresponding confidence intervals. The group with higher odds and the significant association at the 0.05 level are reported in the same table. The odds ratios versus indoor operative temperatures are further plotted in Figure 3.

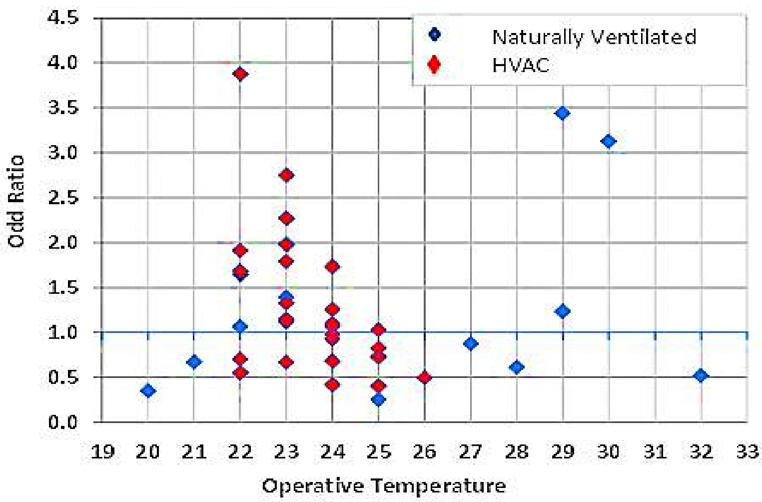

Figure 3. Odds ratio versus operative temperature

Table 3. Odds ratios with their 95% confidence intervals (CIs)

Study Reference	Effect Size	95% Confidence Interval		Group with Higher Odds	Significant Association
	Odds ratio	Lower limit	Upper limit		
S2AT20	0.4	0.1	1.0	Female	No
S2AT21	0.7	0.3	1.5	Female	No
S3T22	0.6	0.2	1.3	Female	No
S10T22	1.9	0.8	4.8	Male	No
S13T22	1.7	0.5	5.4	Male	No
S14T22	0.7	0.2	2.1	Female	No
S15T22	3.9	1.3	11.9	**Male**	**Yes**
S16T22	1.6	0.6	4.3	Male	No
S2AT22	1.1	0.5	2.5	Male	No
S3T23	2.0	1.1	3.6	**Male**	**Yes**
S9T23	2.0	0.9	4.4	Male	No
S10T23	1.3	0.7	2.4	Male	No
S11T23	1.1	0.5	2.8	Male	No
S13T23	1.1	0.4	3.2	Male	No
S14T23	2.3	0.9	5.9	Male	No
S15T23	0.7	0.3	1.4	Female	No
S16T23	1.4	0.6	3.1	Male	No
S36T23	2.8	1.1	6.9	**Male**	**Yes**
S37T23	1.8	0.8	4.2	Male	No
S3T24	1.1	0.6	1.9	Male	No
S9T24	1.0	0.4	2.5	Female	No
S11T24	1.1	0.6	2.0	Male	No
S13T24	0.7	0.2	1.9	Female	No
S14T24	0.4	0.2	1.0	Female	No
S15T24	1.3	0.5	2.9	Male	No
S36T24	0.9	0.5	1.9	Female	No
S37T24	1.7	0.8	3.9	Male	No
S3T25	0.7	0.4	1.4	Female	No
S11T25	1.0	0.5	2.3	Male	No
S13T25	0.4	0.1	1.1	Female	No
S14T25	0.8	0.3	2.3	Female	No
S19T25	0.3	0.1	0.7	Female	No
S3T26	0.5	0.2	1.2	Female	No
S12T27	0.9	0.5	1.7	Female	No
S12T2A	0.6	0.2	1.6	Female	No
S12T29	1.2	0.4	3.7	Male	No
S23T29	3.4	1.2	9.9	**Male**	**Yes**
S12T30	3.1	0.6	17.5	Male	No
S4T32	0.5	0.1	2.6	Female	No
Random Effect	1.1	0.9	1.3	Male	No

The odds ratios were greater than one in 22 case studies but less than one in 17 cases. An odds ratio larger than one indicates an increased likelihood of feeling thermally comfortable among male subjects. The situation is reversed if the odds ratio is less than one. In most cases, the 95% confidence interval (CI) contains the value one. This means that both genders are likely to feel thermally comfortable at the investigated indoor operative temperatures.

It is apparent from Figure 3 that the odd ratios were mostly below two. The odd ratios above two were recorded mostly in Australia. The highest odds ratio of 3.9 was for the case study carried out in Melbourne city at the indoor temperature of 22 °C in air-conditioned buildings. Further, the result was significant. The next highest odds ratio was for the case study carried out in Quettar, Pakistan, at the indoor temperature of 29 °C in naturally ventilated buildings.

The result was significant. This is followed by the Brisbane case study, which had an odds ratio of 3.125. This study was conducted in a naturally ventilated building at the indoor temperature of 30 °C. The results were not significant. The pooled odds ratio with a 95% CI contains the value of one. Thus, the odds ratio is not statistically significant at the 5% level. Table 4 shows the combined effect size for fixed and random effects. Both models led to almost similar point estimates and neither model is statistically significant at the 0.05 level.

Table 4 . Combined effect size for fixed and random effects

Model	Number Studies	Effect size and 95% interval			Test of null (2-Tail)	
		Point estimate	Lower limit	Upper limit	Z-value	P-value
Fixed	39	1.0652	0.9297	1.2204	0.9095	0.363080
Random effects	39	1.0586	0.8830	1.2692	0.6153	0.538338

The results from single studies with a 95% CI and the overall effect with a 95% CI are illustrated in a forest plot (Figure 4). The confidence intervals are considered effective in interpreting non-significant results. There is no dominant study when considering the relative weight of each study.

The area of each square is proportional to the study's weight. The weighting for each effect size consists of the within-study variance and between-study variance. Given that the diamond crosses the line of no effect, which includes the value of one, the gender difference in thermal comfort at the selected temperatures is statistically insignificant at the 5% level. The pooled odds ratio of male subjects being comfortable is between approximately 0.8830 and 1.2692. Nakagawa and Cuthill (2007) reported that when a non-significant result is obtained, the result is only inconclusive.

3.2.1. Publication Bias

Funnel plots were initially made to detect biases in publications (Sterne & Harbord, 2004). Anzures-Cabreraa and Higgins [36] recommended the use of standard error when using funnel plots. It has been emphasized that odds ratios should be plotted on the log scale (Anzures-Cabreraa& Higgins, 2010). Figure 5 illustrates the funnel plot of gender differences in thermal comfort.

Studies with the highest precision are represented by dots positioned at the top of the funnel plot. Studies with small sample sizes scatter towards the bottom of the plot. Small sample size refers to studies with less precision because they have larger standard error. It is apparent from Figure 5 that setting the minimum number of votes to 25 per gender helped exclude results with less precision. Standard errors for most of the studies were in the range of 0.2 to 0.6. However, there are two exceptions, namely studies coded as S12T30, for the case of Brisbane, Australia, in naturally ventilated buildings, and S4T32, for the case of

Bangkok, Thailand in naturally ventilated buildings. Interestingly, in these two cases the indoor operative temperatures were 30 and 32 °C respectively. When referring to Table 3, in the Brisbane case, the group with higher odds was male, whereas the opposite situation occurred in the Bangkok case. However, the results were not significant in either case.

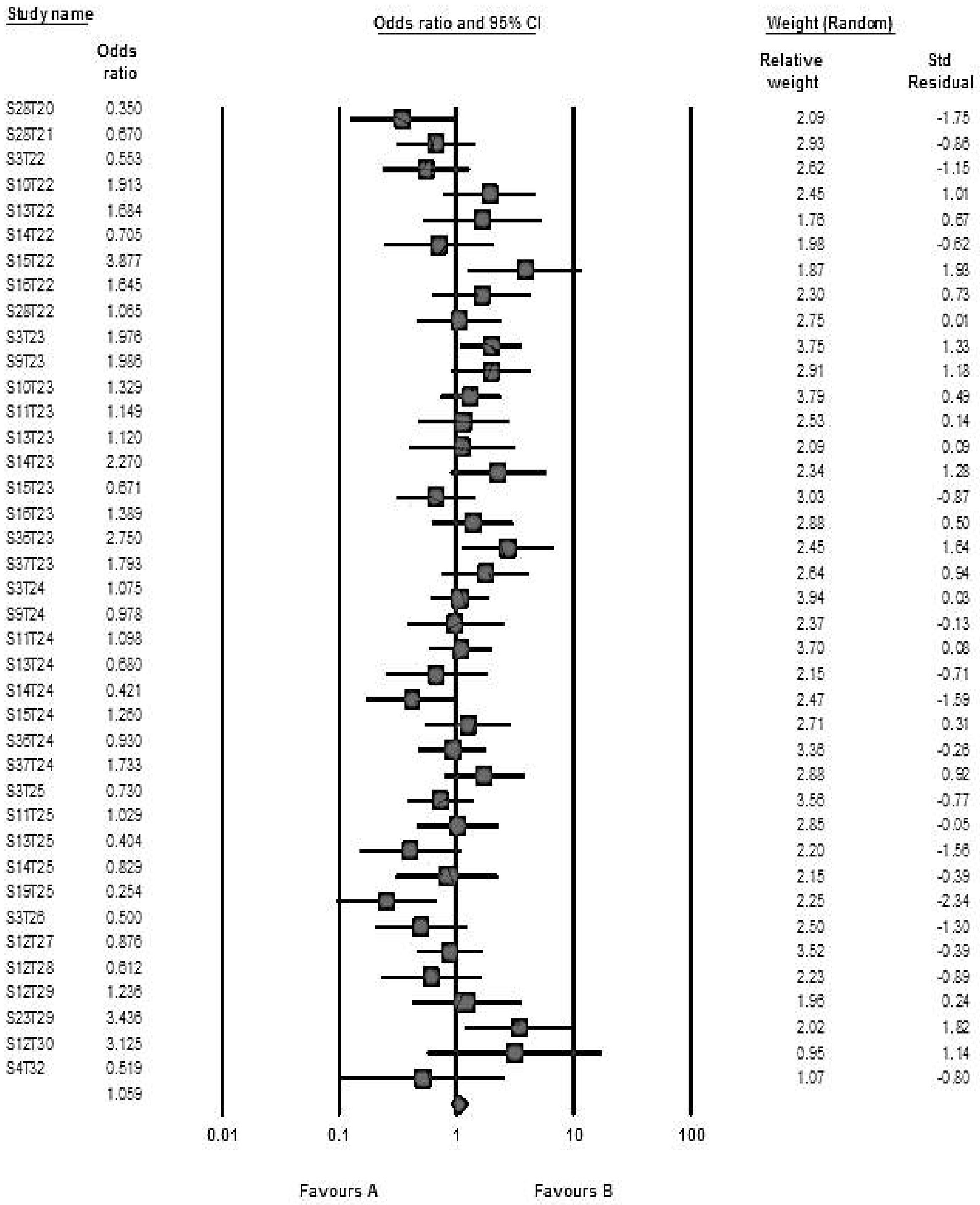

Figure 4. Forest plot of gender differences in thermal comfort at indoor temperatures

According to Borenstein et al (2009), when there is no publication bias, the dots from the funnel plot will be scattered symmetrically about the mean effect size.

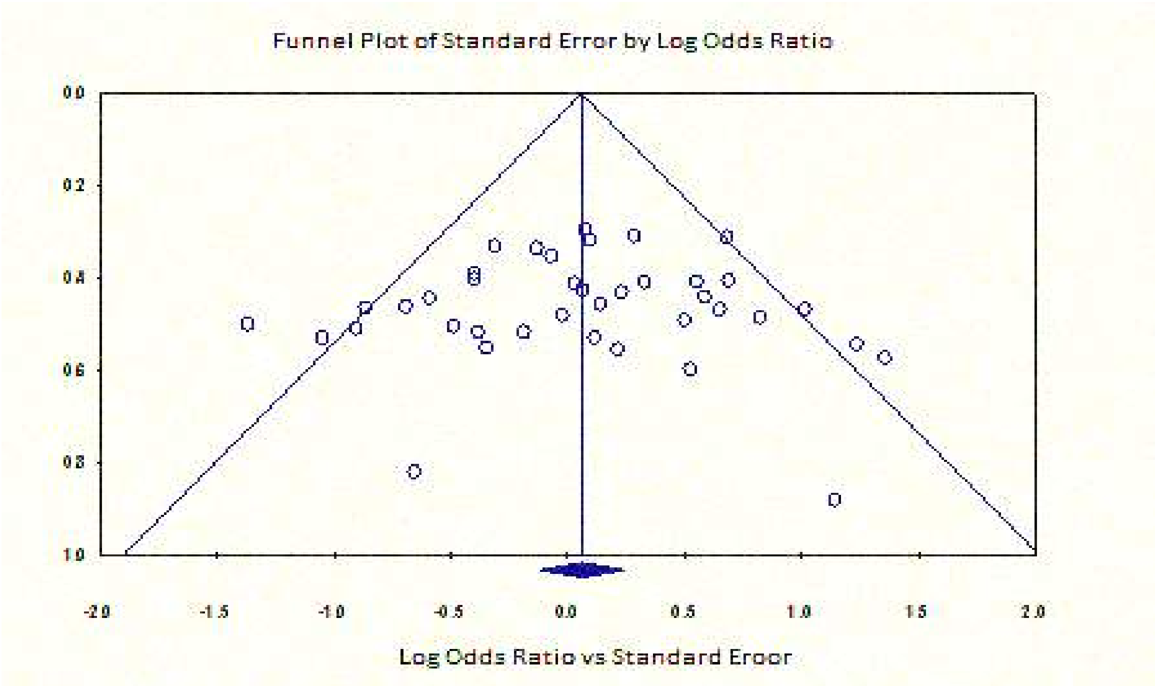

Figure 5. Funnel plot of gender differences in thermal comfort at indoor temperatures

The diamond shape at the end of the plot is the averages results for the entire meta-analysis (Borenstein et al, 2009). The diamond shape crosses the line of no effect. Borenstein et al (2009) mentioned that the interpretation of a funnel plot is generally subjective. Earlier, Egger et al (2001) reported that asymmetry in a funnel plot raises the probability of publication bias but does not prove it. Further, Anzures-Cabreraa and Higgins (2010) mentined that funnel plots with fewer than 10 studies should be interpreted with great care or ignored. This is not the case of the present study.

3.2.2. Heterogeneity Test

In meta-analysis, the evaluation of whether a selected group of studies is homogeneous is done by means of the Q test (Huedo-Medina et al, 2006). It is known also as Cochran's *Q*. The test is used to investigate the probability that the different effect sizes are estimating the same population. The Q statistic reflects the observed dispersion (Lakens, 2013). The results obtained are listed in Table 5.

Table 5. Heteroginity indices from meta-analysis

Q-value	df (Q)	P-value	I-squared
64.32	38	4.84E-03	40.92

The Q statistic of this study is 64.32 with an expected value of 38. The is 4.84E-03. This meets the criterion for statistical significance. There is substantial dispersion, and probably more than we would expect based on random differences. Huedo-Medina et al (2006) clearly stated that the Q test provides only information about the presence or the absence of heterogeneity. From the estimated of 4.84E-03, we may report that there is significant heterogeneity in the effect sizes.

Borenstein et al (2007) explained that the selection of the random effects model should depend not on a statistically significant *p*-value for the Q test but on the manner in which the studies were obtained. Q has a low power as a comprehensive test of heterogeneity

(Gavaghan, 2002), especially when the number of studies is small. Julian et al (2003) reported that the test is poor at detecting true heterogeneity among studies. Marsh et al (2008) added that the model would usually be significant. Thus, the fixed effect model will most likely be rejected.

For the present analysis, the selection of random effects is well justified. Further, both methods provided similar results. Studies are viewed as homogeneous if the CIs of all studies overlap. This is apparent in Figure 4 for most of the cases (Figure 4). Tests of heterogeneity are usually used prior to combining studies and for drawing conclusions about the consistency or inconsistency of findings (Petitti, 2001; ASHRAE RP-884).

The I-squared (t^2) test of heterogeneity measures variability between studies (Ried, 2006) by considering the proportion of the total variation in study estimates that is due to heterogeneity. The main benefit of I-squared is that it allows comparisons across meta-analyses of different sizes, of diverse types of study, and using different types of outcome data. The I-squared helps in investigating the amount of total variation accounted for by the between-studies variance. The obtained results are also listed in Table 5.

In this study, I-squared is about 40.92. This means that about 41% of the observed variance between studies is due to real differences in the effect size. About 59% of the observed variance would have been expected based on random error. It has been reported that if I-squared ≤ 25%, studies are regarded as homogenous, whereas if I-squared ≥ 75% then the heterogeneity is very high (Ried, 2006). In the present study, the obtained value of I-squared is located between those two percentages. In fact, I-squared was recommended as a complement to the Q test. However, the index shares the same problems of power with a small number of studies (Huedo-Medina et al, 2006). It has been stated that in the presence of significant heterogeneity, potential moderator variables are required to explain this variability. This is probably possible by dividing the database into subsets of homogeneous studies. Further, Higgins and Green (2001) mentioned that the thresholds for the interpretation of I-squared could be misleading. As a rough guide, they reported that when I-squared is within the range of 0 to 40%, the heterogeneity might not be important, although it might represent moderate heterogeneity. They also advised that the possible causes of heterogeneity be explored. However, they stated that it is likely that too few studies do this adequately (Higgins and Green, 2001).

Tau-squared is the estimated standard deviation of underlying effects between studies. In this meta-analysis, the value of Tau-squared was 0.1309, which is less than one (Table 6). If there is no variance between studies, tau-squared should be low (or zero). Potential statistical heterogeneity would be expected when Tau-squared is more than one. This is probably due to the difference in several characteristics across studies (Higgins and Green, 2001).

Table 6. Tau-squared from meta-analysis

Tau Squared	Standard Error	Variance	Tau
0.1309	7.46E-02	5.57E-03	0.3618

In this investigation, the moderate heterogeneity might be attributed to the choice of effect measure as it was not possible to use logistic regression. This seems the most appropriate method in meta-analysis of thermal comfort studies. Higgins and Green (2001) suggested that subgroup analysis be carried out when the heterogeneity is considerable.

This is possible by splitting the data into subgroups according to the indoor operative temperatures. However, as the heterogeneity was almost moderate, the present author did not carry out subgroup analysis. Further, both fixed and random effect models provided similar outcomes.

4. Conclusions

This research aimed to make a valuable contribution on the association between thermal comfort and gender. The random effects model was selected for investigating the association between thermal comfort and gender. The results showed no significant differences between males' and females' thermal perceptions when feeling comfortable. There is special interest in replicating the present study by including those who voted "neutral", "slightly cool", and "slightly warm" on the seven-point ASHRAE scale. It is recommended that the present study be replicated in other cases where subjects feel hot or cold. For future investigation of the association between thermal comfort and gender, it is recommended that the widest possible range of indoor temperatures should be considered. Further studies on human thermal comfort under extreme climatic conditions are required. This helps in investigating how far the condition of mind can alter gender thermal requirements. It also helps in addressing human behaviour under abnormally hot weather. Therefore, a new world thermal comfort database for predicting human thermal comfort during heat waves is needed.

Acknowledgment

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Adapting Buildings Rating Schemes for the Extremes

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Abstract: NatHERS (Nationwide House Energy Rating Scheme) which is based on simulated heating and cooling energy requirements has been adopted over a decade in Australia. Most of the houses rated and built in recent years will be in service in the mid-21st century when the Australia weather is projected in average 1 - 2 °C warmer with increasing heatwaves. Consequently, the NatHERS scheme used today will have long lasting impacts on housing energy consumption as well as household health in many years to come. Ideally, the NatHERS scheme should be adapted and improved to ensure energy efficiency of houses in a warming future climate, meanwhile achieve acceptable thermal performance during extreme weather conditions such as heatwaves. This paper overviews and discusses the technical, economic and political challenges for the NatHERS scheme to achieve these two requirements.

Keywords: House energy rating, energy efficiency, extreme weather, climate change

1. Introduction

Australia has been warming and will warm substantially during the 21st century. By 2050 (the period 2040-2059), annual average temperature in Australia is projected to increase by 1.1 - 1.5°C above the climate of 1986-2005 under the Representative Concentration Pathways (RCP) 4.5 (CCIA, 2015). Since 2001, heatwaves have increased in duration, frequency, and intensity in many parts of the country (CCIA, 2015). Heatwaves have been recognized as one of the major natural hazards in Australia and kill more people than any other natural hazards (State of Australian Cities, 2013). The situation will become worse with climate change and consensus among different climate models suggests that there is very high confidence the projected warming will result in more frequent and hotter hot days and warmer cold extremes (CCIA, 2015).

Climate changes will have profound impact on the built environment and the human society. The Australian residential building sector needs to prepare itself for the adaptation and resilience to the future warming climate and the extreme weather conditions. At the same time, the Australian residential building sector should minimise energy use and carbon emissions which currently accounts for 21% of the total national greenhouse gas emissions (DOEE, 2018). For residential building regulation and policy makers in Australia, a critical challenge is how to encourage the residential building sector to minimise energy use and carbon emissions while at the same time maintaining a comfort and healthy indoor environment in Australian homes. In fact, this is also a challenge for building regulation and policy makers in many countries (Hatvani-Kovacs, 2017).

In Australia, all new houses, or existing residential buildings undergoing major renovations, must meet the minimum energy efficiency requirements set in the National Construction Code (NCC). The most common way used to evaluate these requirements is the Nationwide House Energy Rating Scheme (NatHERS) (www.nathers.gov.au), which was initialled in 1993 as a result of commitment by Australia's Commonwealth, State and Territory governments to improve the energy efficiency of buildings, as part of the Greenhouse Response Strategy (Ren and Chen, 2016). Since then, NatHERS has been gradually adopted by Australian state and territory governments and building regulators

(Delsante, 2005). NatHERS is a star rating system (out of ten) that rates the energy efficiency of a house using NatHERS accredited software tools, based on calculated total annual heating and cooling energy requirement considering the house layout, construction (wall, windows, doors, roof, floor), orientation and its local climate. The more stars of the house, the less likely the occupants need cooling or heating to stay comfortable. Occupants of a 10 star house are unlikely to need artificial cooling or heating. Currently, most of the state and territories require a minimum 6 star NatHERS rating for new houses. Increase in the house energy efficiency stringency is believed to contribute to the flatting or declining of the Australian residential sector energy consumption in recent years (DOEE, 2018).

Although monitored heating and cooling energy generally confirms the reduction trend for houses built to higher energy efficiency star ratings (O'Leary *et al*, 2016), there are issues and challenges on the NatHERS scheme. In terms of response to global warming and extreme weather conditions, the existing NatHERS energy rating method has the following issues and challenges:

- The existing NatHERS rating scheme assumes heating and cooling are always available in the house. NatHERS energy star rating is based only on the total heating and cooling energy requirement. This rating methodology can potentially deliver high star rated house overheated when in free-run operation especially during extreme hot weather conditions (Ren et al, 2014; Hatvani-Kovacs, 2017; Hatvani-Kovacs et al, 2017).
- By using a set of weather files compiled based on weather data from 1969 to 2004, the current NatHERS rating methodology does not take into consideration the potential global warming impact (Wang et al, 2010; Chen et al, 2012). Considering that the average service life of a house in Australia is over 50 years (http://www.yourhome.gov.au/housing/adapting-climate-change), the impact of the NatHERS scheme can be significant over many years to come on the Australian residential sector energy efficiency, thermal performance and greenhouse gas emissions.

Taken Australia as an example, this paper discusses the challenges in adapting the NatHERS residential building energy rating scheme to the warming climates and extreme weather conditions.

2. Mechanically Conditioned vs Free-run Operation

With the current NatHERS scheme, a star rating is assigned to a house design based on the calculated total annual heating and cooling energy requirement under the assumption that air conditioning is always available to achieve indoor thermal comfort defined by NatHERS (NatHERS, 2012). However, in Australia many dwellings do not have air conditioning. For instance, in Sydney and Melbourne, around 15% of houses do not have installed air conditioners (DEWHA, 2009). There were also blackouts in many locations in Australia in recent years, especially during hot weather periods. With global warming, heatwaves are expected to be more frequent in Australia. The occupants of affected dwellings, especially the vulnerable elderly, are likely to be exposed to risks of heat stress during heatwaves. Therefore, building regulations should consider both the energy efficiency of houses with mechanical air conditioning and the thermal performance of the houses during free-run operation.

Ren et al (2014) investigated the risks of heat stress in non-air-conditioned dwellings (one house and one apartment) in the weather scenarios similar to 2009 Melbourne summer heatwaves using *AccuRate*, which is a NatHERS accredited house energy rating software used in Australia. The wall insulation, windows, roofs and ceilings etc were modified to achieve various NatHERS energy star ratings while keeping the same floor plans of the house and the apartment. Figures 1 and 2 show the predicted number of hours with the distress index (DI) above 28 °C in the house and the apartment at various energy star ratings in the Melbourne 2009 summer heatwave period. Here, the distress index (DI) is the average of indoor dry-bulb temperature and web-bulb temperature. For DI ≥ 28°C, the health risk of the occupants is considered to be severe (Epstein and Moran, 2006). Figures 1 and 2 showed that high star rated dwellings based on heating and cooling energy requirements do not necessary perform better than low star rated dwellings. Over-emphasising building energy efficiency alone could expose occupants to greater health risks during heatwaves with more hours with DI ≥ 28°C in the house and apartment when in free-run operation. Ren et al (2014) also found that in general, measures that can further reduce both space cooling requirement and the total space heating and cooling requirements, instead of the total heating and cooling requirements only as used by the current NatHERS energy star rating, are effective both in improving the energy efficiency performance and in reducing occupant exposure to heat stress risks during extreme weather conditions.

In order to resolve this deficiency, NatHERS and the Australian Building Codes Board (ABCB) have recently decided to improve the existing NatHERS energy star rating method by splitting the heating energy requirement and the cooling energy requirement separately. While maintaining the energy star rating requirement based on the total heating and cooling energy requirements, the heating energy requirement and the cooling energy requirement must also both below their energy thresholds which were specific for each local climate. This means that both the heating and cooling energy requirements of a higher star rated house must be less than those of a lower star rated house when the house is designed for the same local climate.

It should be pointed out that in Ren et al (2014), the insulation level of the external wall varied in order to achieve different star rating of the house, while the external wall type, i.e., brick veneer wall type did not change. To investigate the free-run performance of different wall types in the current study, *AccuRate* simulations were carried out for a four bed room single story house in Ballarat, Victoria, 110 km northwest of Melbourne. Table 2 shows the calculated annual heating and cooling energy requirements and the NatHERS star ratings for the house with brick veneer external wall and with 300mm rammed earth wall respectively, while maintaining the same house plan. The brick veneer wall house achieves 6 stars which is the minimum energy efficiency requirement in Victoria. It is seen that the rammed earth wall house has higher heating energy requirement and lower cooling energy requirement. Overall, in comparison with the brick veneer wall house, the rammed earth wall house is calculated to have a higher total heating and cooling energy requirement. So, the rammed earth wall house is less energy efficient and has a lower NatHERS star rating of 5.4 stars. The lower heating energy requirement with the brick veneer wall house is reasonable since the brick veneer wall has R1 wall insulation, while the rammed earth wall has a much smaller thermal resistance at 0.24 $m^2 \cdot °C/W$. The high thermal mass of the external walls contributes to the low cooling energy requirement of the rammed earth wall house.

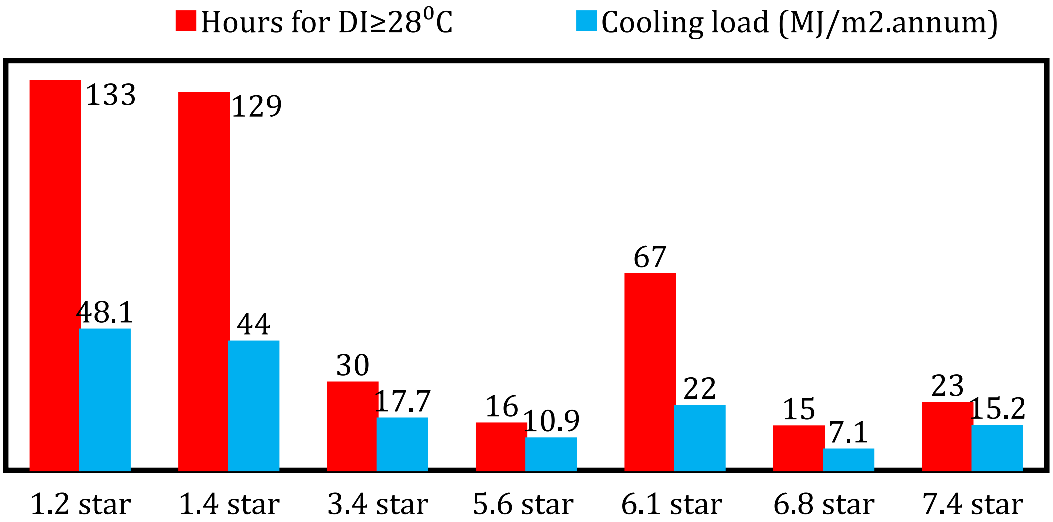


Figure 1 Hours for the houses with various energy star ratings at heat risk of DI≥28⁰C for 2009 Melbourne heatwaves (Ren et al, 2014)

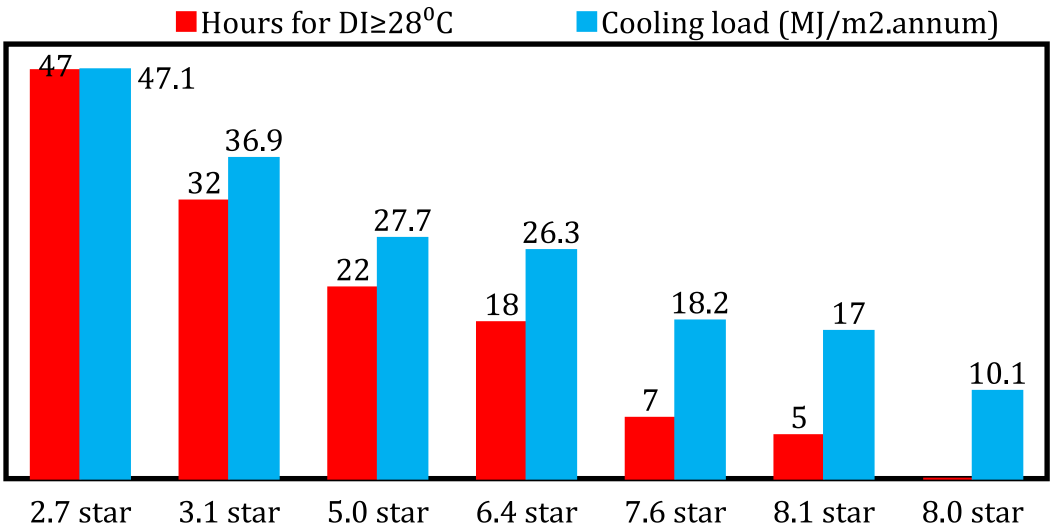


Figure 2 Hours for apartments with various energy star ratings at heat risk of DI≥28⁰C for 2009 Melbourne heatwave (Ren et al, 2014)

Table 3 shows the calculated number of hours that the indoor air temperature is within different temperature ranges over a year. It is seen that overall, the brick veneer wall house has less total hours with indoor air temperatures below 12°C or below 15 °C in comparison with the rammed earth wall house. This is consistent with its lower annual heating energy requirement. However, the rammed earth wall house performs better during extremely cold winter periods with zero hour the indoor air temperature below 9°C in comparison with 27 hours in the brick veneer wall house. As expected, due to the high thermal mass of the wall, the rammed earth wall house performs better in summer hot weather periods with only 1 hour above 30°C in comparison with 41 hours in the brick veneer wall house. In this case, a lower energy efficient rammed earth wall house, which has a 33% higher heating energy requirement and 20% high total heating and cooling energy requirement, performs better during both extremely cold and extremely hot weather periods in comparison with a higher star rated energy efficient brick veneer wall house.

Consequently, with the proposed changes by using energy thresholds for heating and cooling, the improved NatHERS methodology may give a reasonable rating for the general overall energy and thermal performance of the houses. In other words, with the modification, a high star rated house is likely to be more energy efficient when mechanically air conditioned and generally performs better during free-run operation of the house. However, it may not provide a good indication about free-run thermal performance of the house during extreme cold and hot weather conditions. Further improvement in the NatHERS scheme is required to include free-run thermal performance during extreme cold and hot weather conditions. This is becoming increasingly more important considering the projected increase in heatwave frequency and intensity in Australia (CCIA, 2015). It is noted that current knowledge is still incomplete about the methodology through which to develop building regulations on thermal performance during extreme cold and hot weather conditions (Hatvani-Kovacs et al, 2017). Further investigation is required for an improved house energy rating method to achieve both energy efficiency and satisfactory thermal performance during extreme weather conditions.

Table 2. AccuRate calculated annual heating and cooling energy requirements and NatHERS star ratings for the house with brick veneer external wall and with 300mm rammed earth external wall

Wall Type	**Heating Energy Requirement (MJ/m^2·annum)**	**Heating Energy Requirement (MJ/m^2·annum)**	**Star rating**
Brick veneer	172	18	6.0
Rammed earth	223	4.8	5.4

Table 3. AccuRate calculated hour distributions at different indoor air temperature ranges during free-run for the house with brick veneer external wall and with 300mm rammed earth external wall

Wall Type	**Temperature Range (°C)**									
	6-9	9-12	12-15	15-18	18-21	21-24	24-27	27-30	30-33	33-36
Brick veneer	26	942	2001	1733	2231	1236	379	171	37	4
Rammed earth	0	1275	1931	1392	2331	1551	257	21	1	0

3. The Warming Climate

One challenge for an energy rating scheme to take into account global warming is the availability of suitable projected future weather files. All climate projections involve uncertainties in the model itself as well as uncertainties in the assumed greenhouse gas emission scenarios. So far, there is no standard methodology for developing future weather files for building simulations. ASHRAE handbook (ASHRAE 2013) commented that the approach of developing building design conditions based on analysis of the recent record (25 years) was generally adopted. Although this does not necessarily provide the optimum predictive value for representing conditions over the next one or two decades, it at least has the effect of incorporating changes in climate and local conditions as they occur.

For climate change impact analysis, using nine General Circulation Models (GCMs) under three greenhouse gas emission scenarios, Wang et al (2010) investigated the potential impact of climate change on the heating and cooling energy requirements of modern houses in Hobart, Melbourne, Sydney, Alice Springs and Darwin in Australia. These cities have climates varying from cold to hot humid. Wang et al (2010) generated future weather files using the 'morphing' approach developed by Belcher et al (2005). Figure 3 shows the impact of climate change on the total heating and cooling (H/C) energy requirement of 5 star brick veneer houses in the five cities. In Figure 3, the light colour curves are the projections based on the nine GCMs, while the dark curves are the average values of the nine GCMs. It was found that with global warming, the increase in the total heating and cooling energy requirement can be substantial in relatively warm climates such as Brisbane, Alice Springs and Sydney. In heating dominated climates such as Melbourne and Hobart, heating energy requirement will reduce and thus will be benefit from global warming.

In the last section, it was demonstrated that houses with different wall types can perform differently in extreme weather conditions. Chen et al (2012) also showed that houses with different constructions can perform differently in future warming climates. They projected heating and cooling energy requirements using building energy simulation for houses with different energy efficiency levels in Hobart, Melbourne, Brisbane, Alice Springs and Darwin for future global warming up to 6 °C. Two house construction types were investigated, i.e., double brick and metal sheet cladding, which represent heavy weight and light weight house constructions. The heavy weight construction houses investigated were assumed to have a concrete slab floor. The metal sheet cladding light weight houses were assumed to have a 600mm subfloor except that in Darwin, they are traditional elevated metal sheet cladding houses in tropical regions as shown in Figure 4. Figure 5 shows the total heating and cooling energy requirements of the houses with future global warming up to 6 °C. As shown in Figure 5, in warm and hot climates such as Brisbane, Alice Springs and Darwin, a heavy weight house may underperform a light weight house in the future, although the two houses may have the same present-day energy efficiency. On the other hand, a heavy weight house in cold temperate climates such as Melbourne and Hobart may perform much better than a light weight house under future warming climate. The performance differences are larger in relatively cold climates such as Melbourne and Hobart.

The significantly different response to global warming in the total heating and cooling energy requirement between the light weight and heavy weight houses is due to the temperature modulation characteristics of thermal mass. Thermal mass modulates the indoor air temperature by evening out the daytime and night-time temperature differences. Consequently, thermal mass is most effective in reducing the heating and cooling energy requirements when the mean ambient temperature is close to or within the range of occupants' thermal comfort zone. Melbourne and Hobart have heating dominated climates with relative cold winter. Global warming means warmer winter in Melbourne and Hobart and thus pushes the winter daily average temperature closer to the thermal comfort range in winter. On the other hand, global warming make the summer daily average temperature of Brisbane, Alice Springs and Darwin even hotter and away from the thermal comfort range in summer.

Building designs today will have significant impact on the energy efficiency and thermal performance of the Australian building stock in the next 30-50 years. It is recommended that the NatHERS scheme should include a set of future weather files for energy and thermal performance rating in addition to the existing energy star rating. In Australia, future weather files approximately 20 - 30 years ahead could potentially be used for house energy rating purposes. The use of 20 - 30 year ahead future weather files can reduce the uncertainty of future weather projections under different carbon emission pathways (CCIA, 2015). At the same time, it represents approximately the potential average performance of the house during its service life.

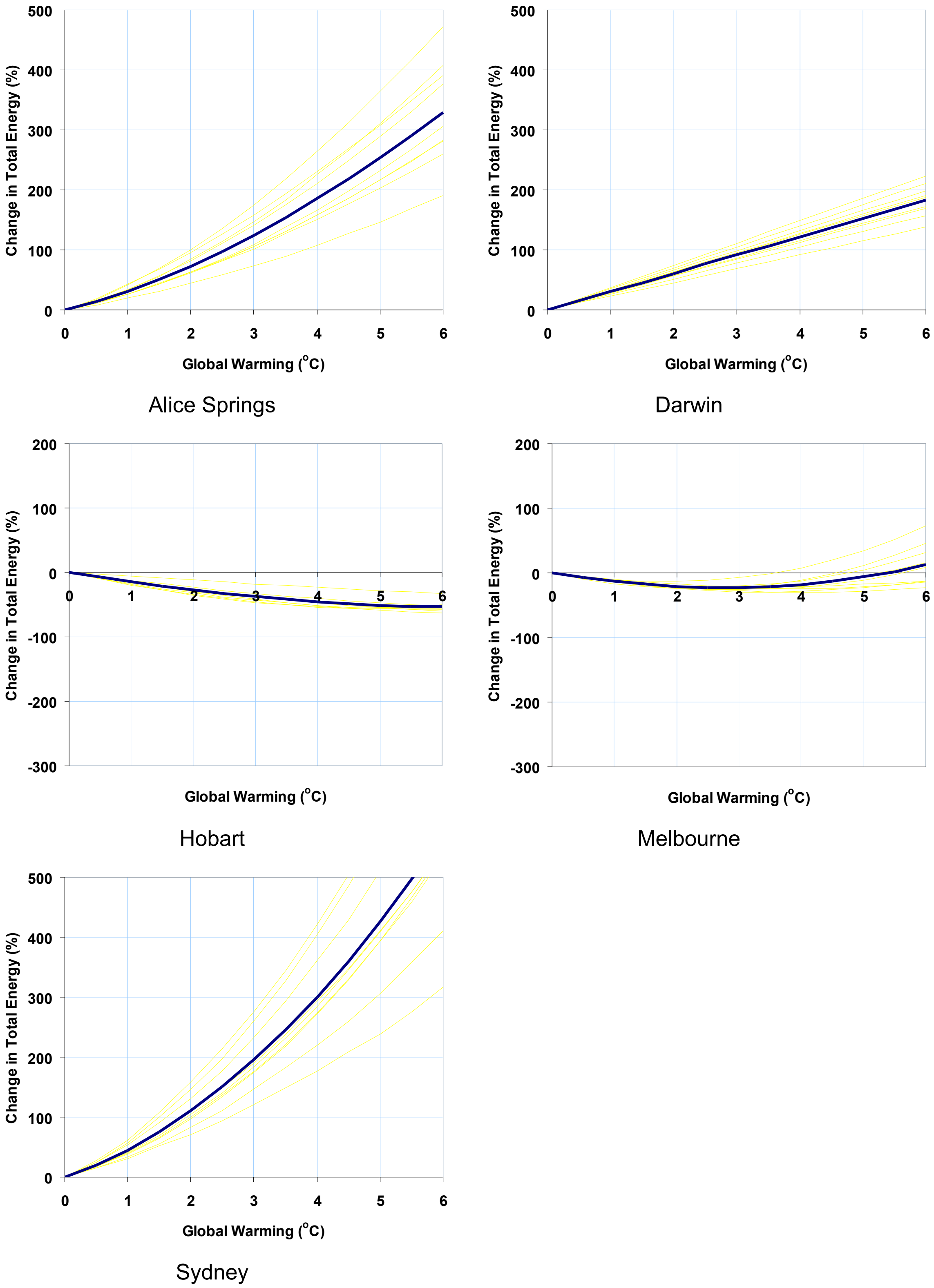


Figure 3. Sensitivity of the total H/C energy demand (in percentage terms) to global warming for a 5 star energy rating house in five cities (Wang et al, 2010).

It is noted that with the warming climate in the future, house thermal performance during extreme weather conditions will be even more crucial. As shown in Figure 5, based on simulated indoor temperatures in dwellings, Chen et al (2014) correlated the indoor mean air temperature (the average of yesterday's daytime maximum in the living room and this morning's minimum in the master bedroom) with the average mortality rate in Melbourne from 1 January 1988 to 31 December 2007. It was found that the average mortality rate increases rapidly after the mean daily indoor temperature above 28.5 °C. Global warming will cause further increase in the mean daily indoor temperature during heat wave periods with free-run operation of the houses. Consequently, in order to adapt to the future warming climate, an improved house energy rating method to achieve both energy efficiency and satisfactory thermal performance during extreme weather conditions is urgently needed for the NatHERS rating scheme in Australia.

4. Economic and Political Considerations

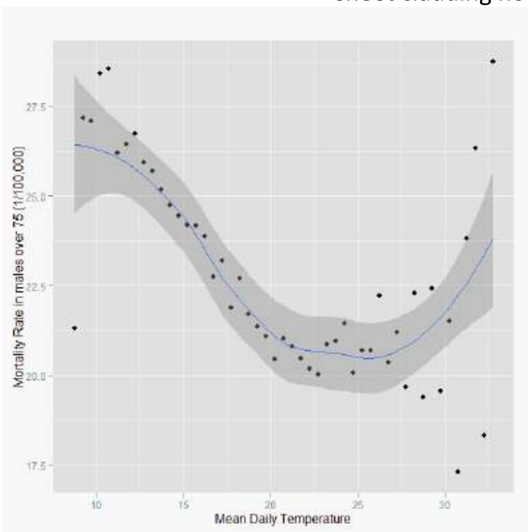
It is understood that changes in building regulations such as the introduction of future weather files and the inclusion of energy rating for free-run operation can cause disruptions to the building industry which may have significant economic and political consequences to the industry and the society. Frequent updates and changes in the energy rating methodologies and regulatory policies are generally not welcomed by the building industry due to economic, resources and political considerations. Proper impact analysis and public consultations of such updates and changes are necessary before their implementation and adoption. In Australia, the NCC updates every three years. Any significant update and change to the NatHERS energy rating scheme has to synchronise with the NCC update. Consequently, in Australia, any substantial improvement starting from research, forming methodologies, performing impact analysis and public consultation, to be approved by ABCB and to finally appear in the NCC energy efficiency code and in the NatHERS scheme may require 4 to 6 years and can be even longer.

A typical example is the update of the existing typical meteorological year (TMY) weather files used for NatHERS energy star ratings. The existing TMY weather files were compiled based on weather data from 1969 to 2004 (Lee and Snow, 2005). It has been criticized that they are too old considering global warming. Work to update the TMY weather files started around 2008. However, due to various reasons, the adoption of these new TMY weather files were delayed. It is expected that the new weather files compiled based on the weather data from 1990 to 2015 (Liley, 2017) will be officially adopted as the standard weather files for NatHERS energy star ratings in 2022, which means a roughly 15 year long process. It is hoped that with over a decade of experiences with the NatHERS scheme, the industry and regulators have learned and will improve the process in the future.

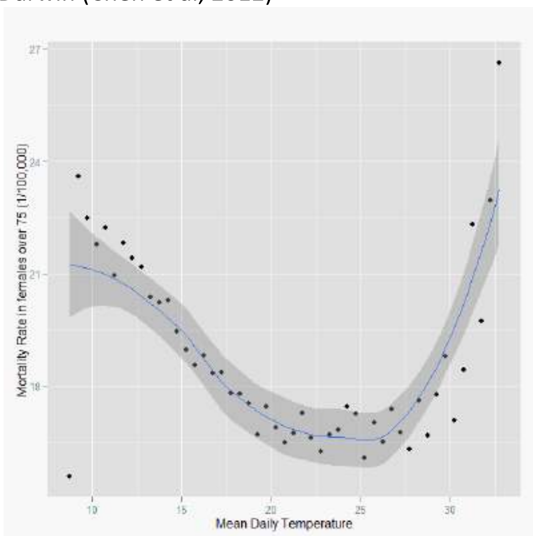
(a)

(b)

Figure 4. 3D impressions of different house constructions (a) double brick houses; (b) elevated metal sheet cladding house in Darwin (Chen et al, 2012)



(a)



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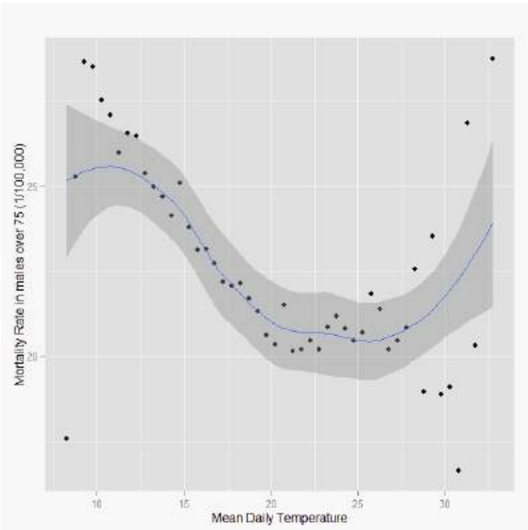
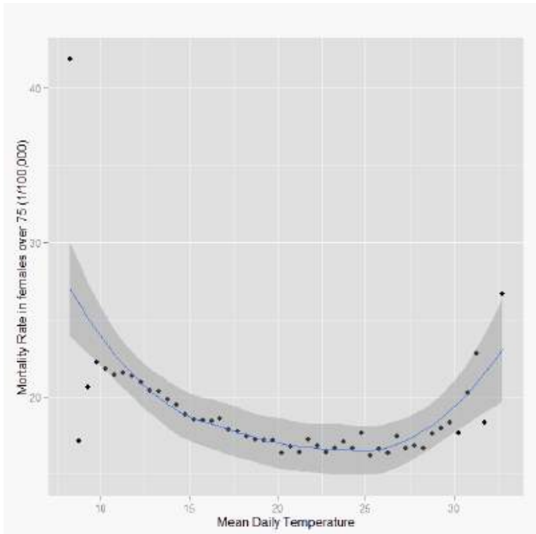
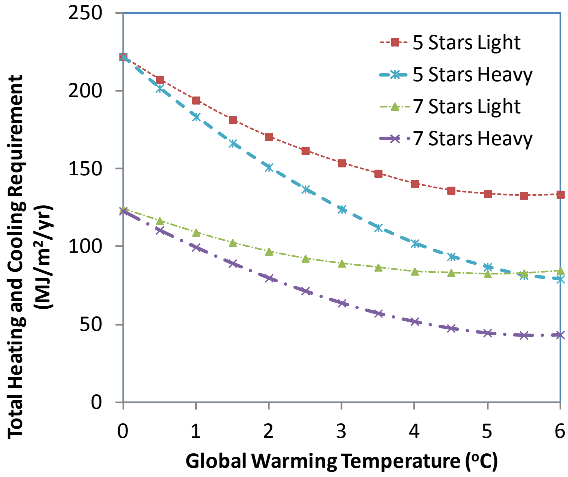


(c)

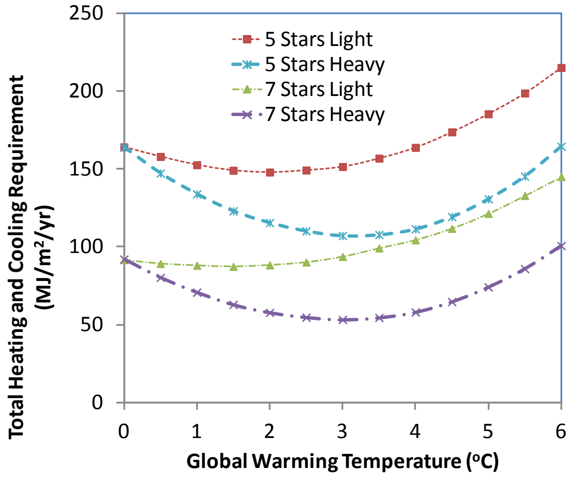


(d)

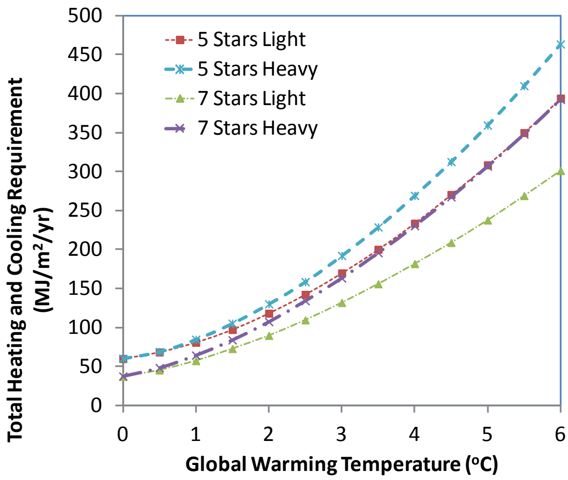
Figure 5. Relationships between the mean daily temperature in House1 and the average mortality rate in Melbourne from 1 January 1988 to 31 December 2007: (a) North facing, males; (b) North facing, females; (c) South facing, males; (d) South facing, females (Chen et al, 2014)



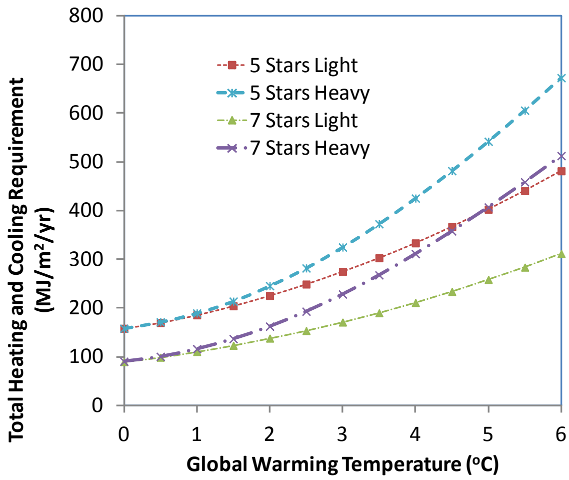
(a) Hobart (cool temperate)



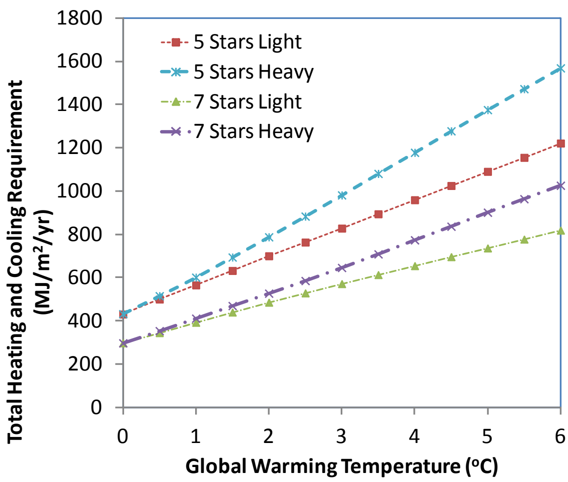
(b) Melbourne (temperate cold winter)



(c) Brisbane (warm)



(d) Alice Springs (hot and dry)



(e) Darwin (hot and humid)

Figure 5 Comparisons of the total heating and cooling energy requirements in MJ/m²/annum projected for the houses in the five Australian cities (Chen et al, 2012)

5. Conclusions

This paper presented and discussed challenges for adapting the Nationwide House Energy Rating Scheme in Australia to global warming and extreme weather conditions. It is demonstrated that with the proposed changes by using energy thresholds for heating and cooling energy requirements, the NatHERS scheme may give a reasonable rating for the general overall energy efficiency and thermal performance of the houses during free-run operation. However, it may not provide a good indication about free-run thermal performance of the houses during extreme cold and hot weather conditions and further improvements are required. In considering the life cycle energy and thermal performance of the houses, it is recommended that a set of 20-30 year ahead future weather files should be included for rating purposes for house energy rating in Australia. In order to adapt to the future warming climate, an improved house energy rating method to achieve both energy efficiency and satisfactory thermal performance during extreme weather conditions is urgently needed for the NatHERS rating scheme in Australia.

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Applying adaptive principles: Developing guidance for planning practice

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Abstract:
One of the major challenges of building industry today is to provide indoor spaces allowing the occupants to make themselves comfortable while achieving low energy consumption. Considering the observed increasing temperatures and a more extreme climate, this becomes even more urgent and difficult to accomplish. It is therefore necessary to rely on approaches than contribute to sustainable building design, such as the adaptive approach to thermal comfort which postulates that people are not passive recipients of their environment but adapt behaviourally, physiologically and psychologically.
The concept of adaptive thermal comfort was formulated many decades ago and has been validated in numerous field studies. Temperature thresholds based on adaptive models have been included in international and national standards. However, the overall understanding of how to translate the adaptive principles into design practice and concepts for operating buildings is still limited. Subtask B of IEA Annex 69 addresses this gap: "Strategy and practice of adaptive thermal comfort in low energy buildings". The subtask aims to develop guidelines for low energy buildings that include the principle of adaptive comfort. This paper discusses the challenges and gaps identified in using the principles of adaptive thermal comfort in building design and operation and outlines the contents of the imminent guideline.

Keywords: adaptive thermal comfort, controls, energy efficiency, climate context, building design

1. Introduction

Establishing a sufficient indoor climate without increasing the energy use in indoor spaces is one of the world's challenges. The adaptive thermal comfort concept is not new and researchers found numerous proofs of the concept in field studies (e.g. Nicol and Humphreys 1973, Auliciems 1981b, de Dear et al. 1997, McCartney and Nicol 2002, Manu et al. 2016), supporting that humans are satisfied with a wide range of indoor temperatures provided they have the opportunity and willingness to adapt by themselves. However, the overall understanding of how to *design* for adaptation in relation to the outdoor conditions, hence how to translate the adaptive principles into a design culture and concepts for operating buildings is still limited. Therefore, 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. Besides establishing a) a new extended database, Annex 69 has the following overall objectives: b) to provide indoor thermal environment criteria based on the adaptive concept; c) to provide a basis for the creation or revision of indoor environment standards; d) to propose passive building design strategies to achieve thermal comfort with low energy consumption and e) provide design guidelines for new cooling and heating devices (EBC 2018). One of the major project deliverables will be 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. This is an ongoing activity of the authors of this paper within Subtask B2 of the Annex.

The aim of the guideline is to enable the application of the principles of adaptive thermal comfort in planning practice, which is currently limited. It is therefore necessary to identify the needs of practitioners and the current gaps and challenges. This first step in the development of the guideline is the focus of this paper, contributing to the interpretation of thermal comfort research in real-world applications and to ongoing standardisation activities.

2. Adaptive principles

In their pioneering works, Auliciems (1969a, 1969b, 1981b, 1981a), Nicol and Humphreys (1973) and Humphreys (1976, 1978) define thermal comfort as a self-regulating system and relate thermal perception to prevailing indoor and outdoor conditions. To the best of our knowledge, they are also the first to mention a) behavioural thermoregulation by changing posture or activity, clothing insulation levels or the thermal environment, b) social factors and constraints related to thermal control (Nicol and Humphreys, 1973), whereas c) thermoregulatory adjustments based on acclimatization processes (Auliciems, 1981b) have been subject of earlier research in the thirties. These adjustments were later summarised to today’s commonly mentioned three adaptive principles, namely behavioural, physiological, and psychological (de Dear et al. 1997).

In their review of research related to these three adaptive principles, Schweiker et al. (2012) conclude that there is still a lack of knowledge with respect to each adaptive principle. However, their basic mechanisms are known. Behavioural adaptation by clothing adjustments or changes in thermal environment by adaptive opportunities (e.g. window opening or using a fan) is affecting the human bodies heat balance and is influenced by outdoor conditions (e.g. Nicol, 2001; Baker and Standeven 1997, de Carli et al., 2007; Haldi and Robinson, 2009; Cândido et al., 2011; Schiavon and Lee, 2013). Physiological adaptation (acclimatisation) to heat or cold affects the response of the thermoregulation system after repeated stimuli and alters several physiological parameters e.g. the onset temperature of sweating (Hori, 1995; Taylor, 2014). The role of psychological adaptation is addressed most commonly through notions of perceived control (e.g. Paciuk, 1990; Fountain et al., 1996; Hellwig, 2015) or changed expectations (Brager and de Dear, 2003; Strengers, 2008; Luo et al. 2016). A higher level of perceived control available to an individual relaxes the individual’s expectations towards indoor temperature.

According to Schweiker and Wagner (2015), the largest effect is that of clothing, i.e. a behavioural adaptation, followed by physiological adaptation especially on the warm side and psychological adaptation. Behavioural adaptation as found by Cabanac and emphasised in the built environment context by Nicol and Humphreys (1973) is the one favoured by humans, hence the first to be applied.

3. Current inclusion of the principles in Standards and guidelines

In their early years of development, standards for the indoor environment have mainly relied on the heat balance approach for providing thermal comfort criteria. Based on ASHRAE RP 884 worldwide database (de Dear et al. 1997), in 2004, ASHRAE was the first to include in its Standard 55 (ASHRAE, 2004) the adaptive approach as a method for naturally ventilated buildings. Its equation relates the band of comfortable operative temperatures to the prevailing outdoor temperature. Based on the results of the European SCATs study (McCartney and Nicol, 2002), EN 15251:2007 (CEN, 2007) provides a similar method for buildings not mechanically heated or cooled (free running).

The second version of the Dutch ISSO 74 combines the heat balance model for heated spaces with an adaptive model based on the data from the SCATs database (Boerstra et al., 2015) for the non-heating period. The upper temperature values at high prevailing outdoor temperatures depend on whether a space offers high or low degree of personal control.

The Chinese Standard GB/T50785-2012 provides two methods for the evaluation of free-running buildings: 1) a calculation method based on an adaptive predicted mean vote (aPMV), and 2) a graphic method based on the method of the adaptive model in ASHRAE Standard 55 (Li et al., 2014).

India based its Model for Adaptive Comfort (IMAC) on field surveys in five Indian climate zones (Manu et al., 2016). The surveyed buildings comprise naturally ventilated, mixed mode and air-conditioned office buildings. The IMAC approach considers explicitly mixed mode buildings, which are becoming increasingly prevalent in India. Two adaptive models were developed, one for naturally ventilated and one for mixed mode buildings. The equations have been included in the National Building Code 2017, the Energy Conservation Building Code 2017 and in building certification schemes.

The standards account for the applicability of the adaptive approach by categorising buildings. Unlike ASHRAE St 55 (ASHRAE 2017) and EN 15251 (CEN 2007) that use the classification of buildings into conditioned (centrally HVAC conditioned, heated or cooled), and occupant-controlled naturally ventilated or free running, ISSO 74 (Boerstra et al 2015) has been using a classification according to the degree of personal control available in a space. The building types, alpha (high occupant control) and beta (low/no occupant control), are determined based on a flowchart of adaptive opportunities. As most of the buildings in the Netherlands (like in other European countries) do not only use one of the two main conditioning modes but a combination of them (van der Linden et al., 2006), this approach therefore evaluates combined options of occupant control. Using the criteria described in EN 15251 to categorise the operation modes of buildings, it has become one planning option of consultancy companies e.g. in Germany to combine the heat balance model for the heating period and the adaptive approach for the non-heating period.

Table 1 shows that current classifications of buildings mainly consider the conditioning mode but not other building design characteristics, such as construction type (e.g. thermal mass, insulation), architectural features or spatial configurations (e.g. openings, layout, orientation, shading) or operation aspects, which also impact on a building's ability to provide thermal comfort. The inclusion of the adaptive approach in standards and guidelines is a step forward and helps to avoid unnecessary use of air conditioning. However, the standards focus on the allowable indoor temperatures but do not provide guidance for facilitating the design of adaptive buildings and their operation to a limited extend.

4. How to make use of the adaptive principles

In this chapter we report on challenges and barriers and summarise exemplary information which could contribute to a future guideline. We would like to point out that there is a strong interaction between the several factors mentioned, meaning that a change in one factor might require changes in another factor and lead to different comfort or satisfaction perceptions (Humphreys and Nicol, 2018).

4.1. Explaining the contribution to lowering energy use in buildings

Applying the adaptive principles in all kind of climates would contribute to lowering the energy used in new and existing buildings. But why can we expect this positive contribution?

The three strategies towards sustainability in buildings are: efficiency, consistency and sufficiency. Efficiency and consistency are linked to technology application but are suspected to cause rebound effects. Sufficiency refers to "the right measure", mainly driven by behavioural factors. But what is "the right measure" of indoor thermal conditions? The adaptive thermal comfort approach contributes to all three strategies: 1) to efficiency strategies because of the necessary bioclimatic building design minimising the energy demand and 2) to the application of ecologically sound technologies (locally available materials) as well as the use of renewable energies (consistency). It's major and unique contribution lies in a design allowing more *sufficient* operation of indoor spaces without compromising on occupants' thermal satisfaction through occupant involvement. [1]

Humphreys & Nicol (2018) summarise that humans are found to live comfortable in diverse climates at temperatures between 15 and 35˚C. So the "right measure" of temperature can be diverse and changes with the prevailing climate, facilitating a low as possible temperature difference between indoors and outdoors resulting in a low demand for active conditioning. At the same time, there is more and more evidence, that thermal exposures slightly outside thermal neutrality lead to a wider range of accepted temperatures and can even have positive health aspects (van Marken Lichtenbelt et al., 2009; Kingma et al., 2011; Pallubinsky et al., 2017).

In *permanently or seasonally conditioned* spaces *rebound effects* have been observed diminishing efforts to reduce the effect of energy efficiency measures. They can occur due to a changed temperature regime (extent, e.g. Hansen et al. 2018), a changed conditioning schedule (temporal: intermittent/night set-back or shut-off vs permanent), an extended availability of conditioning systems to more rooms (spatial: entire unit vs selected spaces of a unit) and changed occupant behaviours (behavioural)[1].

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[1] This paragraph is developed from a talk by Hellwig, R.T.: "On the relation of thermal comfort and sustainability strategies in the built environment" held at the "Thermal Comfort and Low Energy Cooling" Symposium organised by CEPT University, Ahmedabad, India on 31. October 2018.

Table 1. Terms, models and criteria used for different building operation modes (EN 15251 2007; ASHRAE St. 55 2017, Dutch ISSO 74, Indian IMAC)

Standard	Free-running	Mixed mode	Conditioned
ASHRAE Standard 55 (2017), EN 15251 (2007)			
Term	- ASHRAE: occupant-controlled naturally ventilated - EN: no mechanical cooling or heating in operation, thermal condition of space is regulated primarily by the occupants operating windows.	- Not defined	- ASHRAE: centralised HVAC systems - EN: mechanical cooling or heating in operation
Model	- Adaptive model	- EN: heat balance model and adaptive model seasonally altering	- Heat balance model
Criteria	- rather similar in both standards - Operable windows to the outdoors operated by the occupants - Mechanical ventilation with unconditioned air may be utilized in addition to operating windows - Other low-energy methods of personal control such as fans, shutters, night ventilation etc. - Near sedentary physical activities with metabolic rates ranging from 1.0 – 1.3 met - Avoid strict clothing policies inside the building	- EN: Common planning practice: combining the heat balance model for the heating period and the adaptive approach for the non-heating period, e.g. according to German sustainability certification systems (seasonal mixed mode)	- Applicable for all buildings - No specific criteria defined
Dutch ISSO 74			
Term	-	- Alpha	- Beta
Model	-	- heat balance model and adaptive model seasonally altering	- heat balance model (heating), adaptive model (transition), heat balance model (cooling)
Criteria	-	- Criteria set through the use of a flowchart - With occupant control - Free-running conditions in non-heating period with operable windows and other adaptive opportunities - Non-strict clothing policy - Actively cooled spaces, cooling not clearly perceivable by occupants	- Criteria: set through the use of a flowchart - Without or low occupant control - Spaces/zones heated in winter or actively cooled spaces, cooling clearly perceivable by occupants
Indian IMAC ((National Code) National Building Code 2017 India, Energy Conservation Building Code 2017 India and (Voluntary Program) GRIHA – Green Building Rating System, all based on Indian IMAC)			
Term	- Naturally ventilated (NV)	- Mixed mode	- Air conditioned
Model	- adaptive model for NV buildings based on Indian data	- adaptive model for mixed mode buildings based on Indian data	- Heat balance model based on ASHRAE St. 55
Criteria	- No mechanical cooling or air-conditioning systems installed - Ceiling fans and operable windows available	- AC is operated only during extreme outdoor conditions	- AC always in operation

From a study in two mixed mode office buildings in Jordan it can be seen, that although perceived control of the occupants and satisfaction was high, the occupant driven room temperatures tended to be constant all year round. The occupants had access to decentralised air-conditioning units with adjustable thermostats (Al-Atrash 2018). Furthermore, it has been found that occupants, due to the adoption of western lifestyle, change e.g. their clothing behaviour towards more garments in warm and humid climates (Karyono 2018). In a heating dominated region it was found that occupants in energy-*inefficient* houses dressed warmer than occupants in energy-*efficient* houses. (Hansen et al. 2018).

Since the adaptive approach is a model of a complex system, qualitatively incorporating many factors it can contribute to a deeper understanding of e.g. the rebound effects described above. Although there remains research work to be done, the adaptive approach can contribute to find design solutions to diminish their impact.

4.2. Challenges in understanding the adaptive principles

The *conceptual* model behind the bivariate relation of indoor operative and outdoor temperature is far more sophisticated. It *qualitatively* describes the impact of influencing factors, which are not part of *calculation* models of adaptive thermal comfort. It is often described as a black box model. Furthermore, some factors of the model are outside the classic educational training of building designers (behavioural adaptation, psychological adaptation). Acclimatisation as one contributor to physiological adaptation might be necessary to communicate as it has not been part of the common understanding of thermal comfort anymore since the 70ies. Some missing links towards a full understanding of acclimatisation processes within humans remain for future research. In the context of overheating, Hellwig (2018) discusses whether using the term adaptation might be the source of reservations among stakeholders towards the adaptive model, as they would expect adaptation being related to a stressful situation.

On one hand, the bivariate representation of the adaptive approach makes it attractive for dynamic thermal building simulation. On the other hand, for building designers in the planning process, who have been trained according to the previous common understanding of steady state, a grey box model incorporating non-quantifiable factors appears to be a source of difficulty and uncertainty when deciding for a building's design.

As thermal comfort has been often explained using the term satisfaction (ASHRAE 2017), there is a need to explain under which circumstances occupants tend to be satisfied as numerous studies have shown. Excellent summaries are available e.g. by the Usable Buildings Trust[2], or e.g. Humphreys and Nicol (1998).

Definitions for conditioning modes depend on how the conditioning practice in a certain country uses the term. Whereas natural ventilation for instance has been used often as a synonym for free-running buildings, in some countries, natural ventilation refers exclusively to the way indoor air is exchanged with outdoor air. Meanwhile, ASHRAE (2017) uses the term *occupant-controlled naturally conditioned* space. The term *mixed mode* building is often used for buildings with a combination of natural ventilation and mechanical conditioning, mainly using air (Kalz and Pfafferott 2010) in alternating operation or seasonally (Manu et al. 2016). EN 15251 (CEN 2007) uses the term *building without mechanical cooling* but defines at the same time that the heating system should not be in operation. Active cooling is used as synonym for mechanical cooling covering both cooling

[2] http://www.usablebuildings.co.uk/

of air and thermally activated building systems. Regionally common definitions may vary, but a guideline can provide an overview over the terms often used and their meaning.

4.3. Climates, seasons, acclimatisation

The main driver of human adaptation in buildings with a certain connection to outdoor climate (i.e. free-running buildings) is the local climate and the seasonal course of the climate. If exposed, humans adapt to the prevailing outdoor climate. Therefore, a number of adaptive comfort models have been developed for different climate zones (e.g. Manu et al. 2016, Toe 2018). A guideline cannot introduce all of them, but a collection of models could be included in a repository and described in a more general way.

4.4. Building design and building services

The standards describe under which operation mode(s) the adaptive model can be applied. The underlying assumption is that the building's design is capable for this operation mode, namely is designed according to bioclimatic/passive design principles. But the standards do not explicitly state this. Due to modern construction and modern conditioning technologies but also due to the lack of suitable bioclimatic/ passive building design for multi-storey buildings the construction and conditioning practices in many regions of the world have become rather different to their traditional approach. Looking at prevalent building designs all over the world it appears to be necessary to include this kind of advice into the standards. So far, there is few examples of passive design features included in the standards as e.g. shutters. But passive design is more: it is about thermal mass, night ventilation, solar protection/shading, use of passive or active solar technologies etc. in a balanced way and where relevant. It is not within the scope of the guideline to repeat passive/bioclimatic design principles for different climatic zones which have been published elsewhere (e.g. Kubota et al. 2018, Manzano-Agugliaro et al. 2015; Zhai and Previtali 2010; Manu et al. 2019), but basic principles need to be introduced in order to show their relationship to the adaptive principles.

The layout of a floor plan, fenestration and positioning of openings, thermal properties of materials used in the envelope or in internal building elements, room height and depth do not only affect the readiness of a building for the free-running mode. These parameters also affect the choice of the conditioning systems affecting energy efficiency and the level of personal control of the occupants. In an open plan office it might be difficult to provide individual access to windows although it might be still possible to implement natural ventilation.

There is a time lag in adaptation of about one week for clothing adaptation for short-term changes in the weather and up to two weeks for physiological acclimatisation to heat for sudden changes, e.g. in a heat wave (Humphreys and Nicol, 1998). The time lag in human adaptation to changing outdoor conditions is represented in the calculation of the outdoor running mean temperature and buildings designed according to the adaptive principles should therefore provide sufficient buffer (Hellwig 2018) to allow occupants to adapt. The ability of a building to buffer is highly linked to the predictability and reliability of a building's thermal behaviour which is an important building property for occupants (Bordass and Leaman 1997).

Conditioning practices have been changing since the invention and broader implementation of central conditioning systems and there is a clear tendency to condition entire spaces as well as conditioning over long periods. We should therefore consider that people have likely adapted to their often experienced indoor environments. The temperature experienced in these spaces is likely the typical set-point (design) temperature according to a country's standards or regulations. They experience a "normal" environment (Humphreys and Nicol 1998). This does not necessarily mean that they cannot be comfortable at changed temperatures but if changes in the building's temperature operation are intended (in order to improve energy-efficient building operation) this would require an appropriate communication of the topic.

4.5. Personal Control, user behaviour and automation

There are several recent activities (e.g. IEA EBS Annex 66) and review papers regarding the state of the art on behaviour and control. Behaviour has been identified to be as important as the energy efficiency quality of the building design (Gram-Hanssen, 2013). A huge variety of different adaptive behaviours exists, which people can choose to make themselves more comfortable. Schweiker et al (2018) categorised them into physiological, individual, environmental and spatial adjustments. Table 2 shows conceivable adaptive actions categorised according to how they change the thermal environment or their perception. Regarding the impact of control on comfort perception or satisfaction, a conceptual model was presented in Hellwig (2015), showing that social aspects, expectation (Brager and de Dear, 2003) and psychological factors can support or limit adaptive opportunities. The degree of control was identified in many studies as a main driver for thermal comfort (e.g. Leaman and Bordass 1999, Schweiker et al. 2018).

Research has shown that occupants' satisfaction decreases with a higher number of persons in the same room, which can be attributed to a lower degree of perceived control and higher social interactions necessary (Hedge et al., 1989; Duval, Charles and Veitch, 2002; Marquardt, Veitch and Charles, 2002; Wagner and Schakib-Ekbatan, 2011; Al-Atrash 2018). As an example, Schweiker and Wagner (2016) showed that the number of occupants in a room with elevated temperature alters the adaptive opportunities used by occupants: less ceiling fans and blinds were used in four person offices compared to single person offices, but more clothing level adjustments occurred in larger offices. In addition, perceived control and neutral temperature decreased with a higher number of persons. A meaningful layout of work spaces can provide individuals with sufficient space for adjustments and privacy.

In a guideline, some basic principles for designing for control should be implemented. There are still common misunderstandings in the interpretation of personal control among planners regarding the amount of control, the seriousness of this topic and the level of information needed by occupants (Hellwig and Boerstra 2017, 2018). It might be supportive to include an exemplary list of design decisions or operational practices *not* conducive to high perceived control as they impose restrictions to occupants.

Hellwig (2018) points out that behavioural actions might not only help to adapt to a stimulus but also to remove this stimulus, e.g. by using technological means; hence if the technology used has enough capacity to fully remove or avoid the stimulus physiological adaptation (acclimatisation) to the deviating conditions will not take place. In order to avoid this, energy efficient solutions can be chosen. Provided the users are conscious about the "green" performance of their building and understand its importance, the controls are usable and they got factual information on how to make use of certain technological means to adapt, they will be able to use their building in the intended way (Leaman and Bordass 2007).

In this paper we have not included personalised comfort systems as this will be the outcome of another activity of Annex 69.

Table 2. Conceivable adaptive actions in response to warmer or cooler than previously experienced environments, adopted from Humphreys and Nicol, 1998 and Nicol and Humphreys, 2018 and slightly adjusted and amended

categories of adaptive actions	adaptive actions in response to cooler than previously experienced environment	adaptive actions in response to warmer than previously experienced environment
regulating the rate of internal heat generation	- increasing the level of activity - eating a meal - increasing muscle tension and shivering	- adopting siesta-routine (matching level of activity to diurnal temperature course) - reducing the level of activity - eating less
regulating the rate of body heat loss	- adding clothing or blankets - curling up or cuddling up - holding a warm cup of tea	- adopting an open posture - taking off some clothing - opening a window for getting a breeze - sweating - drinking a cup of tea (induces sweating more than compensating for its heat) - Hand fan
regulating the thermal environment	- insulating the loft or wall cavities - improving the windows and doors - adjusting or turning down the thermostat or lighting a fire - notifying the management	- opening a window - switching off heat emitting equipment not needed - activating shading in front of a window - use night time ventilation - adding shading for walls - ventilate the attic space - switching on a fan - adjusting thermostat or turning down the air conditioner
selecting a different thermal environment	- finding a warmer spot in the house or going to bed - visiting a friend or going to the library - building a better house (longterm way of finding a warmer spot)	- finding a cool spot - going for a swim - visiting a friend (hoping for a cooler temperature) - building a better house, e.g. making use of thermal mass or an appropriate window to wall ratio (longterm way of finding a cooler spot)
modifying the body physiological conditions	- vasoconstriction (unconscious) - acclimatising: letting the body become more resistant to cooler environments - emigrating	- vasodilation (unconscious) - acclimatising: letting the body adjust so that they become used to warmth - emigrating
modifying expectation	- letting the mind become more resistant to cooler environments	- letting the mind adjust so that it becomes used to warmth - relax

4.6. The user's role, expectation management and user involvement

Fundamental to the adaptive approach is the role of the user: "*If a change occurs that produces discomfort, people tend to act to restore their comfort.*" (Humphreys and Nicol 2018). Many building professionals' subjective perception is that occupants' behaviour would be random or not logical, and in many cases contradictory to a low energy use of a building. They define the user's role according to their self-image as professionals, marketing strategies for new building technologies or design solutions promising increased comfort through *comfort provision*, which literally assigns a passive role to users (Hellwig 2018).

Discomfort occurs when expectations are not met. It is important that a user has realistic expectations which are consistent with the performance of the building after the building is commissioned, otherwise this can lead to disappointment (Usable Building Trust[2], Hellwig and Boerstra, 2018). A source of misunderstanding has been the comfort classes/categories introduced in some standards (A, B, C or I, II, III). Although explained e.g. in EN 15251 as the level of expectation they are often interpreted as level of quality. For example, sustainability rating systems such as the German DGNB/BNB award more credits for class A/category I buildings. Class A/ category I stands for high expectation and is meant to be applied for very sensitive people, vulnerable groups who might be sick or restricted in their possibilities to adapt either because of missing ability to sense temperature (as e.g. for dementia) or because of disabilities in changing clothing without the help of others. As could be shown by Arens et al. (2010), no relative satisfaction benefit could be found for class A/category 1 buildings.

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. This avoids misunderstandings, minimises misconceptions and enables participation. In the UK, a process has been developed called "Soft Landings" to help implement structural and technical measures for sustainable buildings ("The Soft Landings Framework"[3]). Similar processes exist in other countries.

It is important for building operation not to discourage the user from taking control actions. For overall satisfaction, it is supportive if an occupant – to a certain degree - feels responsible for the indoor climate at their workplace. Otherwise, the occupant has to rely too much on a building's autonomic behaviour or changes to be implemented by the facility manager which can be stressful as it is *indirect* control (Johnson, 1974). To facilitate satisfaction of the users an appropriate complaint management of the facility management of the building is desirable. This includes that complaints of users are taken seriously and comprises an appropriate feedback.

4.7. More contextual factors: constraints

There are some constraints, which should be considered when designing buildings and considering bioclimatic/ passive design strategies as they can limit the opportunities for a functioning adaptive design:

- Outdoor air pollution, and noise
- Missing solutions for natural ventilation preventing disease transmitting insects from entering indoor spaces
- Urban heat island effect: affecting the effectivity of natural ventilation in non-air-conditioned spaces
- Space scarcity in highly populated areas limiting opportunities to design for natural ventilation
- Increased occupants expectation towards temperature (culture, modernity, lack of adaptation to outdoors, learnt attitude)

[3] www.softlandings.org.uk

- Technology challenges, e.g. typical air-conditioners set-point control is based on air-temperature

These challenges can probably not be solved by an improvement of a standard or a guideline alone. For several cases a guideline may be supportive in developing new solutions for some items. It can also be seen that many of these constraints are related to highly urbanised areas in the more extreme climates.

5. Outlook - Outline of a guideline

In this paper, we reported on the challenges and gaps in using the adaptive thermal comfort approach to lowering the energy use in buildings. We identified those areas, which need to be addressed in future standards and guidelines on adaptive comfort. We have done so based on our understanding that human thermoregulation and the physical principles of heat exchange between humans and their environment form *one* basis of adaptive thermal comfort, yet do not represent the *complete set of variables* of this comprehensive approach towards thermal comfort. Although not quantifiable or sometimes not solely in control of building designers, and therefore identified being a source of uncertainty for them, *contextual factors* play another *major role*. Therefore and as expressed earlier by Humphreys and Nicol (2018): "The adaptive model does not fit easily into the current way of expressing standards for thermal comfort".

We identified the following specific objectives for the guideline within Subtask B2: 1) To improve the overall understanding of the adaptive principles; 2) To explain the adaptive principles' relation to building energy use; 3) How to interpret the adaptive model in building practice; 4) To include advice for heated or cooled buildings into the guideline, not limiting the application of the adaptive thermal comfort concept to free running buildings, especially, how to use the adaptive principles in permanently or long-season conditioned spaces.

For the guideline currently under development we are seeking to find a balance between providing concrete guidance on one hand and on the other hand enhancing creative thinking to be open for new low energy facilitating solutions, not limiting solution to what we know currently or are used to. Another challenge lies in adequately considering the requirements resulting from our diverse climates, acknowledging both todays and future climates or seasons, which may not allow for a free-running mode at all times, but facilitating free-running modes in building operation as often as possible. We have not discussed personalised comfort systems (PCS) in this paper as they will be an outcome of another Subtask of Annex 69 but will be included in the final guideline.

The guideline will address practitioners, property developers, sustainable certification consultants and councils. As the guideline is meant to enhance the knowledge on the application of the adaptive principle, it should provide supportive exemplary solution from practice and different climates. It will form the basis for an improved description of criteria for the application of the adaptive approach in standards. It will also be a useful source of knowledge and guidance for educating future building professionals. The authors plan to collect feedback on their draft guideline from building designers and other stakeholders.

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Bahrain Parks: Baselining change for urban resilience

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Abstract: Over the last few years, Bahrain has been increasing the number of urban parks in a bid to improve the quality of life and address public health issues related to physical inactivity; while also providing for the accelerated population growth and increasing the urban resilience of the main cities. With increased volume come the inherent difficulties around planning, design, maintenance, and management. We conducted a comprehensive nation-wide audit of parks, made it available on an online platform and accessible to all stakeholders, on an e-governance approach. In this paper, we outline the role of the project in establishing a baseline of the status quo which a) supports the creation of a coordinated strategic plan for the development of parks, b) provides empirical evidence for decision-making, and c) allows for measuring future progress against this baseline(s).

Keywords: Bahrain; extreme climate; urban resilience; sustainable development; built environment.

1. Importance of Parks for Bahrain

The Kingdom of Bahrain is located centrally off the southern shores of the Arabian Gulf. Rainfall is irregular with a mean of 70.8mm, exclusively between November and May. There are two main climatic periods, from June to September and from December to March, separated by two transitional periods April/May and October/November. The average temperature from June to September is 35.1C and 18.0C from December to March. The maximum relative humidity is above 77% throughout the year, reaching an average of 88% during the winter months; while the minimum average during the summer is 39% (http://www.bahrainweather.gov.bh/web/guest/climate). Bahrain has a 10-hour daily average of sunshine. The highest point is located in Jebel Al Dukhan hills, 134 meters above sea level at the centre of the mainland. With warm temperatures during four months of the year, the parks, with their vegetation, shade, evapotranspiration, and low mass, are the coolest outdoor places, although this has not yet been quantified.

Bahrain Vision 2030 aims to build a sustainable urban society, through principles of sustainable planning and management, enhancing the connectivity of green areas and the diversity of projects and transportation systems. Regarding the environment and urbanization issues, they aim to address climate change, increasing the use of renewable energy resources, and reducing greenhouse gas emissions(ONU HABITAT, 2016) which parks actively contribute to (Janhäll, 2015).

Parks are also frequently used for formal or informal physical exercise. In Bahrain, this is relevant because, in 2010, the National Non-communicable Diseases Risk Factors Survey 2007, showed that 33.4% of the Bahraini population is overweight and obese; with hypertension prevalence of 42.7% among participants; hyperglycaemia occurs in 13.5% of the community; and hypercholesterolemia incidence of 40.6% (Ministry of Health, UNDP -

United Nations Development Plan, 2010). The report also specifies that 57.1% of the country's population does not engage in any physical activity in their leisure time. The high indices of physical inactivity have been confirmed more recently (Pinelo Silva and Akleh, 2018). The role of parks on the levels of the physical activity of the population has not been quantified, but it is empirically evident when visiting the parks that they are frequently used to perform physical activity. Despite the apparent importance of parks for Bahrain, there was no systematic and readily available data on them, which made the study of this key urban infrastructure difficult. The project Bahrain Parks responds to that need.

Crucially, with their lower mass and low radiance properties, parks are instrumental for the reduction of the heat island effect(Susca, Gaffin and Dell'Osso, 2011)(Santamouris, 2014), and a safety net for relative comfort during energy outages, where the lack of active climatization in buildings which may render some temporarily inhabitable.

2. Introduction: Bahrain Parks

Bahrain has 155 public urban parks (including parks, gardens and walkways), many of which have been built in the last ten years, to provide for a rapidly growing population. With the growth of the number of parks, the logistic and financial burden of their planning, design, and management is also increasing. Furthermore, while some parks are incredibly successful, measured by the number of visitors, others are less so. Moreover, there are occasional reports of vandalism, which add unnecessary costs. The mounting challenges have prompted a team at the University of Bahrain to conceptualize and develop the platform Bahrain Parks, which supports the local and central government in the planning, design, and management of parks. The project Bahrain Parks is an initiative that aims at thoroughly documenting the urban parks of Bahrain, allowing for the measurement of their impact on society and the environment. Ultimately, this promotes a healthier and more equitable society and a better environment. Since 2016 we have been conducting a comprehensive nation-wide audit of the public urban parks of Bahrain. The data, collected through maps, satellite imagery, and site visits, has been stored in a centralized database and made available to all stakeholders via several cloud applications (Pinelo Silva, 2016; Pinelo Silva et al., 2018). We have collected data on all 155 parks across the four municipalities, covering the whole country. The data focuses on a quantitative description of the built environment, such as features that are of interest to plan, design, and manage parks. Additionally, the cloud platform offers the users the possibility to rate the parks and provides the municipalities with the functionality for counting users.

The comprehensive and standardized dataset containing the full list of parks of Bahrain will allow for the statistical analysis of the role of design elements in the success of parks based on the number and frequency of users and ratings. Analytical techniques such as multiple regression can be applied to the dataset to create information for the planning and design of parks. Such information can then be used to improve the parks continuously and iteratively. By establishing baselines of usage and ratings and stimulating continuous measurements, the dataset makes it possible to predict and then measure the impact of design iterations on usage and scores. As the knowledge about design increases, the differences between estimated and measured effects shall diminish, reflecting the growth in the effectiveness of the design process.

Figure 1 (a) Al Andalus Park, Capital Municipality; (b) Prince Khalifa Bin Salman Park, Muharraq Municipality; (c) Al Hoor Garden, Northern Municipality; (d) Khalifa Al Kubra Garden, Southern Municipality.

In this article, we describe the motivation, goals and components of the project Bahrain Parks, a cloud platform within an e-governance approach, for the efficient and participative management of the infrastructure of public urban parks in the Kingdom of Bahrain Al-Nabi, M. (2012), which baselines the status quo for the assessment of change. We also refer to the local context for the creation of the project, followed by a description of the advantages of creating a comprehensive dataset of parks. We then describe the main advantages that the platform brings directly to stakeholders, followed by the components of the initiative, technology, the quantification of usage, and user stated-preferences. We briefly discuss the first attempts to include the tool in existing workflows, debate the initiative within an e-governance framework, before cocnluding by referring to future work.

The Kingdom of Bahrain has an area of approximately 765 square kilometres and approximately 155 public urban parks and gardens. Parks are planned and built directly by either the Ministry of Works or one of the four Municipalities. Therefore, there are several teams, in different institutions, who are responsible for planning, designing and maintaining the public parks. Such situation is typical in other countries, often with hundreds of teams involved with building and managing the infrastructure.

3. Goals and Background

The project aims for the knowledge-driven, sustainable and socially inclusive development of the built environment. Our goal is to be the most compregensive and up-to-date source of information on the parks in Bahrain, the go-to platform of choice for both professionals and the general public.

Overall, in Bahrain, the parks share a mix of successful and unsuccessful results, measured by their use. Although park usage is not systematically measured, it is empirically evident that some parks are vastly more successful than others. While some are underused, others are so popular that they often generate more traffic than the infrastructure is programmed to support. Both extreme cases are undesirable. Underuse indicates a waste of both the resources and the opportunity to create a successful park. Often, such cases seem to lead to the lack of maintenance and the decay of the infrastructure, which has the potential to spread through the urban environment and has been known to attract improper uses. On the other hand, overuse penalises both the users of the parks and the surrounding areas. While both situations are detrimental, frequently, the reasons behind success and failure are not clear. Such situation causes concern to the governance and the institution that is ultimately responsible for the built environment; the Ministry of Works wishes to address it to optimise the use of resources in serving the population.

Apart from providing users with socialising and leisure opportunities, the parks play other key roles in the sustainability of the urban environment. For example, the porosity of pavements facilitates aquifer recharge and the management of stormwater. (Baran *et al.*, 2014) The abundance of vegetation breaks down noise pollution(Batty, 2013), and it contributes to the quality of the atmosphere by reducing airborne particles (Coley, Sullivan and Kuo, 1997). Through its relatively low mass (in comparison with concrete and other traditional building materials) and albedo, the vegetation decreases the temperature at the local scale thus playing a part in the mitigation of the heat island effect (Evenson *et al.*, 2009). Vegetation also contributes to the local biodiversity by creating a habitat for species that would otherwise not exist within the urban environment (Holtan, Dieterlen and Sullivan, 2015).

In the particular context of Bahrain, with relatively warm temperatures during three to four months of the year, parks, with their vegetation, shade, evapotranspiration, and low mass, are the coolest outdoor places, although this has not yet been quantified.

Measuring the contribution of parks to the urban ecosystem on the aspects mentioned above would require detailed information regarding the parks. The Department for Desert Farming at the Arabian Gulf University approached us for the inclusion of data beyond our initial plan. For example, the inventory and layout of the vegetation of a park would allow for estimating its role regarding filtration of air pollutants. Quantifying the green waste per park (and therefore for the whole stock) could generate information to support the first national strategy for the transformation of waste into a resource, eventually creating an industry. We share the view of Scott Campbell in believing that environmental protection, economic development, and social justice, three goals of planning, can be perspectives of the same reality and not mutually exclusive aims (Janhäll, 2015).

4. A Comprehensive Grasp on the Parks

The study of parks and their contribution to a sustainable urban ecosystem, whether social relevance or environmental impact, could take two complementary forms: a holistic study of all park characteristics on a case-by-case basis or the study of features of the park stock on aggregate. Both avenues of inquiry require data. As is often the case, this is not readily available. Furthermore, the second avenue of enquiry, the aggregate study of parks, require data that are consistent across the sample. The consistency of data meaning that the same data are available for all parks, measured and processed through the same methods. With the initiative Bahrain Parks, we are creating such a database not of a sample of parks, but of all the public urban parks in Bahrain. Furthermore, we aim to make the full dataset publicly available.

To make the database available in a way that has visibility and is meaningful, we make it accessible through a Web application. The application delivers the data in a straightforward fashion to each of the different user groups of stakeholders. While experts can export the whole dataset and analyse it at will, the application also offers users basic tools to explore data. For users who do not wish to study the data in an active way, algorithms create listings of information ready to be used. The general public can, for example, consult a geographic list of the top ten family-oriented parks. Nonetheless, the application is being prepared to be used by planners, designers, and maintainers of parks in their daily activities, with minimal effort, largely outweighed by benefits.

One other aspect of the application is that it also allows for the creation of data. For example park ratings, user counts, vegetation surveys and logging of green waste are made directly through the application. Such approach contributes towards data availability, the easiness of creating data, and the standardisation of methods and procedures.

The availability of data from all parks, its homogeneity, and integration in one single database creates unique conditions for analysis. The readiness of the data through an application that guides users to simple analysis leverages the intervention of planners, designers and park managers. The application is created to be easy to use and provide immediate feedback. Moreover, since all stakeholders are familiar with the database and the application, this facilitates the transfer of knowledge between planning and design teams at the different institutions. Similarly, when researchers publish the results of elaborate studies not carried out by the stakeholder agencies, the teams at these organisations are familiar with the data used, and can eventually assimilate the interpretation of the results more quickly. Furthermore, being able to access the data directly, the teams have the possibility of quickly check the situation of their stock by referring to the indicators provided by research.

The comprehensive and consistent dataset containing the full stock of parks will allow for the statistical analysis of the role of design elements in the success of parks based on the number and frequency of users and ratings. Statistical techniques such as multiple regression analysis can be applied to the dataset to create information for the planning and design of parks. Such information can then be used to improve the parks continuously and iteratively. By establishing baselines of usage and ratings and stimulating continuous measurements, the dataset makes it possible to predict and then measure the impact of design iterations on usage and ratings. As the knowledge about design increases, the differences between predicted and measured effects shall diminish, reflecting the growth in the effectiveness of the design process. The method for such development must not be a blind search for correlational phenomena but the development of theoretical propositions (Batty, 2013)(Kuo, 1998)(Kweon, Marans and Yi, 2016) The data provides the opportunity for the testing of the new hypothesis. A caveat of such a process, as highlighted by (Batty, 2013) about big data, relates to the fact that despite the potential of covering a broad range of time-spans, in the beginning, it lacks long-term data, therefore excluding most existing urban planning theories. Simultaneously, this opens the possibility for a focus on the short-term, which must be carefully considered (Batty, 2013).

The dataset and the applications presented here does not constitute big data. For now, it does not have the tabular dimensions typically associated with big data (loosely defined as containing over one million rows), nor is it continuously fed by sensors in real-time. However, it has the possibility to become so. First, the application registers all events with a timestamp, which allows for endless time-span aggregations (a typical characteristic of big datasets). Second, we can automate the manual component of most semi-automated features with the use of sensors (another hallmark of big datasets). We see Bahrain Parks as a means of gradual transition between virtually no data to a big data scenario.

5. Tailored and Augmented Information for Stakeholders

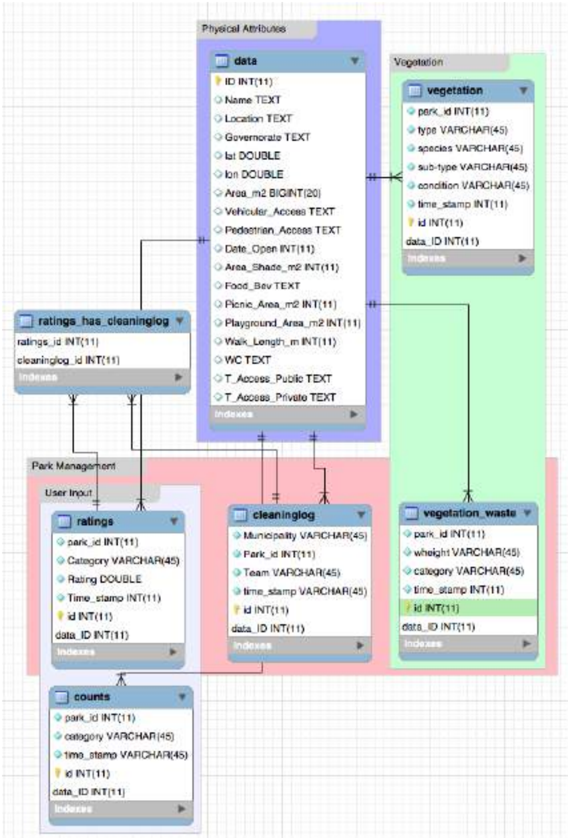
The dedicated nature of the data towards specific goals, its digital format, and centralisation in a unique database allow for ease of use and simple delivery of content. It also permits the provision of augmented information. Through automated methods of analysis and sophisticated operations, users without formal statistical knowledge can get access to information that is more reliable than the data per se. For example, when a park manager consults park usage, the application can deliver results by eliminating outliers, and in the case of small sampling, produce Monte Carlo simulations to improve the reliability of averages. As another example, a designer can, with a few clicks, consult the design features of one park (or any chosen set), and quickly plot the relationship between any two (numerical) variables. Such insights are helpful during design but were not readily available.

6. The Components of Bahrain Parks

The project has three spheres: a) database, b) a suit of three web applications (plus one website), and c) social media, which we describe below. The database (see Figure 1) holds the data related to the parks. Dasu and Johnson (Johnson and Dasu, 2003) report that 80% of the time spent doing data analysis is used to clean and prepare data. Such would not be acceptable for the purpose of the project, and therefore we follow the tidy data protocol as defined by Hadley Wickam (Wickham, 2015), where each variable forms a column, each observation forms a row, and each type of observational unit creates a table. Tables structure the data as they relate to each other through the key 'park id,' forming a relational database (schemata in Figure 1), as described by Codd (Codd, 2002).

7. The Database

The main table, as per Figure 2, consists of manually gathered park features that are relevant to the planning and design of parks. On this table, each row represents one park and has a unique key (identifier). Each column represents one feature (such as the total area of the park, the area shaded, picnic area, playground area, access by public transport, parking, the length of walkways, the presence of toilets, food and beverage facilities, latitude, longitude, location, municipality, opening date, and name). The list of variables is to be expanded based on research outputs and requests from stakeholders. The other four tables follow a similar structure but hold data collected semi-automatically through the application. The four tables are a) user rating, b) user counts, c) vegetation, d) green waste. The table 'user rating' consists of users' votes on five categories: vegetation, amenities, conservation, and schedule and follows the tidy data protocol. Each row consists of one vote, and the columns refer to a) the park ID, b) the rating value (0–5, where five is best), c) the category to which the vote refers, and d) a timestamp. The table 'user counts' is a log of the users spotted at each park. On this table, each row corresponds to one user. The columns refer to the a) park id, b) user category (alphabetically: blind, child, man, senior, wheelchair and woman), and c) timestamp. We address the rationale behind counting and categorizing users below. The table 'vegetation' consists of an account of all such elements of each park. On this table, each row corresponds to one element, such as an individual tree, shrub, planter or grass patch. The columns contain information regarding a) park id, b) type, c) species, d) subtype, e) condition, f) timestamp. The table `vegetation waste' is a log of categorized green waste disposed of at each park. Each row corresponds to one load (for example, a bin bag). Columns contain information for each load, namely the park id, the weight, and a category (grass, green leaves, and dry leaves). The inclusion of timestamps along with data logging, such as user counts, waste removed or ratings, allows for time-wise analysis as well as for the aggregation of data based on different time-spans. This flexibility is advantageous because it makes the data useful to study both different phenomena based on time references, and also the same phenomenon in different time-scales.

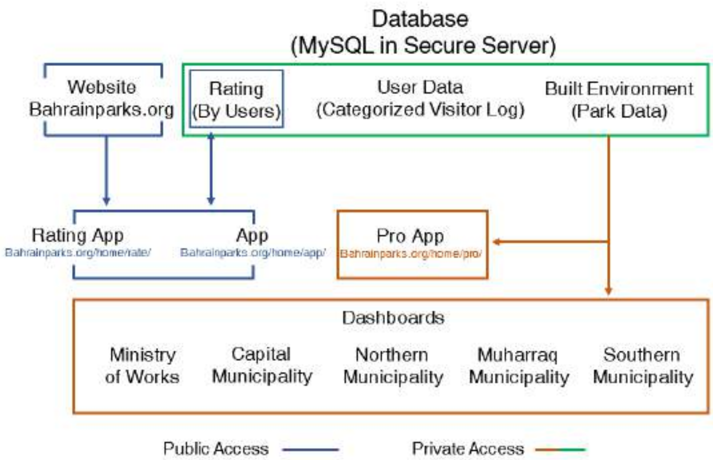


8. Suit of Web Applications

The online presence of the initiative consists of three publicly accessible websites: www.bahrainparks.org is a static application that briefly introduces the project; www.bahrainparks.org/home/rate/ is a secondary, dynamic (data-driven) application that allows users to easily rate a park. The web application dedicated to professionals is available at www.bahrainparks.org/home/pro/. This app shares some tables with the app dedicated to the general public (described below), such as documentation and About. One of the features that distinguishes it is the tab 'Professional', which aims at the planners and designers of parks. It provides the most comprehensive access to the database. It supports filtering/grouping of parks based on features such as municipality (governorate) and location, among others. It also offers tools for instant analysis such as mapping, accessing tabular data, plotting variables such as XY, and quick histograms of individual variables. The features available are not comprehensive and are under constant development. These are not, however, 'researcher' tools in the proper sense of the word, but a device to provide immediate access to the data in an insightful manner, and to stimulate the emergence of research questions. To provide a country-wide sense for the coverage of urban parks, which might be useful for planning, there is a heatmap of the density of park area. The app Pro also contains tabs with functionality dedicated to counting users, as well as park maintenance checklists, both for use by the municipalities. The web application that serves the general public is available at www.bahrainparks.org/home/app/, and it has been organized based on types of search with different levels of data filtering. The homepage is depicted in Figure 3. Following is a description of the tabs available at the time of writing (July 2018). The tab 'Home' introduces the application by briefly describing public parks and mapping the stock on the database. It also provides insight on the social media feeds. The second tab, 'Families', just lists the top 10 parks that have the right attributes to be considered adequate for families. The criteria are car access, parking, walkway, children playground, picnic area, shade, food and beverage facilities, and toilet facilities. The application algorithmically calculates the list of parks (truncated to ten) to include in the suggestion to families based on the criteria described. The tab 'Rating' illustrates the scores in a ranking that aims at instigating healthy competitiveness between park managers and municipalities. It also has a link; our dedicated rating application is available at www.bahrainparks.org/home/rate/. For ease of use, this application is exclusively dedicated to rating. Ratings can also be plotted by park, by period (via date filtering), and by rating category (as described below). The application also makes the ratings available on a table on the relevant sub-tab. The tab 'Explorer' allows any user to filter the parks based on six criteria such as name, and amenities such as a walkway, playground, WC, picnic area, food, and drink. The tab, 'Documentation' (available on Pro app as well) provides general information about the project and the data, such as the variables available, sources of data, and units. This tab also contains information about the how the application creates (algorithmically) the other variables based on data input. A full list of parks available in the dataset completes the tab, and is organized both alphabetically and by 'park id.' The tab, 'About,' explains the genesis of the project as well as the main goals and objectives; it also names the team and other contributors to the project. The tab, 'Get Involved,' provides the user with the opportunity to express their willingness to contribute to the project, as well as simply provide feedback or point out inaccuracies in the data. The tab 'Park Manager' allows park managers to carry out categorized counts of park users. A feature under development by request of the municipalities is a way of measuring the performance of park cleaners based on the user ratings. Another feature under development as requested by the municipalities, if a digital checklist for park maintenance, with automatic weekly, quarterly and annual reporting.

9. Social Media

The social media streams are part of the project in the sense that they stimulate user



engagement with the parks and with the application. We strive to keep the feeds educational as well as informative. Examples of educational topics are health benefits of exercise and the social and environmental benefits of parks. We have been hosting a photo competition with the parks as the theme, which has been running via Instagram. In the medium-term, we aim at amplifying the role of the social media by analysing its data, semantically and geographically.

In this paper, we present a preliminary description of the infrastructure of parks based on the exhaustive dataset made available by the main Bahrain Parks application, which can be found at http://www.bahrainparks.org. Although there might have been isolated studies of individual parks, it is the first time that the entire collection is indexed, and data collected based on the same model and standards. This unprecedented effort presents a first and unique insight into the state of affairs of the park infrastructure of Bahrain. On this short paper we present the work in progress of towards the comprehensive description. After a brief introduction of the Bahrain Parks project, from which the data presented here is drawn, we summarize the social and environmental relevance of parks. The central part of the paper provides a quantitative description of the parks, accompanied by a qualitative description of the context. The description is reported at the national and the municipal levels. We terminate with a comparison of the parks between municipalities and highlight how the local context might influence the differentiation. Figure 1 depicts one park in each of the four municipalities.

10. Data Framework

The project has three domains: (a) database, (b) two web applications (plus one website), and (c) social media. The database holds the data related to the parks. The framework of the relational database consists of five tables that follow a similar structure. Each variable forms a column, each observation forms a row, and each type of observational unit creates a table. Tables structure the data as they relate to each other through the key 'park id,' forming a relational database. The team collects the park features that are relevant to the planning and design of parks.

The main table in the database has 20 columns: ID, name, location, governorate, geographic coordinates, opening date, park area, vehicular access, pedestrian access, shaded area, foods and beverages, picnic area, playground area, walk length, WC, public access, private access, lawn area, boundary, and sensible enclosure. The list of variables is to be expanded based on research outputs and requests from stakeholders. The application is being prepared to be used by planners, designers, and maintainers of parks in their daily activities, with minimal effort, largely outweighed by benefits. All the stakeholders are familiar with the database and application, which facilitates the transfer of knowledge between planning and design teams at different institutions. Description of each criterion is available in the application (Pinelo Silva et al., 2018). The other four tables follow a similar structure but hold data collected semi-automatically through the application. The four tables are (a) user rating, (b) user counts, (c) vegetation and (d) green waste. User rating is active since January 2017. A pilot test on user counts occurred in one selected park for one year in chosen days, weekdays and weekends. The database has input variables/attributes and variables that are algorithmically created by the web applications. Variables are described on the applications, as described in (Silva, Mestarehi and Lamela; Pinelo Silva, 2016b).

11. Park Rating

There are spatially-fixed and non-modifiable aspects that can determine the potential and the frequency of park use, such as their location and size, that should be taken into consideration when analysing the park usage (Zhang et al,. 2011) (Kweon et al., 2016). There are also modifiable factors, such as the ones that an intervention can change through new design solutions or policy, such as safety, park maintenance (conservation and cleanliness), availability of amenities, distribution of vegetation and suitable schedule (Washburne & Wall 1980) (Kweon, Marans and Yi, 2016). The rating framework allows for the assessment of the modifiable factors, which can significantly influence participation in outdoor activities and park usage.

Vegetation is an aspect of the rating. Studies suggest that users, primarily female, tend to have higher levels of MVPA (moderate-to-vigorous physical activity) in shaded trails and paths (Baek *et al.*, 2015). Others have showed that treed areas are more frequently used than treeless spaces, and the presence of trees is associated with a greater number of simultaneous users (Coley et al., 1997; Holtan et al., 2015; Kuo et al., 1998; Kweon et al., 2016). The second variable rates amenities. Whether the park has facilities, such as sitting areas, shading, WC, playground, sports fields, busy as well as quiet areas. Conservation is the third parameter to be rated - does the park need maintenance work? The fourth parameter assesses the park cleanliness. The last variable is opening hours and reflects if the park schedule is convenient for daily use.

Park ratings are other baselines, which can be used for measuring the effectiveness of both management and design changes as part of pilot testing, integrated in evidence-based design processes.

12. Methods

We analyzed two complementary sources of data and tested the results for statistical significance.

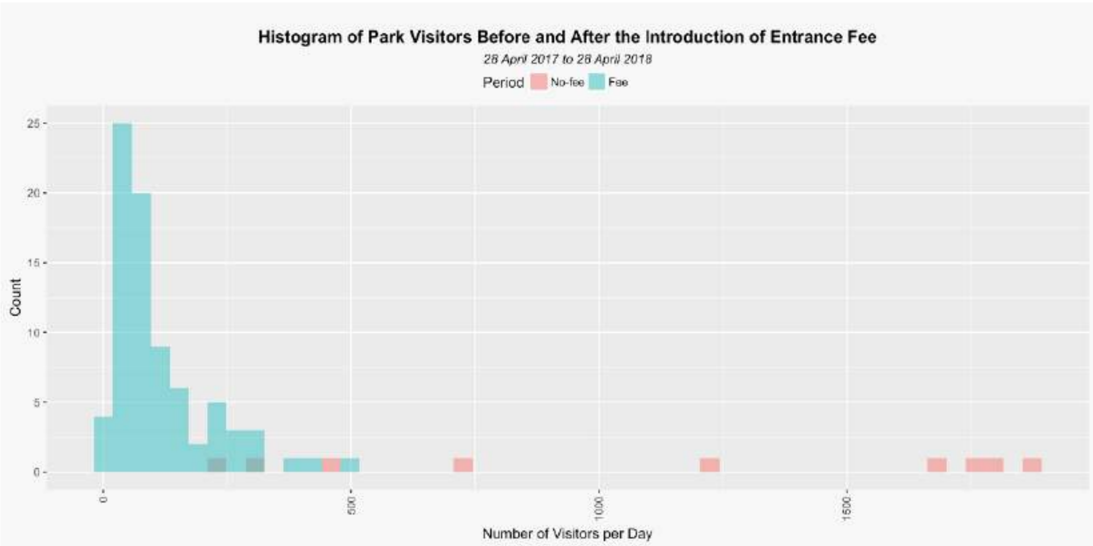
The project Bahrain Parks carried out visitor counts at the park for a whole year, from 28 April 2017 to 28 April 2018. The entrance of each visitor through the main (northern) gate during the counting periods, was counted as a timestamped event via one of the Bahrain Parks web applications (www.bahrainparks.org/home/pro/). The presence of each visitor was recorded by a trained observer by taping on a tablet. The observer had unimpeded view of the entrance and was unobtrusively and inconspicuously placed. Initially, the weekly counting period was 18:00 to 23:00 (evening opening hours) on Fridays. However, on Friday the 07 July 2017, the municipality introduced entrance fees and women-only days (every Friday). From this date, counts took place on Fridays and Saturdays. The evening opening hours on Saturday are from 18:00 to 21:00, which was the counting window used on that day.

This study reports on the following 51 weeks of data (week number-year), which capture the yearly pattern of park use: 17-2017 through to 34-2017, 36-2017 through to 48-2017, 50-2017, 51-2017, 52-2017, 1-2018 through to 17-2018. Data was not collected on the weekends 35-2017 and 49-2017 due to unexpected circumstances. Data collection took place after one successful day of pilot testing, completed after the training of observers. The total tally is 19,745 visitors (events), in six categories: Visually impaired[1], Child, Man, Senior, Wheelchair, and Woman, as in Table 1. Note that throughout this work, the comparisons between the volumes of visitors on Friday and on Saturday, are based on the number of visitors normalized by the number of hours counted per day (visitors per hour, rather than the overall number of users). This is due to the fact that the counting periods were different, with five hours on Fridays and three on Saturdays.

Category	Count	Percentage
Visually impaired	6	0.03
Child	10071	51.01
Man	4198	21.26
Senior	413	2.09
Wheelchair	22	0.11
Woman	5035	25.50

13. The effect of the introduction of entrance fee and women-only days

The exploratory analysis of the 19,745 timestamped park visits on record over a period of one year, firstly revealed, somehow surprisingly, that the distribution of park users is not



normally distributed. As illustrated by Figure 4, altogether, the data is positively skewed.

1 Throughout this work, the category Visually Impaired, is frequently referred to in plots as ‘blind’, despite the differences in meaning between the two terms. There are several reasons for this, including the degree of familiarisation with the word by all users of web applications, for providing emphasis to the category, as it comes higher up in alphabetic lists, and for simplification of computer programming. We embedded this design throughout the Bahrain Parks Platform as a means to develop awareness of this group, which is particularly sensitive to the conditions of the built environment.

Statistical analysis of the timestamped visitor logs allows us to measure the effectiveness of the measures to reduce park visitors. Cross-sectional surveys, for example on physical activity in the park, may complement the longitudinal analysis of the weekly year-long visitor log. Opportunities for learning how to deal with previously unavailable data, on the selection and use of data, and on methods to link different data streams.

At this stage, the data is collected manually by the team, by meauring areas based on satellite imagery and maps, by visiting the parks, and by consulting with the municipalities. User data is gathered presentially at the parks, using the application to log in users as they are seen entering a park. User ratings are collected through the dedicated app that is available to use by the general public. User ratings are not inserted by the research team, but directly by park users.

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A socio-technical performance evaluation of green office buildings in the composite climate of India

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Abstract: India has one of the largest registered green building footprints in the world, yet there are limited studies investigating whether actual energy use and occupant satisfaction in such buildings is meeting expectations. This paper uses a socio-technical building performance evaluation (BPE) approach to assess the actual energy and environmental performance (during monsoon season) of two LEED platinum certified green office buildings located in the composite climate of India. The in-use energy and environmental performance of the buildings was examined using a technical building survey, energy data, environmental monitoring, along with occupant satisfaction surveys. Interestingly results showed that the two case study buildings used less energy annually than design predictions and performed better than comparative benchmarks. Building energy use had a high correlation with cooling degree days. However energy generation systems (rooftop photovoltaic systems) did not perform as intended. Indoor temperatures were found to be lower and CO_2 levels higher in cellular offices, as compared to open plan offices. Occupant survey results revealed that users were satisfied with the overall design of the building, comfort levels and indoor air quality, but perceived indoor lighting to be more than required. Such empirical studies will help to build trust in the Indian building industry, which is currently shy of exposing itself to liability risk resulting from actual building performance.

Keywords: Building performance evaluation, low carbon building, monitoring, LEED, GRHIA

1. Introduction

Rapid growth and urbanization (IEA, 2015), the desire to be comfortable and a changing climate (combined with the compounding feed-back cycle of the urban heat island and air-conditioning (AC)) will, among many things, lead buildings in India to use more energy intensive means for cooling (Kumar et al., 2018). For these reasons, India is an important focus for mitigated energy consumption in buildings and green building certification councils have seen this as an opportunity. The Indian Green Building Council (IGBC) claims that India is the second country in the world with the largest registered green building footprint with over 4,981 projects registered for green building ratings, of which 1,571 certified and fully functional (as of November 2018) (IGBC, 2018). Research, however, continually demonstrates that green building rating and certification systems do not always ensure greater energy performance (Sawyer et al., 2008, Sabapathy et al., 2010), occupant satisfaction (Alborz and Berardi, 2015, Gupta and Gregg, 2016) or better indoor environmental quality (IEQ) over conventional buildings (Tham et al., 2015).

The energy performance gap has been thoroughly demonstrated in international research. Research has shown a LEED (Leadership in Energy and Environmental Design) certified building using twice the energy beyond model predictions in the USA (Chen et al., 2015). In the UK this has been reported as up to nine times the energy predicted for exceptionally energy efficient designed buildings funded by the UK government's Building Performance Evaluation (BPE) programme (Palmer and Armitage, 2014). Also, in India (Sabapathy et al., 2010), LEED certified buildings are not performing as expected with respect to certification, i.e. the LEED Silver and Gold facilities of the same type are performing better than one certified as LEED Platinum. The frequency of the performance gap internationally indicates the necessity to demonstrate claims of efficiency, sustainability and comfort through evaluation in India.

BPE is a useful way to identify, quantify and resolve the gap between 'as-designed' and 'built / in-use' performance through a systematic collection and analysis of qualitative and quantitative information related to fabric performance, energy performance and environmental conditions. BPE can involve feedback and evaluation reviews at every phase of the building delivery from strategic planning to occupancy, adaptive reuse and recycling (Preiser, 2001). This paper seeks to apply a customised post-occupancy BPE approach developed in (Gupta et al., 2019) (I-BPE) for Indian green buildings, to evaluate the actual performance of two high-certification level green office buildings in the composite climate of India, from both technical and occupants' perspectives. Following with the next section, the paper first reviews literature on what has been performed to-date in post-occupancy evaluation (POE) / BPE on non-domestic buildings in India. The paper then introduces the case study buildings and the methods used to evaluate the case studies. The results are then presented followed by a discussion on future application and the conclusion.

2. Review of building performance evaluation in India

As BPE can vary in form, intensity, and length of time required, the following review differentiates between field studies in thermal comfort (FSTC) and POE / BPE but counts them all as performance evaluation studies with something to learn and take forward to improve future building. FSTC differs in that it is used to observe the occupant's immediate response to a building and the immediate measurements taken in relation to that response (Nicol and Roaf, 2005). FSTC generally involves spot readings and predicted mean vote (PMV) analysis. In contrast, POE/BPE collects a long range memory of the occupant's response along with energy and environmental features for a glimpse of the building's performance (Nicol and Roaf, 2005, Bordass et al., 2006) but BPE, beyond POE can also include the entire life-cycle of the building, whereas POE is limited to the life of the occupied building (i.e. post-completion / in-use) (Preiser, 2005).

There is a notable collection of published research that demonstrate the use of BPE-related methods in India. Most of these studies are focussed on FSTC utilising thermal comfort questionnaires, interviews, temperature and relative humidity (RH) logging, and spot measurement devices as tools to evaluate environmental parameters of the buildings. A useful development in the FSTC research has been the customization of clothing (clo) values for the Class-II field experiment protocols for thermal comfort (Indraganti, 2010b, Indraganti, 2010a, Manu et al., 2016, Kumar et al., 2016a, Mishra and Ramgopal, 2014). Interior environment assessment methods in the literature included, spot measurements at the time of survey (Manu et al., 2016, Kumar et al., 2016b), thermal comfort questionnaires (including long-term/seasonal outlook and/or thermal sensation and preference votes) (Manu et al., 2016, Kumar et al., 2016b, Dhaka and Mathur, 2017, Thomas, 2017) and long-term logging/monitoring of temperature , relative humidity and other environmental parameters (Ford et al., 1998, Dhaka and Mathur, 2017). In addition, several studies, of naturally ventilated domestic and non, concluded that occupants are comfortable at temperatures greater than comfort ranges recommended by ASHRAE 55, ISO-7730 standards, and the National Building code of India (Sharma and Ali, 1986, Indraganti, 2010a, Kumar et al., 2016b).

Generally, POE/BPE studies differ from the FSTC in that they include the addition of a long range questionnaire on such variables as work area satisfaction, lighting, productivity, and health (Manu et al., 2016); a review of project information, interviews with key stakeholders (Thomas, 2017); the impact of material changes on the interior environment (Garg et al., 2016); design and system installation review, monitoring plan walkthrough, monthly energy bill collection for one year combined with seasonal energy monitoring, data logging of electricity distribution, spot measurements of lighting, temperature, RH, and envelope temperature (Bhanware et al., 2017); and aggregated, sub-metered and appliance energy consumption monitoring (Batra et al., 2013). The largest gap in BPE methods relate to those generally applied before post-occupancy, e.g. evaluation of systems installation, commissioning, and fabric performance.

Table 1 lists the Indian non-domestic studies and their coverage of BPE elements. The table clearly shows the heavier focus on occupant and environment as opposed to energy with a gap in fabric and systems analysis. Overall, most studies are focused on thermal comfort and less on energy consumption, with little cross-over between the two subjects.

Table 1. Review of Indian non-domestic building evaluation related methods

Building type	Source	Design	Fabric/ system	Energy	Environ.	Occupant
Research facility (n=1)	(Ford et al., 1998)				x	
	(Thomas and Baird, 2006)	x		x		x(BUS[A])
IT facility (LEED/ non-LEED) (n=26)	(Sabapathy et al., 2010)			x		x
Office (n=16)	(Manu et al., 2016)				x(FSTC)	x(FSTC)/ (BUS)
Office (n=14)	(Kumar et al., 2016a)				x(FSTC)	x(FSTC)
Office (n=1)	(Bhanware et al., 2017)	x		x	x	
Office (n=19)	(Dhaka and Mathur, 2017)				x(FSTC)	x(FSTC)
Office (n-4)	(Thomas, 2017)	x			x(FSTC)	x(FSTC)/ (BUS)
Academic (n=1)	(Gupta et al., 2019)	x	x	x	x	x(BUS)

[A]The Building Use Studies (BUS) (ARUP, 2014) methodology obtains feedback data on building performance through a self-completion occupant questionnaire; the results can be compared against a national benchmark database. The questionnaire prompts the respondents to comment on the building's image and layout, comfort, and daily use of the building features.

3. Case studies and research methods

A previously developed BPE methodology (Gupta et al., 2019) developed for the Indian context (I-BPE), as part of a Newton Fund UK-India research project, was tested on two green buildings in the composite climate of India, as part of a postgraduate dissertation (by one co-author), with the intent to provide feedback on the relevance and effectiveness of the I-BPE methods as a research tool in the Indian context. A key aim of the case study is to better understand the challenges in applying the methods and tools of the I-BPE methodology, and how these might be improved to continue BPE studies in India.

The first case study building[1] (B1), a sustainable development research facility located in Gurgaon, India, is a LEED Platinum building completed in 2008. The building is constructed of heavy thermal mass with double glazed windows, and highly reflective roof surface and exterior paving materials to reduce heat gain. Shading devices reduce solar heat gain in the summer but permit solar gain in the winter. Internal courtyards provide natural light inside the building to reduce electrical lighting consumption throughout the year. The building also utilizes rain water harvesting, permeable paving, and waste water recycling for irrigation and toilets. During construction, excavated soil was used to make the bricks used in the building and renewable materials were used throughout. Table 2 lists important aspects for both case studies.

Table 2. Further building details

Detail	Building 1 (B1)	Building 2 (B2)
Green rating	LEED Platinum	LEED Platinum / GRIHA 5-star
Occupancy (typical)	150 occupants; Monday – Friday 8am – 6pm	900 occupants; Monday – Friday 9:30am – 5pm
Built-up area / Built-up area excluding unconditioned basement[A]	3,250m^2 / 2,660m^2	32,000m^2 / 19,130m^2
Programming/ form	Offices: ground, 1st and 2nd levels. Ground level: auditorium, reception, classrooms, conference room, cafeteria and kitchen Basement: control room	Four wings around central courtyard; ground level plus seven stories and a basement. Offices, conference rooms, meeting rooms, a dining room, cafeteria, library and auditorium.
Cooling	AC	AC
Energy/ renewables	Electricity from grid; diesel generator backup; PV 58kWp, solar thermal	Electricity from grid; diesel generator backup; PV 930kWp
Fabric details (U-values)	Wall: 0.36 W/m^{2}K Roof: 0.35 W/m^{2}K	Wall: 0.37 W/m^{2}K Roof: 0.26 W/m^{2}K

[A]Used to calculate Energy performance Index (EPI), a normalization of energy consumption used for benchmarking in India represented as kWh/m^2/yr (BEE, 2017).

The second case study building (B2) is a GRIHA (Green Rating for Integrated Habitat Assessment) 5-star and LEED Platinum government office building in New Delhi, completed in 2014. The building is constructed of heavy thermal mass with double glazed windows. The roof is a terrace garden with extended photovoltaic (PV) panels to provide shade to areas of the roof and the upper stories. The exterior shell and all paving materials were also designed to reduce heat gain. Shading devices reduce solar heat gain in the summer but allow solar gain in the winter. Access to daylight was also designed to reduce electrical lighting consumption throughout the year. The building utilizes rain water harvesting and a

[1] B1 is the first phase in a two-phase development of three buildings. Phase 1 comprised an office building and a guesthouse. Throughout the paper B1 will refer to the study of the phase 1 office building only; however, in the design phase, the guesthouse was included with the main office building for energy consumption simulation; therefore, the guesthouse is included in the energy analysis.

geothermal heat exchange system adopted for AC in the building, is contributing to the reduction in water consumption by eliminating the need for a cooling tower.

3.1. BPE field study methods

The field study was carried out for one month in the monsoon season (6 July – 13 August 2018). Due to the nature of student dissertations, there were limited resources and time. The primary components of the study included design and construction audit, energy audit, environmental audit and occupant survey. Table 3 shows the I-BPE recommend study elements divided in four levels of increased complexity. For each level, the table indicates the action taken and/or tools used. The review of design, fabric, and systems for both buildings included plans, simulation report, commissioning report, LEED credit report, interview with design team and facility manager (FM), and a walkthrough survey to observe design aspirations as they relate to reality of the occupied product. Though documentation was available, the review of installation and commissioning of systems was not performed due to student's limited knowledge.

Although the campus in which B1 is located is relatively data rich with submetering data available through a building management system (BMS), some submetering choices made analysis difficult. For example, the HVAC energy for both phase 1 & 2 buildings are metered through a single panel; however, the AC air handling unit (AHU) for B1 office building is metered separately. In addition, the design energy simulation breakdown of systems for consumption analysis did not match the metered panels in the building, making comparison challenging. B2 energy data were only available through energy bills as the BMS was not working at the time of study.

In B1, indoor environmental parameters, e.g. temperature, RH, CO_2 concentrations, etc. were successfully monitored; however, as B2 is a government building, they did not allow the installation of environmental loggers or photographs in workspaces. An occupant satisfaction survey (BUS) was conducted in both buildings to ascertain satisfaction with the work space and indoor environment. The BUS survey was distributed to regular occupants in B1 on 7 August 2018 and collected the next day. The response rate for B1 was high due the high level of interest from the owner in the process and survey findings. In B2, the BUS survey was distributed to regular occupants from 2-5 August 2018 due to the large number of occupants.

4. Results

4.1. Review of design intent: *B1*

The occupants, building owner and the management team were satisfied with the building design, facilities, image of the building, and fulfilment of their needs. These findings are also confirmed by the BUS survey. The FM received appropriate handover and operation manuals; however, as a non-technical person, the FM has established a good working relationship and communication with sub-contractors who are responsible for maintenance of the building.

All buildings on the campus were designed for mixed-mode operation. For the cool season, all spaces have operable windows. There is also the designed-in ability to night purge heat when nights are cool; however, there is no automated system for this. Furthermore, it was found that for reasons of security, dust, and insects, windows are rarely opened even when conditions are ideal. The temperature setpoint for the building is 26.5^{o}C. This is 0.5^{o}C below the Indian Society of Heating, Refrigerating and Air Conditioning Engineers (ISHRAE) (2016) maximum operative temperature threshold in summer for offices. In addition, all spaces have ceiling fans as it was anticipated that those who find the space too warm would turn on ceiling fans. The fans were in fact observed to be used in this way.

Table 3. Adaptation of the I-BPE methodology for this study *(NP = not performed)*

BPE study elements	Level 1	Level 2	Level 3	Level 4
Review of design intent	Collection and review of design docs.: *Drawings, occupancy details, applicable standards, and green bldg. cert. docs.*	Review of services and energy systems: *review of commissioning documents*	Interviews with key stakeholders: *Design team and FM*	Walkthrough with key stakeholders: *FM*
Technical building survey	Inspection of build quality and services: *with FM, photographic survey*	Controls interface survey: *limited review of lighting controls in B1 only*	Review of installation and commissioning of systems: *NP*	Thermographic assessment of building fabric: *NP*
Energy assessment	Annual / monthly energy data: *Monthly energy consumption, and PV generation (1 yr data)*	Energy monitoring: *NP*	Sub-metering: *B1 only: Access to daily energy use for all systems (lightning, power, etc.) through BMS*	Plug load monitoring of individual appliances: *NP*
Env. monitoring	Temperature and RH spot readings: *NP*	Temperature and RH monitoring: *B1 only: Hobo UX-100 reading temp. and RH (4 weeks at 5-min. freq.);* *I-button reading temp. (4 weeks at 5-min. freq.)*	Additional spot read/ logging (e.g. CO_2, lux, wind speed): *Watchdog measuring internal CO_2, environmental meter reading lux levels and noise.*	Additional pollutant measurement (e.g. PM, VOC): *B1 only: Foobot reading particulate matter (PM2.5) (μgm^3), CO_2 (ppm) and VOC (ppb) (4 weeks at 3-hr. freq.);* *Tinytag reading CO_2 (ppm) (2 weeks at 5-min. freq.)*
Occupant feedback	Occupant satisfaction survey: *B1: BUS (91 of 130 returned) (70%)* *B2: BUS (270 of 900 returned) (30%)*	Occupant interview: *NP*	Thermal sensation and preference survey: *B1 only: thermal comfort (TC) diary (37 of 130 returned) (28%)*	Focus group: *NP*

Note: darker shading indicates application in both buildings; lighter shade indicates only implemented in one building.

The open plan offices were designed with good acoustics; however, the BUS survey revealed noise from colleagues to be no better than expected, i.e. in line with the BUS benchmark. Despite the design of internal courtyards to help provide abundant natural light inside the building and thereby, reduce electrical lighting consumption, there were many instances where electrical lighting was left on where not needed. Furthermore, BUS survey results indicate there was enough natural and electrical lighting at the time of survey.

4.2. Review of design intent: *B2*

The occupants and the management team were satisfied with the building design, facilities, image of the building, and fulfilment of their needs. These findings are also confirmed by the BUS survey. However, many occupants complained about the furniture, space at their desk and storage. The FM did not receive proper handover and operation manuals and there has been a frequent turnover in FM position. This frequent change leading to little time to invest in the FM position could be a contributing factor to why the installed monitoring equipment and BMS remain offline and unrepaired since 2013. The green pavers, intended to reduce impervious, hardscaped surfaces has separated creating large gaps and safety concerns.

The open plan offices do not have good acoustics; however, the BUS survey revealed noise from colleagues to be as expected, i.e. in line with the BUS benchmark. There were many instances where electrical lighting was left on when not needed. Furthermore, BUS survey results indicate there was enough natural and electrical lighting at the time of survey.

4.3. Energy and indoor environment

The following energy analysis considers only energy data for the year covering 1 April 2017 – 31 March 2018. Overall, B1 is found to perform better than intended. There is almost no difference between the as-designed and as-built energy consumption for B1 (energy performance gap (EPG) of -0.3%); however, the renewable systems are not performing as intended resulting in an EPG of renewable systems of +9%. This raises the net EPG to +0.9%. B2 is performing relatively well also. The as-built energy consumption is below the as-designed prediction resulting in an EPG of -3%; however, B2 was designed to be a net-zero energy building. To achieve this, the building is highly dependent on the PV system to perform as intended. Unfortunately, the renewable system is not performing as intended, resulting in an EPG for the PV system of +19%. Table 4 shows the results for the as-designed and as-built energy consumption, generation and CO_2e emissions.

Energy performance evaluation limitations:

- The guesthouse was modelled together with B1 office building in design; therefore, the guesthouse is included in both as-designed and as-built results.
- B1 sub-metering designations did not match the simulated consumption for specified uses (e.g. lighting, HVAC), therefore, as-designed and as-built comparisons could not be made. As an example, in the simulation calculations the guesthouse energy requirements are combined with the main office building; however, the guesthouse is sub-metered as a single value.
- B1 was modelled for peak occupancy of 200 occupants per day. Though there is not a large difference in consumption this may contribute to the EPG.
- B1 energy predictions did not include the backup diesel generators in the model. The 5% of total annual energy used by diesel resulted in 4% less CO_2e emissions than modelled.

Table 4. Annual energy data for both buildings from 1 April 2017 – 31 March 2018

	Building 1 (B1)		Building 2 (B2)	
	As-designed	In-use	As-designed	In-use
Total energy use (kWh/yr)	378,266	377,310	1,400,000	1,356,615
Renewable generation (kWh/yr)	44,571	40,531	1,400,000	1,138,027
Net energy use (kWh/yr)	333,695	336,779	0	218,588
Net energy use/m^2 ($kWh/m^2/yr$)[A]	125.4	126.6	0	11.4
Net CO_2e emissions (kg/CO_2)[B]	273,630	265,243	0	153,958
Net CO_2e emissions/m^2 ($kgCO_2/m^2/yr$)	102.9	99.7	0	8.0

[A]Energy Performance Index (EPI)
[B]CO_2e emissions factors (kg/kWh): electricity=0.88 (Bhawan and Puram, 2014), diesel=0.267 (Ali et al., 2016)

Figure 1 shows the case study buildings' EPIs against relevant Indian benchmarks (Kumar et al., 2010, BEE, nd). Both buildings are performing better than the Indian Energy Conservation Building Code (ECBC) office building benchmark for the composite climate; however, B1 is not performing as well as some actual measured benchmarks of public sector buildings, though it is a LEED Platinum rated building.

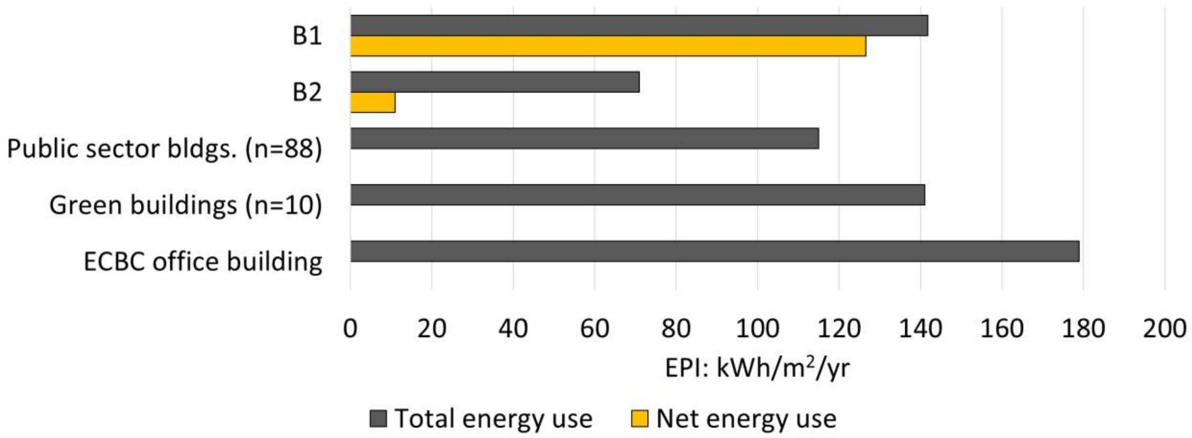

Figure 1. Annual energy data for both buildings and benchmarks from 1 April 2017 – 31 March 2018

Figure 2 shows the relationship between energy consumption and cooling degree days (CDD) (BizEE, 2019). Both buildings appear to have a strong correlation between respective energy consumption measurements used in the graph and CDD. Obviously, the relationship between AC AHU consumption and CDD for B1 is more helpful in understanding responsiveness to climate. This can be seen in the way that most months are close to the trendline except for September 2017. If September were removed the correlation would be r=0.91. To help compare like-for-like, total energy consumption correlation with CDD for B1 is r=0.82.

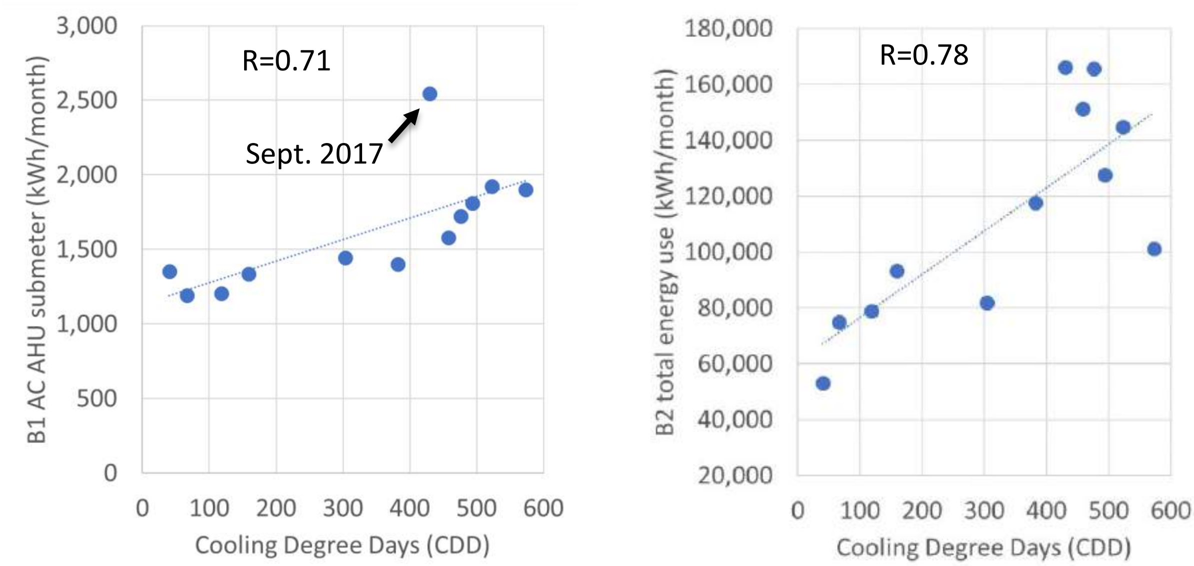

Figure 2. Energy & cooling degree day relationship 1 April 2017 – 31 March 2018 (B1 left/B2 right)

Unfortunately, as the B2 BMS system stopped monitoring environmental data and management would not allow data loggers to be installed in the building for the study, only the environmental data for B1 is reported. Figure 3 shows the maximum (max), mean, and minimum (min) temperatures and RH during occupied hours (in table 1) for one measured office on each floor, ground floor (GF) enclosed office, first floor (FF) open office, and second floor (SF) open office. The acceptable operative temperature range for offices in summer (24.5^{o}C +/- 2.5) and RH according to the ISHRAE standard (ISHRAE, 2016) is shown with the gradient boxes. As operative temperature was not observed, dry bulb temperature is used here as a proxy. In the temperature graph, the setpoint is indicated by the yellow line. From this temperature graph, though there are maximums outside the recommend range, it appears that temperatures are remaining reasonably close to the setpoint and within recommended range. This is also true for RH; however, the average RH in the SF office is close to the max. This may indicate window opening behaviour. The lower temperature and RH in the GF office is likely indicating the enclosed nature; this is also more apparent in figure 4.

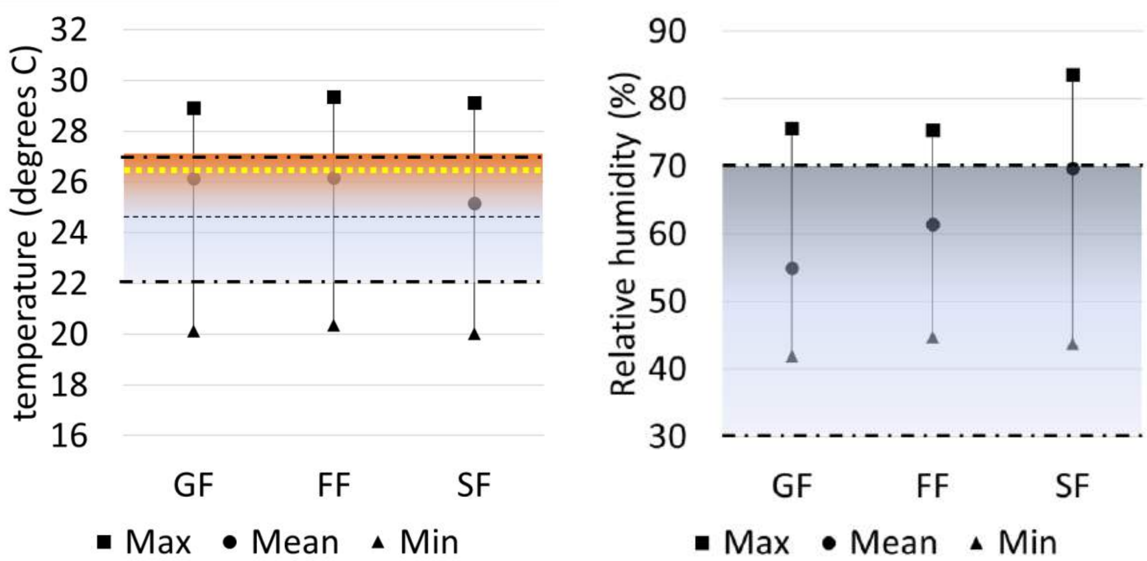

Figure 3. B1 office temperature and RH measurements, and recommended ranges for the period 6 July – 13 August 2018

Figure 4 shows the percent of occupied hours within (blue and yellow) and outside (red) of the acceptable temperature range. The same three offices are shown in the graph. Within these hours, it appears that there is a notable difference between the temperatures on each floor. On the ground floor only about 2% of occupied hours are above the threshold but on the first floor this is over 25% of occupied hours.

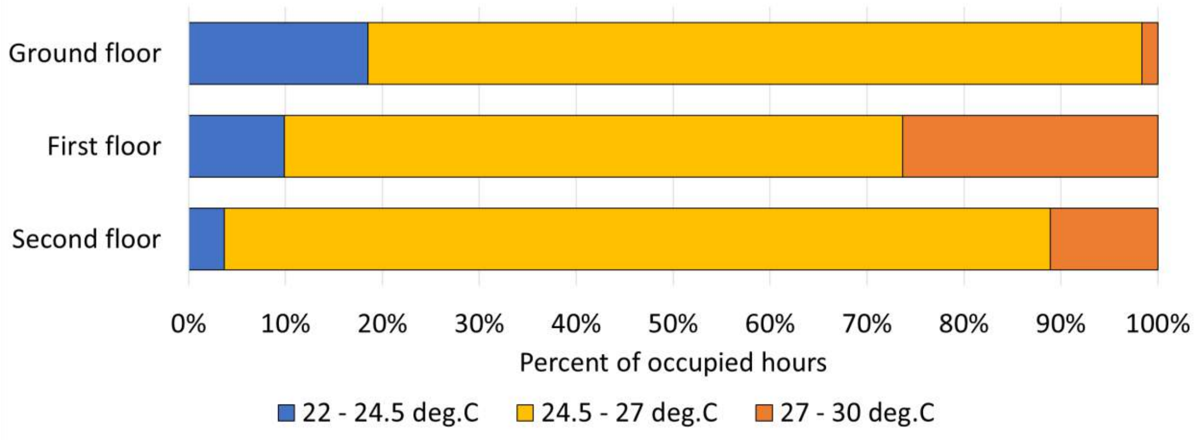

Figure 4. B1 office temperature measurements: percent of occupied hours at specific temperature ranges for the period 6 July – 13 August 2018

Figure 5 shows the indoor air quality measurements taken in the ground and second floor offices during the periods 18-25 July 2018 and 11-17 July 2018 respectively. ISHRAE (2016) thresholds are shown in the graphs for PM2.5 and CO_2. For these graphs the lower band indicates the Class A threshold: *aspirational* and the upper band indicates the Class C threshold: *marginally acceptable.* Mean PM2.5 concentrations in the SF office are above the ISHRAE Class C threshold but CO_2 is lower. As with higher RH, this may also indicate a higher frequency of window opening or access to open windows and cross-flow ventilation in the open plan SF office.

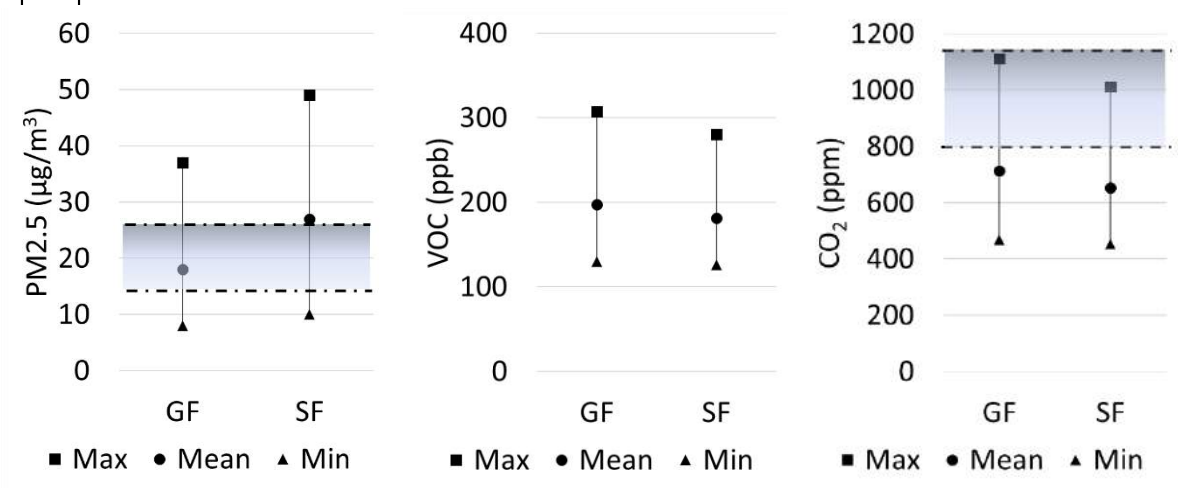

Figure 5. B1 GF and SF office IAQ measurements and ISHRAE standard thresholds

4.4. Occupant survey

According to BUS survey results, the design, the building's image to visitors, whether the building meets the user's needs and effectiveness of the use of the space of both buildings were all considered highly satisfactory in B1 and moderately satisfactory in B2. Overall lighting is considered satisfactory in the two buildings. In addition, the respondents in both buildings considered there to be enough natural light on the scale toward 'too much';

however, the mean response suggests there is little to no issue with glare in the buildings. Control over lighting in B1 is considered good and better than the BUS benchmark mean; the occupants in B2 appear to have less control, below the benchmark mean.

Overall comfort is rated moderately high in both buildings for both seasons; higher in B1. In both seasons the temperature is considered to be on the cooler side and the air is considered dry and still but also fresh and odourless for both buildings. Though comfort and temperatures are considered satisfactory, the respondents in both buildings consider control over heating, cooling and ventilation to be unsatisfactory. In both buildings productivity at work is perceived to have increased because of the environmental conditions in the building; furthermore, occupants feel healthier when in the building.

5. Discussion

In conducting the BPEs, between the two buildings, differences were found between between B1, a privately owned building wherein the owner showed great interest in conducting building performance evaluation study whereas in B2, a government building had high levels of restriction and continual barriers and permissions to seek.

Many people in both the buildings were not able to understand questions in the BUS survey. Much time was required from the evaluator to explain the meaning of questions. For this reason, it is recommended that the BUS questionnaire be modified and tested for the Indian context to simplify language and/or translate the forms. Many occupants simply refused to take the BUS survey and TC diary. People are generally busy, especially in a workplace environment; for a higher rate of return an incentive would be ideal. The TC diary is not recommended in its current paper form. It was difficult to get occupants to fill the long and monotonous TC diary. People didn’t find it interesting to fill which led to missing blanks, day skipping, and a low response rate. A reminder from the management team in B1 to each occupant was set three times a day but this was only possible provided the interest of the owner in the project. Though again this may require an incentive, especially to install an application on an individual’s smart phone, but TC diaries would be less difficult to complete if it were app-based with notifications to prompt simple quick responses.

Regarding the energy consumption of the buildings, the current EPG is considered reasonably acceptable as some variation in both predictions and measurements due to the realities of uncertainties (inherent in predictions) and data scatter (inherent in measurements) should be allowed (De Wilde, 2014). Furthermore, as these buildings are performing better than intended, it would not be desirable to increase energy consumption to meet design predictions. The simulation methods and the installed efficiencies of the PV systems should be reviewed to understand where the EPG is most affected to avoid repeat results. Though the EPG is far worse for B2 it is performing exceptionally well as compared to the benchmarks and as compared to B1, also a LEED Platinum rated building. B1 is not performing as well as certain benchmarks; therefore, it brings into question what should be expected considering the energy performance of LEED Platinum buildings. In the certification process, there are many credit paths to achieve this certification level; however, a certain level of energy performance would preferably be inherent. That is, for example, a LEED Platinum building should be guaranteed to have a lower EPI than Gold which is not always the case (Sabapathy et al., 2010).

6. Conclusion

This study shows the process of testing the I-BPE methodology on two LEED Platinum office buildings in the composite climate of India. The field study was carried out for roughly 30 days which included data monitoring, walkthroughs and occupant surveys. The field study offers a template for replication of BPE and benchmarking data for green buildings in India. The next step in the Learn-BPE project involves testing the I-BPE approach on several other case studies implemented by students using a programme developed for this purpose. The I-BPE case studies intend to demonstrate actual performance of certified green buildings in India, publish the data, and continually provide a testing platform for refinement of the I-BPE framework for application in India. Finally, the I-BPE case studies are also intended to build trust in the Indian building industry, which is currently shy of exposing itself to liability risk resulting from actual building performance

Acknowledgements

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MATERIALS FOR HEAT ISLAND MITIGATION – THE STATE OF THE ART

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Abstract

Urban overheating may exceed 6-7^0 C compared to the surrounding suburban environment. Increased ambient temperatures have a serious impact on the energy consumption used for cooling purposes, heat related mortality and morbidity, indoor and outdoor thermal comfort, pollution levels while influence highly the economic life of cities. To counterbalance the problem, several mitigation technologies have been developed and applied in numerous large-scale urban projects. Among the proposed mitigation technologies, the development and the use of low surface temperature materials to be used in the urban fabric and the envelope of buildings, has gained increasing interest while numerous applications shown that it presents a very high mitigation potential. This paper reviews the more recent progress regarding the development and use of low surface temperature mitigation materials. The most advanced material technologies for mitigation purposes are reviewed and presented in a comparative way, while quantitative data on their thermal performance when applied in cities is given and analysed.

Introduction

Urban overheating is the more documented phenomenon of local climate change, causing serious energy, environmental and health problems. Extensive measurements carried out the recent years have documented that more than 400 major cities around the world suffer from increased ambient temperatures, (1,2). The magnitude of the urban overheating varies as a function of the layout and the density of the city, the landscape characteristics, the materials used, the intensity of the local sources and sinks and the local climate and the local climate. It may vary between 1 to 10 C, while the average maximum intensity of the urban overheating is between 5 to 6 C.

Urban overheating has a serious impact on the energy spent for the cooling of buildings as well as on the peak electricity demand in cities. As reported in (3), urban overheating causes an average energy penalty per unit of city surface, (GEPS), close to 2.4 (±1.5) kWh/m ^{2}, a global energy penalty per unit of city surface and per degree of the UHI intensity (GEPSI) of around 0.74 (±0.67) kWh/m ^{2}/K, a global energy penalty per person (GEPP) of around 237 (±130) kWh/p, and a global energy penalty per person and per degree of UHI intensity (GEPPI) that is close to 70 (±45) kWh/p/K. In parallel, it is estimated that the higher temperature of cities increases the peak electricity demand per person by 21 (±10.4) W per degree of temperature increase, (4).

Apart of the energy penalty, urban overheating and the urban heat island phenomenon have a serious impact on human heat related mortality and morbidity. Several studies, (5,-7), have shown that higher ambient temperatures are strongly associated with increasing mortality and morbidity and reduced capacity to adapt and heat stress. Other studies aiming to identify the global impact of the urban overheating, have revealed that increased urban temperatures may almost double the ecological footprint of cities, (8), or deteriorate dramatically the levels of outdoor thermal comfort conditions, (9), disrupt the operation of the transport system in cities and cause a serious economic burden. (5)..

To face the problem of urban overheating, several mitigation and adaptation technologies have been developed and applied in cities, (10,11). Technologies involve the use of greenery techniques for buildings and cities, the use of advanced materials for the building envelope and the urban fabrics, evaporative and other dissipation technologies based on the use of cool sinks, solar control technologies and various combinations of the above technologies. Analysis of the existing large scale applications of mitigation measures, shown that the cooling potential of the existing mitigation technologies is considerably high and it is possible to decrease the peak temperature of cities up to 2.5-3 C, (12).

Among the various proposed mitigation technologies, the development and the corresponding use of appropriate materials for the building envelope and the city fabric, seems to present the highest interest. Research on the analysis of the existing and the developed of new advanced materials, able to decrease the temperature of cities, has succeed to provide several new technological products presenting a very high mitigation potential, (13,14). While twenty years ago, the surface temperature of materials used in cities exceeded substantially the corresponding ambient temperature, new structures and materials present a surface temperature much below the ambient one, while the new generation materials can be adapted to the varying climatic conditions of the urban environment.

The present paper aims to review and present the recent progress on the development of advanced materials for urban mitigation purposes. The various proposed material technologies are presented while the potential to reduce their surface temperature is presented in a comparative way using existing experimental assessments. The cooling potential of the proposed material technologies and their potential for mitigation is also analysed using existing experimental and theoretical studies. The priorities and the prospects of future research on the topic are discussed and analysed.

2. Progress on Material Science and Technology for Mitigation Purposes

Materials determine at large the energy balance in the urban environment. The envelope of buildings as well as pavements and other structures in the open urban spaces, absorb solar and atmospheric radiation, emit infrared radiation and exchange heat through convective processes with the ambient air, while they have conductive gains and losses with their immediate environment. The absorbed solar and atmospheric radiation is the major mechanism that increases the surface temperature of the materials, while infrared emission and convective – conductive losses contribute to cool the surfaces. While the emitted by the materials infrared radiation is almost not absorbed by the surrounding ambient air, the released sensible heat under the form of convective losses is the main heating mechanism in the ambient environment. Sensible heat depends on the temperature difference between the material surface and the ambient air as well as of the convective heat transfer coefficient.

To reduce the urban overheating, the magnitude of sensible heat released in cities must decrease as much as possible while the surface temperature of the materials should be kept low. Thus, materials should present a low absorptivity in solar radiation and a high emissivity in the whole spectrum they emit or in the atmospheric window. Also, emission of other type of radiation, like fluorescence can be very beneficial to decrease the surface temperature of the materials.

Research on advanced materials for urban mitigation purposes, has resulted in the development of several new technological products presenting enhanced optical and thermal properties together with a very significant cooling potential. Among the various proposed material technologies, advanced light coloured, IR reflecting coloured, PCM doped, thermochromic and fluorescent materials and day time radiative structures, seems to present the highest mitigation potential Figure 1, reports the historical development and progress of the more advanced new mitigation material. In parallel, Table 1 reports the required optical characteristics of the considered technologies. As shown, most of the developed technologies are aiming on the reduction of the material's solar reflectance in the whole solar spectrum or just in the visible or IR part. Also, except of the daytime radiative structures, all technologies require a high emissivity in the IR spectrum to dissipate the maximum possible energy through radiation. However, a high emissivity in the whole IR spectrum corresponds to a high absorptivity of the materials to the incoming atmospheric radiation in the same wavelengths. On the contrary, day time radiative coolers, present a high emissivity in the atmospheric window, 8-13 μm, where the atmospheric radiation is almost negligible.

In the following the thermal and optical characteristics as well as their cooling capacity is discussed. A comparative assessment of their potential to decrease the sensible heat released in the atmosphere, is presented based on existing measurements, (Figure 2). Data for all type of materials, except the radiative coolers, is collected from (15,16, 18, 28,31), and refer to almost the same climatic and monitoring conditions. For simplicity reasons, only data for white and black color materials are reported.

2.1 Natural and Conventional Materials

The surface temperature of natural and conventional building and paving surfaces is mainly determined by their colour, surface texture and construction material. Light colour natural and artificial materials present most of the required optical and thermal characteristics for mitigation purposes and are widely used in the traditional architecture of cooling dominated cities. However, most of the dark colour natural materials have a low solar reflectance in the whole solar spectrum, resulting in high surface temperature and an increased sensible heat released in the atmosphere. As an example, measurements of natural and conventional materials performed under sunny summer conditions, (15), shown that the average surface temperature of white concrete paving tiles was close to 33.7 C with a standard deviation close to 7.5 C, while the corresponding average surface temperature of the same material in black colour was almost 13 C warmer and the standard deviation was 15.4 C. As it concerns the impact of the material texture on the surface temperature of the materials, comparative experiments shown that tiles with smooth and flat surface are cooler than the tiles of the same colour and material with rough and anaglyph surface. Smooth white concrete tiles were found to be 1.7 C cooler than a rough tile of the same colour and material, (15). The type of material is also of high importance. White marble tiles where found in average almost 3 C cooler that similar concrete tiles, (15). As shown in Figure 2, the surface temperature of several natural and conventional black pavement tiles, having different surface textures and composed by different materials may vary between 47 C to 68 C measured in summer under the same testing conditions. The tiles were composed either by concrete, mosaic, granite, various types of natural stones, pebble and asphalt with specific surface textures. Asphalt presented the highest surface temperature followed by pebble, concrete, granite, marble and dark stone.

2.2 High Reflectance White Materials

Advanced artificial white materials presenting a very high reflectance in the solar spectrum are developed and are commercially available and widely used, (16). Monitoring of the developed artificial high reflectance white coatings shown that their surface temperature may be a few degrees higher than the ambient temperature and substantially lower than that of the natural white materials. Comparative testing of 15 high reflectance coatings applied on similar concrete tiles, shown that despite the same colour, their daily surface temperature could vary significantly. The average daytime surface temperature difference between the white materials exceeded 14 C, while the difference of the daily maximum surface temperature was close 17 C. Materials covered with high reflectance metal paints, presented the highest daily ambient surface temperature mainly because of their low emissivity value. On the contrary those materials presenting the highest reflectance and emissivity values were the coolest ones. The peak daily surface temperature of the coolest of the white materials was close to the corresponding ambient temperature, while the warmer tiles presented up to 12 C, higher surface temperature than the corresponding ambient one, (Figure 2). Compared to white natural materials, the coolest of the tested artificial materials presented up to 6.0 C lower surface temperature than tiles of white marble. However, weathering seems to be an important problem for some of the artificial reflecting materials. After 60 days of exposure, the peak daily temperature difference of the acrylic elastomeric materials and the ambient temperature is fount to increase by 5 C, from 4 to almost 9 C. As a conclusion, developed industrial high reflectance and emissivity artificial white materials present a low surface temperature, a few degrees above the ambient one, release a low sensible heat to the atmosphere and contribute to mitigate the urban overheating, however weathering may affect their optical and thermal performance.

Type of Material	Optical Properties of the Materials				
	High Solar Reflectance in Visible Spectrum	High Solar Reflectance in IR spectrum	High Broadband Emissivity	High Emissivity in the Atmospheric Window	High Fluorescent Emission
Light Colour Reflective Materials	+		+		
Coloured IR Reflective Materials		+	+		
Reflective					

Materials with nano PCM.	+	+	+		
Thermochromic Materials	+	+	+		
Fluorescent Materials	+	+	+		+
Photonic Materials and Components for Daytime Radiative Cooling	+	+		+	

Table 1 : Main optical characteristics of the different material technologies proposed for urban mitigation

2.3 IR Reflecting Coloured Artificial Materials

Spectrally selective coloured materials presenting a high reflectance in the IR part of the solar radiation combined with a high thermal emissivity, are developed and are already used in a numerous urban mitigation project, (17,18). The total solar reflectance of those materials is substantially higher than that of the conventional materials of the same colour. For example, while the total solar reflectance of conventional black surfaces is close to 6 %, IR reflecting black materials reflect almost 24 % of the solar radiation, (18). Also, blue IR reflecting surfaces have a total solar reflectance close to 33 % against 18 % of the conventional blue materials. Because of the increased reflectance IR reflective surfaces present a much lower surface temperature compared to the conventional materials, that results in a reduced release of sensible heat in the atmospheric environment. The so called cool coloured pavement and roofing materials are developed, by replacing conventional pigments used to colour their mass, with IR reflecting pigments. Important research is carried out aiming to develop new pigments of higher optical efficiency.

The surface temperature of the IR reflecting coloured materials, applied either In roofs or pavements is measured and simulated by several authors, (18-22). In all works the surface temperature of the IR reflecting tiles was found to be significantly lower than that of the same colour conventional materials. The magnitude of the temperature decrease was depended on the achieved increase of the total reflectance. Figure 2, reports the surface temperature of black paving materials measured during the summer period against conventional black tiles of the same material and surface texture. Infrared reflective black paving materials is found to present almost 10 C lower maximum surface temperature than the corresponding conventional tiles of the same texture and material. A maximum surface temperature reduction between 3 to 8 C is also measured for the IR reflective materials of more light colours.

The low surface temperature of highly reflective materials is a possible problem in climates presenting a significant heating load during the winter period, (23). Cool roofs during the heating period may increase the heating load of buildings, however many studies shown that the achieved reduction of the cooling is much higher than the increase of the heating demand, (24,25). Experimental assessment of the impact of a cool roof applied in an industrial building in the North of Europe, shown that the use of IR reflecting materials can decrease the cooling load of the building up to 70 %, while the corresponding increase of the heating load was close to 6 %, (24).

The total solar reflectance and the emittance of the IR reflecting surfaces when exposed to outdoor conditions may change over time as a result of ageing, weathering and soiling, (26). Ageing tests have shown that IR reflecting coatings presenting a high initial solar reflectance exhibit the higher decrease of the solar reflectance. Also, most of the optical losses happen during the initial months after the installation, (18). Analysis of large-scale application of IR reflecting coatings in building roofs, has shown that their total solar reflectance can decrease up to 25 % after 4 years of exposure, (26). This was due to the deposition of atmospheric pollutants like quartz, illite, dolomite and epsomite. In parallel, an important load of microbiological contamination was measured on the samples. Regular cleaning and maintenance improve the optical characteristics of the considered coatings.

2.4 PCM Doped IR Reflecting Materials

Phase change materials store heat in a latent form and can enhance the thermal inertia of the structures. The addition of phase change materials in the mass of the IR reflective coloured coatings can stabilize and decrease their surface temperature and discharge the stored energy with time delay, (27).

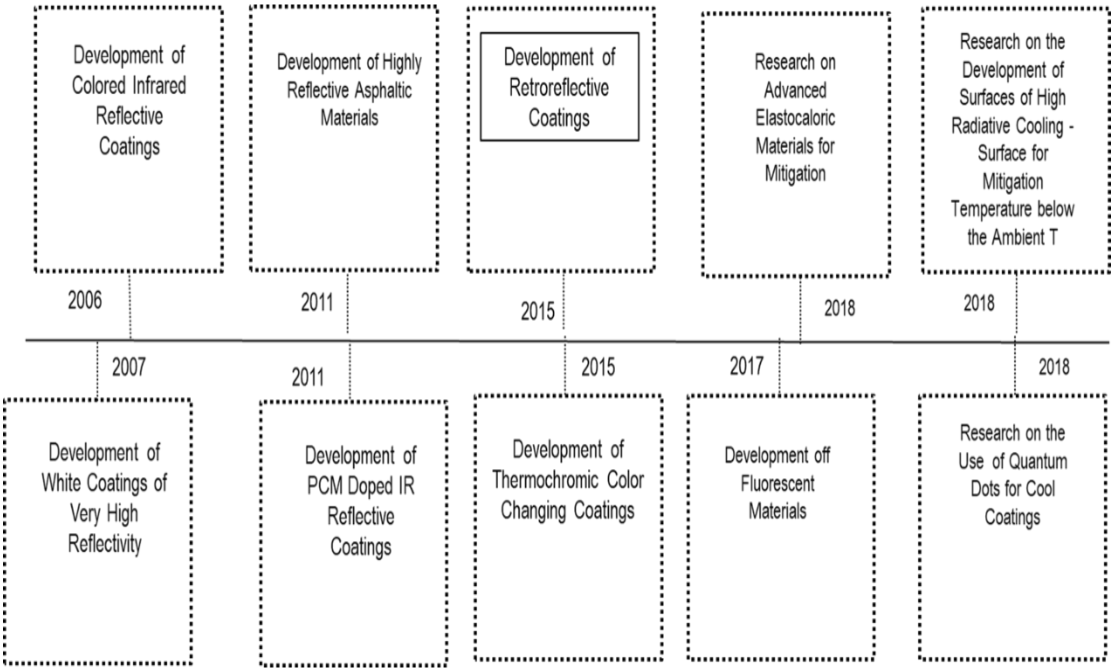

Figure 1 : Historical Development and progress of the more important material for urban mitigation purposes

The potential decrease of the surface temperature of the cool coatings doped with phase change materials varies as a function of the melting temperature of the PCM and its concentration in the mass of the colour coating. Experiments using different melting temperatures and concentrations of PCM shown that the surface temperature of the dark colour IR reflecting coatings may decrease up to 2.5 C,(28), (Figure 2) The highest temperature decrease occurs when the melting temperature of the PCM's approaches the maximum daily temperature. Once the concentration of the PCM's is quite low, the achieved temperature difference is occurring in the morning hours while during the peak day period, the impact of PCM is negligible. Increase of the PCM concentration results to a time shift towards noon time, however, even for the maximum possible concentration, the peak temperature difference may not occur after 10:00 am, (28). Issues of reduced thermal cycling and ageing of PCM have also to be considered.

2.5 Thermochromic Materials

The development and application of thermochromic materials able to change their surface colour and reflectance as a function of their surface temperature seems to be an excellent alternative for cities and buildings in temperate climates. Thermochromic materials exhibit a reversible transformation of colour and can be dark during the winter time and absorb solar radiation while during the warm summer season can be white reflecting solar radiation. There are several substances that present thermochromic properties, however leuco dyes are the most explored of the thermochromic materials. Leuco dye mixtures are usually composed by three components: a solvent that controls the transition temperature at which the colour changes, a cyclic ester that determines the colour of the final product in the coloured state, and a colour developer that is responsible for the colour intensity. Such a colour transition is reversible and is due to a transformation of the molecular structure of the materials that produces a change of the visible colour, (29).

Thermochromic materials for the building envelope and urban structures are developed and used experimentally in many projects, (30,31). Figure 2, reports the results obtained in (31), where concrete paving tiles coated with thermochromic paints based on leuco dyes of various colours. The samples were tested during the summer period against IR reflecting and conventional paving materials of the same colour and structure. Because of the colour transformation, the reflectance of the materials in their colourless stage has increased significantly compared to the coloured stage. For dark coatings the total solar reflectance increased from 0.4 in the coloured stage to 0.53 in the colourless stage. The mean maximum daily temperature of the black thermochromic tiles was measured almost 13 C lower than that of the IR reflecting black tiles and 18 C below the conventional black ones.

Colour changing materials although present a high thermal performance and a very significant mitigation potential, suffer from important ageing problems. Several studies have shown that thermochromic coatings based on leuco dyes lose their reversibility after a few weeks period, (32). Several protection techniques including UV stabilizers and optical filters are proposed and tested under accelerating ageing conditions, to coat and protect the thermochromic materials, and minimize the impact of ageing. Although the use of the UV filters was not found to be very efficient, the use of optical filters has improved significantly the optical performance and the life span of the thermochromic coatings, (32). However, more research is necessary to stabilize the optical performance of thermochromic leuco dyes and improve their reversibility potential and capacity.

Important research on alternative to leuco dyes thermochromic materials is carried out Preliminary data and results shown that quantum dots, plasmonics, photonic crystals, conjugated polymers, Schiff bases and liquid crystals, present fascinating and impressive thermochromic characteristics. It is expected that the new generation of thermochromic materials will enhance significantly their cooling potential while may offer advanced opportunities to develop and use cutting-edge optical materials for mitigation purposes, (33).

2.6 Fluorescent Materials

Fluorescent materials absorb solar radiation at specific wavelengths and re-emit photons of longer wavelengths, presenting an advantage of additional radiation that decreases the surface temperature of the materials, (34). Several fluorescent pigments as well as the use of quantum dots presenting a high fluorescent potential are proposed and tested with encouraging results, (35,36). The cooling potential of ruby crystal as a fluorescence material has been tested in [35]. As reported, the surface temperature of ruby covered sample was almost 6.5 °C lower than the reference sample. Unfortunately, there are not available comparative measurements against other materials in the outdoor environment.

Quantum dots are fluorescent materials of nano scale mainly composing of elements from groups II–VI or III–V of the periodic table. Because of their unique optical characteristics that distinguish them from their bulk counterparts, quantum dots, have gained increased attention, (37). Quantum dots, present a high potential to tune their optical properties with surface chemistry, (38) and size [39].

The use of quantum dots for mitigation purposes it is proposed in (36). Quantum dots can be mixed with monomers such as MMA, then expose the spin coated coating under UV radiation to polymerize monomers and finally apply them on a surface, (40). A second techniques is to mix QDs colloidal solution with polymer and deposit the film on the substrate. In this way, luminescent degradation caused by QDs aggregation is avoided. Experiments using QD's as a coating of low surface temperature for mitigation purposes are already carried out with spectacular results.

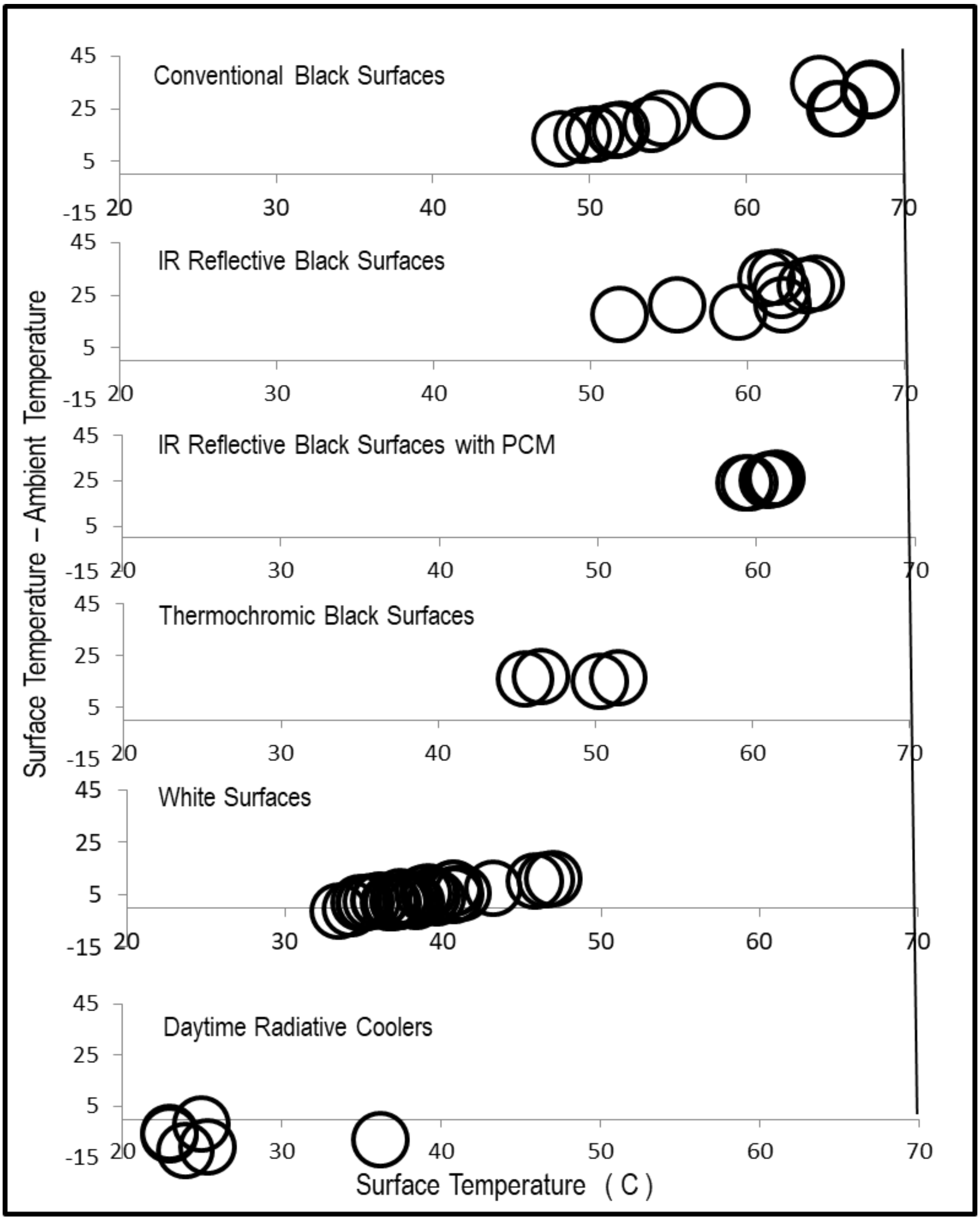

Figure 2 : Comparative presentation of existing experimental data of various urban mitigation technologies, relating the surface temperature decrease against the corresponding surface temperature of the materials.

<u>2.7 Daytime Radiative Coolers</u>

Radiative cooling of materials and structures aims to decrease the surface temperature of the coolers below the ambient temperature and provide cooling to the buildings or to the ambient environment by exploiting the temperature difference between the cooler and the ambient air. While radiative cooling techniques are investigated for many years, it is quite recently that sub ambient surface temperatures have been achieved during the day time and under high solar radiation conditions. A negative thermal balance of the radiative cooler requires a high emissivity of the structure in the atmospheric window together with a very low absorption in the whole solar spectrum. Selective materials and structures, although are very effective during the night time, can't satisfy these optical characteristics and until recently daytime radiative cooling was not possible, (41). The recent development of photonic, plasmonic and metamaterial structures have boosted research on daytime radiative cooling and resulted in the development of several efficient daytime radiative coolers. Numerous types of daytime radiative coolers including 2D and 3D photonic devices, photonic structures like multilayer planar photonic thin films, metamaterials and plasmonic structures have been proposed and tested presenting a very high emissivity in the atmospheric window in parallel with a high reflectance in the total solar spectrum. A full review of the existing developments on daytime radiative cooling is given in (42). Extensive testing of the proposed coolers concluded that it is possible to operate under sub-ambient surface temperature conditions, (42).

Quite recently, new advanced low cost and complexity radiative coolers based on polymeric photonics, (43) and passive radiative systems, like advanced paints are developed and tested successfully, (44). The developed polymeric photonic coolers are based on the use of electromagnetic resonators collectively excited inside a polymer material resulting in a increased emissivity in the atmospheric window spectrum. Passive systems under the form of paints provide superior advantages, however problems related to optical ageing because of the deposition of dust and other atmospheric constituents as well as unnecessary cooling during the winter seem to be important drawbacks. To overcome the winter cooling problem, it is proposed to integrate in the cooler phase change materials presenting a temperature dependent emissivity, (45). The experimental testing of such a technology provided some promising results and further developments are expected soon.

Figure 2 reports the existing experimental results regarding the measured decrease of the surface temperature of the daytime radiative coolers against the corresponding ambient temperature. Surface temperatures up to 17 C below the ambient one, are achieved. Data reported in Figure 2, is from references (46-52).

2.8 Other Material Technologies for Mitigation

Several other materials are proposed and used to enhance mitigation of the urban overheating. Cool asphalt materials, pervious and water retained pavement technologies and retroreflecting structures, are some of the more interesting and promising among them.

Asphalt in cities reaches a very high surface temperature during the summer time and increases considerably the sensible heat released in the atmosphere and the magnitude of the urban overheating, (53). Surface temperatures of bitumen materials in cities, exceeding 70 C have been reported, (53). Several alternative technologies to black asphalt are proposed and tested to decrease the surface temperature of roads and pavements.

Thin layer asphalt components developed by mixing an elastomeric asphalt binder (colourless) and adding special pigments and aggregates of special sizes and colours is reported in (54). The solar reflectance of the developed components varied between 27 % to 55 %, while the reflectance of the black asphalt was 4 %. The surface temperature of the asphaltic thin layers was measured between 4- 12 C below the surface temperature of the black asphalt.

Almost 4600 square meters of reflective bitumen materials are used in an urban rehabilitation project aiming to mitigate urban heat, (55). The reflectance of the bitumen pavements has increased by using transparent asphaltic resin and quartz chips from marble and granite in powder form. The solar reflectance of the bitumen materials was 26 % compared to 4 % of the conventional black asphalt. Measurements shown that the surface temperature of the developed bitumen material was almost 7.9 C lower than that of the conventional black asphalt

In another urban mitigation project, almost 18000 square meters of reflective yellow thin layer asphalt was used, (56). The alternative bitumen material was developed by mixing an elastomeric asphalt binder with infrared reflective pigments and aggregates and the final application was achieved with slurry surfacing techniques. The solar reflectance of the final product was close to 35 %. The average temperature reduction, compared to black asphalt was close to 7.5 C, while the maximum one exceeded 11 C

Pervious, water retentive and permeable materials to be used as pavements in the urban environment, are designed to allow water to flow through their mass into the sub-layers and the ground. Permeable pavements include additional voids for water flow while may include holding fillers to store water. Reduction of the surface temperature of the materials is achieved through evaporation of the contained water and contribute to the mitigation of the urban heat island while the risk of flooding is reduced, (57). Several technologies of permeable pavements are developed and used in large scale projects. Surface temperature reductions up to 20 C compared to conventional bitumen pavements are reported, especially after rainfalls, (58). Recent research on permeable materials has developed advanced new materials using additional agents in their mass, like fine blast furnace powder, steel bioproducts, pervious mortar, etc. However, the thermal performance of the permeable pavements depends highly on the availability of water.

Retroreflectance refers to the ability of a specific surface to reflect the incident light back towards its source regardless of the direction of incidence, (58). The use of retroreflective materials in urban canyons in association with IR or highly reflective materials contributes to decrease glare and the unnecessary reflection of solar radiation to the neighbouring buildings. Recent research has shown that retroreflective materials present a much higher mitigation and cooling potential than the traditionally used diffusive coatings and restrict seriously the energy circulating inside the urban canyons, (58).

Conclusions

Urban overheating is a serious energy and environmental problem causing an important impact in cities. To decrease the sensible heat released in the urban environment and mitigate the urban overheating, materials of low surface temperature should be used. Apart of the traditional white natural and artificial materials widely used in warm climates, new low surface temperature materials have been recently developed and used in many large scale urban mitigation projects. While, the increase of the solar reflectance of the materials may provide a substantial surface temperature reduction and a subsequent decrease of the released sensible heat, most of these materials technologies fail to achieve sub ambient temperatures under sunny conditions. However, advanced reflective materials may present almost 10 C lower surface temperature than the conventional materials of the same colour, while the achieved temperature reduction may be much higher in dark colour materials.

The recent development of daytime radiative cooling technologies provides revolutionary material solutions for the urban environment. Daytime radiative coolers may achieve surface temperatures almost 18 C below the ambient temperature and reverse the flow of the sensible heat in the urban environment. Although there are many issues to be clarified with the newly developed material technologies for mitigation purposes, it is evident that they provide a very substantial potential to fight urban climate change.

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Passive Cooling for Comfort in Extreme Climates

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Abstract: This paper describes the process implemented by the authors, and in one case with students, to implement passive cooling strategies in projects in hot climates. In a warming planet, overheating is becoming an ever-important issue at all latitudes and locations, even in areas which traditionally did not have this problem. The first section describes a community center in Tecate, that includes very low-cost passive heating and cooling strategies, built by volunteers and local residents. The second section discusses recent tests in a green roof originally developed by Yeom and La Roche that combines evaporative cooling with a radiant system. The third section illustrates, through a project in development in the middle east, how these passive strategies can be combined to substantially improve outdoor thermal comfort in an extreme climate with no mechanical cooling.

Keywords: Passive Cooling, evaporative cooling, green roofs, outdoor thermal comfort, low cost sustainability

1. Passive Cooling

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. Because of their simple design, they can also be built at lower costs, using local labour and resources, generating income that stays in the community.

A passive cooling system reduces indoor temperature by transferring heat from a building to various natural heat sinks (Givoni, 1994). They are typically classified according to the heat sinks that they use to store energy (Givoni, 1994): ambient air (sensible or latent), the upper atmosphere, water, and under surface soil. The applicability of a passive cooling system is affected by multiple climate variables and not all systems can be used in all climates. The examples below demonstrate how some of these can be used in a hot and dry climate.

2. Low Cost Cooling in a Hot and Dry Climate in Mexico

Students from the author's Cal Poly Pomona studio, with feedback from Corazon (a southern California NGO) and local residents, designed a Community Center for Tecate, Mexico, fifteen kilometers south of the border with the USA, in a high desert climate with very hot and dry summers and cool winters.

To make better use of volunteer and resources, Corazon wanted the center's construction to be achievable in phases, so the students proposed separate buildings (Fig 2). Students met with the community in Mexico, and Corazon staff participated in the reviews and provided detailed input during their design process. Later, in several courses the students worked on specific issues and systems that included rain water harvesting, low cost solar hot water, a variable insulation-shading window, roof ponds, radiators, cool towers; cooling with phase change materials, passive heating with direct gain, Trombe walls, and water wall systems. Some of these systems were developed only to the level of conceptual design adapting original concepts to local conditions. Other systems such as the evaporative cooling tower and the solar attic were further refined and tested by the students at the Lyle Center for Regenerative Studies.

In the summer a downdraft evaporative tower provides cool air inside the building. The construction and materials of this tower are very simple, creating a very low cost cooling option. Simple showerheads mist the air, increasing its density, and pulling warm air from the exterior into the tower and into the space at the bottom of the tower (Fig. 3). The air exits the space through the solar attic or an open window. These openings for the air to exit are necessary for the cool air to enter. Measurements taken on site demonstrate that the downdraft evaporative cool tower is able to cool the air, from an outdoor temperature of 36.7 °C with a RH 24% outside in the shade and entering the tower, to 20.8 °C and 100% RH exiting at the bottom.

The center began operation in early 2017 and is providing skills training workshops for adults, day-care facilities, meeting spaces for the community and volunteer housing. The next step is to design modular passive systems that could be built in the center by members of the community and then incorporated to new and existing dwellings (currently people in the community do not have mechanical heating or cooling). Fabrication at the center would provide a source of income to the community while improving living conditions; this is true social, economic and environmental sustainability. Projects such as this also provide North American architecture students with the opportunity to learn about other cultures and do good, while at the same time learning from hands-on work.

Figure 1: View of several buildings in the Community Center

Figure 2: Community Center under Construction with Down Draft Evaporative Cool Tower and Solar Attic

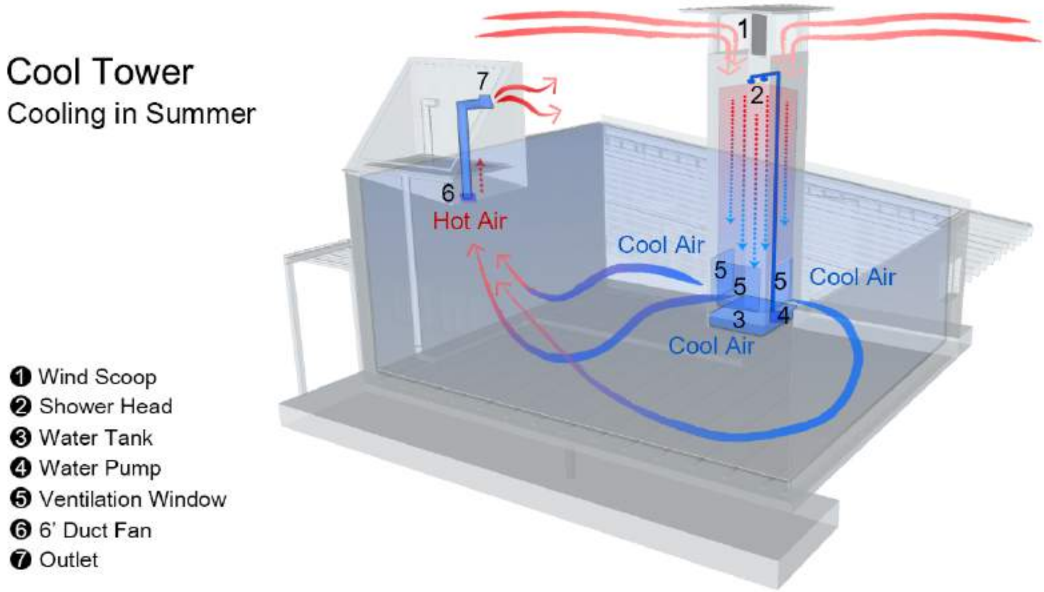

Figure 3: Cool tower system working through evaporative cooling

3. Cooling with Green Roofs

This section discusses the a radiant-evaporative cooling green roof. The cooling potential of different green roof configurations has been evaluated over several years using test cells, located outdoors and exposed to the weather at the Lyle Center for Regenerative Studies at Cal Poly Pomona University, 30 km east of Los Angeles, in California (Fig 4). The climate is hot and dry with an average high temperature of 31.5 °C in August and an average low of 5.3 °C in January. All test cells are similar in size (1.35 m. × 1.35 m. × 1.35 m.) with a window facing south. Their only difference is in the roof which is the variable that is compared. The walls of the test cells are 178 mm thick, with drywall on the inside, 50.8 mm × 101.6 mm studs with glass wool insulation, OSB board, XPS insulation board, and plywood on the outside. The floor of the cell is OSB board and XPS insulation board. The U-value of the wall is 0.308 W/m2 K and the U-value of the floor is 0.299 W/m2 K. Walls are painted white to reduce the heat gains. A double-glazed window 610 mm wide × 610 mm high was installed in the south wall and was tested with and without shade. An exhaust fan was installed for night ventilation.

Data loggers by Onset computer were used for data collection (Model: U12-012, UX 120-006 M, TMC6-HD). These sensors were installed in multiple positions inside and outside of the test cells to monitor dry bulb temperature and relative humidity. Every sensor was connected to the data logger, and the sensors were installed following DIN EN 60751 regulation.

Several green roofs are compared to the radiant-evaporative roof: an insulated green roof, an uninsulated green roof, and an insulated roof (not green). The insulated green roof has rigid insulation underneath the planting material. The U value of the insulated green roof was 0.282 W/m2 K. In the uninsulated green roof, the planting material is thermally coupled with the interior of the space via a metal plate under the green roof. Combined with night ventilation it cools in two ways: during the night, the cell is night ventilated and cooled with outside air and during the daytime the vegetation shades the roof, reducing solar gains while the growth medium acts as a heat sink.

Figure 4: Green roof test cells

The radiant-evaporative green roof configuration consists of a radiant system with a water pipe embedded in the soil and exposed to the space below, and an evaporative system with a sprinkler system. The radiant system consists of a closed-loop pipe with a total length of 33 m. The upper portion is embedded in the soil of the green roof and the lower portion is exposed at the ceiling of the cell. A pump circulates the water inside the pipe and is operated by a digital timer, turning on or off according to selected schedules (Fig 5). The evaporative component is achieved by a sprinkler system that irrigates above the ground and reduces the air and soil temperature by evaporative cooled water and air. The cooled soil then lowers the water temperature of the radiant pipe embedded in it, which then absorbs heat from the space below as it moves from the ceiling, through the ground and to the surface. The heat is thus transferred from the space to the ground and dissipated to the exterior by evaporation above. According to (Yeom, La Roche, 2017) the most effective schedule to operate the flow of water through the embedded pipes is continuously moving the water, and the most effective schedule for the use of the sprinklers was to turn on when exterior humidity was lowest, typically around mid-day. We are currently testing a 24-hour schedule with 5 minutes of irrigation every 55 minutes. During this time there would be more air cooling and more cooled water to the substrate, reducing its temperature and increasing its capacity to absorb heat from the interior. Some series were also tested combining the radiant evaporative green roof with night ventilation (Fig 6).

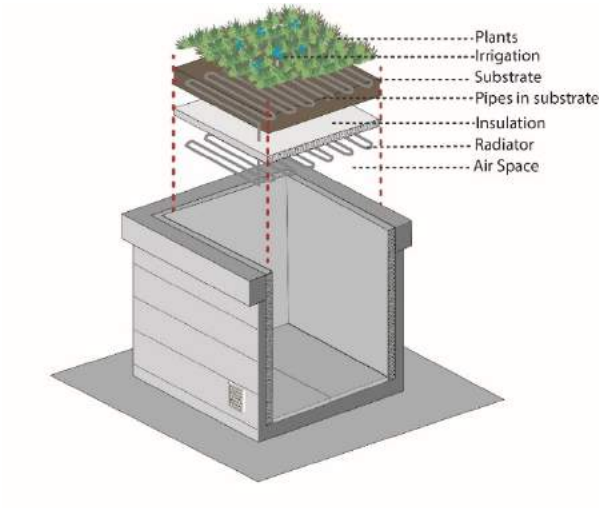

Figure 5: Components of the Radiant evaporative green roof

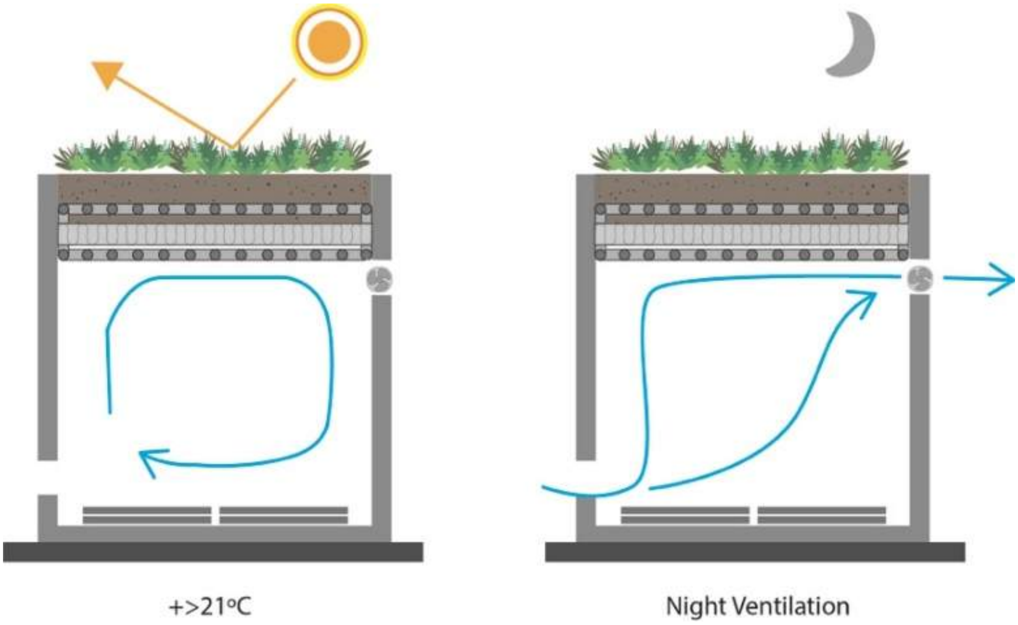

Figure 6: Radiant Evaporative Green Roof Combined with Night Ventilation

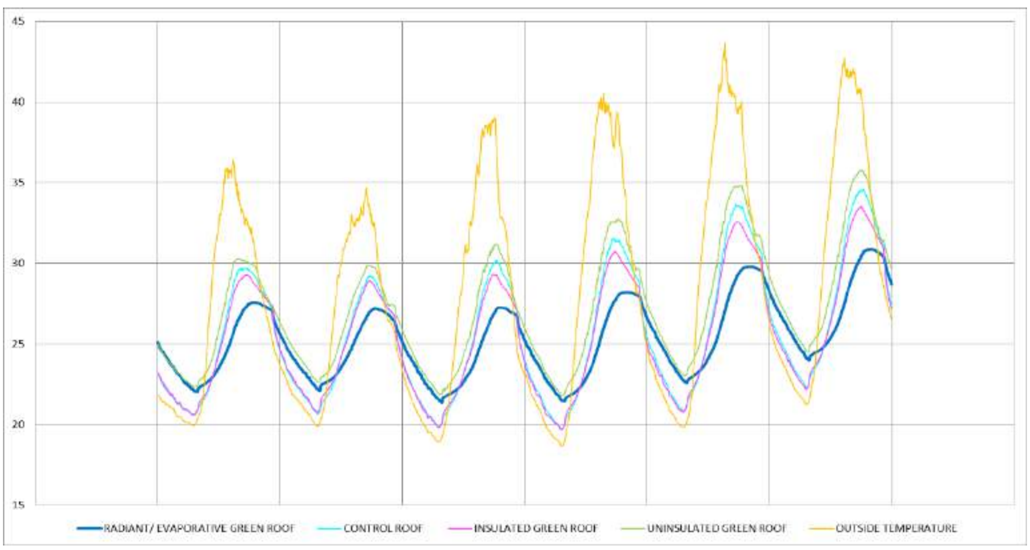

Figure 7: Series comparison July 18-July 23, 2018

Results combining night ventilation with the radiant evaporative system were best in hot and dry days with cooler nights. Dry days provide more potential to cool by evaporation during the day with the radiant/cooling system, while cooler nights provide more potential for cooling with night ventilation and radiant cooling at night. Figure 7 shows a series in July of 2018. During this period all test cells had windows shaded, night ventilation provided with a fan, from 9 PM to 6 AM and the irrigation system operating from 1 PM to 1:30 PM. The embedded water pipes were operating continuously 24 hours.

Outdoor dry bulb temperatures were above 40 °C while inside the test cell with the radiant/evaporative system temperatures were 9 to 13 °C below exterior temperatures and several degrees below the other test cells. The maximum average temperature in the radiant evaporative green roof was 27.6 °C compared to 29.7 °C in the control cell with the insulated roof, 30.3 °C in the uninsulated green roof, 29.7°C in the insulated green roof and 36. 4°C outside. The average minimum temperature outside during the night was 19.9 °C.

Equations were developed for the cell with the radiant evaporative system, shaded, with night ventilation. Figures 8, 9, and 10 show the relationship between the reduction of the maximum temperature (difference between maximum outside and maximum inside) and the outdoor temperature swing in cells with different amounts of mass: low, medium and high. Concrete bricks in the floor were used to adjust this amount of mass: there are no bricks in the low mass cell (0 kg/m^2), 8 bricks in the medium mass (20 kg/m^2), and 16 in the high mass (40 kg/m^2). Each point in the figure contains one day's data, comparing the difference between the indoor and outdoor maximum temperature (y axis) with the outdoor diurnal temperature swing (x axis). As the swing increases, the difference between indoor and outdoor maximums also increases. This trend line describes the equation that predicts maximum indoor temperature as a function of the outdoor maximum temperature and the outdoor temperature swing.

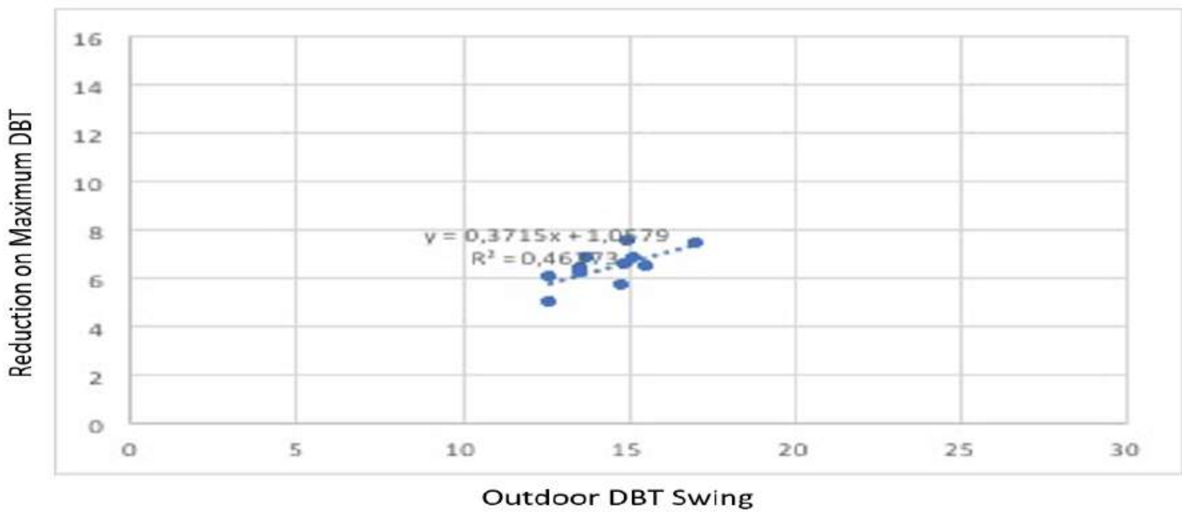

Figure 8: Comparison between reduction of Maximum DBT and Outdoor DBT Swing Low Mass

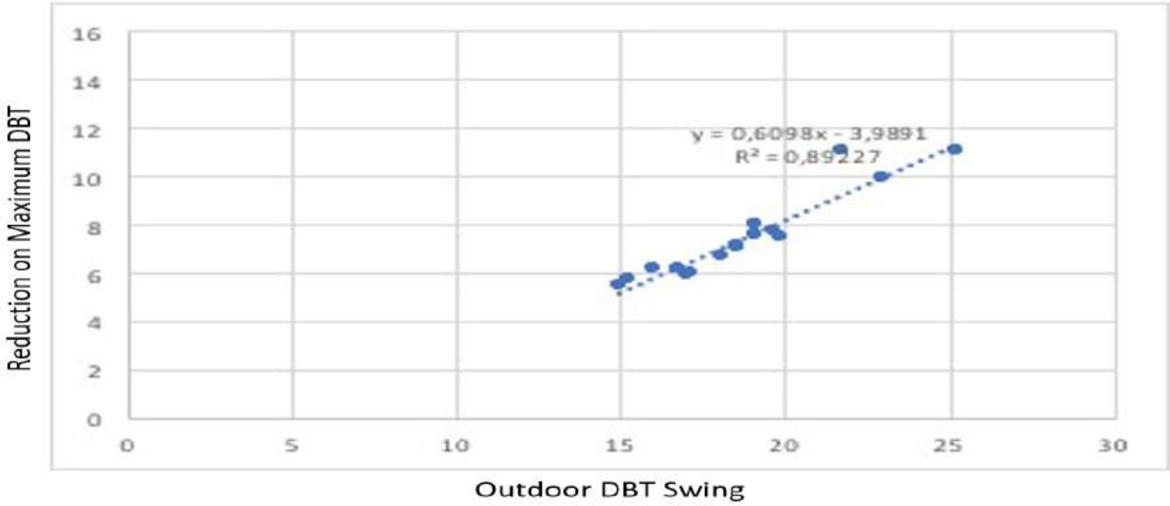

Figure 9: Comparison between reduction of Maximum DBT and Outdoor DBT Swing Medium Mass

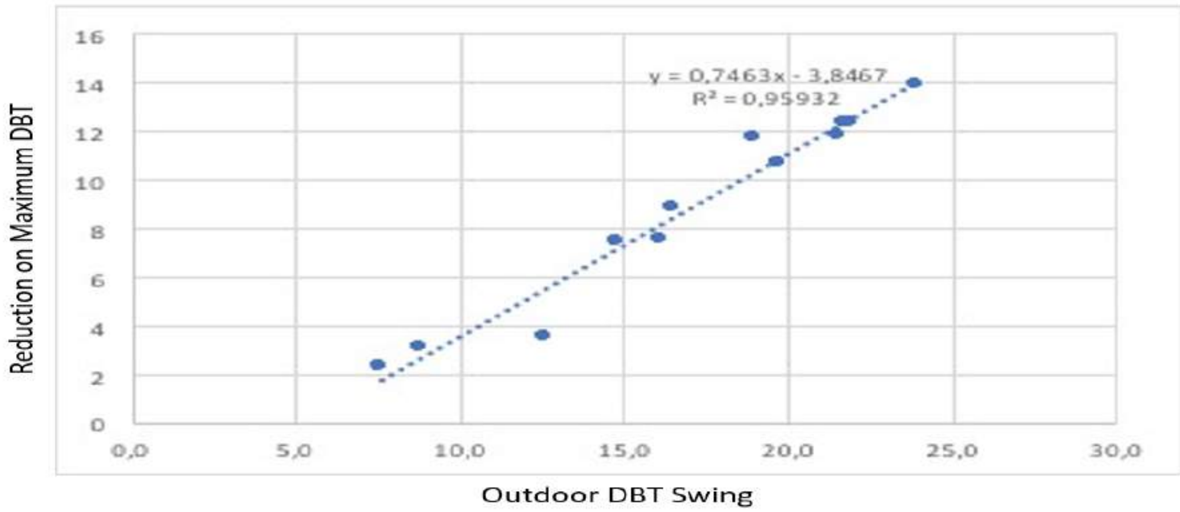

Figure 10: Comparison between reduction of Maximum DBT and Outdoor DBT Swing High Mass

In all three test cells and all series, better performance as indicated by higher reduction in the maximum indoor temperature, is achieved with higher temperature swings, typically also associated with lower humidity. More variability in outdoor conditions provide more precision in the equations. Unfortunately, during the data collection period in the series with low mass there was not enough variability to generate an equation with a good coefficient of determination.

The equations are below:

Low Mass

$T_{maxint} = T_{maxext} - (0.37 \times T_{swing}) + 1.05$ ($R^2 = 0.46$)

Medium Mass

$T_{maxint} = T_{maxext} - (0.61 \times T_{swing}) + 3.99$ ($R^2 = 0.89$)

High Mass:

$T_{maxint} = T_{maxext} - (0.75 \times T_{swing}) + 3.87$ ($R^2 = 0.96$)

Predictive equations can be generated from the data collected:

Low Mass	$T_{maxint} = T_{maxext} - (0.37 \times T_{swing}) + 1.05$
Medium Mass	$T_{maxint} = T_{maxext} - (0.61 \times T_{swing}) + 3.99$
High Mass	$T_{maxint} = T_{maxext} - (0.75 \times T_{swing}) + 3.87$

Where:

T_{maxint}	=	Maximum Temperature Inside
T_{maxext}	=	Maximum Temperature Outside
T_{swing}	=	Outdoor Temperature Swing

These equations are valid for these test cells, with specific physical properties and amounts of thermal mass tested, and while they do not predict temperature in buildings with different configurations, they provide an indication of performance in larger spaces with similar properties.

Indoor and outdoor measurements were compared on the same day and compared to the comfort zone to determine the effectiveness of the strategies (Rodriguez, La Roche 2018). The blue area in the psychrometric diagram in figure 11 describes the conditions under which this radiant evaporative cooling system will be most effective. This area is similar to the evaporative cooling area typically proposed in most psychrometric diagrams, up to a dry bulb temperature of 42 °C, an absolute humidity below 12 g/Kg and wet bulb temperatures below 24 °C. Above 42 °C there will still be cooling but comfort will be difficult to achieve.

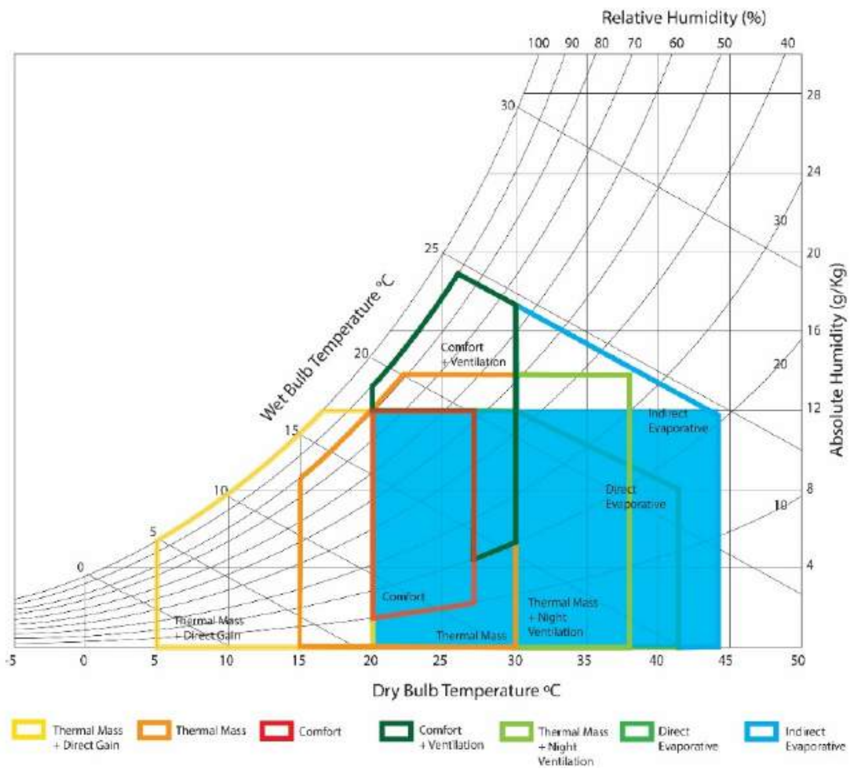

Figure 11: Climate Applicability of the Radiant Evaporative Cooled Roof

Different types of green roofs are more effective for cooling in some climates. However, in all types of green roofs, the following two conditions improve performance:

a) The vegetation in the canopy layer improves the performance by providing shade and some evaporative cooling.

b) All test cells with green roofs when combined with night ventilation and shade provide more comfort inside buildings, with increased energy efficiency. Additional thermal mass will also increase their performance.

These experiments evaluate the performance of the cooling systems and the architectural design can be different if the heat flow paths are maintained. The concepts tested in the cells can take multiple forms, more appropriate to the architectural concept being developed. An example is the Xylem, that implements several principles of the radiant/evaporative test cell system on an outdoor space (La Roche, 2017).

Conditions with high temperature and high relative humidity have not been tested for any of these green roofs. In hot and humid climates, the vegetated canopy will provide shade and insulation will reduce exterior heat gains, but evaporative cooling and night ventilation will not be as effective. The Xylem proposes a green roof system that can also be implemented in a hot and humid climate using the strategies tested at the Lyle Center for Regenerative Studies and described below.

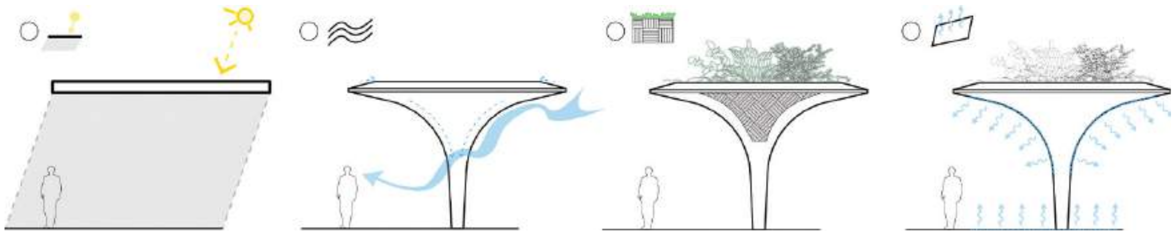

Figure 10: Xylem combines shade, natural ventilation, green roofs and radiant cooling.

The goal of the Xylem is to improve outdoor thermal comfort while mitigating the heat island effect. Four cooling strategies are integrated: a large canopy for shading, natural ventilation, a vegetated roof for thermal mass, and water circulation for radiant cooling (Figure 10). 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. As in the radiant evaporative cooling green roof previously tested, liquid-filled tubes embedded in the soil of the planting material are cooled to a lower temperature than the air temperature. In this case the water in the pipes does not go to the ceiling of a space but instead the water in these tubes cools panels at the occupant level and in the ground around the center of the pod, cooling the person by radiation from the ground or the panels (Figure 11). An air space between the earth and the panels also helps to insulate the earth while providing an opportunity to also cool the air as it flows from the top to the ground providing cool air at the lower level. Photovoltaic panels integrated at the top of the Xylem provide electricity to the pumps that circulate the water.

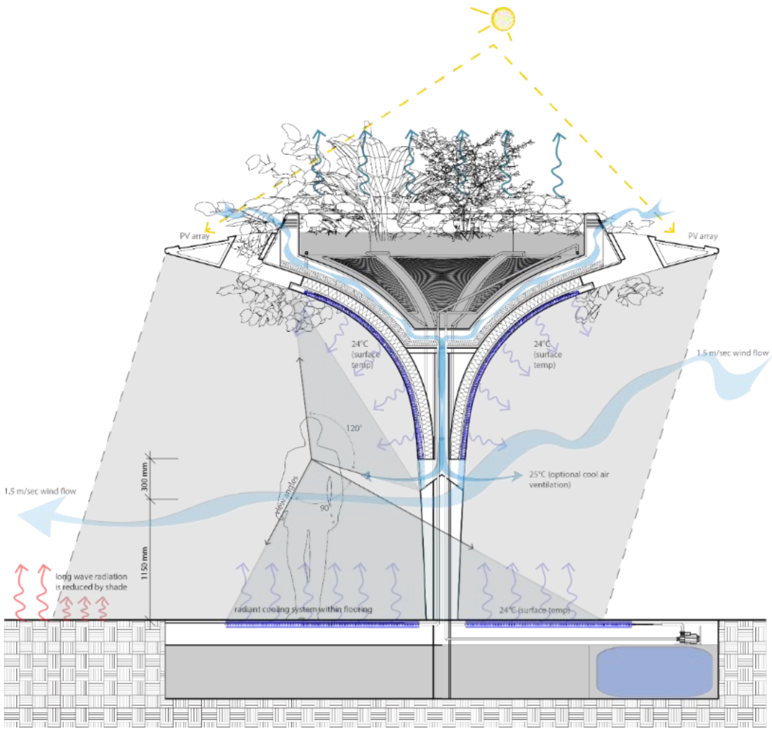

Fig. 11: Radiant Evaporative Green Roof

As cities replace vegetation with paved surfaces, "islands" of higher temperatures increase energy consumption in buildings, emissions of GHG, and pollutants while compromising human health. As in the green roofs that have been tested at the Lyle Center, the Xylem incorporates multiple strategies to reduce the heat island effect; the vegetation above the Xylem shades its surface while evaporation from these vegetated surfaces also cools the air by using heat from the air to evaporate water; the Xylem itself shades the ground below reducing heat absorption (Figure 12). According to the Environmental Protection Agency (EPA) evapotranspiration, alone or in combination with shading, can help reduce peak summer temperatures by 1°C – 5°C. When combined in canopies they can lower local temperatures by an additional 2°C and reduce peak loads in the summer and overall energy consumption. Kurn et al. (1994) estimated that near-surface air temperatures over vegetated areas are 1°C – 2°C lower than air temperatures in cities.

Figure 12: Multiple Xylems combined can improve performance substantially.

4. Outdoor Comfort in a Hot and Dry Climate

It is possible to implement multiple passive strategies to improve outdoor comfort. For example, in a shopping mall under development the middle east, shade, air movement, evaporative cooling, thermal mass with embedded pipes and green surfaces are proposed to improve outdoor comfort. None of these are effective by themselves to achieve thermal comfort during all outdoor conditions of the year. However, together, they can improve conditions during all the year improving occupant experience and thermal comfort in the courtyards.

Shade is needed most of the year and in this climate provide two important benefits, it blocks solar radiation to the human body which would increase discomfort on warm days and reduces solar gains on exterior surfaces which would otherwise be absorbing solar radiation, storing it and then re-radiating it as long wave radiation towards the courtyard, negatively affecting thermal comfort. Solar studies have been done to propose shade where it will be more effective. Shade can be retractable or operable and can be adjusted as appropriate, opening at night to provide additional cooling of the surfaces to the night sky. During days with high outdoor temperatures, shade by itself is not enough to achieve thermal comfort because it does not reduce air temperature and other strategies must be implemented.

Air movement can improve comfort when the air temperature is below 32 °C so that the body feels several degrees cooler. However, with higher outdoor temperatures, air movement is not helpful because it will feel as warm as it passes through the skin. Fans provide air movement where it is most needed in the dining area and an exterior solar chimney provides an opportunity for warm air to exit the courtyard. Air movement is helpful during most of the year to increase comfort but it some cases must be previously cooled through evaporative cooling before it passes through the body.

As already discussed, evaporative cooling is an effective strategy to reduce air temperature through evaporation of water when the air is hot and dry. In this process, the sensible heat in the air is exchanged for the latent heat of water droplets or wetted surfaces and the air temperature is reduced with a gain in humidity. This process is adiabatic, which means that no energy is gained or lost. Evaporative cooling in the courtyard is activated through different mechanisms, misters cool the air above the dining areas while water features at the ground and lower levels provide additional evaporating cooling, also enhancing the qualities of the space with aesthetics and sound. Evaporative cooling is most effective during the daytime when relative humidity is lower, and temperatures are higher, and during the shoulder seasons when transitioning to the hot muggy season. Water bodies at the ground level also keeps the ground from overheating and re radiating energy to the exterior.

Thermal mass has cool radiant pipes embedded in it. When the water features are activated, the water is cooled by evaporation. The embedded pipes are thermally coupled with the water features, acting as a heat exchanger, transmitting the energy from the slab to the water and then to the air. This cool slab will provide radiant cooling and improve comfort to the people sitting above. This strategy is especially effective during the late afternoon and dinner when evaporative cooling is not as effective. Care must be taken to keep the slab in the shade and it temperature below the dew point temperature to avoid condensation.

Green surfaces have a double objective, they protect and shade the west wall so that it does not overheat, and they also provide some evaporative cooling. The courtyard floor includes water and green areas that also reduce solar gains. Green on the solar chimneys keeps the walls from overheating and can be integrated with misters to improve comfort.

Figure 13: Integration of passive cooling systems in a courtyard

5. Conclusions

It is possible to continue developing and improving the performance of passive cooling systems integrating them with other building components such as roofs, green roofs, walls, and windows as long as the materials and design respond to required heat flow paths and climate. By integrating these systems into building components, the building components can do more, and value is added to them. The green roof with the radiant / evaporative system is an example of a system with added value since the green roof is an already useful component. This type of green roof performs better on hot and dry climates and when combined with night ventilation in climates with daily temperature swings above 12 °C.

It is also important to integrate Passive Cooling Systems in the design, so they are not simply accessories attached to the project. They should be integral to the architectural design intent which is what each of these projects tries to demonstrate. In the Tecate community center the cool tower and the solar attic are part of the architectural expression and massing of the project; the form and construction of the xylem responds to the flow of energy from the green roof to the people below to achieve comfort; and the integrated strategies in the courtyard provide an opportunity to cool through the beautiful integration of all of these strategies adapted to daily and seasonal cycles.

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Boosting Comfort Locally with Personal Micro-Climate Systems

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Abstract: The commonly used total volume systems cannot provide high quality indoor climates in an energy efficient manner. Also standard systems are not able to guarantee the comfort and air quality demands of individuals in spaces. Thus, there is need to introduce systems that can provide user-centered climate systems in which users are able to control their own indoor micro-environments. Micro-climate systems makes it possible to enhance users' perception of their local indoor climate conditions. With personal ventilation, it is possible to provide clean air close to the breathing zone and also control thermal comfort locally. Another possibility to create local micro-environments is by using ceiling integrated systems that divide spaces into different subzones. In the near future, it will be possible to develop room systems that can be constantly reacting to human physiological signals to maintain conditions across a space that best fit the comfort requirements of individuals within it.

Keywords: Thermal comfort, user-centric, micro environment, biosignals

1. Introduction

Thermal comfort was historically defined to be able to best ensure that most people in a space can feel thermally comfortable. The original definitions have been in use for decades, and are prevalent in subsequent studies on how to improve knowledge and understanding of satisfaction within thermal environments. Present standards (EN 15251, 2007) recommend maximum values for the indoor climate parameters for both winter and summer conditions in order to achieve thermally comfortable environment for occupants. However, in rooms with high cooling demands it becomes challenging to achieve the targeted indoor climate without sacrificing occupants' thermal comfort due to the increased convective flows.

Room airflow patterns in cooling conditions depend on the relative locations of air distribution units and the strength of heat sources. Consequently, one of the main challenges in modern offices is to distribute clean air to the workstations, without draught risk, in an energy efficient manner. Recently, local thermal comfort of draught have been found to be a common in various public buildings. Draught is defined as an unwanted local convective cooling of a person. The risk of draught increases when the airflow temperature decreases and the mean velocity and turbulence intensity increase.

It should be noted that nowadays, air-conditioning systems are designed for the average person, where it is assumed that individual demands on thermal conditions are not possible to fulfil. Thus, more advanced personalized air distribution methods should be introduced to improve thermal comfort of all occupants where radiant and convective cooling methods play a major role when responding temporal and spatial changes of the user-centric environment.

The term 'smart buildings' refers to the capability of a building to sense, interpret, communicate and to respond to changing conditions, which are introduced as requirements of a) individual occupants to indoor climate; b) the operation of technical building systems and c) the demands of intelligent energy systems. The possibility of new systems to adapt in response to the perception and requirements of occupants, to and further empower end-users makes it now possible to enhance individual users' satisfaction with their own local indoor climate. In smart buildings the readiness of managers to facilitate maintenance and ensure the efficient operation of technical building systems guarantees optimal performance of systems at their point of end use.

The objective of this paper is to discuss couple of possible micro-environment concepts for the smart control of indoor climate conditions and system performance. In the following conceptual designs in development, users may provide the agreed room air temperature and boost ventilation according to their perceived requirements.

2. Some methods to control micro-environment

The most common air distribution system currently in use involves mixing ventilation where air is supplied at a high velocity to enhance the entrainment and mixing within the room air. The supply diffusers are installed above the occupied zone close to the ceiling level to utilize the Coanda effect so that cold air jet does not directly impinge on the occupants. Mixing ventilation is supposed to create uniform indoor environments in both thermal and air quality aspects over the whole ventilated volume. However, in the well-mixing concept, it is not possible guarantee individual demands of occupants.

To enhance occupants perception, a personalized ventilation system has been introduced. The main idea of personalized ventilation (PV) is to provide clean and cool air to the breathing zone of each occupant. The PV in comparison with total volume air distribution (TV) has two important advantages: first, its potential to improve the inhaled air quality and second, each occupant is delegated the authority to optimize and control temperature, flow rate (local air velocity) and direction of the locally supplied personalized air according to his/her own preference, and thus to improve his/her thermal comfort conditions.

The supply air terminal devices (ATD) used for PV are located close to the breathing zone of occupants. ATDs of different design, allowing control of airflow rate and some of them for control of flow direction, have been tested in several studies. The amount of inhaled clean personalized air has been shown to depend on the design of the ATD and its positioning in regard to the occupant, the flow rate (typically from 5 L/s up to 20 L/s) and the direction of the personalized airflow, as well as the difference between the room air and the PV airflow temperature, size of target area, etc. (Melikov et al., 2003). With this respect the interaction of flows in the vicinity of user's body, especially at the breathing zone is important. The most important flows affecting the performance of these systems are presented in Figure 1.

Figure 1. Personalized ventilation - Airflow interaction around human body: ① – free convection flow, ② – personalized flow, ③ – respiration flow, ④– ventilation flow, ⑤ – thermal flow

PV improves peoples' thermal comfort (Kaczmarczyk et al. 2002). The acceptability of the thermal environment with PV compared to without PV significantly improves at room temperature above 23 °C. Control over supplied airflow rate, i.e. local air velocity, obviously makes it possible to avoid draught discomfort. The freedom of control over direction and flow rate of personalized air is important for lowering the risk of draught sensation and to improve occupants' satisfaction.

Substantial energy savings have been reported when PV is used. Due to convective cooling of the body PV can provide occupants with thermal comfort at elevated room temperature, 25 °C – 27 °C. Apart of the elevated room temperature occupants' activities, i.e. use of PV only when the person is on the workstation, also contribute to the energy saving with PV.

A system using textile surfaces as supply air terminal devices for the PV is a design which has been tested for both chairs and beds (Figure 2). For a seat, the air can be supplied through a neck rest, a pillow behind the head or through part of the chair (Nielsen et al.,2007).

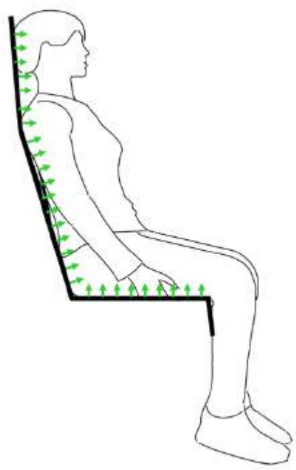

Figure 2. Personalized ventilation through chair textile.

The free convection flow generated by the human body forms the convective boundary layer around the body which transforms into a thermal plume that rises above the head. The generation of the convective boundary layer will cease locally for areas where due to local radiant cooling the cloths surface temperature has decreased (Melikov 2015). When the cloths surface temperature becomes lower than the surrounding air temperature, local downward flows opposing and disturbing the main upward flow of the thermal plume may occur (Figure 3). All this indicated how sensitive are the local convection flows close to the body for radiant and convective boundary conditions.

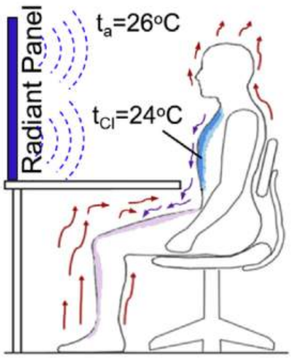

Figure 3. Personalized cooling with a radiant panel.

In many cases, it is easier to install the terminal units in the ceiling level than integrate them in the work stations. By using ceiling integrated system, an internal space may be divided into different personal work areas or subzones using downward directed jets and/or local radiant cooling and heating, which separate the space and provide local micro-environment control. One possible solution is to have local chilled beam solution for workstation convective cooling and to have general cooling for the space with radiant ceiling system (Figure 4). By controlling supply air flow rate of the chilled beam, there is also possible to adjust throw pattern and enhance cooling if the user prefers to have higher velocity close to body. In Figure 5, smoke visualization of the thrown pattern control is shown where user can be directly cooled by the air flow based on individual preferences.

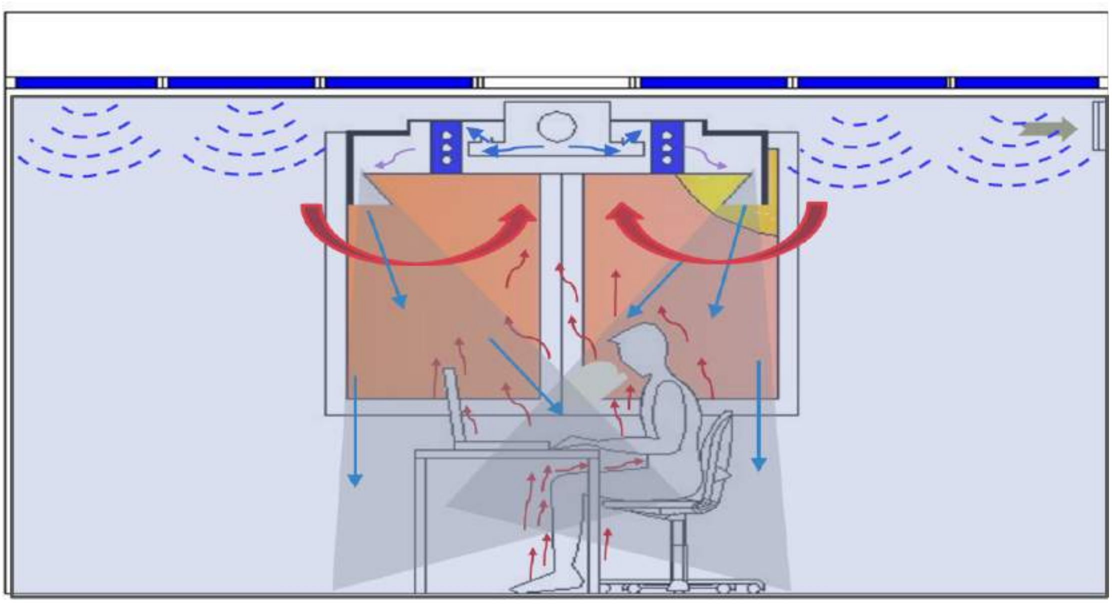

Figure 4. A concept for micro-environment control.

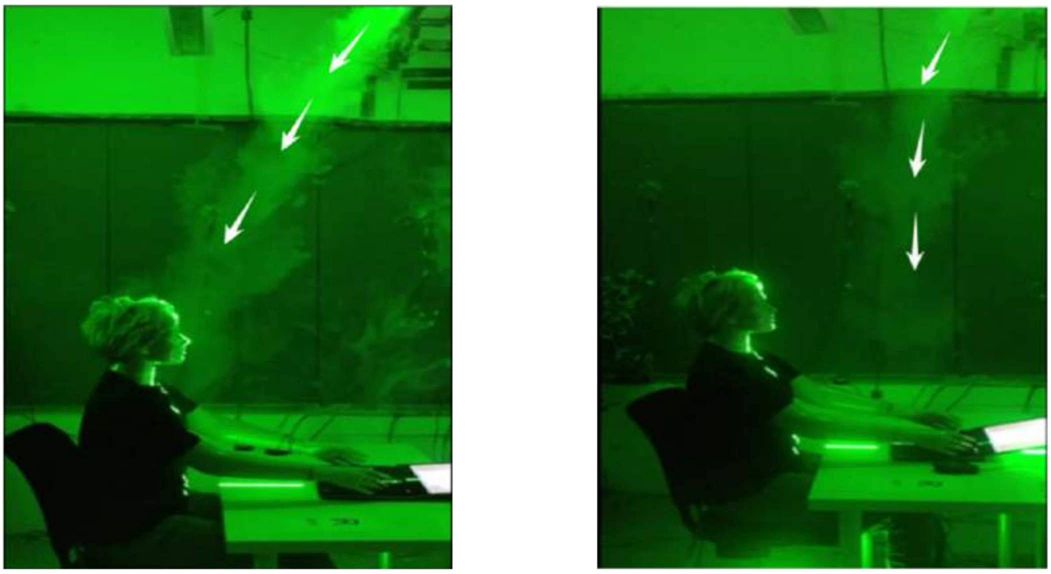

Figure 5. Smoke visualization of air distribution control.

The response of 24 subjects to the local environment established by localized chilled beam combined with chilled ceiling (LCBCC) was studied and compared with response to the environment generated by mixing ventilation combined with chilled ceiling (CCMV) at two temperature conditions of 26°C and 28°C (Arghand et al, 2016). The supply airflow rate from the LCBCC was controlled by the subjects within the range of 10 to 13 L/s where in the case of CCMV subjects did not have control over the flow rate. The experimental conditions during the five experiments are listed in Table 1. The designed supply flow rate and room temperature were according to category II, EN 15251 (2007) for very low polluting building.

Table 1. Test conditions

Case	System	t (°C)	Supply airflow rate (L/s)
1	LCB+CC	26	10- 13 (individual control)
2	LCB+CC	28	10- 13 (individual control)
3	LCB+CC	28	10- 13 (individual control)
4	CC+MV	28	13 (no individual control)
5	CC+MV	26	13 (no individual control)

Overall body thermal sensation (OTS) and local thermal sensation (LTS) of body parts were evaluated by continuous seven point ASHRAE thermal sensation scale. Two-part continuous scale with end points coded as -1 (clearly unacceptable) and +1 (clearly acceptable). The scales are recommended in EN15251 (2007).

Each experiment took two hours, divided into 30 min acclimatization period and 90 min exposure period in the office room. Experiments in the simulated office comprised three sessions of 30 min at each WS. The first 30 min spent at WS1 (close window in the perimeter zone), followed by 30 min at WS2 (in internal zone) finally last 30 min again at WS1.

All the values of OTS can be classified within the range of neutral and slightly warm (Figure 6). Thermal sensation in cases with LCBCC system at WS1 was more close to neutral level than cases with CCMV system ($p<0.05$). In fact, the positive impact of the higher convective cooling at WS1 can be seen during the exposure in conditions with LCBCC. The first vote at WS1-2 under LCBCC shows OTS reduced and approached the neutral level in the studied conditions. Conversely, because of the effect of the simulated window and floor, OTS at WS1-2 was assessed close to slightly warm under CCMV.

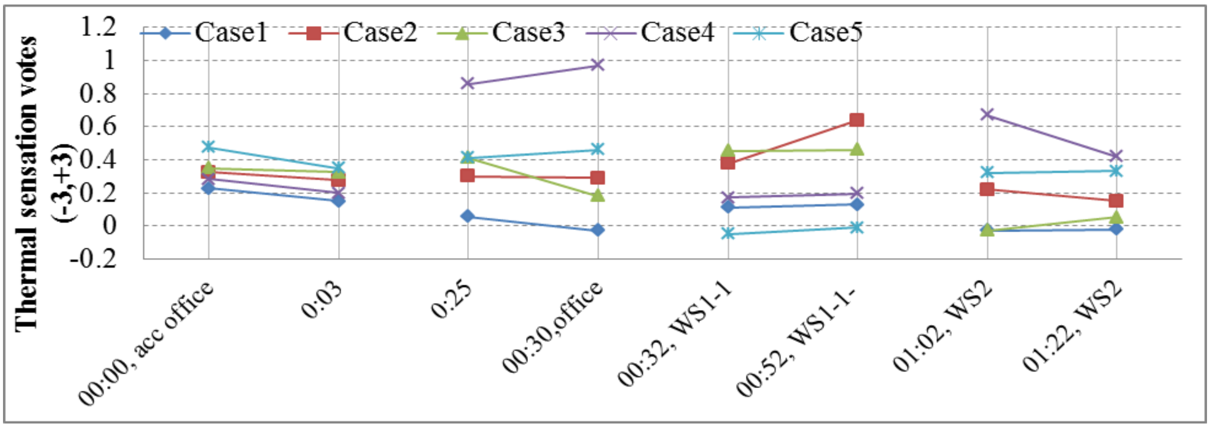

Figure 6. Smoke visualization of air distribution control.

The results of thermal sensation reported by the subjects at the workstation showed that the LCBCC created a thermal sensation close to the neutral level for the occupants. Most of the subjects were satisfied with the air movement at WS1 in the cases with LCBCC, while they reported request for more air movement in the case of CCMV.

All this indicates clearly that there is possible to enhance thermal perception with local micro-environment control even the average room space temperature was relatively high (26°C and 28°C).

3. Utilization of bio-signals in control

People are increasingly comfortable with wearable technology, using devices ranging from smart watches to activity trackers. The explosion of the internet of things means that more everyday objects are interconnected and exchange data with one another. Wireless sensors are also becoming commonplace, creating a natural environment to start deploying smart building technology.

In future comfort control systems, instead of adjusting your thermostat, the room system could be constantly reacting to human physiological signals like your heart rate, skin temperature and skin moisture to maintain a condition that is the best fit to your comfort. Automated temperature controls could be just one aspect in the future of our built environment: together with building automation system, smart buildings use biosensors to create the best settings for wellbeing and productivity. To help determine whether employees are comfortable, a smart device similar to a fitness tracker might be strapped to the wrist to measure body temperature, sweat and other indicators. In Figure 7, there is depicted a concept of using bio-signals for controls (Choi 2018).

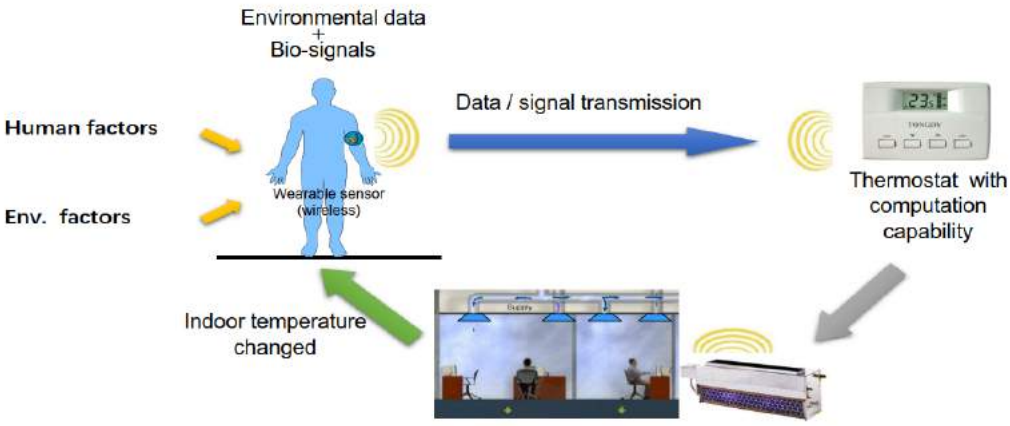

Figure 7. Utilization of bio-signals in control.

4. Conclusions

The current norm of having comfort conditioning systems that are designed for the average person, where on the thermal comfort conditions of individuals are deemed to be impossible to fulfil, are changing fast. The development of more advanced personalized air distribution systems should be, and are being, introduced to improve thermal comfort of all the occupants of a space, not just the mythical average man. It is also clear that large energy savings can be achieved, with enhanced comfort by heating or cooling the occupants of the building, not the room volumes within a building itself. This paper has described the development and testing of individual personalize ventilation systems and demonstrated that such personal ventilation systems have the potential to improve the inhaled air quality and control temperature according to an individual's own preference. Micro-environment controls are also in development in the form of ceiling integrated systems that divides spaces into different subzones. In the future control system, instead of adjusting your thermostat, the room system could be constantly reacting to human physiological signals.

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Localised air conditioning: comfort with sustainable energy demand

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ABSTRACT: Emissions from rapidly expanding use of room air conditioning in emerging economies is likely to increase global temperatures by 0.5 °C by 2100. However global greenhouse emissions need to be eliminated by 2045 – 2055 to stabilize warming at 1.5 °C. To meet this requirement, an affordable, alternative, low-energy, low emission technology needs to be deployed on a mass scale within 25 years. Since new technologies typically take 30 – 40 years to deploy globally, it will be easier with technologies that are available now.

Experience demonstrates that small portable air conditioners (spot coolers) with appropriate air delivery technology can meet this need. They create a localized micro-climate for up to three people providing acceptable comfort using only 180 – 300 Watts. They work in any building with no requirement for installation, piping, draft sealing, insulation, or structural modifications. They also work outdoors in sheltered locations.

For sleeping in extremely hot conditions, a specially designed bed tent retains a layer of conditioned air above a bed and provides protection from biting insects. Air delivery is designed to create sufficient air movement past exposed parts of the head and neck of users to gain about two degrees of additional perceived cooling, enhancing comfort sensation.

KEYWORDS: sustainability, localized air conditioning, energy, emerging markets, comfort.

1. Need for low energy air conditioning solutions

Air conditioning, backed up by almost unlimited electricity generation capacity in the USA, triggered the economic transformation of the hot and humid south of the country (Gordon, 2000). Large populations in emerging economies, including most of Africa, South Asia and other hot and humid low income regions are seeking similar benefits and air conditioning usage is increasing rapidly. However, the use of 20th century room air conditioning technology for this would require an enormous and unsustainable expansion in electricity generation capacity and unacceptable greenhouse emissions. Recent estimates suggest that direct emissions from refrigerant loss and indirect emissions from power generation for residential room air conditioners using conventional technology will add 0.5 °C climate warming by 2100 (Campbell, Kalanki, & Sachar, 2018; Isaac & Van Vuuren, 2009). Air conditioning solutions are needed requiring 5-10 times less energy and refrigeration technology with negligible emissions. The 2018 update from the UN Intergovernmental Panel on Climate Change (IPCC) demonstrated the need to *eliminate* global greenhouse emissions preferably by 2045, no later than 2055 (Allen et al., 2018). This timescale limits solutions to technologies ready to deploy on a mass scale in the next twenty years.

Uncontrolled installation of conventional air-conditioners in emerging economies has already crippled electricity grids, necessitating frequent load shedding, and significantly raising the cost of electricity in most of the poorest regions of our planet. Most of the additional cost is indirect. For example, women have to obtain fresh food every day: the leftovers cannot be put in the fridge because the power is intermittent and unaffordable if battery backup or generator power supplies are used instead. Excess food uneaten by people has to be discarded or fed to animals at much greater cost than normal animal feed. Other indirect costs include limited employment opportunities due to higher business costs, more frequent equipment failures and lower operating efficiency. Throughout much of Africa and South Asia, also in many parts of Indonesia, regular one or two hour power interruptions are normal, often occurring several times during the day and night. 10-15 hour interruptions are not infrequent.

In many low-income countries, the electricity grid was originally installed and supported by low interest loans from the World Bank on generous terms, enabling governments to provide very low cost electricity. Later, as the infrastructure has had to be upgraded or replaced and fuel costs have risen, governments have been unable to foster a social consensus to raise electricity prices enough to keep the systems running. As supply quality has fallen, more and more people default on bill payments: politicians, government employees and other powerful figures simply ignore power bills even if they receive them. Meter tampering and bypassing have become commonplace. As maintenance resources become more and more inadequate, new connections are made in disorganized ways that make it easy to install additional undocumented and illegal connections.

One of the most significant factors, however, has been adoption of room air conditioners. In Pakistan, for example, it is estimated that air conditioners draw between a third and half of the peak summer demand for electricity. Governments are desperately seeking ways to install more generation capacity to meet this demand, and the financial consequences for low-income countries are crippling their economic development. Currently the Pakistan government is spending 1-2% of GDP on power subsidies and related costs, with no allowance for infrastructure replacement.

Few if any buildings in low-income countries are insulated and a large air temperature and humidity reduction is required for comfort. If air room conditioning is used, the running cost of an air conditioner is much higher than in the industrialised world. Almost all the energy is used to counteract heat and humidity entering the building through openings, walls, floors, and ceilings. Typical South Asia buildings stabilize with indoor temperatures around 40 – 42 °C for about six months. Air conditioning is a necessity in many areas for up to 10 months a year.

Figure 1. Split air conditioner fitted to uninsulated brick building in Lahore (2016: outdoor unit can be seen at far left side)

There is little chance of developing alternative room air conditioning technologies that could be deployed on a mass scale soon enough to meet IPCC requirements. Campbell *et al* (2018) concluded that there are no existing technologies, and the typical time to deploy new technologies on a global scale is 30-40 years. All current room air conditioning technologies require highly insulated, low thermal mass, draft sealed buildings to achieve energy reduction targets. There is no reasonable possibility that all the current buildings that do not meet these requirements can feasibly be replaced in a short enough time to meet IPCC emission reduction requirements.

There are solutions on the technological horizon, but these cannot feasibly be deployed quickly enough. Solar and geothermal powered absorption cycle technology is feasible in some locations, but requires large up-front capital investment and reconstruction of existing buildings. Membrane dessicant technology is being developed at the National Institute of Standards in the USA. Phase change materials absorb heat effectively, reducing the energy needed for mechanically driven room air conditioning. It is taking time to refine these technologies sufficiently for commercially feasible operating results, and it is unlikely these technologies can be deployed on a mass scale well before 2055.

Indirect evaporative cooling also offers large energy reductions, particularly in drier climates. This technology can be used to cool hot outside air without increasing the moisture content, yet still exploiting the latent heat absorbed by evaporating water to achieve the temperature reduction. This leads to significant energy savings, especially for cooling make-up air, hot air from the outside that needs to be cooled before entering a building air conditioning system. However, the need for water with sufficient purity is unlikely to be sustainable if this is used on a mass scale.

Displacement air conditioning has been used for several decades for buildings accommodating a large number of people, relying on cool dehumidified air being denser than the ambient air. The huge mosques in Saudi Arabia, for example, provide a cool environment for worshippers by maintaining a layer of cool air which is only two or three metres deep. The air conditioning even extends into sheltered open air spaces.

2. Localized air conditioning

Spot cooling people, rather than cooling an entire space within a building offers a feasible alternative to room air conditioning.

Frequent visits to South Asia in summer months motivated the author to seek such a solution. One particularly hot night with power interruptions led to the realisation that it is only necessary to cool the face and neck of a person to achieve reasonable comfort. The rest of the building space does not have to be cooled.

Subsequent technical and commercial development has led to a small portable air conditioner using compressor refrigeration that can provide personal comfort for up to three people. The power required is only 180 – 300 Watts, 75%-85% less than a conventional room air conditioner.

Conventional room air conditioners are designed such that conditioned air enters the room at sufficiently high speed to mix the room air with the result that a single unit achieves relatively uniform conditions throughout the room. A localized air conditioner, on the other hand, has to create a localized micro-climate so air mixing has to be limited. A different approach to the design is needed.

There are two operating modes:

Mode 1) The air conditioner produces a jet of cool air with negligible initial vorticity and with an initial velocity of 2.5 – 8 m/s, resulting in an effective cooling range of 1.5 – 3 m depending on air velocity and temperature. The air jet is aimed at the faces and necks or upper bodies of the users who must be located relatively close to each other, for example sitting on a couch side by side (fig. 2). At the furthest effective distance, the air velocity has been reduced to about 0.5 m/s due to mixing though, even at this distance, the air velocity still produces 2° of apparent cooling in addition to the dry bulb temperature reduction. At higher temperatures, 38 – 45 °C, the effective cooling distance is reduced, and is usually suitable only for one person.

Figure 2. Localized microclimate for up to three people

Mode 2) The air-conditioner supplies conditioned air into a specially designed self-erecting bed tent that also provides insect protection (fig. 3). The upper part of the enclosure consists of relatively pervious fabric such as fine mosquito netting. The lower part of the enclosure consists of relatively impervious fabric. Different designs can be adapted from commercial mosquito nets widely available in tropical countries. The apparent temperature inside the lower section of the tent for a sleeping couple can be as much as 13 °C below the ambient bedroom temperature, providing sufficient comfort for indoor temperatures up to 42 °C (Nicol, 2004).

Experiments with several designs have demonstrated that these two operating modes provide comfortable working conditions and high-quality sleep for people adapted to the local climatic conditions, even for many people who are adapted to cooler weather. It is important to note that some people who spend much of their day in fully air conditioned buildings, both for work and sleeping, lose part of their adaptation in hot weather (Nicol, 2004) and may report less comfort with localised air conditioning.

Several other similar solutions have been proposed.

A conceptually similar design has been proposed by Evening Breeze in The Netherlands (www.evening-breeze.com) in which a low-power split system air conditioner provides cooling air that flows through a pervious canopy over a bed. This design has been specifically tailored for applications in tropical island eco-resorts and continental Europe.

Another design which is conceptually similar to mode 1 above was proposed by Task-Air, a company manufacturing office equipment and furniture in Australia (www.taskair.com.au). Individual air outlets at each workstation allow people to adjust the conditioned air supply to satisfy their needs.

A design similar to mode 2 above is being sold by Tupik in India (https://tupik.in/).

Figure 3. Air conditioned bed tent

3. Design challenges

The most significant challenge in designing such an air conditioner is removing the waste heat. Conventional portable air conditioners rely on large diameter flexible tubing to discharge air from the warm side of the air-conditioner through a nearby window. However, this causes a substantial loss in thermal efficiency because much of the cool air produced by the air conditioner re-enters the inlet vents to be used to cool the condenser, is reheated, and exhausted through the pipe connected to the window. Outside air entering the room to make up for the exhaust air discharged through the window creates a substantial inflow of heat and humidity. Humidity in the room steadily increases as the exhaust cannot keep up with the inflow.

Close Comfort air conditioners operate at such low power that the warmth from the condenser can be discharged into the room. The air rises to the ceiling in the same way as warm air from the rear of a kitchen refrigerator. The net heat that needs to be dissipated in the room is the electrical power input – approximately 300 Watts. This is equivalent to heat produced by three or four active people in the room. The change in room temperature is imperceptible – measurements have shown the temperature rise at the ceiling to be less than 0.5°C, less with doors or windows open. In South Asia, the lack of insulation and draft sealing promotes effective absorption of waste heat at the ceiling.

It is challenging to achieve high levels of thermal performance with small refrigeration components. With careful attention to heat exchanger design, it is possible to achieve a coefficient of performance of about 3.3, depending on the environmental conditions. Using a nominal 250 Watts compressor it has been possible to obtain effective cooling power between 650 Watts in dry air and 1200 Watts in moist humid air (test conditions 33°C, 80% relative humidity). Water condensed at the evaporator is sprayed onto the warm condenser heat exchanger to improve the thermal efficiency, and eliminate the need for a drain tank or hose.

The air conditioner is small: 30 cm x 40 cm x 55 cm and weighs 17 kg. Caster wheels provide easy mobility within rooms, and it is easily carried when needed.

Currently, about 0.3 kg of R134A circulates as refrigerant with a global warming potential of 1300. In future 0.08 kg of R290 (propane) will be used with a global warming potential of 1. Even though R290 is flammable, the quantity is small enough to be well within safety limits for hermetically sealed refrigeration machines.

It was necessary to design the heat exchangers from first principles (Wang, Chang, Hsieh, & Lin, 1996; Wang, Chi, & Chang, 2000; Wang, Tao, & Chang, 1999) so as to minimize the temperature difference between the evaporating or condensing refrigerant in the tubes and the air leaving the heat exchanger. One advantage of a localised air conditioner design is that the temperature difference between the condenser and the evaporator side of the refrigeration cycle is typically less than in a conventional air conditioner design where the condenser is in the outside environment. This means it is possible to obtain higher energy efficiency ratios than would otherwise be the case. Careful heat exchanger design, therefore, partially compensates for the effect of size, and allows a higher energy efficiency ratio to be achieved. The relationship between heat exchanger parameters such as size, fin spacing, air velocity and tube diameter is extremely nonlinear and small changes in the dimensions can have a big effect on performance.

Conditioned air passes through an air straightener and open-cell foam to remove turbulence and vorticity created by the circulation fan (vorticity is the angular momentum component of the total momentum of the air flow). The conditioned air outlet is at the top of the air conditioning unit. The curved air deflector changes the direction of the air flow from substantially vertical to substantially horizontal. The angle of the deflector can be adjusted to aim the resulting air jet at the face and neck of a user, typically seated 1 – 2 m away.

The air conditioner is very quiet (46 – 54 dBA) and the noise is similar to a pedestal fan. The noise can be helpful in suppressing perception of night time sounds in typical communities that come in through open windows.

The return air inlet is below the cold air outlet. This arrangement is necessary in order for the air-conditioner to be connected to the bed tent.

The technology has being commercialised by a small start-up company Close Comfort Pty Ltd, based in Western Australia (www.closecomfort.com).

3. Conclusion

With modest further improvements in power consumption, this technology could provide air conditioned comfort for almost everyone living in hot and humid climates without requiring large increases in electric energy production. It runs conveniently from solar energy (during the day) or a battery backup power supply when grid power is not available. Thermal battery technology based on phase change materials could almost eliminate the requirement for night-time energy supplies (Davis, 2015). However, an appropriate thermal battery is likely to be too heavy to be portable.

Based on current (subsidized) electricity costs in Pakistan, the five year cost of a localised air conditioner running for 10 hours every evening less than half of the cost of a 1800 W (electrical) split system air-conditioner required for a typical bedroom in Lahore (5 year discounted cash flow). A split system air-conditioner stops operating during power interruptions. The localised air conditioner runs continuously because it can operate with power from a typical domestic uninterruptible power supply with a battery backup (UPS). Electricity savings relative to a conventional air conditioner can repay the purchase cost within a few months, depending on how and where it is used.

This technology has the potential to boost human productivity in many parts of the world by enabling people to have a sound night's sleep and work comfortably during the day, without having to expand electricity generating capacity. It is possible to meet energy and greenhouse emission reduction targets without replacing existing buildings.

This technology removes many of the constraints on architecture currently being considered for future buildings. Older style buildings with superior passive performance are equally suitable for localized air conditioning. Traditional open buildings made from light weight bamboo in, for example, South East Asia can be air conditioned this way. Low cost buildings made from locally available materials can be provided with energy efficient air conditioning using this technology.

The commercial prospects for this technology are attractive with appropriate marketing. However, it is necessary to understand the social and economic environment where the technology is to be applied to appreciate the opportunities. With appropriate investment, it will be possible to deploy this technology on a mass scale at a cost affordable to almost everyone within 20 years, eliminating the presently predicted problems associated with room air conditioning technology.

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Phase Change Materials as part of building construction systems and indoor passive thermal regulators within the Sonoran Desert: a zone in Mexico with increasing air temperatures and vulnerability to climate change

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Abstract: This work studies and compares the thermal performance of construction systems including adobe, insulation, and Phase Change Materials (PCM) based on the amount of thermally comfortable hours provided within indoor spaces. The study is conducted through an energy computer simulation, using past, present, and future climatic data corresponding to Hermosillo, a Mexican municipality within the Sonoran desert, which is one of the most vulnerable regions to climate change in Mexico, and where outdoor temperature oscillate 14°C in average giving extreme thermal conditions. It appears the earth materials, such as adobe, are still the materials with most thermal mass effects. On the other hand, PCMs also present a very high performance relating to thermal mass effects (very close to a thick adobe wall), but with less material allowing envelopes to be lighter.

Keywords: adobe, phase change materials, indoor thermal regulation

1. Introduction

Within vernacular architecture, materials based on earth have been implemented worldwide as indoor passive thermal regulators within climates with temperature oscillations of 10°C degrees or higher. These materials have thermal lag and thermal damping effects. Mexico presents 4 climate zones, and within these, vernacular earth materials have been present for more than one thousand years. The states of Baja California and the northwest of the state of Sonora are located in a very arid climate zone corresponding to the Sonoran Desert, and are also one of the most vulnerable zones to climate change in Mexico. Hermosillo municipality (Figure 1) corresponds to the state of Sonora and is the municipality with the highest degree of vulnerability to climate change (Gobierno de México, 2016).

1.1. Vernacular materials

Traditionally, earth materials have been implemented as construction materials and as indoor passive thermal regulators; nowadays, these materials have been replaced by thermal insulators, and indoor climate is artificially regulated by mechanic means. However, during the past ten years, climatic conditions in Hermosillo have become more extreme: outdoor temperatures have raised, and air humidity has decreased. This fact, in addition to the global need to reduce carbon dioxide emissions, oblige us to reconsider the type of materials to be implemented in building construction systems in this zone of Mexico.

1.2. Phase Change Materials

New materials capable of “working” with larger amounts of thermal energy are needed in order to increase indoor passive thermal regulation, decrease use of mechanical systems, and keep providing thermal comfort conditions within climate change and the increasing extreme weather conditions. Phase Change Materials (PCMs) are currently being studied for these purposes, as these “work” with latent heat besides sensible heat. Managing latent heat implies managing a much larger amount of thermal heat. This work presents a study of different construction systems on their thermal performance in Hermosillo municipality’s climate in the zone of the Sonoran Desert. Thermal performance of adobe, a vernacular material, and thermal insulation materials currently used, are compared to that of PCMs within the Sonoran Desert climate.

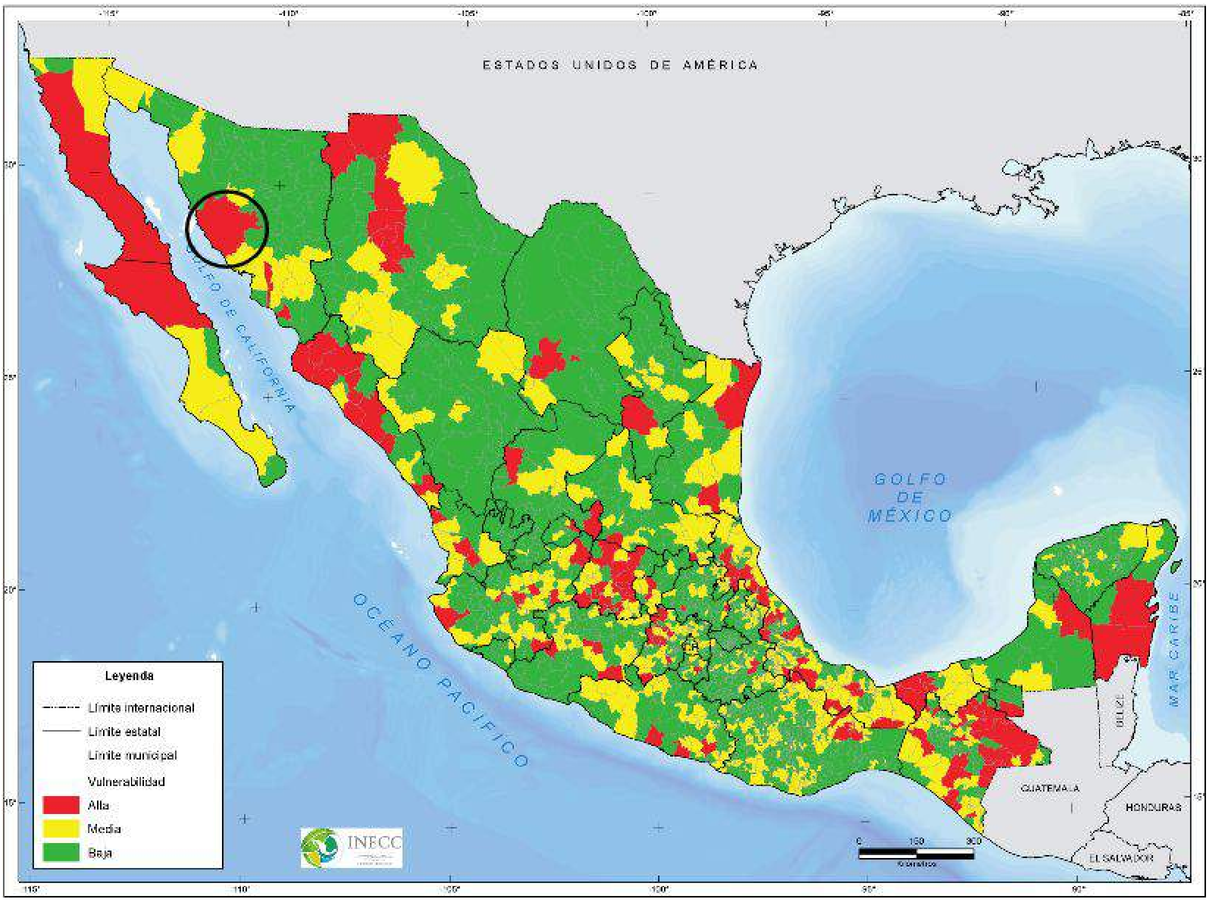


Figure 1. Map of Mexico showing the zones vulnerable to climate change. The Hermosillo municipality is circled in black and appears in red corresponding to a high vulnerable zone (Gobierno de México, 2016).

2. Methodology

The energy performance of a traditional Mexican house, for past (1981-1991), present (2000-2010) and future conditions (2050), was simulated using the EnergyPlus software. The thermophysical properties of a Mexican adobe were measured in the laboratory; those corresponding to the insulation and PCM materials were obtained from the manufacturer technical data sheet.

2.1. Thermal mass materials

Seven adobe samples 0.12 x 0.12 x 0.08 m (figure 2a) were made following PROTERRA´s techniques (PROTERRA, 2003). The thermophysical properties of the samples were measured with a KD2-Pro analyser with a double needle sensor (figure 2b). A polysynthetic silver grease was applied to the needles to enhance thermal conductivity between the needles and the samples. In total, 35 lectures were obtained (5 measurements per sample). The measurable temperature (*T**) depends on the heat flux (*q'*) applied by the sensor and on the initial temperature (T_0) and the final temperature (*T*), based on equation (1).

$$T^* = \frac{4\pi\,(T-T_0)}{q'}$$ $$T^* = \frac{4\pi\,(T-T_0)}{q'}$$

(1)

The measurement process is done in a two phase transient state: a heating phase (when the material sample is heated), and a cooling phase. During the heating phase, measurable temperatures are calculated by the instrument based on equation (2), and during the cooling phase, on equation (3).

$$T^* = b_0 t + b_1 Ei\left(\frac{b_2}{t}\right)$$ $$T^* = b_0 t + b_1 Ei\left(\frac{b_2}{t}\right)$$

(2)

$$T^* = b_0 t + b_1\left[Ei\left(\frac{b_2}{t}\right) - Ei\left(\frac{b_2}{t-t_h}\right)\right]$$ $$T^* = b_0 t + b_1\left[Ei\left(\frac{b_2}{t}\right) - Ei\left(\frac{b_2}{t-t_h}\right)\right]$$

(3)

Where *t* is the time needed for the measurement to be performed, t_h the time need for the sensor to heat, b_0, b_1, and b_2 are constants of the least squares method to adjust the temperature distribution curve, and *Ei* is an exponential integral constant (Abramowitz et al., 1972) for any function u(x), given by equation (4).

$$Ei(x) = \int_{-\infty}^{x} \frac{e^u}{u}\,du$$ $$Ei(x) = \int_{-\infty}^{x} \frac{e^u}{u}\,du$$

(4)

Based on the previous algorithm, the thermal conductivity (*k*), and the thermal diffusivity (α) were calculate based on equations (5) and (6).

$$k = \frac{1}{b_1}$$ $$k = \frac{1}{b_1}$$ (2)

$$\alpha = \frac{r^2}{4b_2}$$ $$\alpha = \frac{r^2}{4b_2}$$

(3)

a) b)

Figure 2. a) adobe samples; b) samples thermophysical properties measurements

The obtained measurements were thermal conductivity (W/mK), volumetric heat capacity (MJ/m^{2}K), thermal diffusivity (mm^2/s). From these, the mass density and heat capacity were calculated. The adobe thermophysical properties are shown in table 1.

Table 1. Thermophysical properties of the studied adobe

Thermal conductivity (W/mK)	0.793 ± 0.0401
Mass density (Kg/m^3)	1,798.107 ± 0.00004
Specific heat (J/KgK)	1,038.3142

In order to obtain indoor temperatures with less oscillations with respect to the outdoor temperatures by implementing a PCM as part of a construction system its fusion temperature must be close to the maximum thermally admissible temperature, corresponding to the thermal comfort range upper limit temperature (Fleisher, 2015) so indoor temperatures are able to remain within the thermal comfort range as long as possible. The cyclical exterior temperature variations reflect as indoor cyclical temperature variations as well, but out phased and dampened due to the thermal inertia effect of the building construction envelope materials.

A paraffin based organic Rubitherm PCM from the RT series and HC type, was selected for the present study. The HC type PCMs can store more amount of latent heat per mass unit. The selected PCM was the RT28HC with a fusion temperature close to the mean comfort range upper limit temperature (Table 3). The thermophysical properties of the selected PCMs are presented in Table 2.

Table 2. Thermophysical properties of the RT28HC PCM

Property	RT28HC
Region of phase transition[1] [°C]	Tsf_{min} Tsf_{min}= 27

	Tsf_{max} = 29
Thermal conductivity[2] [W/mK]	0.2
Density [Kg/m^3]	Solid (15°C): 880 Liquid (40°C): 770
Specific heat capacity at constant pressure [J/KgK]	2000
Heat storage capacity (latent + sensible heat) [J/Kg]	250,000
Maximum operative temperature [°C]	50

[1] Tsf_{min} and Tsf_{max} are the minimum temperature at which the PCM's fusion phase starts, and the maximum temperature at which the PCM's fusion phase finishes.

[2] The manufacturer indicates the all PCMs have the same thermal conductivity during both phases (solid and liquid).

2.2. Climate and the adaptative model for thermal comfort

Because one objective of the present work is to study construction systems for passive indoor thermal conditioning (without mechanical means), two adaptive models were used for the calculation of the thermal comfort range. The implemented models are correlated to Mexico's arid climate mean seasonal temperatures. The thermal comfort range is defined based on the thermally neutral temperature T_c calculated based on equations (4) and (5) (Oropeza-Perez et al, 2017).

$$T_{c\_heating} = 0.48 * T_{out} + 15.96 \quad (4)$$

$$T_{c\_cooling} = 0.59 * T_{out} + 11.62 \quad (5)$$

Where T_{out} is Hermosillo´s mean seasonal ambient (outdoor) temperature, $T_{c\_heating}$ is the thermally neutral temperature during the heating season, and $T_{c\_cooling}$, during the cooling season. From equations (4) and (5), the thermal comfort range was calculated by adding and subtracting 2.5°C from the thermally neutral temperature in order to obtain the maximum thermally admissible temperature (thermal comfort range upper limit) and the minimum thermally admissible temperature (thermal comfort range lower limit).

$$T_{c\ min} = T_C - 2.5\,℃ \; ; \; T_{c\ max} = T_C + 2.5\,℃$$

$$T_{c\ min} = T_C - 2.5\,℃ \; ; \; T_{c\ max} = T_C + 2.5\,℃ \quad (6)$$

Monthly upper and lower limits of the thermal comfort range for Hermosillo are given in Table 3.

Table 3. Seasonal thermal comfort range upper and lower limits in °C for Hermosillo.

Season	$T_{c\ min}$ $T_{c\ min}$ (°C)	$\overline{T_c}$ $\overline{T_c}$ (°C)	$T_{c\ max}$ $T_{c\ max}$ (°C)
Winter (heating season)	17.61	20.11	22.61
Spring (heating season)	20.26	22.76	25.26
Summer (cooling season)	27.70	30.20	32.70
Autumn (cooling season)	24.41	26.91	29.41

2.3. Case Studies

A typical vernacular house of Mexico was 3D-modelled, using the DesignBuilder version 3.4.0.041 software, with envelopes of construction systems that adobe, insulation, and PCM layers. The plan and elevation drawings of the house are presented in Figure 3; a more detailed drawing of the construction system is presented in Figure 4.

Figure 3. Plan and elevation drawings of one of the typical vernacular houses in Mexico.

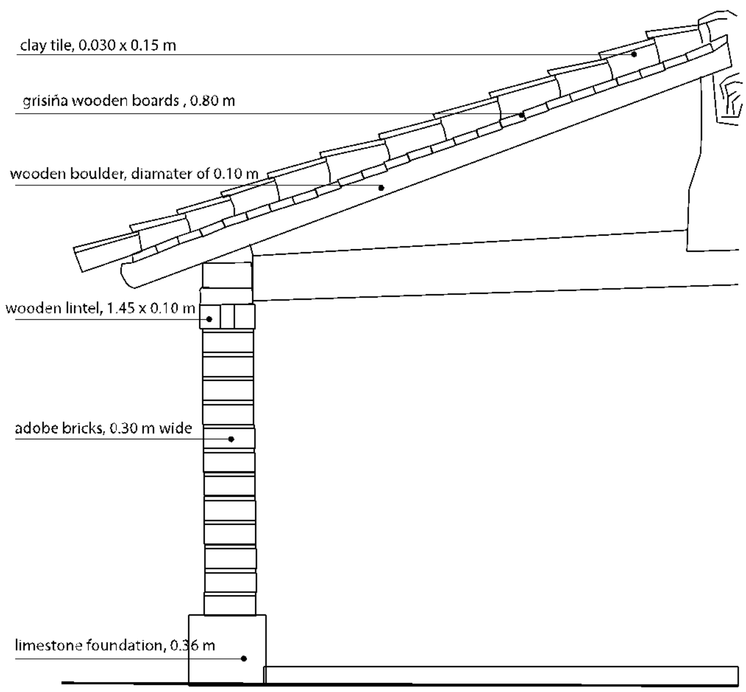


Figure 4. Section drawing of the construction system with adobe.

Six construction wall systems were studied for three different climatic conditions, past (1981-1991), present (2000-2010), and future (2015), giving a total of 18 case scenarios. Climate data was obtained from the Meteonorm software; past and present climatic data was corroborated through the official Mexican government climate webpage (CONAGUA, 2018).

The base case scenario was the original house with 0.30 m thick adobe bricks; both North and South facades present a wooden door and a window as shown in figure 5. The wooden lintels, roof clay tiles, clay gluing the adobe bricks, and the limestone foundation were present and unchanged in all case scenarios. The construction system configurations changing in each case scenario were those corresponding to the walls.

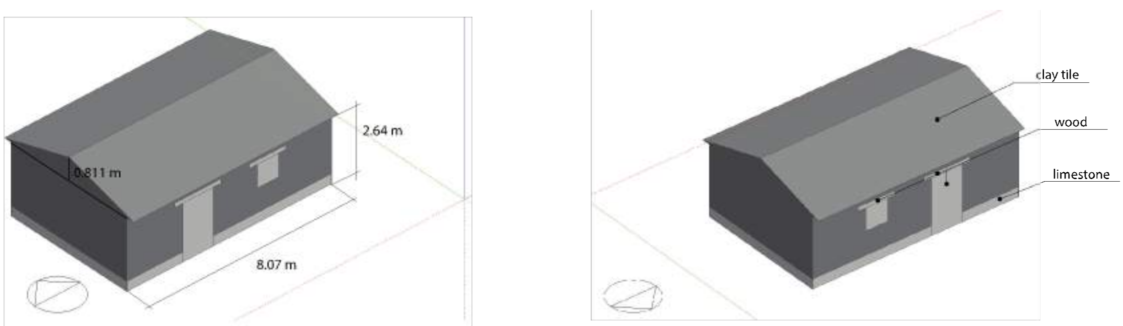


Figure 5. Perspective of the computer 3D model showing the unchanged construction materials throughout the case scenarios.

The thermophysical properties of the construction materials are shown in table 4.

Table 4. Construction materials thermophysical properties

Material	Thermal conductivity [W/mK]	Mass density [Kg/m^3]	Specific heat [J/KgK]	Thickness [m]	Thermal mass per unit area [J/ m^{2}K]
Clay tile	1.00	2,000.00	800.00	0.01	16,000.00
clay	1.50	1,500.00	2,085.00	0.02	62,550.00
wood	0.12	510.00	1,380.00	0.02	14,076.00
adobe	0.7931	1,798.00	1,038.00	0.30	559,897.20
Limestone	1.40	2,000.00	1,000.00	0.40	800,000.00
mortar	0.88	2,800.00	896.00	0.15	376,320.00
Base coat	0.42	1,200.00	840.00	0.0015	1,512.00
Gypsum	0.16	768.90	1,000.00	0.0159	12,225.51
Thermal insulation	0.035	32.00	960.00	0.01	307.20
Thermal insulation	0.035	32.00	960.00	0.04	1,228.80
Adobe color paint	0.20	1,050.00	1,500.00	0.001	1,575.00
PCM RT28HC	0.20	880.00	2,000.00	0.04	70,400.00

Figure 6 show the wall construction systems showing the material layers for each of the six case scenarios. The Adobe_0.30 case presents a one layer with a 0.30m thickness of brick; the Ins_0.01_PCM_0.04 case presents 4 layers (0.01m thickness of gypsum, 0.01m thickness of insulations, 0.04m thickness of PCM, and 0.01m thickness of gypsum); the PCM_0.04 case presents 3 layers (0.01m thickness of gypsum, 0.04m thickness of PCM, and 0.01m thickness of gypsum); the PCM_0.30 case presents 3 layers (0.01m thickness of gypsum, 0.30m thickness of adobe, and 0.01m thickness of gypsum); the Ins_0.05 case presents 3 layers (0.01m thickness of gypsum, 0.05m thickness of insulation, and 0.01m thickness of gypsum);and the Ins_0.04_Adobe_0.30 case presents 3 layers (0.01m thickness of gypsum, 0.04m thickness of insulation, and 0.30m thickness of adobe). All most exterior and most interior surfaces of each case scenario presented the same optical properties, presented in Table 5, so that the same amount of heat would be absorbed by the construction system.

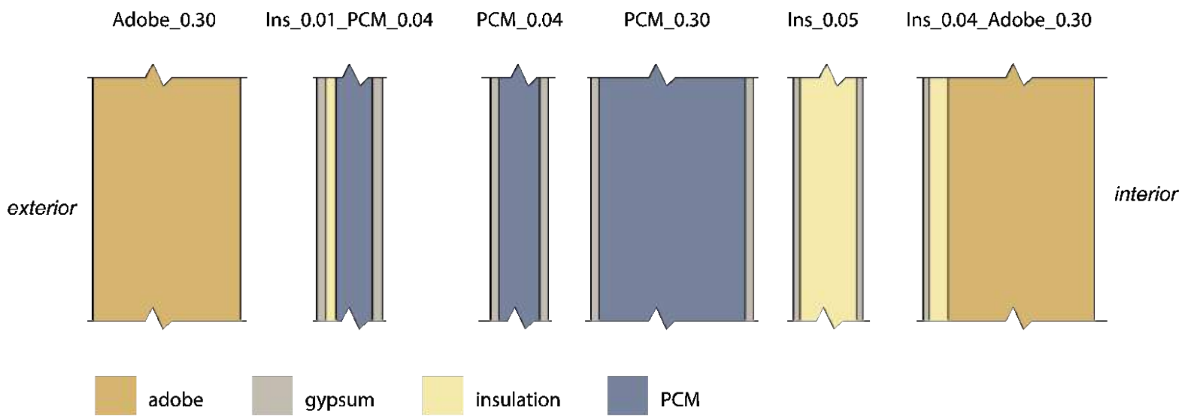


Figure 6. Wall construction systems showing the material layers for each of the six case scenarios.

Table 5. Exterior material optical properties

Material	Thermal absortance	Solar absortance	Visible absortance
adobe	0.8930	0.7280	0.2720
Adobe color paint	0.8930	0.7280	0.2720

2.4. DTS Analysis

Dynamic thermal simulation (DTS) using the EnergyPlus software version 8.5.0 were performed on all case scenarios; the implemented solution algorithm was based on the finite differences heat conduction equation (CondFD) (Tabares-Velasco et al, 2012), with a 0.333 discretization factor, and a 60 time-step calculation. The latent heat energy storage property of a PCM needs to be described based on its temperature-enthalpy function. A PCM's enthalpy, at a given T temperature, is a function of the stored sensible and latent heat (proportional to the liquefied PCM mass), correlated as described in equation 7:

$$h_{PCM}(T) = \left[cp_{PCM}\int_{T_0}^{T} dT\right] + \left[\psi_{melt\_PCM} L_{PCM}\right]$$

$$h_{PCM}(T) = \left[cp_{PCM}\int_{T_0}^{T} dT\right] + \left[\psi_{melt\_PCM} L_{PCM}\right] \quad (7)$$

where $h_{PCM}(T)$ is the PCM's enthalpy at a T temperature, cp_{PCM} is the PCM's specific heat at constant pressure, T_0 is the initial temperature needed as a reference to evaluate $h_{PCM}(T)$, L_{PCM} is the PCM's phase transition latent heat, and ψ_{melt_PCM} is the fused PCM mass fraction at a T temperature which is calculated based on equation (8),

$$\psi_{melt\_PCM} = \frac{T - Tsf_{min}}{Tsf_{max} - Tsf_{min}}$$

$$\psi_{melt\_PCM} = \frac{T - Tsf_{min}}{Tsf_{max} - Tsf_{min}} \quad (8)$$

Figure 7 presents the temperature-enthalpy function of the RT28HC.

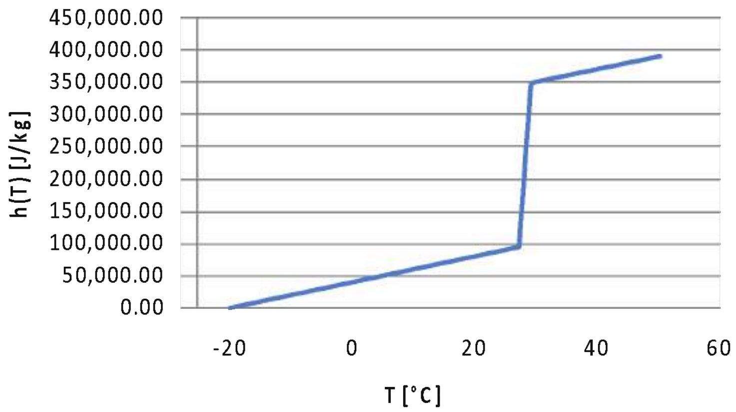


Figure 7. Temperature-enthalpy functions of the RT28HC.

The simulation calculation hypothesis assumed by the EnergyPlus software were the following:

- Heat transfer through the constructive elements of all test units was considered as monodimensional.
- Isotropy in relation to the material properties was considered.
- The solidification and the fusion temperature ranges of all studied PCMs were always the same.
- The specific heat capacity of all materials were considered as constant.
- The latent heat of fusion of all studied PCMs were constant.
- The effects of subcooling, hysteresis and phase segregation were neglected due to the software's non-capability to read the effects of these phenomena.
- Convection calculations at outside surfaces follow the logic of the DOE-2 algorithm and at inside surfaces follows the logic of the TARP algorithm, explained in detail in.

The mathematical model of heat conduction solved by EnergyPlus is related to the Fourier's Law, as stated in equation (9).

$$\rho cp\frac{\partial T}{\partial t} = -k\frac{\partial^2 T}{\partial x^2}$$ $$\rho cp\frac{\partial T}{\partial t} = -k\frac{\partial^2 T}{\partial x^2}$$
(9)

Where ρ is the mass density of the material, cp is the specific heat capacity of the material, k is the thermal conductivity of the material and $\frac{\partial T}{\partial t}$ denotes the time-dependent component of the heat flux through the material and $\frac{\partial^2 T}{\partial x^2}$ denotes the thermal gradient along the coordinate *x* of the material.

By using the CondFD algorithm, the equation (X) for PCM-constructive systems can be solved by dividing up the walls and ceiling in a certain number of slices according with the discretization factor of 0.333. CondFD model is stated in equation (10)

$$\rho_i cp_i\frac{T_{i+1}^{n+1}-T_i^{n}}{\Delta t} = k_i\frac{T_{i+1}^{n+1}-T_i^{n+1}}{\Delta x^2} + k_i\frac{T_{i-1}^{n+1}-T_i^{n+1}}{\Delta x^2}$$
$$\rho_i cp_i\frac{T_{i+1}^{n+1}-T_i^{n}}{\Delta t} = k_i\frac{T_{i+1}^{n+1}-T_i^{n+1}}{\Delta x^2} + k_i\frac{T_{i-1}^{n+1}-T_i^{n+1}}{\Delta x^2}$$ (10)

Where the subindex *i* is related to the space coordinate of each slice of the wall or ceiling, whereas the index *n* relates to the time coordinate. Fully implicit scheme is used for CondFD solver algorithm.

Incident heat flux at the outside surfaces of the constructive system are transferred by conduction through the walls and ceiling to the inside space. The heat balance in outside surfaces of the constructive system is given in equation (11).

$$\dot{q}_{asol} + \dot{q}_{LWR} + \dot{q}_{hc} = \dot{q}_k$$ $$\dot{q}_{asol} + \dot{q}_{LWR} + \dot{q}_{hc} = \dot{q}_k$$

(11)

Where $\dot{q}_{asol}$ is the absorbed global solar radiation heat flux for area unit, $\dot{q}_{LWR}$ is the net thermal radiation flux exchange (infrared) with the air and surroundings for area unit, $\dot{q}_{hc}$ is the convective flux exchange with outside air for area unit and $\dot{q}_k$ is the heat conduction though the wall or ceiling for area unit. Simplified procedures generally combine the first three terms by using the concept of a sol-air temperature, which is calculated implicitly by the software.

After preforming all monodimensional heat transfer simulations for all case scenarios, the number of hours when indoor air temperatures remained within the thermal comfort range, presented in table 6, were quantified. The purpose of this quantification was to relate that case scenario, corresponding to the higher number of hours within the thermal comfort range during the year, to the one with the best thermal performance in Hermosillo's climate.

3. Results

The amount of hours when indoor air temperatures remained below (cold hours) and above (hot hours) the thermal comfort range were quantified. As the next step, the number of hours the indoor air temperature remained within the thermal comfort range (comfort hours) were quantified based on equation (12).

$$t_{comfort} = 8760 - (t_{cold} + t_{hot})$$ $$t_{comfort} = 8760 - (t_{cold} + t_{hot})$$

(12)

Where $t_{comfort}$ is the number of the total thermally comfortable hours from all 8760 annual hours; t_{cold} is the number of total cool hours within a year, and t_{hot} the number of total heat hours within a year. These numbers are presented in table 6 for all case studies.

The case scenario with the highest number of thermally comfortable hours was the base case scenario (Adobe_0.30), the second one was the Ins_0.04_Adobe_0.30 case, and the third one, the Ins_0.01_PCM_0.04. The case scenario with the worst performance (less hours within the thermal comfort range) was the Ins_0.05 scenario (see Table6).

Table 6. Number of hours within a typical year when indoor temperatures corresponding to all case scenarios remained within the thermal comfort range ($t_{comfort}$ $t_{comfort}$), below the thermal comfort range (t_{cold} t_{cold}) and over the thermal comfort range (t_{hot} t_{hot}).

Wall construction system		1981-1991	2000-2020	2050	Less comfort hours compared to the base case scenario 1981-1991	Less comfort hours compared to the base case scenario 2000-2020	Less comfort hours compared to the base case scenario 2050
Adobe_0.30 (base case scenario)							
	t_{cold}	3,927	2,098	1,776			
	t_{hot}	2,271	2,883	2,896			
	$t_{comfort}$	4,137	3,779	4,088	0	0	0
Ins_0.01_PCM_0.04							
	t_{cold}	3,254	2,722	2,338			
	t_{hot}	2,090	2,741	2,778			
	$t_{comfort}$	3,416	3,287	3,644	-721	-482	-444
PCM_0.04							

	t_{cold}	2,809	2,285	1,962			
	t_{hot}	2,557	3,236	3,286			
	$t_{comfort}$	3,394	3,239	3,512	-743	-540	-576
PCM_0.30							
	t_{cold}	3,463	2,910	2,487			
	t_{hot}	1,932	2,560	2,552			
	$t_{comfort}$	3,365	3,290	3,721	-772	-489	-367
Ins_0.05							
	t_{cold}	3,796	3,365	2,974			
	t_{hot}	2,247	2,796	2,792			
	$t_{comfort}$	2,717	2,599	2,994	-1420	-1180	-1094
Ins_0.04_Adobe_0.30							
	t_{cold}	3,293	2,709	2,264			
	t_{hot}	1,757	2,431	2,439			
	$t_{comfort}$	3,710	4,057	4,057	-427	278	-31

In order to quantify the case scenarios construction systems thermal inertia based on their thermal damping and thermal lag effects, those results were analyzed for each annually and seasonally.

Thermal damping was quantified as the magnitude of temperature oscillations which were calculated as the difference between the highest peak temperature and the lowest peak temperature, based on equation (13).

$$dT = T_{min} - T_{max} \quad (13)$$

Where dT is the temperature difference between the maximum temperature T_{max} and the minimum temperature T_{min} of a specific day (it applies for both outdoor and indoor temperatures).

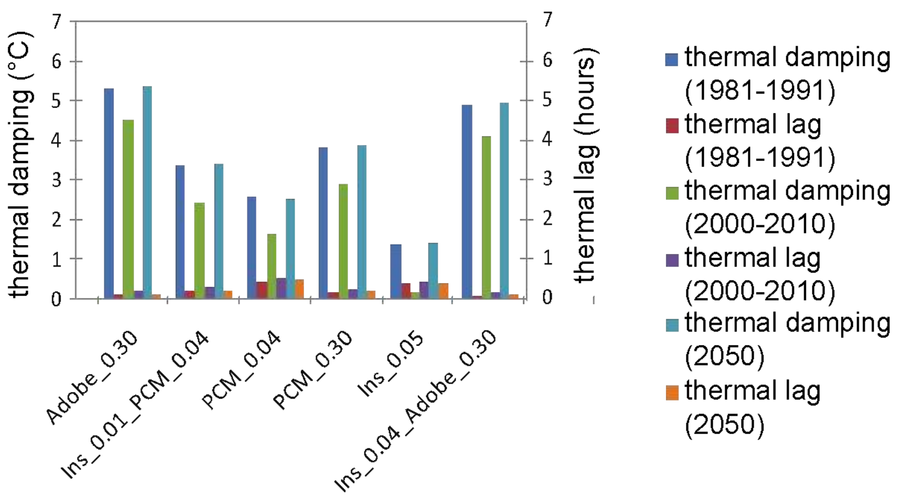
Thermal lag was calculated as the time difference between the time the maximum outdoor temperature occurs, and the time the maximum indoor temperature occurs during a specific day, based on equation (14).

$$dt = t_{\max\ in} - t_{\max\ out} dt = t_{\max\ in} - t_{\max\ out} \quad (14)$$

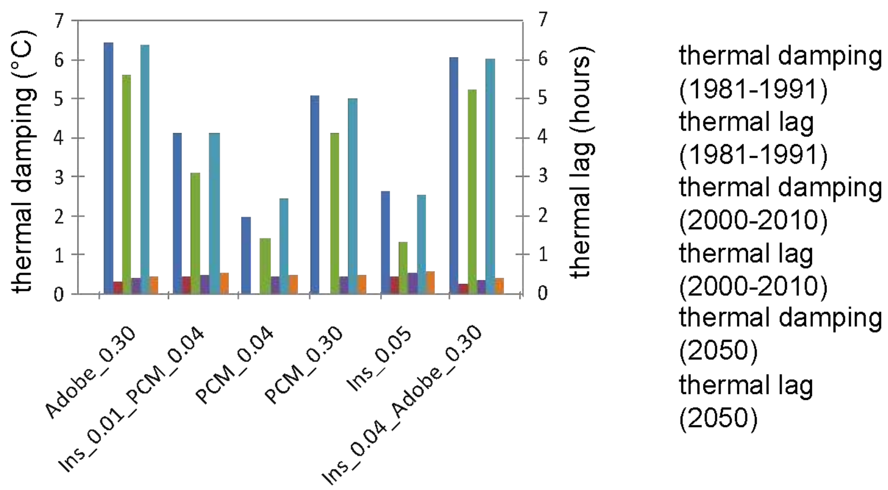
Where dt dt is the time difference, $t_{\max\ in}$ $t_{\max\ in}$ is the time the maximum indoor temperature occurs and $t_{\max\ out}$ $t_{\max\ out}$ the time the maximum outdoor temperature occurs, during a specific day.

Figures 8a to 8e show all case scenarios thermal damping and thermal lag effects; Figure 8a corresponds to the annual analysis, Figure 8b corresponds to the Winter analysis, Figure 8c corresponds to the Spring analysis, Figure 8d corresponds to the Summer analysis, and Figure 8e corresponds to the Fall analysis.

a)



b)



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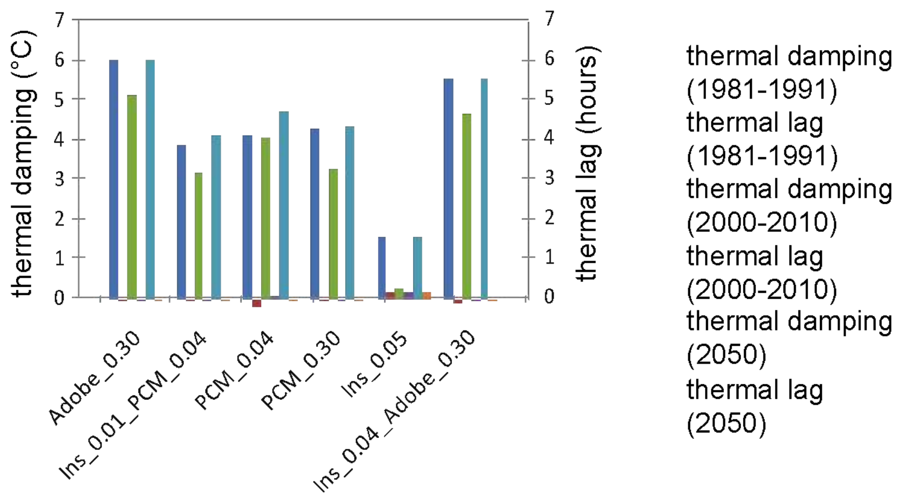

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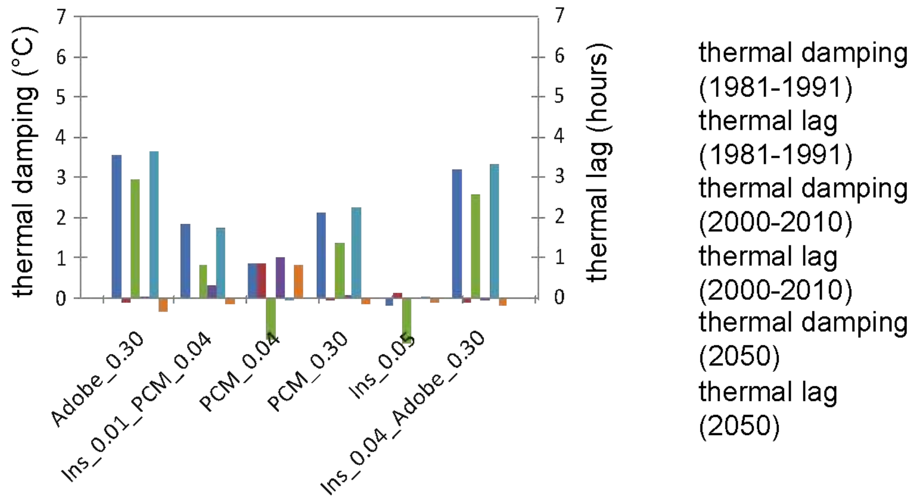
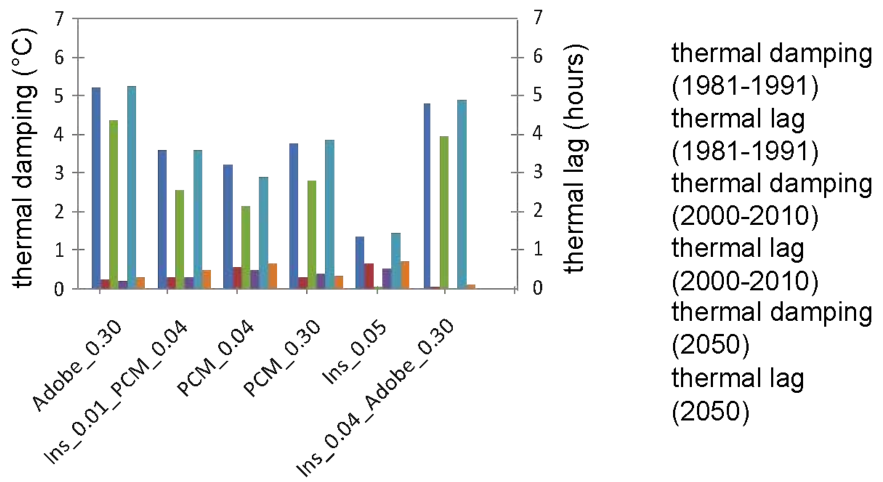


e)



The base case scenario (Adobe_0.30) provides the most damping effects (annually and seasonally), firstly followed by the adobe wall with an exterior layer of insulation

(Ins_0.04_Adobe_0.30), and secondly by the PCM wall with an exterior layer of insulation. The case with both the insulation and adobe layers (Ins_0.04_Adobe_0.30) also present fewer comfort hours than the base case scenario for past, present, and future climatic conditions (see Table 6).

The case scenario with the less thermal damping effects (annually and seasonally) was the fully insulated wall (Ins_0.05).

Conclusion

Materials with thermal mass effects, such as the adobe and the PCMs, should be considered as construction materials for building envelopes within extreme temperature conditions when indoor air temperature conditions are modulated by passive means without mechanical equipment. It is a present and future increasingly important need to thermally condition indoor spaces without mechanical equipment. Thermally insulated construction systems enhance a building energy performance when heating and cooling mechanical systems are implemented. However, when these mechanical systems are not used, and outdoor air temperatures are extreme, such as the case of Hermosillo with a mean 14°C degree daily oscillation, thermal mass best enhances a building energy performance.

It appears the earth materials, such as adobe, are still the materials with most thermal mass effects, and that best modulate indoor temperatures when outdoor temperatures are extreme presenting large oscillations during a 24 hour cycle. However, these are currently less used because of its brittleness, the large amount of material needed for the thermal mass to be present, and the false idea that these need more maintenance than contemporary construction materials such as red brick or concrete. However, more studies on the thermal mass effects of multi-layered construction systems combining earth and insulation materials should be conducted in order to approach a less thick envelope construction system.

On the other hand, PCMs also present a very high performance relating to thermal mass effects (very close to a thick adobe wall), but with less material allowing envelopes to be lighter.

Today, our planet is facing an important change in its climate system affecting comfortable and even liveable conditions. Consequence of this is that climates at different scales are becoming more extreme, as hot periods are becoming hotter, and cold periods, colder. This implies that in shorter periods there are bigger differences in the amount of heat present in the atmosphere. However, it is very difficult for many living species to live in healthy conditions under these circumstances; thus, we must deal with excessive heat and scarcity of heat in shorter times. An alternative is heat storage; when heat is excessive, it may be stored to then be released when heat becomes scarce. Building envelopes have become one of several of the artificial skins of humans, and therefore, important thermal regulators for the human liveable space. We have to rethink our current building envelope design strategies under these new developing extreme climatic conditions, and the selection of materials with thermal mass, meaning capable of storing and releasing larger amounts of heat may acquire a key role, as opposed to light weighted materials.

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Development of an innovative compact hybrid electrical-thermal storage system for historic building integrated applications in the Mediterranean climate.

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Abstract: Currently in the EU, there are limited examples of operationally integrated solutions capable of achieving optimal interaction of energy networks, combining both electricity and heat-cooling energy supply and storage. There is thus, a need for the efficient use of renewable energy resources through hybrid systems utilising generation and storage of energy. The present study proposes a novel concept for the development of an innovative compact hybrid electrical-thermal storage system for stand-alone and district connected buildings. The proposed hybrid storages will be used to upgrade existing building configurations and will be monitored in real-life operation in a historic building in Cyprus. The building has been selected to be part of a hands-on technology exhibition area of renewable energy systems complimented with visual means to enhance the experience of visitors. The RES systems will be enhanced with enabling technologies offering the benefits of smart digitalised home solutions that can seamlessly be integrated in the neighbouring communities / districts to form energy communities. The municipality is to use the systems as a hands-on experience for informing society about the use of new technologies in their homes capable of offering a transition to the low-carbon economy achieving high levels of energy savings. Moreover, the integration of such systems in this specific application is to be used as an exploration of the sensitive issue of the architectural integration of technologically advanced systems into the listed buildings of historical centers. The concept presented herein is part of the ongoing research programme HYBUILD, which is funded by the European Union through HORIZON 2020.

Keywords: Innovative hybrid systems, electrical-thermal storage, architectural building integration, Mediterranean climate, historic buildings.

1. Introduction

One of the main concerns globally is that of how to address the phenomenon of climate change - which is mainly caused by human activities. Many countries worldwide establish and implement new policies to address climate change and its dramatic consequences. The European Commission has set the renewable energy directive which establishes a common policy for the countries in the European Union for the promotion of renewable energy sources. The plan includes the electricity, heating and cooling and transport sectors (Pantano et al. 2016, Urabe et al. 2013, Zhao et al. 2015). In this context, buildings must be more energy efficient and with lower carbon dioxide emissions. For this purpose, the required energy of buildings is targeted to be produced mainly from renewable energy sources (photovoltaic solar power systems on building's roofs or facades supported by batteries where possible) and would be more energy efficient if heat pumps are used for the heating and cooling needs of the building but in a controlled mode that will efficiently meet the needs of the building where is actually used. Architects and builders are including solar systems as a way to meet green building standards and property owners are seeking PV as a way to reduce their utility bills, as well as their carbon footprints.

The installation of renewable energy sources should be seen as part of a holistic building design to improve the energy efficiency of a building and its carbon footprint utilizing on the way solutions that offer higher efficiencies than current state of the art solutions. This objective becomes slightly more difficult when solar energy systems should be installed in historic buildings to achieve the zero energy objective. Taking a holistic building approach is a logical process which enables the best possible balance to be struck between saving energy and reducing carbon emission, sustaining heritage significance, and maintaining a healthy building area.

The aim of this paper is to examine the available technologies related to the exploitation of solar system for energy saving and determine the integration of such systems in this specific application of architectural integration into listed buildings of historical centres. Furthermore, the objective of this study is to introduce the novel concept in the development of an innovative compact hybrid electrical-thermal storage system for stand-alone and district connected buildings and its application into a demo-site that constitutes a historic building in Cyprus.

This paper is organized as follows: 'Section 2' describes and analyzes solar technologies for building integration and describes the difference between BAPVs and BIPVs, while 'Section 3' describes the background behind the solar energy integration into historic buildings. 'Section 4' shows some case studies where solar systems are integrated in historic buildings, while 'Section 5' presents the HYBUID project and the demo site of Aglantzia, Cyprus, and finally 'Section 6' draws the conclusions and future prospects.

2. Solar technologies for building integration

There are several different types of solar energy systems available for building integration. One type is commercially exploited Solar Thermal Systems (STSs). These technologies absorb solar radiation and convert it into thermal energy used for heating water. The main types of these systems are:

- Glazed Flat Plate Hydraulic Collectors (Glazed Flat Plate Hydraulic Collectors)
- Unglazed Flat Plate Hydraulic Collectors
- Flat Plate Air Collectors
- Vacuum Tube Hydraulic Collectors
- Concentrating Hydraulic Collectors
- Unglazed Plastic Collectors

Another type of solar energy technology system that can be integrated in buildings is photovoltaic, which receives solar radiation and converts it into electricity. In particular, when solar radiation falls into materials known as "semiconductors," the energy of the incident radiation (also known as photons) releases some electrons to these materials. The potential difference developed within the material translates into direct electricity generation. These photoelectric cells are, in the state of the art solutions, made of monocrystalline or, polycrystalline or amorphous silicon (Thomas, 2006).

Photovoltaic technology is used largely on buildings due to its versatility and low cost production of electricity at the point where is needed. However, installed systems prioritize energy generation while ignoring aesthetic considerations and thus often creating a negative visual impact. These concepts have been developed in numerous publications popularizing the terms "Building Integrated Photovoltaics" (BIPV) and "Building Applied Photovoltaics" (BAPV). Currently, most PV modules are secured to a roof or onto a facade using a metal structure. The PV system is an additional or applied structural element with the sole function of generating energy hence the definition Building Applied PV (BAPV). In contrast, Building Integrated PV (BIPV), refers to the application of PV in which the system, as well as having the function of producing electricity, also takes on the role of a building element. A Building Integrated Photovoltaics (BIPV) system is a PV system integrated into the building envelope (e.g. roof, façade, window, etc.). Thus, it replaces a building element i.e. a conventional construction material.

Technologies that are available for building integration (BIPV) are among others the following:

BIPV modules

Photovoltaic panels used for building integration are almost similar to conventional photovoltaics. The difference, however, lies in the fact that the BIPV panels are made to function as a shell resistant to weather and that some are manufactured to replace different types of construction materials, while some are prefabricated units with thermal insulation.

Flexible (Foil) BIPV

Flexible BIPV is a relatively new product that allows for attractive integration options in a building as it is lightweight and flexible, which is beneficial to its ease of installation (Jelle et al 2012). Photovoltaic cells are often made of thin-film cells to maintain flexibility and to be effective in high temperatures (e.g. in non-ventilated roofs). Flexibility is achieved mainly due to its very thin structure, combined with its ability to be installed on flexible substrates (stainless steel sheets or polymer film), giving it a handy and compact form (Chopra et al. 2004). It has also been observed that it can yield as much as 20% better than other types of photovoltaic at high temperatures (Carr and Pryor 2004). However, it should be noted that Flexible BIPVs have reduced performance due to the non-uniformity of the intensity of sunlight on their surface as well as due to the large resistances of thin-film solar cells.

BIPV tiles

The sloping surfaces of the buildings (roofs) are still considered to be the ideal place for PV application. Roof integration is done with the BIPV approach, with photovoltaic modules (without a metal frame) replacing and installing on the same level as tiles, covering the entire roof or selected parts of it. They are usually integrated with the same logic and properties of conventional roof tiles in which some of the conventional tiles are installed and replaced, thus allowing easy roofing to be reconstructed (Heinstein et al. 2013). BIPV tile products may cover the entire roof or selected parts of the roof. They are normally arranged in modules with the appearance and properties of standard roof tiles and substitute a certain number of traditional roof tiles, thus also enabling easy retrofitting of roofs. The cell type and tile shape varies. Some tile products may resemble curved ceramic tiles and will not be as area effective due to the curved surface area, but may be more aesthetically pleasing (Jelle and Breivik, 2012).

Solar Cell Glazing

The solar cell glass panels consist essentially of glass-enclosed photovoltaic cells and provide several options for windows, glazing or sloping facades and ceilings.

Photovoltaic windows have (semi) transparent modules that can be used to replace a number of architectural elements commonly made with glass or similar materials such as windows and skylights. In addition to producing electric energy, these can create additional energy savings due to superior thermal insulation properties and solar radiation control.

Other technologies

Over the last 30 years, a large amount of research on PV-Thermal (PVT) collectors has been carried out. Hybrid PV / T Systems are units that combine the characteristics of PVs and

STSs, converting solar energy into electricity and heat simultaneously. To maximize electrical power then the photovoltaic unit must be at low operating temperature upon arrival of incoming solar radiation. This can be achieved by using this heat to heat the fluid, which upon leaving the system can be used for space heating or water preheating. Additionally, a new and promising photovoltaic technology is the Perovskites. Perovskite solar cells have stunned the PV community the last few years. Since the 9.7% first efficiency of a solid-state perovskite cell was reported in 2012, rapid progress by several groups has improved this efficiency above 20% (M. Saliba et al. 2016). Furthermore, multi – junction solar cells is a new technology that attracts more and more attention the recent years. A multi - junction photovoltaic cell is a solar cell with multiple p-n connections of different semiconductor materials. Each p-n junction of each material generates electrical current in response to a different wavelength of light. A single cell produces electric current at a single wavelength in the sunlight spectrum. A multi - junction solar cell will generate an electric current at multiple light wavelengths, which increases the energy conversion efficiency of sunlight into usable electricity.

3. Historic preservation designations

The architectural and visual integration of solar panels on historic buildings are treated in different way compared to contemporary buildings as are characterized by cultural value (Moschella et al. 2013). Several researches study the architectural restoration to establish a balance between the need of conservation versus innovation and energy saving. High-quality design can play a key role in minimising any adverse effects of projects. Fundamental to achieving high-quality design is a sound understanding of the character and importance of the historic asset involved, whether at the scale of individual buildings and sites or more extensive historic areas and landscapes (Historic England, 2018).

The construction standards of historic buildings were built differ from the contemporary and often do not meet current energy and comfort needs (Lopez and Frontini 2014). The construction elements rarely can differ from the protected elements in order to provide good level of thermal insulation since the aesthetic appearance would be affected. Renewable energy sources can be used to cover the high-energy consumption with sustainable sources. The challenge is to maintain the preservation of the original form and value of the historic district considering the rules of local legislations and policies and on the other hand, to recognize the importance of accommodating renewable energy technologies where they are appropriate (NREL, 2011). Solar panels in a sensitive historic context is very critical as they have an appearance which is not always coherent with the historical building in terms of aesthetics, colours, shapes, dimensions and surfaces (Lucchi et al. 2014). The objective is to select reversible and compatible technologies that will increase the economic value and avoid any kind of damage.

Based on ICOMOS Charter for the Conservation of Historic Towns and Urban Areas , article 8, “new functions and activities should be compatible with the character of historic town or urban area”. Furthermore, “adaptation of these areas to contemporary life requires the careful installation or improvement of public service facilities”. Active solar systems are considered as contemporary elements. Thus, according to Article 10 of the same charter, these “should be in harmony with the surroundings” and should not be discouraged since (they) can contribute to the enrichment of an area” (ICOMOS, 1987, Bougiatioti and Michael 2015).

4. Case studies in historic buildings

The introduction of systems for the exploitation of renewable energy sources in built heritage is well-established in some existing buildings. The following examples trying to make the impact of the systems on the building historic fabric and surroundings as minimal as possible.

4.1. Case 1

The Building of the Tourist Office in Alès (France) is a listed sixteenth-century building that uses integrated PV in three façades. Specifically, the surface of integrated PV is 100 m^2 and the energy output is 9,5 kWp (Heinstein et al., 2013). This project focuses on certain characteristics of the cells or modules. It uses these as a tool to maintain continuity in the built environment and to match the context and overall design, while at the same time presenting the characteristics of the material. For example, the colour was chosen to suit other materials used on the building skin and the form and framing of the module was used as a new façade cladding (Farkas et al., 2009) (Fig.1).

Figure 1. Integrated photovoltaics in the façade of historic building of Tourist Office in Alès (France) https://www.france-voyage.com/cities-towns/ales-9535/tourist-office-ales-5799.htm

4.2. Case 2

The Reichstag parliamentary building in Berlin is a major tourist attraction. It symbolises the transparency of governance and a commitment to environmental sustainability. It is one of the more spectacular examples of the drive for energy efficiency and sustainability in public buildings appearing around the world, as part of the global effort to meet rising energy costs and adopt alternative energy sources. Completed in 1894 and surmounted by a glass and steel dome, the original Reichstag housed the German government until severely damaged by fire in 1933. It was only after the reunification of Germany in 1990 that restoration was completed in 1999 and the Reichstag once again became the seat of government and one of Berlin's major landmarks. A biofuel powered, Combined Heat and Power (CHP) provides approximately 80% of the annual electricity and 90% of the heat load of the building. A large Ground Source Heat Pump (GSHP) acts as a seasonal store of both heat and cools. Photovoltaics on the roof power the solar shade within the light sculpture. Specifically, on the flat area of the Reichstag roof, 300m^2 of photovoltaic panels are placed. Moreover, a total of roughly 3,600 m^2 of photovoltaic elements with different collector designs (some of which are heliotropic) are installed on the roofs of the Reichstag Building, the Paul Löbe Building and the Jakob Kaiser Building supplying electricity in these complexes (KBP Ingenieure GmbH 2018, Foster +Partner 2018) (Fig. 2).

Figure 2. Photovoltaics elements on the roof of the historic Reichstag parliamentary building in Berlin https://www.webpages.uidaho.edu/arch464/Hall%20of%20Fame/Arch464/Spring2014/CS3/Reichstag%20Germany%201.pdf

4.3. Case 3

The Paul VI Audience Hall (Italian: Aula Paolo VI) also known as the Hall of the Pontifical Audiences is a building in Rome named for Pope Paul VI with a seating capacity of 6,300, designed in reinforced concrete by the Italian architect Pier Luigi Nervi and completed in 1971.

On 25 May 2007, it was revealed that the roof of the building was to be covered with 2,400 photovoltaic panels, generating sufficient electricity to supply all the heating, cooling and lighting needs of the building throughout the year (Fig. 3). It was officially placed into service on 26 November 2008, and was awarded the 2008 European Solar Prize in the category for “Solar architecture and urban development”.

The 2,400 installed photovoltaic modules face exactly south and have been installed in replacement of the deteriorated concrete panels, reproducing the dimension according to the original project of Pier Luigi Nervi. Thus, they fulfill the dual "passive" function of protecting the building from radiation and the "active" conversion of solar energy into electricity, giving the aesthetic value an exemplary environmental surplus value.

The average power of the modules is equal to 90 watts each and the producibility is increased by about 5 percent from the 2,400 panels facing north, partially reflecting aluminum, which are the only ones visible from the dome of St. Peter, whose panoramic view does not has been minimally affected.

The electric energy is produced by the generator in direct current and is sent to the inverter apparatuses that convert it into alternating and from there it is transferred to the transformer cabin, located in the base part of the same room.

The 300 megawatt-hours (MWh) annual "clean" electricity, produced by the solar generator, will be fed into the Vatican power grid to partially cover the consumption of the Hall and the neighboring buildings and each year will allow to avoid emissions in the environment of 225,000 kilograms of carbon dioxide, saving about 80 tons of oil equivalent (toe) (Archilovers, 2018) .

The Government of the Vatican City State and the competent Directorate of Technical Services see in this first installation, together with a "solar cooling" plant currently being completed in the "industrial" area of the State, an exemplary expression of the effort made to implement renewable energy generation systems in the Vatican. In the near future, more substantial programs are planned, so that a significant percentage of their energy needs are met by highly innovative renewable energy conversion systems.

Figure 3. Photovoltaics panel on the roof of the historic Paul VI Audience Hall in Italy
https://www.archilovers.com/projects/14001/copertura-solare-dell-aula-paolo-vi-in-vaticano.html#images

5. HYBUILD project

The HYBUILD project is funded by the European Union through HORIZON 2020, and focuses on the development of two innovative compact hybrid electrical/thermal storage systems for stand-alone and district connected buildings. HYBUILD will develop an innovative hybrid storage concept for cooling and heating energy provision, as well as for domestic hot water production, suitable for both the Mediterranean and the Continental climate. These configurations will allow for energy savings ranging from 20 to 40% on an annual basis in both Mediterranean and Continental climates.

The HYBUILD systems combine thermal (sorption, latent and sensible) and electric storages in one system. Solar energy can be stored in the sorption storage (Mediterranean concept) as well as in an electric storage. The electric power within the systems is provided by a DC-bus system, which is more efficient than a state-of-the-art AC based system. The DC architecture is expected to reduce the volume of conversion and distribution by 1/3 as compared to an AC architecture while, a long term reduction of the costs by about 20% is realistic.

The electrical storage will be properly selected among the most efficient technologies already in the market, and will be adapted to the operation of the domestic building environment. Particularly, the building management system (BMS) will be designed and adapted to the expected operating conditions, with a view to maximize the lifetime of the electrical storage itself.

The two concepts are presented below as described in the research proposal of the 'Innovative compact HYbrid electrical/thermal storage systems for low energy BUILDings' project (HYBUILD 2017, grant agreement N° 768824):

• Mediterranean Concept

The primary function of a heating / cooling system in the Mediterranean climate is the provision of cooling energy during the summer period, which is usually achieved in installed systems by means of electrically driven steam compression cooling systems. However, to cover space heating and demand for hot water, gas boilers and solar collectors are usually installed, as common distribution systems are based on high temperature radiators, which limit the applicability of the heat pump by compression. This leads to a high primary energy consumption during both cooling and heating periods due to the lack of system integration and the limited performance of the components. The proposed hybrid storage philosophy for the Mediterranean climate aims to incorporate an electric heat pump by compression with a heat-guided sorption storage unit for DHW to increase overall system efficiency by effectively saving the surplus electric power to heat when needed. This makes the idea attractive for both existing and new buildings as it harmonises the function of the already installed elements. In addition, an electrical storage package and a low temperature storage unit are also incorporated in order for the system to be able to store and reuse as much as possible electrical and thermal energy produced from renewable sources.

- Continental Concept

The hybrid storage concept for Continental Climate is based on a thermal PCM latent storage for DHW and an electrical storage. Contrary to the Mediterranean solution, the prioritized operation here is heating during winter and the production of domestic hot water (DHW), whereas cooling during summer plays a minor role compared to the other two. Nevertheless, due to global warming and an increased desire for comfort, cooling during summer becomes more and more important even for northern Europe and therefore, moderate cooling operation is also possible with the proposed system. The Continental concept can increase system efficiency and renewable sources exploitation through the integration of a high density, high temperature latent storage employed to store the sensible energy of the hot gas exiting the compressor which is powered by a DC driven inverter and fed by renewable electricity. The system can also implement an electrical storage, which allows a further increase of the share of renewable energy both for buildings connected and non-connected to district heating networks. The operation mode can be reversed, to provide cooling energy and DHW during the summer season. Therefore, the latent storage for DHW is used throughout the year.

HYBUILD's hybrid storage systems will be used to upgrade facilities in existing buildings in three different demo sites. One of the project applications will be implemented by the Municipality of Aglantzia in cooperation with FOSS Research Centre for Sustainable Energy of the University of Cyprus and other partners. The proposed system will be installed on a vernacular dwelling located in the historic core of Aglantzia, which will be used as a Renewable Energy and Smart Solution Center by the municipality with the support of the University of Cyprus. The proposal aims at redefining the traditional core with the aim of developing a destination that will be a cornerstone of social interaction and creative employment (Fig.4).

Figure 4. External view of the square and the building under study

The building has been selected to become a hands-on technology exhibition area of renewable energy systems complimented with visual means to enhance the experience of visitors. The RES systems will be enhanced with enabling technologies offering the benefits of smart digitalised home solutions that can seamlessly be integrated in the neighbouring community / district to form energy communities. The effort is to increase environmental awareness of the community for sustainable energy supply and sustainable growth (Phocas et al 2011, Philokyprou et al 2013). Environmental awareness has an effect on the willingness to pay about electricity that is generated from renewable energy sources and according to a study carried out by Karaoglan and Durukan (2016), when the environmental conscious consumer is between the economic situation and the environmental impact, he will consider environmental impact.

In this context, the proposal aims at creating a multifunctional space where besides the promotion of modern technologies, it will have the possibility to host events, seminars, artistic performances etc. and at the same time it will function as a reading room - a digital library for young citizens and students (Fig.5).

Figure 5. Internal view of the building under study

Particular emphasis will be placed on the preservation of the building's cultural heritage values and on the assessment of innovative technologies' contribution to the rehabilitation of historic buildings and settlements (Savvides et al 2016).

The integration of active solar systems into the building sector is an innovative experimental process of the program. The regulatory framework for the protection of the traditional character of buildings prohibits in most cases the installation of technical systems that are visible and consequently the installation of active solar systems in the listed building envelopes. Despite this fact, solar collector for domestic hot water are eligible to be installed in order to cover the users' need. It is noted that, due to a number of aesthetical and regulatory issues, it has been decided to place the hybrid systems in an independent metallic shelter which will be placed in the square (as part of a comprehensive landscape design), while on the roof of the building it is proposed to install photovoltaic panels which offer increased integration possibilities (Fig. 4 and Fig. 6) (Savvides et al. 2014, Michael et al. 2010,).

Figure 6. Plan of the square and the building under study

Within the framework of the operation of the "Renewable Energy Sources Center" the continuous renewal of these technologies with newer production systems is expected, aiming at the projection of the architectural integrated active solar systems. Replacing systems, apart from technological development, will aim at exploring the sensitive issue of architectural integration of technology systems into listed buildings of historic centers.

6. Conclusions

The objective of this paper was to review the available active solar systems that can be integrated to buildings and examine the integration of those systems in historic buildings through case studies. Moreover, it introduces an innovative concept that utilises the solar resource with storage to generate and manage the energy of buildings extending its application into a historic building in Cyprus. A key sustainable design strategy to preserve, reuse and maintain historic structures but at the same time recognize the importance of accommodating renewable energy technologies where they are appropriate. The integration of active solar systems on built heritage, needs a multidisciplinary design that takes into account the requirements of minimum intervention and reversibility.

Energy consumed in a residential building for heating, cooling and hot water accounts for a large part of the world's energy consumption. Therefore, the integration of renewable energy into buildings is a must for the purposes of reducing carbon dioxide emissions and reducing the devastating effects of climate change. Until the previous years, the integration of photovoltaic systems was mainly done on the roofs of buildings with the addition of conventional photovoltaic panels for the sole purpose of producing energy. In recent years, several BIPV technologies have been developed which, in addition to generating electricity, have additional properties, such as thermal, and can replace different construction materials of a building's envelope. The main technologies used in the BIPVs category as presented in this paper are BIPV modules, Flexible (Foil) BIPV, BIPV tiles, and Solar Cell Glazing. The most common integrated photovoltaic technology is Flexible (Foil) BIPV and thin film technology, which are mainly used in building facades as well as BIPV tiles technology. Novel technologies such as Perovskite solar cells and PV/Ts are also gaining interest nowadays.

Despite a large portion of the potential of PV integration in existing buildings, several factors make their application into historic buildings more difficult such as economic reasons, lack of knowledge among decision makers and architects, general unwillingness for 'new' technologies and architectural/aesthetic aspects. To ease the use of technology in historic buildings, several steps should be reinforced. Firstly, local authorities, professional, agencies and historic organization should work together to identify the heritage features and values and write guidelines that will help designers for historic evaluation and solar design integration. Secondly, for the installation of solar active systems in sensitive context is good to develop a formation of designers and decision makers that will provide technical and formal possibilities of PV systems.

The overall objective of the present project is the development of an interdisciplinary and holistic approach that incorporates energy generation, energy storage and energy distribution for cooling-heating energy provision and domestic hot water production, suitable for both the Mediterranean and the Continental climate. Both hybrid electrical-thermal storage systems will be able to efficiently cover both heating and cooling demand respectively. The potential to install and monitor the developed systems in real demo-sites in three countries with different climatic conditions allows the exploitation of the results from countries with similar climatic characteristics.

The real demo-sites will be able to increase the energy consumption awareness of consumers and of the social community based on interaction. The development of the novel concept will help in writing guidelines and standardization for the reduction of energy consumption and CO_2 emissions. Apart from the implementation of the system as mentioned above, the full concept can be used both in new and retrofitted residential buildings in order to minimize the total EU energy consumption and keep up with the European directives. Moreover, the integration of such systems in a demo-site that is characterized as historic building is utilized to explore the sensitive issue of the architectural integration of technologically advanced systems into listed buildings of historical centers.

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Wintry Thermal Environment and Domestic Energy Use in Nepal

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Abstract: Nepal is a mountainous country with low energy use so far and its climatic patterns remarkably differ from one place to another due to its geographical variation. In the North summer is cool and winter severe, while in the South summer is tropical and winter is mild. Indoor thermal environment and household energy use of residential buildings has attracted considerable attention however, there has not been sufficient number of studies in the thermal environment and household energy use in Nepal. In this study, we aim to analyze the current situation of household energy use and indoor thermal environment of residential buildings in different ecological regions of Nepal. This study was carried out in Mountain, Hill and Terai regions in Nepal from 21 December, 2017 to 20 January, 2018. Indoor and outdoor air temperature and humidity were measured with the help of data logger for every 10-minute interval from 5 households from each region. The mass of firewood used was also measured at those houses. Household energy-use data of 516 houses were collected by the method of questionnaire survey. We found that mean indoor temperature was 8.6℃, 12.8℃ and 16℃ in Mountain, Hill and Terai regions respectively. Based on this field study, we concluded that firewood is the important source of household energy for cooking. The present finding suggests that an intensive and extensive improvements of the indoor thermal environment together with less use of energy must be responsible in the winter season.

Keywords: Nepal, Energy use, Thermal environment, Mountain, Hill

1. Introduction

Based on topography and distinct climatic features, Nepal is broadly classified into three ecological regions; the Mountain, Hill and Terai regions, all of which extend from east to west with some irregular widths from North to South [1]. Outdoor thermal environmental conditions of these regions varies according to the geographical location. In the north, summer is cool and winter is severe, while in the south, summer is tropical and winter is mild. Adjustment of indoor thermal environment suitable for comfortable living is directly related to the energy use pattern and the availability of commercial fuels. In Nepal, due to high cost and limited supply of commercial fuels, 80% of rural people still rely on traditional fuels like firewood, agricultural residue and animal dungs for cooking and space heating [2-4]. They usually maintain their indoor thermal environment by applying different passive measures without mechanical devices for heating that require the input of commercial fuels. The harsh thermal environment without proper heating and cooling system creates many serious problems every year which results range from discomfort to illness and death [5]. While in the developed countries, the use of heating and cooling devices play an important role for thermal environment adjustment, in developing countries like Nepal, rural areas in particular, the mechanical heating and cooling systems have not yet been widely used and most of the people living with passive means of heating and cooling such as clothing adjustment, window opening, and taking hot or cold drinks depending on the occupants' surrounding conditions [2]. Suitable design of houses under local climate and use of locally available suitable materials for the construction of houses in different regions play an important role for the thermal environment improvement; Nepal is no exception. Various studies [1-5] illustrated that the energy access situations and energy use in Nepal are far below the level of basic human needs, and firewood must be expected to remain the dominant fuel source for cooking and heating. Recently, researches have been done with respect to energy use and its socio-economic and environmental effect. However, there have been very limited researches on thermal environment and energy use in Nepal. It is therefore necessary to conduct research further aiming at a better quantitative knowledge on the current energy situation its relation to the indoor thermal environment under the effect of different out door environment; this is in order hopefully to identify the solution for creating better living conditions in Nepalese houses. This paper describe the current situation of the household energy use and indoor thermal environment of different ecological regions based on the field study. The purpose of this paper is to provide basic information of energy use and thermal environment of studied regions.

2. Methodology

2.1 Study area

The three research area are Solukhumbu district from Mountain region having sub-alpine climate, Panchthar district from Hill region representing warm-temperate climate, and Jhapa district from Terai region having sub-tropical climate. The altitude of the Mountain region is over 2000m, while the Hills are between 300m to 2000m and Terai area is below 300m from the sea level. All of the studied houses in Terai region and 40% of houses of Hill region are connected with rural electrification networks of national electricity grid while no any houses of Mountain regions are connected with rural electrification networks during our survey, however many of them are using the electricity locally generated by small scale hydro-power plants.

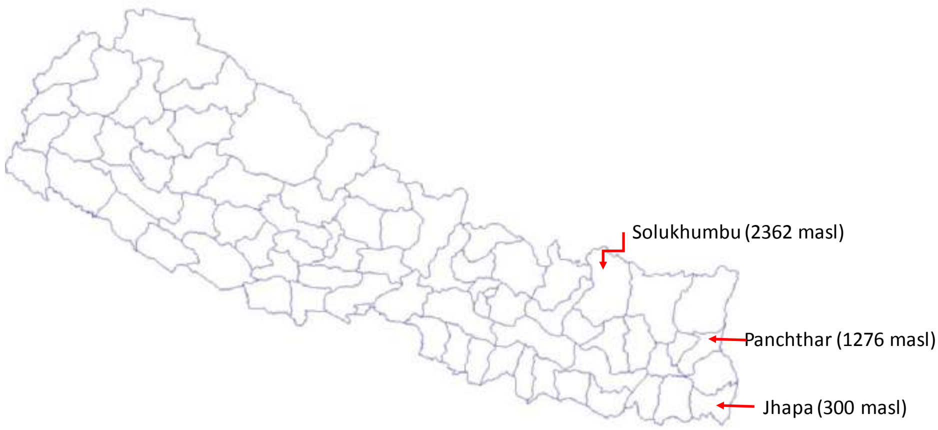

Figure 1. Map of Nepal showing study area; numbers in the brackets indicates the altitude (meter above sea level).

2.1. Source of data

From each region, five houses were selected randomly for thermal environment measurements and energy use measurements for five days. The survey period was from 21 December 2017 to 20 January 2018. Measurement of indoor air temperature, outdoor air temperature and relative humidity were performed at 10-minute intervals by the use of TR-

74Ui data logger. Daily firewood use was measured by weight survey method [6]. For this purpose, we first measured the weight of air dried firewood ready for use by the help of spring balance and left in kitchen of each households with instructions to burn firewood only from the weighted bundle. On the next day remaining wood was weighted to calculate the actual firewood use per day. Household electricity use (kWh) was obtained from previous months' electricity bill provided by electricity supplier. Besides that, 78 houses from mountain region, 260 houses from hill region and 168 houses from Terai region were interviewed for household energy use pattern. The interview questionnaires were based on family size, occupation, amount and types of energy used, source of firewood, distance of firewood source, time required for cooking activities, participation in cooking activities.

3. Results and discussion

3.1. Thermal environments

One-day mean indoor and outdoor air temperature variation during the field study period in three ecological regions have been presented in Figure 2. It is possible to see that the indoor air temperature of Mountain and Hill region is always higher than outdoor air temperature while in the Terai region the corresponding temperature goes up and down alternatively with outdoor air temperature. Availability of solar radiation, building materials, energy use behaviour and window opening behaviour could affect the temperature variation in three regions.

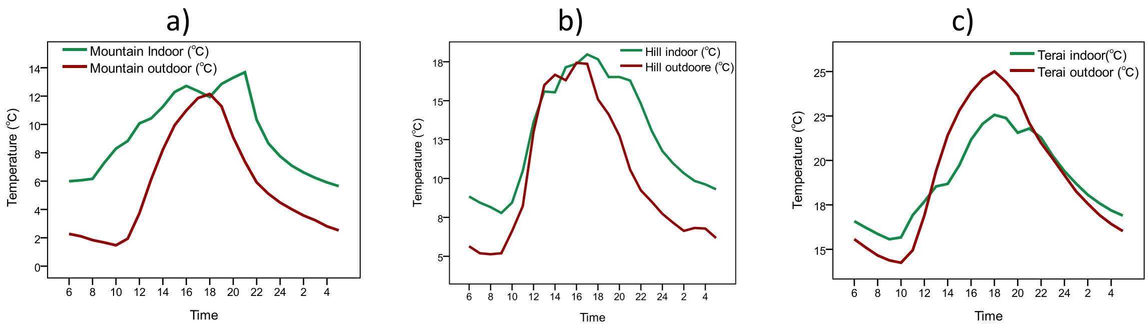

Figure 2.Indoor and outdoor temperature variation a) Mountain region b) Hill region c) Terai region

Table 1 summarizes the information of indoor and outdoor air temperature and relative humidity of three ecological regions of investigated buildings. It is possible to see that the mean indoor air temperatures of different regions differ remarkably and the values were found 8.6°C, 12.8°C and 16°C for Mountain, Hill and Terai region. The indoor air temperature ranged from 0.3°C to 20.8°C in Mountain region, 7°C to 21.1°C in Hill region and 3.3°C to 29°C in Terai region. High minimum indoor air temperature in Hill region is due to the climatic characteristics of warm-temperate climate. Susan et al. [7] mentioned that temperature in warm temperate region of Nepal does not drop down drastically in winter. Mean indoor air temperature of all region was found higher than mean outdoor air temperature. That may be due to the heat storing capacity of building and the production of heat energy inside house due heating and cooking activities. The difference between mean indoor and mean out door air temperature was found 3.1°C in Mountain, 2.7°C in Hill and 1.1°C in Terai region. It indicates that the buildings constructed in the cold region are adapted for low heat transfer by applying appropriate design and material. Window size and window opening behaviour of different regions also affect the indoor air temperature.

Table 1. Statistical results of thermal environment

Parameters	Region	Indoor			Outdoor		
		Min.	Max.	Mean	Min.	Max.	Mean
Temprature(°C)	Mountain	0.3	20.7	8.6	0.1	16.7	5.5
	Hill	7.0	21.1	12.8	0.4	29.6	10.1
	Terai	3.3	29.0	16.0	3.0	27.6	14.9
Relative Humidity (%)	Mountain	38	81	60.6	47	88	66.99
	Hill	35	71	54.4	16	100	73.38
	Terai	34	100	81.68	35	100	84.37

Figure 3 represent the trends of one-day mean indoor air temperature variation during investigation period. As seen in Figure 3, the indoor air temperature in the Mountain region started to ascend at 5:00 while it is 9:00 in the Hill region and 10:00 in the Terai region. The reason behind that might be the energy use behaviour of people living in different thermal environment. In Mountain region particularly in winter season low indoor air temperature creates uncomfortable for living therefore one household member wake up first and burn firewood which helps to increase indoor air temperature. While in Terai and Hill region there was quite suitable thermal environment and it does not require to burn excess firewood for thermal environment improvement so that indoor air temperatures start to increase only after getting solar heat energy through outdoor air temperature.

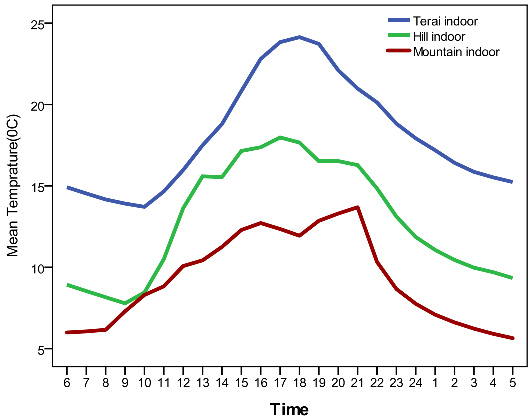

Figure 3. Mean indoor air temperature variation in three ecological regions of Nepal

3.2. Household energy use in different ecological regions

In this study we found firewood, electricity and liquefied petroleum gas (LPG) are the main source of household energy for cooking, heating and lightning purpose. Firewood was used for cooking and heating purpose in all regions. After cooking meal firewood was used for boiling water and improving thermal environment of the houses in winter season. Per-capita and household firewood use of three ecological regions exhibited that the Mountain households require highest and Terai household require lowest firewood as their energy sources (Figure 4. a and b). In this study we calculated average per-capita firewood use as 2 kg, 1.6 kg and 1kg and household firewood use as 12kg, 8.5kg and 5kg for Mountain, Hill and Terai region respectively. The low firewood use in the Terai region probably due to the availability of commercial fuel and lack of firewood sources in that region. High firewood use in Mountain and Hill region may be due to the lack of access to the commercial fuels and use of firewood for space heating. Bhatta and Sachan [6] reported that the firewood use was 2.61-fold higher at high altitude (above 200m) compared to firewood used at low altitude (up to

500m). Li et al. [8] also reported that the higher value of firewood consumption in high altitude because more consumption is needed for space heating.

Figure 5 (a) shows the household LPG use and figure 5 (b) shows the electricity use of three regions. Electricity was mainly used for lightning and for electrical appliances. The distribution of national electricity supply grid among different regions varies significantly due to various reasons such as geographical difficulties and remoteness. We analysed the monthly per capita electricity use and found 11 kWh, 3.3 KWh and 6.5kWh in mountain, Hill and Terai region respectively (Figure 5.b). The cause of high electricity use in Mountain and Terai region was due to the use of electricity for cooking purpose. Average LPG use among three regions was found 8.2 kg, 3.3kg and 7.4kg in Mountain, Hill and Terai region respectively.

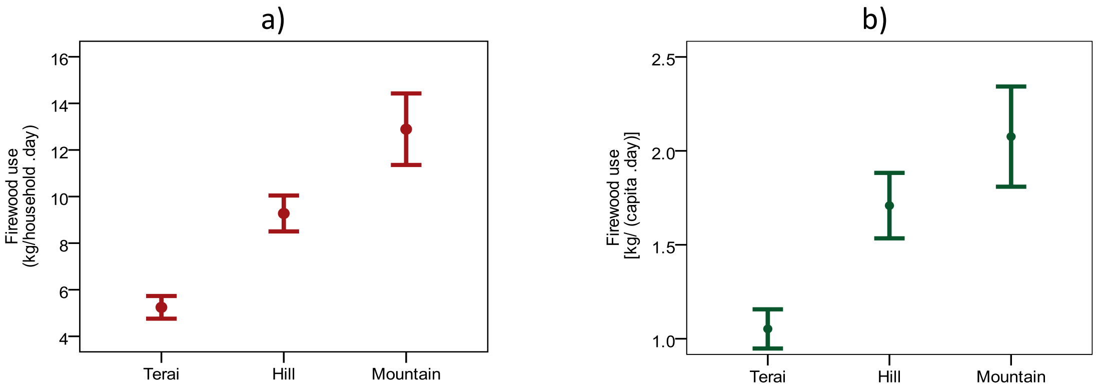

Figure 4. Firewood use in different ecologycal regions of Nepal a) Household firewood use and b) Per-capita firewood use

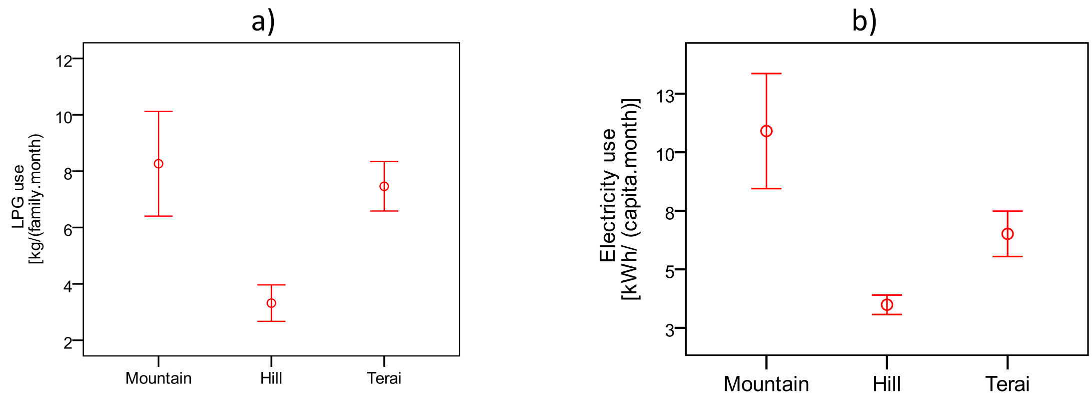

Figure 5. a) Commercial fuel use in different ecological regions of Nepal a) Household LPG use and b) Per-capita electricity use

3.3. Relationship between thermal environment and energy use

To evaluate the relationship between thermal environment and energy use in different regions, regression analysis between household firewood use and reference temperature was carried out. For this analysis we took temperature as independent variables and firewood use as dependent variable. Figure 6 demonstrate the relationship between the household firewood use and indoor temperature (at 6:30) of five studied households for five days from each region (n=75). In this Figure different marker represent the different regions as indicated in the right side of the Figure. The correlation coefficient (r2= -0.72) shows the negative linear relationship between household firewood use and reference indoor air temperature. It means that household firewood use decreases with increase in the reference temperature or vice versa. It also indicates that low amount of firewood have been using in Terai region and high amount of firewood have been using in Mountain region. The difference in firewood use might be due to the variation in the thermal environments in these regions.

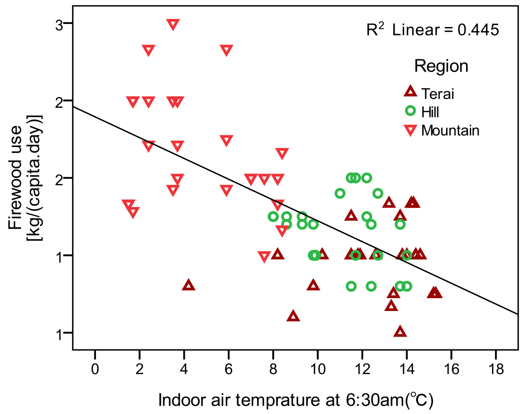

Figure 6. Relationship between indoor air temperature and firewood use

4. Conclusions

Household energy use and thermal environment of different regions are very important data required for basic understanding and to draw the future consideration about energy saving policy in developing country like Nepal. This study suggests that an intensive and extensive improvements of the indoor thermal environment together with less use of energy must be responsible in the winter thermal improvements in cold climatic regions because people living in the cold climatic region depend highly on biomass energy for cooking and space heating. The conclusions of household energy use and thermal environment of different regions can be made as follows:

1. Firewood and electricity are the main sources of household energy in all regions for cooking, heating and lightening purpose.
2. Average daily per-capita firewood use was found 2 kg, 1.6 kg and 1kg for Mountain region, Hill region and Terai region respectively and it is significantly correlated (r^2= -0.72) with thermal environments of these regions.

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Indoor air quality, cold stress, and thermal comfort in multi-family timber-frame buildings

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Abstract: This paper examines the indoor air quality, cold stress, and occupants' comfort in multi-family timber-frame buildings located in Hartford County, Connecticut, United States. The study considered the physical measurements of environmental variables (such as temperature, relative humidity, air velocity, and CO_2 concentration) at 0.6m, 1.1m, and 1.7m above the floor level as specified in the ASHRAE Standard 55. The wet-bulb globe temperature (WBGT) was computed using the variables measured during the survey to understand the temperature at which the residents will be subject to cold stress. The results showed the mean temperatures at various heights varied from 17.1°C-20.3°C. The average relative humidity (RH) ranged from 32%-46%. The average CO_2 values differed from 405.9ppm-482.8ppm. The mean air velocity of 0.1m/s was measured across different levels. Overall, the mean temperature of 18.6°C and an average RH of 39% were recorded in the buildings. The overall average indoor temperature was below the comfort temperature thresholds (20.3°C/23.9°C) recommended by ASHRAE. The results showed the occupants might be prone to cold discomfort. Higher CO_2 values were recorded in the evening and night-time. Behavioural actions of some of the occupants as observed during the field measurements might be a contributing factor to the higher CO_2 values measured at these periods. The occupants reported stiffness and unpleasant odours in the evening and night-time while the measured CO_2 values during the period supported the complaints (CO_2 values above 700ppm). However, the CO_2 values were below the acceptable level recommended by ASHRAE (the values are below 1,000ppm) for healthy indoor conditions in buildings. By applying the WBGT stress index to find the threshold for occupants, the study recommends the WBGT of 13.6°C as a cold stress index for vulnerable occupants in timber-frame buildings during the cold season. The research revealed that an increase in CO_2 level also increases the air velocity while the indoor air quality decreases within the spaces. The study found out that behavioural actions of occupants can affect the indoor air quality of buildings.

Keywords: Indoor air quality, thermal comfort, cold stress index, timber-frame buildings, wet-bulb globe temperature (WBGT), cold season

1. Introduction

The research examines the indoor air quality, cold stress, and thermal comfort of occupants in multi-family timber-frame buildings. Existing papers have reviewed (Taleghani et al., 2013) and examined the thermal behaviour and occupants' comfort in buildings (Raja et al., 2001; Adekunle and Nikolopoulou, 2018). The thermal performance of buildings in the cold season (Adekunle and Nikolopulou, 2019) and warm season (Adekunle and Nikolopoulou, 2014, 2016) has been extensively considered. Indoor air quality within the thermal environment of buildings has also been investigated (Földváry et al. 2017; Steinemann et al., 2017; Fazil and Stephens, 2018; Huang et al., 2018). Many of the existing papers have examined indoor air quality, thermal behaviour, and occupants' comfort in heavyweight buildings (Huang et al., 2018; Atarodi et al., 2018) and non-heavyweight structures (Földváry et al. 2017). Some of these studies have evaluated non-residential buildings (Atarodi et al., 2018; Krawczyk and Wadolowska, 2018); while a few studies considered the investigation on residential buildings (Kaunelienė et al., 2016; Földváry et al. 2017; Huang et al., 2018). Recently, existing papers have been focusing more and more on indoor air quality and thermal comfort in different buildings such as educational buildings (Krawczyk and Wadolowska, 2018), office buildings (Atarodi et al., 2018), hospitals and other healthcare facilities (Chamseddine et al., 2019), industrial buildings, residential buildings (Földváry et al. 2017; Fazil and Stephens, 2018; Huang et al., 2018), commercial buildings (de Robles and Kramer, 2017), and other buildings (Shiue et al., 2019) used for various purposes.

Occupants' comfort and elevated temperatures and overheating in summer have been assessed in timber buildings (Adekunle and Nikolopoulou, 2014, 2016). Also, heat stress (Adekunle, 2018a) and cold stress (Adekunle, 2018b), as well as occupants' comfort (Adekunle 2018a, 2018b), have been investigated in such buildings. In the existing research, the thermal mass of timber is found to be an important parameter for improving the thermal behaviour of timber buildings in different seasons (Adekunle and Nikolopoulou, 2016). A recent publication also examined winter performance, cold stress and thermal comfort of occupants in timber buildings (Adekunle and Nikolopoulou, 2019). The study (Adekunle and Nikolopoulou, 2019) explained the tendency of slight cold stress for occupants of the buildings. However, not a single paper out of the existing papers on timber buildings has evaluated indoor air quality, cold stress, and occupants' comfort concurrently in multi-family timber-frame buildings.

On indoor air quality in buildings, a set of combined building energy and indoor air quality models for residential buildings was considered by Fazil and Stephens (2018). The study (Fazil and Stephens, 2018) explained that many people in the study location spend most of their time indoors where they are susceptible to several pollutants of indoor and outdoor sources. Huang et al. (2018) examined indoor air quality of residential buildings based on field measurements and more extensive monitoring. The research (Huang et al., 2018) found out that the average indoor concentration of pollutants including volatile organic compounds (VOCs) and CO_2 exceeded the standard threshold and they varied with seasonal features. Huang et al. (2018) also recommended the opening and closing of windows to improve ventilation of indoor spaces in different seasons. Steinemann et al. (2017) considered ten questions regarding green buildings and indoor air quality. The study (Steinemann et al., 2017) argued that green building certifications might not adequately improve indoor air quality, while green products and practices can probably affect indoor air quality. Steinemann et al. (2017) concluded that the overall performance of green buildings could be enhanced by a greater emphasis on indoor air quality. Based on the findings highlighted in the existing papers, it is important to evaluate the indoor air quality of residential buildings built with green or natural materials such as timber.

This paper examined multi-family timber-frame buildings in the study location because they are commonly found in the Northeast of the United States. Many of the multi-family residences in the region exhibit the features of Colonial Revival Style architecture such as dormer windows, multi-pane windows, prominent front area, gable roof and others (Adekunle, 2018c). In the region, the construction of different buildings with Colonial architecture characteristics commenced as far back as the 1600s. As outlined in the document published by CERC, more than 40% of the current building stock in the study location is constructed before the 1950s (CERC, 2017). Out of the 40% of the pre-1950 buildings, multi-family timber-frame buildings account for a large percentage of the buildings. The findings presented in the document highlighted the significance of multi-family buildings in the region (CERC, 2017).

Similarly, the research evaluated timber-frame buildings because over 90% of the US residential buildings are built with timber (CEI-Bois, 2010). The existing paper also explained that based on the recent building stock of multi-family timber-frame buildings, occupants might be prone to heat stress and elevated temperatures in the buildings (Adekunle, 2018c). Hence, it is crucial to study the indoor air quality, occupants' comfort and cold stress in multi-family timber-frame buildings.

Existing papers have examined cold stress (Adekunle, 2018b; Adekunle and Nikolopoulou, 2019) in residential timber buildings. The Wet-Bulb Globe Temperature (WBGT) model expressed in Equation 1 is described as the function of the natural wet bulb temperature (T_{nwb}°C) and black globe temperature (T_g°C). The WBGT model has been extensively studied and applied for assessing stress indexes in various thermal environments in existing research (Zare et al., 2018; Adekunle, 2019). The stress index will be compared with the WBGT stress indexes outlined in the existing papers. Table 1 explains the temperature limits and classes of the stress thresholds for the WBGT.

$$WBGT_{ind} = 0.7T_{nwb} + 0.3T_g \qquad \text{Equation 1}$$

Table 1. Temperature limits and classes of the stress indexes for the WBGT.

The WBGT stress index	Risk Mitigation	Thermal perception
Temperature below 18.0°C	Take hot/warm drinks to adjust to the thermal environment	A wide range of thermal perception from extreme cold stress (very cold) to moderate to cold stress (cool) to slight cold stress (slightly cool)
Temperature at 18. 0°C		No thermal stress (comfortable) to slight heat stress (slightly warm)
Temperature between 18. 0°C and 23.0°C	Maintain a comfortable thermal environment	Moderate warm stress (warm)
Temperature between 23.0°C and 28.6°C	Drink water before and after exercise.	Strong heat stress (hot)
Temperature at 29.3°C	Drink at least one quarter of water/drinks every 20 minutes.	Very strong heat stress
Temperature at 30.6°C	Take rest breaks during exercise and keep drinking fluids.	
Temperature between 31.8°C and 38°C	Consider reducing workout intensity.	Extreme heat stress
Temperature above 38°C	Extreme caution. Carry out activities indoors in a cooler setting.	

2. Experimental Approach

The research explored the field measurements of environmental variables as the methodology to collect data for the analysis. The study also applied the WBGT mathematical model to compute the stress indexes within the case study buildings. The sensors measured the environmental variables (temperature, RH, air velocity, and CO_2 concentration) at every 15 minutes within the thermal environment of the case study buildings. As recommended by ASHRAE 55 (ASHRAE, 2017), the sensors were installed on the indoor wall at the height of 0.6m, 1.1m, and 1.7m above the floor level. The heights represent the average height of the lower (0.6m), middle (1.1m), and head (1.7m) regions of a man in standing position. For a man in sitting position, the heights of 0.6m and 1.1m represent the lower, and head regions. The field measurements were carried out during the cold season of 2016. The outdoor environmental data observed at a meteorological station not far from the study location were considered for the analysis. The variables observed in the buildings were used to calculate the WBGT indexes. The indexes were also compared with the thermal classes of the WBGT model. The number of hours of temperatures below the recommended thresholds for cold season (20.3°C/23.9°C) is examined to evaluate occupants' comfort within the case study buildings.

3. Case Study Buildings

The case study buildings are multi-family timber-frame buildings. The case studies are in Hartford County, Connecticut, United States. The case studies are pre-1950 buildings and currently, account for a noticeable percentage of the present residential buildings stock in the Northeast of the nation. Many of the case studies have two units per building. On average, the case studies are located on an approximately 689.5m^2 area of land. The case studies have a mean floor area of about 144.5m^2. Each of the units of the case studies has a living area, dining/kitchen, a bath on the lower floor, and often two-bed and a full bath on the upper level. Each unit also has a basement area that is used for various purposes such as laundry, recreational as well as learning spaces for children during the non-warm seasons. The environmental monitoring was considered in the living rooms (lower floor), bedrooms (upper floor), and the basement part of each unit. Based on the data collected during the field measurements, between three and four occupants are residing in each unit.

Regarding the thermal properties of the case studies, the average U-values of the outside walls ranged between 0.30 W/m^{2}K and 0.50W/m^{2}K. The average U-value of approximately 0.35W/m^{2}K is computed for windows and doors. This study examined the field measurements considered in some of the case studies. The figure below shows the views of some of the multi-family timber-frame buildings evaluated during the field surveys.

Figure 1: Approach views of some of the case study buildings.

4. Analysis of Data

For the outdoor weather conditions, the average outdoor air temperature for the duration of the field measurements was 6.6°C. A maximum outdoor air temperature of 18.3°C and a minimum outdoor air temperature of -3.2°C were measured during the field investigation. The average maximum outdoor air temperature was 11.8°C, and the average minimum outdoor air temperature of 1.7°8 was observed for the study location. The average outdoor dew-point temperature of 1.5°C was reported for the location. The mean outdoor relative humidity of 71% was observed at the location. The average precipitation of 55.0mm and a mean air velocity of 4.9m/s were reported for the site. For the period of the physical measurements, the mean outdoor WBGT of 5.2°C was computed for the study location. As expected, the analysis showed the period of the field measurements was cooler than the warm season of the year (Figure 2). Table 1 summarises of the outdoor weather data for the duration of the field measurements.

Table 1: Summary of the outdoor weather data for the geographical location of the study.

Mean values/Month	October	November	December	Average
Mean temperature (°C)	12.6	6.6	0.7	6.6
Maximum temperature (°C)	18.3	12.1	5.0	11.8
Minimum temperature (°C)	7.3	1.4	-3.2	1.8
Mean Relative Humidity (%)	74	71	68	71
Mean Dew-point (°C)	7.5	1.3	-4.4	1.5
Mean vapour pressure (Millibars)	1019.2	1016.4	1018.8	1018.1
Mean air velocity (m/s)	4.7	4.8	5.1	4.9
Mean precipitation (mm)	45.7	58.4	61.0	55.0
Mean WBGT (°C)	11.0	5.1	-0.6	5.2

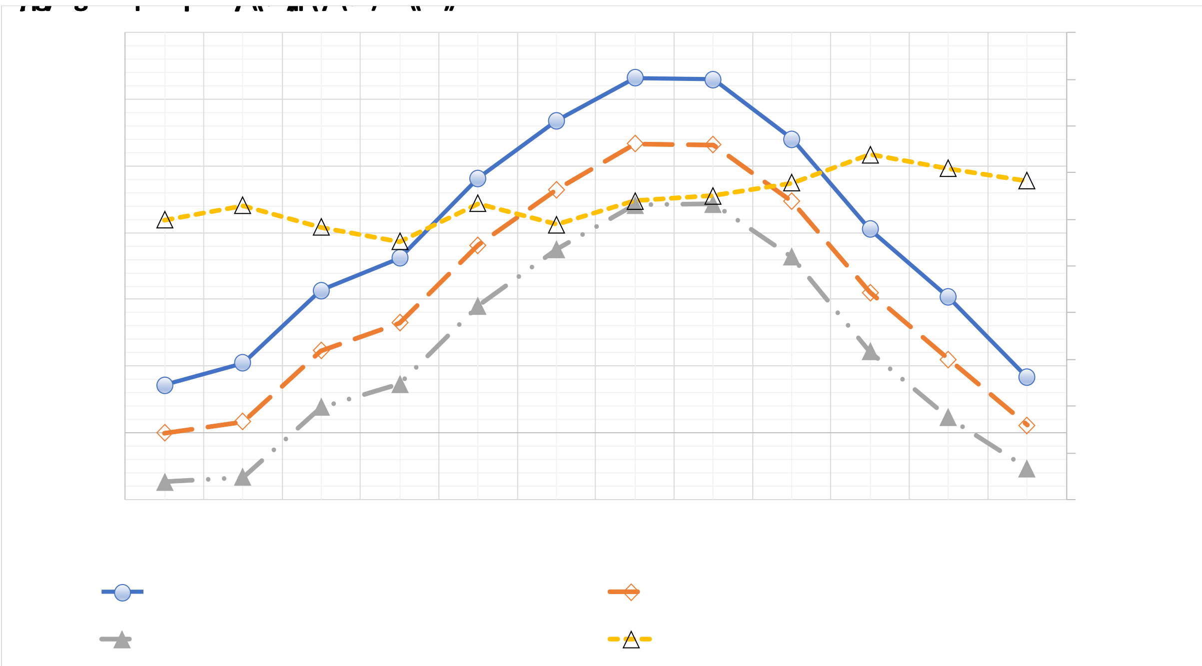

Figure 2: Mean outdoor temperatures from January-December 2016.

Relating the outdoor air temperatures during the cold seasons (October to December) of 2016 and 2017, the research found out mean values of environmental variables for the duration of the physical measurements in 2016 was slightly less than the mean values reported for the cold season in 2017. The analysis showed occupants within the outdoor thermal environment may be subject to a range of slight to moderate cold stress in the study location. The study also showed that the average outdoor temperatures were within 0.7°C and 12.6°C. The outdoor temperature did not rise above 28.0°C throughout the field measurements.

5. Results and Discussion

5.1 Indoor Environmental Conditions

The average indoor temperatures in the case study buildings varied from 17.1°C to 20.3°C. The mean relative humidity values ranged between 32% and 46%. On the one hand, higher average indoor temperatures were measured at the height of 1.7m in all the living areas and bedrooms than the values obtained at the heights of 0.6m and 1.1m. On the other hand, higher average relative humidity values were observed at the height of 0.6m within the spaces than the mean RH values reported at the heights of 1.1m and 1.7m. The average CO_2 concentration of 482.8ppm was measured in the living areas. The mean CO_2 level of 405.9ppm was recorded in the bedrooms (Table 2). The research revealed the mean comfort temperature of 20.3°C was measured in the living areas at the height of 1.7m. The study showed the possibility of the indoor to be within the comfort threshold in the living areas than the bedrooms. The overall average indoor temperatures were below the upper limit (23.9°C) for comfort temperature in buildings. The research showed the average indoor temperatures did not exceed the critical comfort threshold of 28.0°C. Across the different levels of measurements, higher temperatures were measured in the living areas than the bedrooms. The research showed the living areas are warmer than the bedrooms during the cold season. The extended hours spent in the living areas than the bedrooms during the cold season may be a contributing factor to higher temperatures reported in the living areas than the bedrooms. Also, the frequent use of personal control such as a portable heater, as well as activities carried out in the living areas may contribute to increasing temperatures observed in the spaces than the bedrooms.

Table 2: Summary of the average values for the measured indoor environmental variables

Average values	Living areas			Bedrooms		
	0.6m	1.1m	1.7m	0.6m	1.1m	1.7m
Mean temperature (°C)	18.9	19.6	20.3	17.1	17.6	18.1
Maximum temperature (°C)	22.1	22.9	23.5	22.0	22.8	23.3
Minimum temperature (°C)	10.7	10.9	11.2	8.1	8.5	8.8
Mean Relative Humidity (%)	34	33	32	46	45	45
Mean air velocity (m/s)	≈ 0.1			≈ 0.1		
Mean CO_2 concentration (ppm)	482.8			405.9		

5.2 Relationship Between the Indoor and Outdoor Variables

About the relationship between the indoor and outdoor temperatures, the findings showed the links are found between the indoor temperatures taken at different heights within the spaces and the outdoor temperatures. The results revealed the indoor temperatures are reasonably influenced by the outdoor temperatures in the bedrooms than the living areas (Figure 3). Higher temperatures were measured in the living areas than the bedrooms. The use of control, orientation, and the proximity of the living areas to kitchen/dining may influence higher temperatures reported in the living areas than the bedrooms. Temperatures were found be within a smaller band at different heights in the living areas than the bedrooms. Across the spaces, the temperatures measured at the height of 0.6m above the floor level were found to be significantly lower than the temperatures measured other heights especially the values obtained at the height of 1.7m above the floor level. The findings showed the indoor temperatures are within a range of approximately 17.0°C to 20.8°C in the living areas. The internal temperatures are within a range of about 15.0°C and 19.6°C. The results revealed the possibility of constant slight cold stress in the bedrooms than the living areas. Figure 3 shows the relationship between indoor and outdoor temperatures in the living areas and bedrooms.

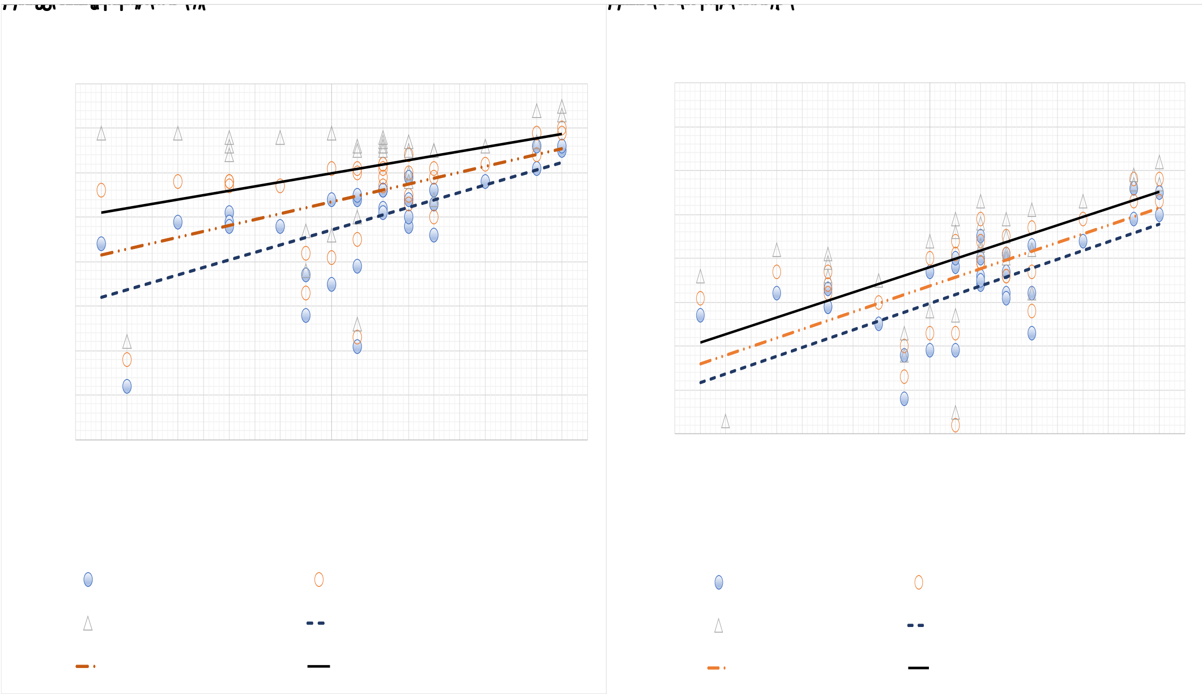

Figure 3: Relationship between the indoor temperatures taken at different heights during the physical measurements in the spaces and the outdoor temperatures.

5.3 Comfort Temperatures

The study considered the number of hours of measured temperatures that exceed the lower and upper comfort temperature limits (20.3°C/23.9°C). The study found out none of the measured temperatures exceed the upper comfort temperature limit (23.9°C) within the spaces. However, the number of temperatures that exceed the lower comfort temperature was significantly higher in the living areas than bedrooms (Figure 4). The results showed the measured temperatures in the living areas exceed the lower comfort threshold for more than 50% of the time when the measurements taken at the heights of 1.1m and 1.7m were evaluated. Moreover, the measurements were taken in the living areas at the height of 0.6m also exceed the lower limit of comfort temperature for over 40% of the time. The results showed the measurements taken in the bedrooms at the heights of 1.1m and 1.7m exceed the lower limit for over 10% of the time.

On the one hand, the results showed the measured temperatures were within the comfort temperatures for most of the time in the living areas. On the other hand, the observed temperatures were significantly below the comfort temperature thresholds in the bedroom for at least 75% of the time. The results revealed the possibility of cold discomfort at a frequent rate in the bedrooms than the living areas.

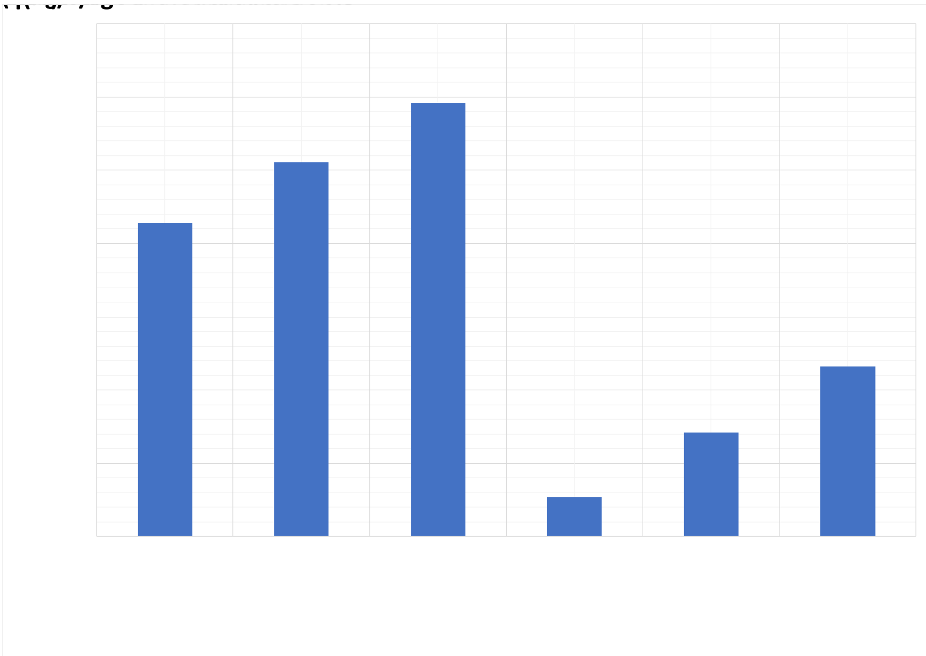

Figure 4: Number of hours of temperatures above the comfort lower limit in the living areas and bedrooms

5.4 The Applicability of the Mathematical Model (WBGT)

The mathematical model was reviewed and applied to determine the WBGT cold stress index as highlighted earlier in the paper. The findings revealed the WBGT index ranged from 12.9°C to14.4°C in the living areas and bedrooms (Table 3). The research showed a higher WBGT value was computed in the living areas for the measurements taken at the height of 1.7m than the measurements taken at the heights of 0.6m and 1.1m in the spaces discussed in this paper. Overall, the average WBGT of 13.6°C is proposed as the cold stress threshold for occupants of the case study buildings. This investigation revealed the possible cold stress threshold at which the vulnerable occupants may be subject to the risk of cold stress within the thermal environment.

Table 3: Summary of the average indoor temperatures, RH, and WBGT values.

Average values	Living areas			Bedrooms		
	0.6m	1.1m	1.7m	0.6m	1.1m	1.7m
Mean temperature (°C)	18.9	19.6	20.3	17.1	17.6	18.1
Mean Relative Humidity (%)	34	33	32	46	45	45
Mean WBGT (°C)	13.4	13.8	14.4	12.9	`13.2	13.7

5.5 Relationship Between the Indoor Temperatures and WBGT

The study also investigated the relationship between indoor temperatures and WBGT values. The research found out that relationships exist between the measured indoor temperatures and the WBGT at different heights within the spaces. The higher R^2 values between the variables were calculated for the measurements taken at the height of 0.6m in the living areas and bedrooms (at least $R^2 = 0.3850$) than the measurements taken at other heights in the spaces. The study showed a change in indoor temperature influences the WBGT values at 0.6m height than the values reported at the heights of 1.1m and 1.7m above the floor level.

5.6 Relationship Between the Average CO_2 Concentrations and Air Velocity

Similarly, the investigation revealed that higher CO_2 concentrations were measured during the evening (6pm-10pm) and night-time (6pm-7am) than the values obtained during the day (8am-5pm) within the spaces. The research evaluated the behavioural actions of the occupants observed during the field measurements and found out their actions might contribute to the higher CO_2 concentrations measured at these periods. For instance, some of the occupants reported stiffness and unpleasant odours in the evening and night-time while the measured CO_2 values during the period supported the complaints (average CO_2 values above 700ppm). However, the CO_2 values were below the acceptable level recommended by ASHRAE (the values are below 1,000ppm) for healthy indoor conditions in buildings.

Comparing the average CO_2 concentrations obtained in this study with the existing research on indoor air quality in buildings (Kaunelienė et al., 2016; Földváry et al. 2017), lower average CO_2 concentrations were reported in this study than the values (above 1000ppm) reported in the existing research (Földváry et al. 2017). This paper showed that even though lower CO_2 values were reported in this study, higher CO_2 concentrations may be observed when extended field measurements are considered in the case study buildings. Therefore, the paper recommends an extended study to evaluate the indoor air quality within the spaces in different seasons. Table 4 provides a summary of the findings obtained in this study with the existing research in the field.

Table 4: Summary of the findings obtained in this study and the existing research.

Average values	This study			Földváry et al. (2017)		
	Living areas	Bedrooms	Average	Renovated buildings	Non-renovated buildings	Average
Mean temp. (°C)	19.6	17.6	18.6	22.2-25.3°C	18.3-23.6°C	20.3-24.5°C
Mean RH (%)	33	45	39	34-65%	31-61%	33-63%
Mean CO_2 (ppm)	482.2	405.9	444.1	1290.0	1100.0	1195
Mean WBGT (°C)	13.9	13.3	13.6	Not provided	Not provided	Not provided

Equally, the study found out that a change in the air velocity also influences the CO_2 level within the spaces. The values obtained from the physical measurements showed that as the CO_2 level increases (average values above 500ppm), the air velocity also increases (average values above 0.2m/s) and the indoor air quality decreases (Figure 5). The study found out that air velocity and CO_2 level are crucial parameters to consider while assessing the indoor air quality in different spaces. The study recommends field measurements of additional variables to understand the indoor air quality within different spaces in multi-family timber frame buildings.

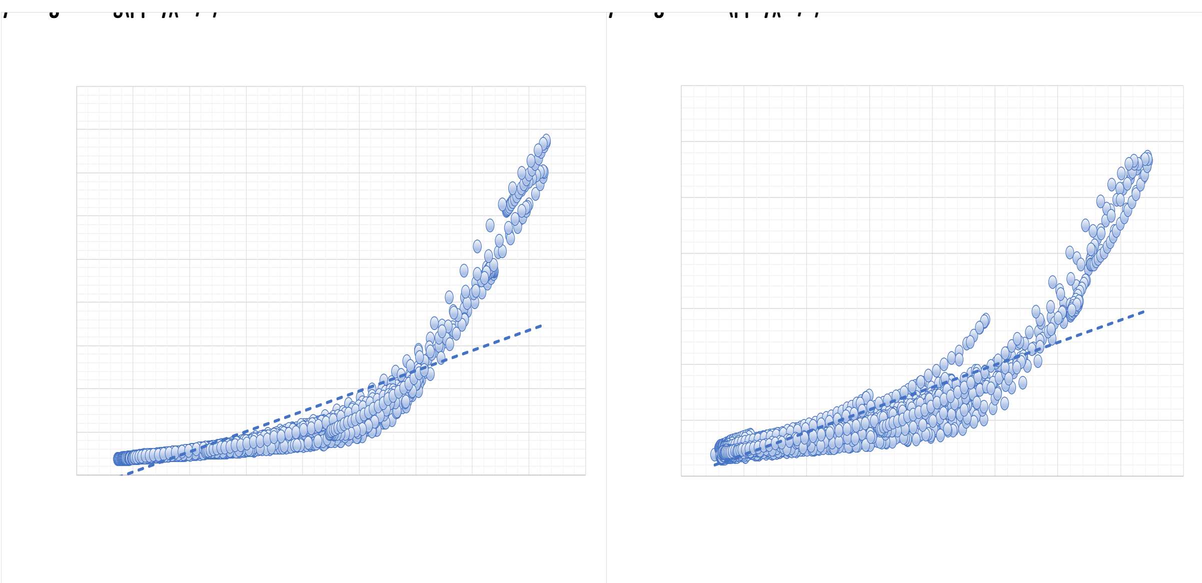

Figure 5: Relationship between the average indoor air velocity and CO_2 concentration in the living areas and bedrooms.

6. Conclusions

This study evaluated the indoor air quality, cold stress, and thermal comfort of occupants in multi-family timber-frame buildings in the Hartford region, Connecticut, United States. The study explored the physical measurements of environmental variables at different heights above the floor level. The results showed the average temperature of 18.6°C and a mean RH of 39% in the case study buildings. The overall mean indoor temperature was lower than the comfort temperature limits (20.3°C/23.9°C) suggested by ASHRAE. The results showed higher temperatures were reported in the living areas than bedrooms.

On the relationship between the indoor and outdoor temperatures, strong associations were found between the variables. The study showed the indoor temperatures are considerably influenced by the outdoor temperatures in the bedrooms than the living areas.

Regarding the comfort temperatures, the paper found out that the temperatures in the living areas exceed the lower comfort limit for over 50% of the time when the physical measurements recorded at the heights of 1.1m and 1.7m were assessed. The physical measurements considered in the living areas at the height of 0.6m also exceed the lower comfort temperature for more than 40% of the time. The measurements observed in the bedrooms at the heights of 1.1m and 1.7m exceed the lower limit for more than 10% of the time. The measured temperatures were within the comfort temperatures for most of the time in the living areas; while the observed temperatures were considerably below the comfort temperature limits in the bedrooms. The results showed the possibility of cold discomfort at a constant rate in the bedrooms than the living areas.

The study showed that strong links are found between the measured indoor temperatures and the WBGT values at various heights within the spaces. The higher R^2 values between the two variables were found for the measurements recorded at the height of 0.6m in the living areas and bedrooms than the measurements taken at other heights in the spaces. The study showed that stronger relationships exist between the variables as the height of measurements decreases.

Higher CO_2 values were reported in the evening and night periods than the day-time. Behavioural actions of some of the occupants might influence the higher CO_2 concentrations observed at the evening and night periods. The study found out that as CO_2 level increases, the air velocity also increases and the indoor air quality decreases.

By considering the WBGT model to find the threshold for occupants, the study proposes the WBGT of 13.6°C as a cold stress threshold for vulnerable occupants in multi-family timber-frame buildings. The study also found out that the mean stress index reported in this study is less than the stress value (20.0°C) reported in the existing paper (Adekunle, 2019). The study highlights the need for field measurements of additional variables to assess the indoor air quality of buildings. The research recommends the use of materials that could enhance the indoor air quality in buildings. The study found out that behavioural actions of occupants can affect the indoor air quality in buildings.

7. Acknowledgements

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Sustainability Literacy and Higher Education; Paradigm and Challenges in the Built Environment of the Gulf Region

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Abstract: There is growing movement to transform educational systems into high impact education on sustainability that prepares more effectively students to live in and address this changing world. Achievements are, however, contextually variable. Educating and training tomorrow's professionals who abide by and deliver an ecologically sensitive design is a critical mission that has been extensively embraced by architectural, design and engineering schools worldwide. Similarly, the Architectural Engineering program at the United Arab Emirates University has embedded sustainability throughout its curriculum, resulting in students technically knowledgeable in delivering high performing buildings. Nonetheless, while the program has delivered the technical knowledge, the analytical and problem-solving skills to meet the green building targets, it has not necessarily translated into a higher awareness level and ethical commitment to sustainability. This may be particularly evident in the region, where high earnings coupled with subsidized energy, do not reflect the true energy usage. In particular, the ethical commitment to sustainable development in the built environment remains yet to be fully reached. This paper presents some educational activities developed in an elective course aiming to bridge the "ethical commitment" gap. Among these exercises, the retrofitting exercise to greener standards of the student's own home yielded substantial benefits well beyond the target objectives. The energy and water usage in the home was critically assessed in relationship to the house building design and construction. In addition, occupants' lifestyle, behaviour and attitudes were explored through observations and interviews and were an eye opener, triggering inquisitive responsiveness. The critical overview of the building and its occupants' behaviour played a significant role in understanding the intricate relationships governing the targeted goal, highlighting that the only way to address the issues is collectively, calling on everyone involvement in response to moral responsibility. Above all, this paper aims to foster a wider debate on contextual educational strategies to really meet the sustainability targets.

Keywords: Sustainability literacy, built environment, Educational strategies, Ethical commitment, Awareness, Context, Architectural Engineering, UAE

1. Introduction

The world is changing. The implications of a rapid population growth coupled with an unprecedented resources-intensive urbanization led to critical environmental issues. As it is widely known now, the recognition of climate change and global warming as a major risk has set sustainability as a worldwide agenda, triggering multidimensional initiatives. International agreements coupled with public policy commitments strive to set sustainability targets in the built environment. In this context, the United Arab Emirates (UAE), similar to all the other Gulf countries, witnessed tremendous economic and urbanization expansion in the last forty years with a damaging downside that is a minimal consideration of resources and energy-related implications. The built environment in the UAE for instance, accounts for 70% of energy consumption, mainly used in cooling, compared to the global average of 40% (almost twofold). A fact that positioned the UAE as one of the world's largest energy consumption per capita, a situation worsened by its harsh climate (World Energy Council, 2011; Amaya, 2013; Khondaker et al, 2016) (Figure 1).

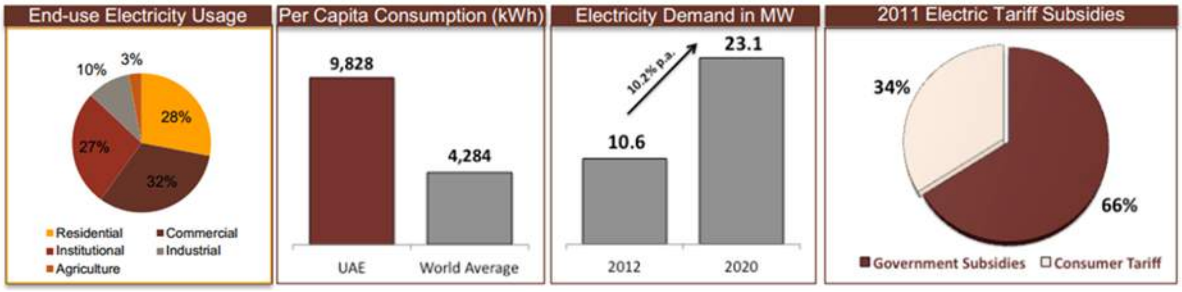

Figure 1: UAE electricity consumption; status and prevision (Amaya, 2013)

The UAE government recognizes the energy–carbon reduction challenge and identified several key indicators for change in its Economic Vision 2030, including reducing the power demand by 15% by 2020 from the 2010 levels (UAE Ministry of Public Works 2015). The identified challenges to reach the target lie in a number of issues including lack of policies directed to energy efficiency, limited standards related to products and systems performance, and perhaps more importantly, the lack of public awareness and education regarding the critical need for resources conservation (Amaya 2013). This last concern is in line with the already well-established global call for an education for a sustainable development, set as a strategic target since the 1992 Rio Earth Summit. Additionally, the UNESCO dedicated a decade from 2005 to 2014 for the development of sustainable education (AASHE 2010) a target now globally integrated in higher education (UNESCO, 2012, EDUCATE, 2012, AASHE, 2015, AASHE, 2017). Unfortunately, effectiveness remains contextually grounded and calls for continuous improvements (Corcoran & Wals 2004).

From this perspective, the broad target of this paper lies in stimulating a public debate on the optimal and contextual integration of sustainability in higher education, while the specific focus is grounded in the education of future architectural engineers in the Gulf region. It explores means and impact activities that attempt to bridge the gap between technical knowledge and the ethical commitment to sustainability with a particular interest in the built environment.

2. Background: Sustainable Education and the Built Environment

Education in general and, in particular higher education, is facing its greatest challenge in meeting its responsibility to prepare its graduates into a responsible, knowledgeable and innovatively creative workforce that can respond to today's socio-economic and environmental challenges (AASHE 2017). In this context, education for a sustainable built environment is an incumbent imperative. Higher education, our focus in this presentation, is a leverage point for advancing a sustainable built environment. It is widely agreed that all construction professionals have an obligation to ensure that the buildings and urban spaces that flow from the design process are a product of careful and responsible practice. "This has not always been the case and, rightfully, the finger has in part been pointed at academia for not providing the education that would help such professionals respond to contemporary sustainability challenges" (Altomonte et. Al 2014, p. 3; Corcoran, Wals 2004,). In addition, often enough engineering professionals move into management, policy and government, financial institutions, and do not always follow traditional engineering paths

(Beder 1998). Thus, the engineers' potential contribution beyond their original field of expertise may span to all these areas using their technical knowledge to improve and promote sustainable business and policy outcomes (Altomonte et. al 2014).

The sustainable education target had been recognized and embraced worldwide. The Association for the Advancement of Sustainability in Higher Education lists academic programs in sustainability and related fields within over 500 organizations in Northern America alone (AASHE 2015). Intensive research spurred around the integration of sustainability in higher education (AASHE 2015, AASHE 2017) highlighting challenges, gaps, framing issues while exploring models and best practices (Altomonte et. al 2014, Desha et al 2003, Gough & Scott 2003, Moore 2005, de la Harpe Thomas, 2009, Waas et. al 2010, Arjen, 2002, McFarlane, A.G. Ogazon. 2011). In response, several educational institutions within the UAE advocate the delivery of an undergraduate and/or graduate program articulated around a sustainable built environment.

While the importance of education to foster a sustainable life has been internationally accepted as a critical agenda, spurring numerous initiatives, achievements and performance are yet to be verified. In particular, the ethics of sustainability may largely be affected by economic, political discourses and cultural norms (Kibert et. al 2010). The meaning attached to a phenomenon might also be largely culturally-nested (UNESCO 1996). Hence, approaches in one socio-cultural setting might be quite different in another one and call for a critical appraisal of education effectiveness. For instance, in high levels of material affluence and consumption societies, education may fall short of reaching its target by only imparting scientific and technical skills (AASHE 2017).

2.1 Sustainability in architectural engineering program at UAEU

The Architectural Engineering (AE) program at the United Arab Emirates University (UAEU) embedded education for a sustainable built environment across the curriculum, as every academic area within the program contributes to sustainability. It embraced an integrated design teaching and thinking approach as the complexity of built structures exceeds the expertise on isolated individual building systems or components. This attribute has been recognized as one of the main program's strengths in its 2016 reaccreditation by the Accreditation Board for Engineering and Technology (ABET). Students are particularly knowledgeable at designing high performing or Zero Energy buildings through building energy efficiency optimization, material selection and integration of renewable energy systems. Although the program has deepened students' technical knowledge, heightened their analytical and problem-solving skills in these areas, this has not necessarily translated into a higher awareness level and ethical commitment to the sustainability issue. Such gap is detected and heightens the "need to refocus many existing education policies, programs and practices so that they build the concepts, skills, motivation and commitment needed for sustainable development" (UNESCO 2002).

This may be particularly evident in the Gulf region, where high incomes and subsidized utilities overshadow the true energy usage. The ethical commitment to the sustainable development in the built environment is yet to be fully attained. In the light of recent economic adjustments, there is an evident pressure to consider ways to raise sustainability awareness and ethical commitment versus sole technical expertise. Considering these concerns, a set of basic activities have been embedded in an elective course at the Department, with a stated attempt to build a complete picture and raise awareness.

2.2 Sustainable Built Environment; Course Target

The Sustainable Architecture and Urban Environments in Hot Climate (ARCH532 2017) is an elective course typically taught in the 4th or 5th year. It is one among a limited number of select courses that account for the Bachelor/Master (BS/MS) dual degree that undergraduates with a strong academic record may take as part of an accelerated BS/MS Program. The course is developed to complement the core curriculum courses and spans over a range of scales and topics. Upon its successful completion, students are expected to be able to a) Define the environmental impacts of urbanization/buildings and discuss implications of using non-renewable energy, b) Identify the appropriate urban and architectural responses in hot arid and hot humid climates, c) Recognize the requirements of Green Buildings and select optimum strategies and d) Assess critically the strategies used in green buildings that responds to climate and meets the fundamental requirements of energy efficiency and water conservation.

The course was designed to tightly knit the environmental impacts of urbanisation to their mitigation strategies from the urban to the building scale. Topics such as climate change, global warming, ecological footprint, urbanization and environmental impacts were addressed at the early stages of the course to connect environmental impact to the built environment. Through sets of short in-class activities, students connected a range of issues such as lifestyle and impact on ecological footprint, explored impacts of extreme weather events and their regional impacts, especially in vulnerable contexts such as the UAE's with a purpose to clearly apprehend the related health, economic, social and environmental consequences. Framing the initiatives to address these issues was covered through the remaining topics spanning twelve weeks, covering sustainable urbanism, the Green Rating System and high performance buildings, energy and water conservation strategies in the built environment, building retrofit strategies and finally performance under hot climate conditions. The final term project spanning the four final weeks investigated the retrofitting potentialities of their own homes to greener standards while also exploring the impacts of occupants' behaviour on energy usage. The learning protocol was based on a critical approach to real issues, challenging students to explore and engage in real problems fostering intuitiveness, promoting effective reasoning while hopefully also increasing motivation for life-long learning. The educational activities presented here are the ones that triggered a critical inquisitiveness in the addressed topics and seem to have had a higher impact in terms of a need to commit to sustainable development.

3. Learning Activities; Method

This section is to introduce and examine how a set of learning activities were designed, conducted and assessed in a course alongside their evaluated outcomes. The sample of learning activities was designed to explore some of sustainable development themes. The themes include dealing with complexity, other disciplines, people, environmental limits and trade-offs. The key target of these exercises is to build a wider understanding of the intricate relationships among the sustainable development goals, while raising awareness for the specific relationship to the built environment and the importance of their roles as future professionals in this field.

The learning activities or assignments were of two types, a) short in class activities consisting of individual thematic critical reviews, comparisons, group discussion, class debates and role-play on assigned themes and b) a four-week-long project. The latter, a group assignment running over four weeks, was a retrofit assessment for energy and water conservation of their own homes and consisted of a critical review of building design, operation and occupants' behaviour versus energy usage. The common underlying objective was to engage students in critical reviews, discussions and group debates ranging from the socio-behavioural review of personnel lifestyle, to urban and architectural design decision and their environmental implications while seeking contextually appropriate design solutions. Assessment consisted of pre and post exercise evaluation of knowledge gained as well as routine feedback on perceived benefits and challenges of each activity as well as at the end of the course a self-reflection on the most important learning gained from the course.

4. Learning Activities; Scope, Procedure and Outcomes

4.1 Short in Class Activities

The short in class assignments were often run in the Lab sessions following a lecture on related topics. One of the most basic exercises requested every student to assess how sustainable is their lifestyle through individual ecological footprint calculation. An online freely available ecological footprint calculator was used. The output in the form of the number of planets earth needed to sustain their lifestyle was compared first with their group members, then to the world average with the objective to identify variances and discuss the underlying causes of the differences. A class discussion collected the possible reasons behind the results.

This basic evaluation and analysis emphasized disparities linked to lifestyle, consumer behaviour and lack of awareness. Ecological footprint differences among students triggered a scrutinization of the underlying reasons. It highlighted that means of transportation was a critical factor that had urban design implication as well as links to personnel choices; i.e. individual cars versus public transportation. Variation with world average triggered a discussion that identified contextual specificities such as the extreme hot climate and limited water, as specific regional influential factors. This very basic activity in this affluent context reflected primarily the risk of a lack of social and global awareness, as students evaluated their roles as individual consumers and future professionals with choices and decisions carrying social, economic and environmental consequences.

In another warm-up, activity students were given copies of a local daily newspaper spanning over a full week and were asked to identify topics that may be linked to climate change, global warming, urbanization and environmental impacts as well as any related mitigating initiatives. Then, a brief summary of one topic was shared with the class. The first agreed upon striking observation for all was the recurrent or daily related events from natural disasters such as flooding, hurricanes or drought and their consequences on vulnerable populations causing varying damages; to displacements, migration, starvation, diseases, deaths as well as negative impacts on loss of eco-systems, biodiversity or animal natural habitats were all recurrent topics. They also noted the large number of initiatives ranging from adhesion to international protocols, energy related events such as conferences, trade show exhibit and many local or regional initiatives to increase renewable energy usage. In brief, it carried a broader perspective on environmental risks, impacts and the need to adequately and urgently address them.

Another activity, designed as role-play scenarios, relied on critical inquisitive data mining that aimed to build a critical approach to first-hand data. In this exercise, the students were provided with a world atlas of pollution in the form of CO2 emissions by country for a given year (Figure 2). They were asked to review the data, discuss it in small groups, then through class debates, explain it and comment on the status, roles and responsibilities, with an underlying quest to identify the nation that is the most responsible factors for climate change as per its CO2 emissions.

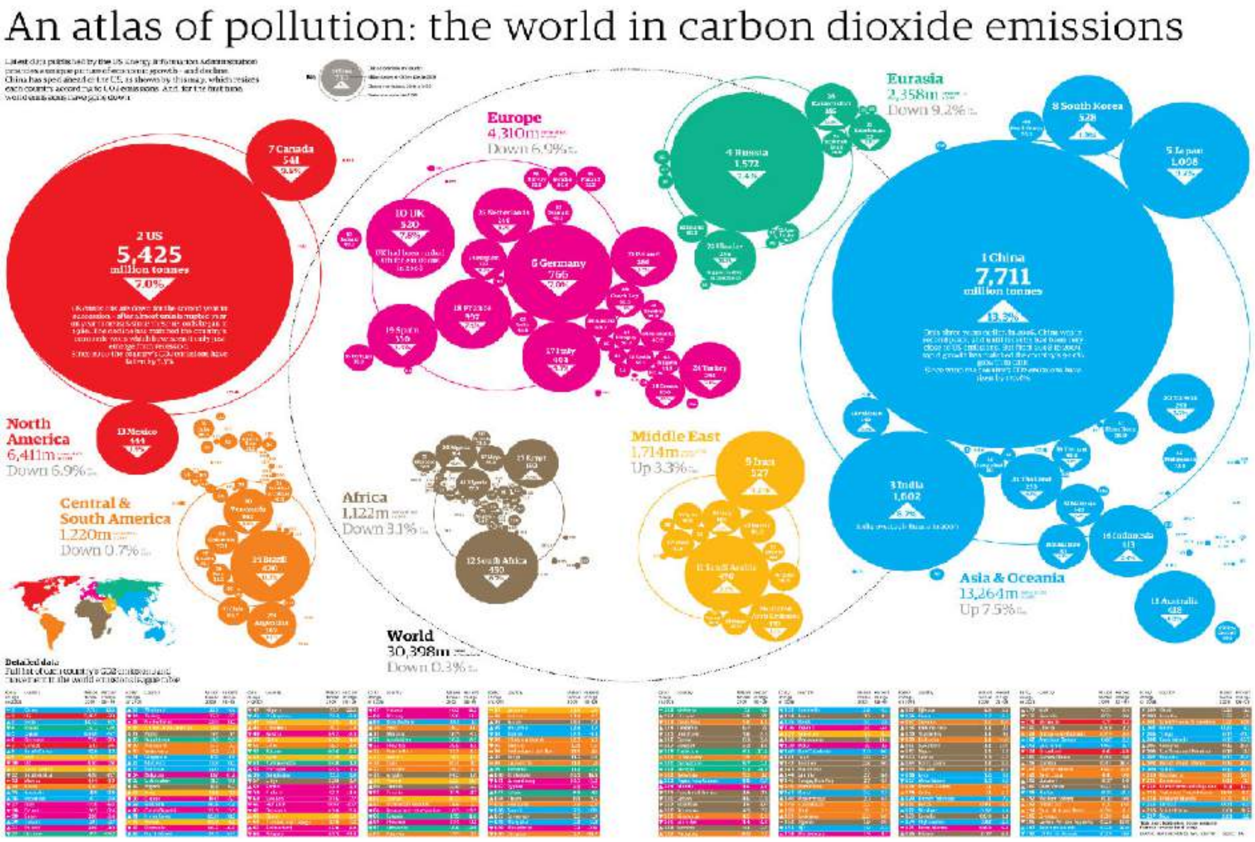

Figure 2: An atlas of pollution: the world in carbon dioxide emissions (The Guardian 2012)

The currently high emitting countries were quickly blamed for their extremely high emission and therefore their contribution to the detrimental global warming phenomenon. Next, the class was divided into 4 groups (3-4 students) each representing either the United States, China, Europe or the developing nations. They were asked to consider that they are delegates of these entities attending international climate summit where reduction on CO2 emissions will be imposed. Their role was to best defend the country's position regarding CO2 emission and reduction measures. Time was given to search and build the right arguments to defend their country's position prior to a general argument-presentation-debate. This activity resulted in an extremely engaged and lively debates that broaden their views to the concept of "climate justice" and equity. The notion of historical responsibilities and the right for growth and development were sustained with very creative arguments. They realized that all have a common goal but different responsibilities.

4.2 My home: Retrofitting potentials, households' behaviour and energy usage

The term project that spanned through the last four weeks of the course and was a group assignment. It aimed at exploring the energy and water savings opportunities in existing buildings for which their own home was the case study targeting its retrofitting to greener standards. The inquiry explored all parameters affecting energy and water usage in the home, including house design, materials, mechanical and lighting systems, landscaping and occupants' behaviour to energy and water usage (Figure 3). A qualitative assessment of all the building components affecting energy and water usage were thoroughly reviewed and alternate optimum scenarios were explored then assessed through simulation using eQuest software to evaluate the most cost effective solutions. Most students easily carried this section of the project as it builds on existing knowledge, covered in a number of the program courses.

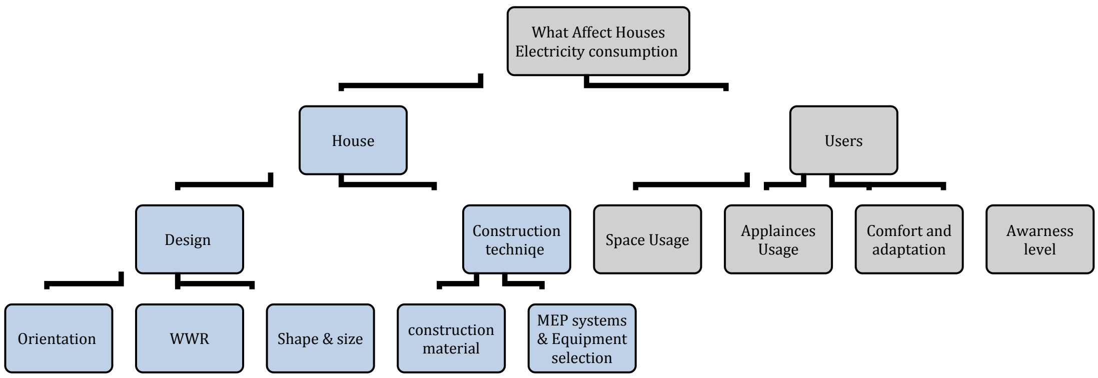

Figure 3: Factors influencing residential electricity consumption

Next, building occupants' behaviour relationship to energy usage was investigated through observations and interviews. The focus was on assessing occupants' pattern of space usage, their quest for thermal comfort and adaptation as well as their level of awareness regarding their own energy consumption. Most of the cases were nationals living in large detached villas (Figure 4), representing a residential segment that has been identified as using up to three times more energy compared to non-nationals (Figure 5). It should be noted that the UAEU, a federal university caters primarily to nationals on a free educational basis. Exemption and large subsidies may well be the underlying factor that called for exploration of the reasons behind such high-energy consumption.

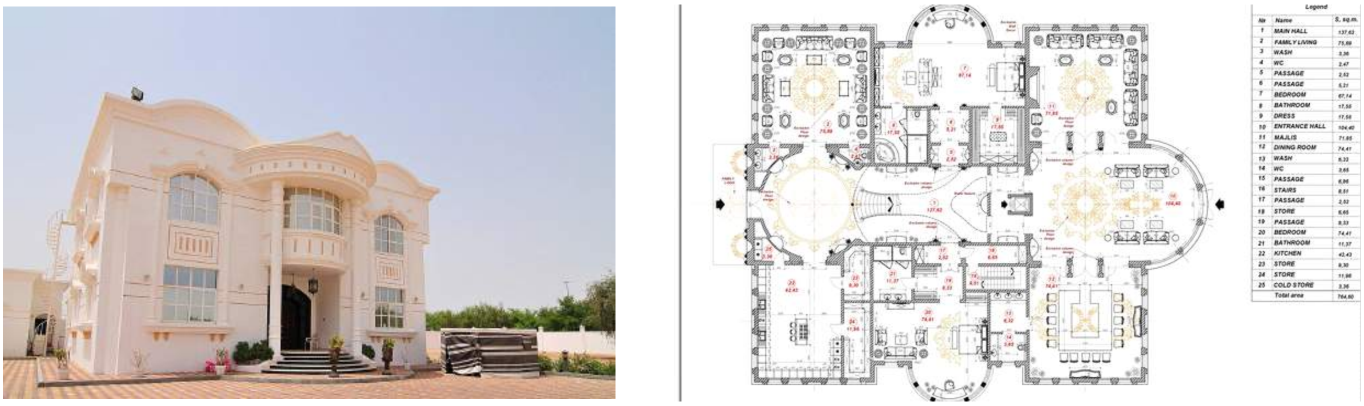

Figure 4: Views of some of the considered villas

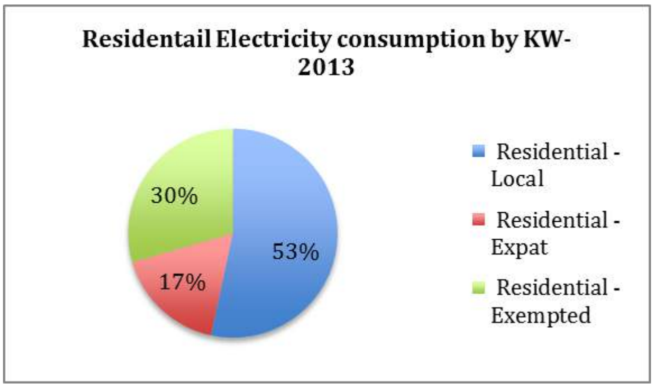

Figure 5: Al Ain city Residential Electricity Consumption national versus expatriate – (AADC, 2017)

An interview developed and piloted outside this course was given to students along training in conducting effective observations and interviews. The interview protocol covered first, an identification of the occupants in terms of numbers, gender, education level and yearly energy consumption (Table 1).

Table 1 General demographic, housing and energy information of the presented sample

	Home 1	Home 2	Home 3	Home 4
Habitable surface area (sqm)	646.9	666	838	1121
Number of occupants	11	9	9	15
Annual electricity consumption (kwh)	120,680.50	86,390	135,722.50	230,926
Ratio (kwh/sqm)	186.55	129.71	161.96	206
Ratio (kwh/person)	10,970.95	9,598.90	15,080.28	15,395.10
Ratio (sqm/person)	58	74	93	74

The main themes explored, in compliance with the identified impacting factors in the literature while taking into considerations specific contextual factors may be categorised into four areas: First, patterns of space usage were identified along energy usage practices including the use of appliances during occupation. Second, the quest for comfort and adaptation was explored, particularly how thermal comfort is achieved during the extremely hot summer period as well as in the milder short winter season. Third, space usage and the relation between space function and energy consumption was explored. Finally, awareness of energy usage, and house electricity consumption information were sought.

Observations of daily space usage was recorded over a week period. Interviews were carried mostly with the Mothers and took around 20 to 40 minutes to complete. The main outcomes as related to the themes explored can be summarized as follows: In terms of occupants' space usage, in all cases, occupants categorized their homes based on their daily usage and functional spaces. Daily gathering were in the living room while occasional ones and celebrations took place in the "*Majlis*" - a formal living area dedicated to guests. Absence or undefined living room resulted in family members using most of the spaces as living room as observed in Home 1 (H1) and Home 4 (H4). It was also noted that, for example, the absence of important functions such as study room, led occupants to use alternate spaces such as Al Majlis to fulfil their needs. The Majlis, a gathering designed space, may often be double or three times bigger than a regular study room size, such as in H1, H2 and H4 and will therefore be an energy intensive space for the given activity. Furthermore, considerations of the adequacy of house design highlighted mainly the oversized house intended for future use of an extended family, while currently accommodating a small family.

The quest of thermal comfort was always achieved through use of air conditioning of all spaces in over nine months of the year and sometimes year around out of habits as indicated by one respondent: "the children are used to the sound of AC as it helps them sleep". Another finding was of the omission to recourse to natural ventilation, even in the cooler season.

Awareness of energy usage and cost were in most cases, except in one, unknown to the mothers. Most of them, reported that the father usually pays the electricity bills, while family members were not aware of either consumption or cost. Educated mothers were aware of the government subsidies but were not aware of the percentage subsidised and were shocked to discover its extent. The energy conservation campaigns through television or phone messages went unnoticed and did not seem to have any impact.

Observations of space usage in relation to the house design triggered several critical observations as highlighted by one student's survey. This included, in some cases furniture layout blocking any daylight admission, resulting in artificial lighting used anytime of the day.

Although the outcome of the interview was not of a research level, it overwhelmingly triggered a comprehensive critical review of households' space usage, daily behaviour practices and more importantly, it highlighted the significance of lack of awareness.

5. Course Outcomes

The overall course outcomes are traditionally evaluated via direct and indirect assessments including students' opinions, exams and projects. In this regard, feedback on the knowledge acquired was taken periodically. However, the most prominent course learnings were assessed at the end of the term through the inclusion of a written question in the final exam as well as during the final oral exam. The written exam question required the students to "Comment on what they have learned in this course and how it may benefit their studies and/or professional work? While the final term oral discussion was mainly related to feedback on the critical review of their home performance.

Over ninety percent of the students' responses to the written question indicated that the most important learning outcome has been the increased awareness of environmental impacts and the need for a holistic approach to sustainability as expressed by one student: "*This course provides eye-opening knowledge about just how detrimental our lifestyle is both to ourselves and to our environment. Everything from the urban form to daily life of the individual has many issues that can be easily solved with a little awareness from all.".* It specifically highlighted the gap between the acquired technical knowledge and the wider causes and implications of choices as stated by another student *"Before this course, I was thinking that being sustainable means designing buildings that are efficient, operate with PV panels and reduce their energy consumption. While through the first part of the course, I realized that identifying the problem, causes and impacts will assist in finding the best solution…"* Similarly, another respondent mentioned, "*The course opened my eye to a lot of things, especially when we started with global issues of climate... I was shocked that all this is happening… I learned that there is a lot of things in the architects and urban planners' hands that will have far-reaching consequences..."* The impact of a raised awareness seems to have outweighed the remaining parts of the course as stated: *"The beginning of the course has been an eye opener in terms the impacts on the environment and the problems and challenges facing it".* Another student further stressed the gap between the needed basic knowledge expressing as *"I have calculated what an ecological footprint was and even calculated my own, which in turn had me change a few aspects of my life... I have also learned that there is an active form of duties that we have not been prepared for. I have realized that a lot of information learned here should be general knowledge for all but, people do not have any awareness about the issues which are not being taken very seriously…"* Additionally, a potential impact on future career choices where evidenced in a number of responses as indicated by one "*I would like to continue my studies towards sustainability and have a big change in my career, because the solutions are available we just need to be aware…It really opened my eye to a bigger perspective not just design and construction but also how our choices and decisions as individuals and professionals which will affect a bigger scale*..."

The discussion during the final term oral exam probed their learning out of the examination of their home design and occupants' behaviour. Most students rediscovered their home and were quite critical, while suggesting possible solutions. For example, the oversized house in relation to family size triggered thoughts and considerations of flexible and expandable design.

Although the outcomes of these exercises require further validation, the responses are an indicator of the gap between technical knowledge acquired and, in this context, the critical need to effectively reach out to embrace sustainable development. Beyond the inherent ambiguities involved in defining sustainability, there are calls to ensure that such initiatives are moving in the right direction. This leads to the question of "What is a more appropriate form of environmental education and research? We believe that it is the one which includes consideration of both human consciousness and political action and can, thus answer moral and social questions about educational programs which is the dominant form of research paradigm] cannot" (Robottom & Hart 1993).

6. Conclusion

This paper aims, first, to foster a wider debate on optimum ways to include sustainability in higher education in general and more specifically in the context of the Gulf region. The rapid changes that have taken place in the region shaped citizens beliefs and attitudes grounding them in luxury and consumer culture, part of a global culture of materialism that leaves little room for real ethical commitments to sustainable development. In this context, it questions outcomes of sustainable architectural education grounded mainly in technical knowledge, with a risk of limited real impacts, especially when policies and regulations are still under development.

This paper also provides a reflection on different pedagogical approaches aiming to explore key sustainable themes and reports students' own perception of the value of these activities. A selected sample of course activities that engaged students to inquisitively and critically assess the deeper and ramified amplifications of resources intensive choices ranging from lifestyle to urban planning decision, building design and material selection are presented. The outcome of the course, although covering various related topics, seems to have mainly contributed to raise awareness of the implications of these choices on the environment and natural resources. This raises the critical need to address the ethical commitments to sustainability in education on a contextual basis for a comprehensive impact. It highlights the need to go beyond curriculums orientation to explore different teaching approaches and strategies. It ultimately stresses the role of education to continuously challenge and critique value knowledge claims. Part of this challenge lies in engaging students in environmental, economic and socio-scientific arguments and calls for a critical review of how the sustainability concept is conveyed, as it requires its contextualization and consideration of conflicting values, beliefs, norms and interests.

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Envisioning a climate adaptation plan for the city of São Paulo: a starting-point framework

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Abstract: The world's cities are growing in size and number and the warming pattern has changed. Sao Paulo is the 5th biggest megacity in the world and the overtime data observation reveals a progressive temperature rising: from the measuring start in 1933, there was an increase in annual average temperature of 3ºC. Besides that, future climate scenarios point out an increase in discomfort hours. In this context, this work envisions a climate adaptation plan for Sao Paulo, as a starting-point framework, in three scales: 1) metropolitan scale, as a result of a local study of the impact of vegetation suppression in land surface temperature (MODIS); 2) local scale, including measured and simulated green infrastructure as well as the benefits of mutual shading of buildings, balancing urban density with climate amenities (ENVI-met); 3) building scale: future climate scenarios simulation including the new stock of residential multifamily buildings (TAS/EDSL). A radical change in building regulations must take place, including climate change considerations for the life span of buildings. The aim is to explore design-related adaptation measures and provide subsidies for public policies, establishing objectives, roles and actors, improving urban and building standards, progressively adding recommendations, incentives or requirements, besides monitoring and evaluating.

Keywords: climate adaptation, adaptation plan, urban regulation, urban design, building design

1. Introduction

The world's cities are growing in size and number; the global warming pattern has changed, also at the regional scale, including South America. In 2016 (UN, 2016), 54.5% of the world's population lived in urban settlements; there were 31 megacities globally and their number is projected to rise to 41 by 2030.

At the same time, the global climate change is a phenomenon of shift in global climate patterns, rising global average temperatures as well as increasing weather extreme events. The latest Intergovernmental Panel on Climate Change special report, *Global Warming of 1.5ºC* (IPCC, 2018), states that climate models project robust differences in regional climate characteristics between present-day and global warming of 1.5°C, and between 1.5°C and 2°C. These differences include increases in mean temperature in most land and ocean regions (high confidence), hot extremes in most inhabited regions (high confidence), heavy precipitation in several regions (medium confidence), and the probability of drought and precipitation deficits in some regions (medium confidence). Most adaptation needs will be lower for global warming of 1.5°C compared to 2°C (high confidence). There is a wide range of adaptation options that can reduce the risks of climate change (high confidence). There are limits to adaptation and adaptive capacity for some human and natural systems at global warming of 1.5°C, with associated losses (medium confidence). Pathways limiting global warming to 1.5°C with no or limited overshoot would require rapid and far-reaching transitions in energy, land, urban and infrastructure (including transport and buildings), and industrial systems (high confidence). These systems transitions are unprecedented in terms of scale, but not necessarily in terms of speed, and imply deep emissions reductions in all sectors, a wide portfolio of mitigation options and a significant upscaling of investments in those options (medium confidence). Limiting to 1,5ºC is not impossible, but requires unprecedented efforts in all sectors, with a whole mitigation portfolio for each one of the sectors; to achieve this, 2050 CO_2 emissions should be zero, but there are also residual emissions to be considered. Besides that, climate and Sustainable Development Goals - SDG are linked, and limiting to 1,5ºC helps to achieve other SDG. Adaptation options specific to national contexts, if carefully selected together with enabling conditions, will have benefits for sustainable development and poverty reduction with global warming of 1.5°C, although trade-offs are possible (high confidence).

According to the *WMO Provisional Statement on the State of the Global Climate in 2018* (WMO, 2018), the long-term warming trend has continued in 2018, with the average global temperature set to be the fourth highest on record. The 20 warmest years on record have been in the past 22 years, with the top four in the past four years. The global average temperature for the first ten months of the year was nearly 1°C above the pre-industrial baseline (1850-1900). Decadal predictions suggest an increasing risk of temporary exceedance of 1.5°C above preindustrial conditions. Although the Paris Agreement refers to a long-term exceedance of 1.5°C and not individual months or years, such short-term exceedances will become more common as the threshold is approached, highlighting the importance of closely monitoring the Paris Agreement targets. Large parts of Europe experienced exceptional heat and drought through the late spring and summer of 2018, leading to wildfires in Scandinavia. In July and August, there were numerous record high temperatures north of the Arctic Circle, and record long runs of warm temperatures, including 25 consecutive days above 25°C in Helsinki, Finland. Parts of Germany had a long spell of days above 30°C, whilst a heatwave in France was associated with a number of deaths. It was also an exceptionally warm and dry period in the United Kingdom and Ireland. A short but intense heatwave affected Spain and Portugal in early August. Other countries like UK, Swiss and Australia recently published updated reports showing their warming trends.

Continuing urbanization makes cities, in particular, also important foci of action for climate and health. The number of vulnerable people exposed to heat waves increased by 125 million between 2000 and 2016 especially due to cardiovascular diseases; over 70.000 deaths occurred over Europe in 2003. Many times individuals die before they reach health care, when illness is not sufficient severe to require hospital attention and that has not been captured by these studies (GHHIN, 2018). Heat goes unreported and underreported, as a silent killer (IAUC, 2018). The WHO COP24 special report, *Health and climate change* (WHO, 2018), documents projects on health and adaptation to climate change, from 2008 to the present; besides many plans in in Australia, US, Canada, India, none was registered in South America.

Currently, WMO community is enhancing the translation of science into Services, developing tailored climate services to reduce risks associated with climate change and increasingly extreme weather, established in the *Guide for Urban Integrated Hydro-Meteorological, Climate and Environmental Services. Part 1a: Concept and Methodology*. WMO is also working to develop integrated tools to monitor and manage greenhouse gas emissions and carbon sinks (WMO, 2018).

In urban areas, the land use and the heat residues emissions by mechanical systems are playing a more significant role in ongoing warming trends than greenhouse gas emissions (Stone, 2012). Heat islands in relatively hot climates or seasons can increase discomfort and potentially raise the threat of heat stress and mortality, and heighten the cost of air conditioning and the demand for energy (Stewart, Oke, 2012). In certain cities, there are thermal increases similar to the expected in the global scale for several decades (Grimmond, 2006).

Taking into account the climate scenario, for the urban scale the increase of urban vegetation cover is seen as a powerful strategy to cooling cities and save energy. Urban growth typically decreases space for green areas and urban environment creates obstacles to planting of new trees. These include soil compaction, lack of space for roots, overhead (and underground) provision of services and the lack of adequate management of trees. Consequences of neglecting green and water infrastructure - factors that modulate urban climate - are evident: recurrent and severe flooding, excessive heating of urban surfaces, low air quality and increase in urban heating, even daytime urban heat island in the tropics, among other factors (Emmanuel, 2005). The situation is worse in high-density cities, where land is scarce and there is little provision of space for the incorporation of urban greenery such as urban parks and landscaping. Land-use pressures and overheated property markets limit the potential for large-scale green infrastructure (Ong et al., 2012). The integration of greenery in buildings and dense urban spaces faces many constrains (CHEN, Y., WONG, N.H. 2006), in spite of some cases of success, such as Singapore, with the adoption of Green Plot Ratio by local legislation (Ong, 2002).

In addition, both global and local urban heating phenomena can potentially influence the thermal building performance. The associated urban heat island and the global warming increases the cities surface temperature, which is responsible for serious consequences in city energy, environmental and social balance (SANTAMOURIS, 2014), as well as human health and comfort.

Following the IPCC Cities (2018) statement, “the science we need for the cities we want”, better informed climate decision-making should be supported by scientific evidences, aligned with UN SDGs, including nature-based solutions - NBS and ecosystem services – ES; a new report from *The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services - IPBES*, called the IPCC for biodiversity, is to be launched in May 2019, the most important document in the field since the Millennium Ecosystem Assessment – MEA, from 2005.

2. Review of adaptation plans and other local initiatives

This topic provides a brief review of adaptation plans and related initiatives in different cities of the world.

Starting with the unique case of Germany, following almost one century of planning with climate, progressively incorporating climate change adaptation. According to a German Law, the *Federal Building Code* (chapter 1, General Urban Planning Legislation), air and climate has to be respected for any future development. Germany has also the VDI Guidelines, from the German Association of Engineers, stating how to deal with urban climate and urban planning scales.

In 2008 the Federal Government of Germany adopted the *German Strategy for Adaptation to Climate Change*. It lays the foundation for a medium-term process to progressively identify the effects of global climate change, assess the risks, and develop and implement adaptation measures, followed by the *Adaptation Action Plan* of the *German Adaptation Strategy*. The action plan commits to concrete steps in the further development and implementation of the adaptation strategy. It follows an integrated approach, which takes account of the interactions between sectoral and regional activities and strives to anchor consideration of the possible impacts of climate change in all relevant policies. Besides that, there are several sub-national Adaptation Strategies, which encompassed discussion of the policy processes to promote adaptation to the impacts of climate change and diverse research activities in Berlin, Hamburg, Hessen and many other cities.

Another relevant case is Australia, with recent guiding documents such as *Cooling Cities, Strategies and Technologies to Mitigate Urban Heat* (July 2017), giving emphasis on public spaces. The guideline addresses urban form, climate type and the nature of intervention, highlighting process (methods) and products (the design outcomes) for Brisbane, Sydney, Parramatta, Canberra, Melbourne, Hobart, Adelaide, Perth, Darwin and Cairns. The range of urban typologies include the dense inner city, middle ring and outer suburbs. The focus for design intervention include streetscapes, plazas, squares and malls. Urban surface properties, vegetation cover, shading and orientation are key variables. Interventions cover both active (e.g. misting systems and operable awnings) and passive systems (street trees, green roofs/walls, water bodies, cool roofs and façades).

Besides that, other documents such as *Cooling Western Sydney* (the role of water) the *Adaptation Plan for Melbourne* (2017, previous version 2009) and the initiatives in building codes are worth noticing, improving building standards, the places communication for the people and establishing roles and responsibilities of local government.

In Barcelona, Spain, the *Plan Clima 2018-2030* is very comprehensive, presenting how climate changes affect the city in different ways, presenting vulnerability analysis, showing differentiation among neighbourhoods and relating economic context to health issues.

In Paris, France, the existing *Paris Climate and Energy Action Plan* from 2007 was updated in 2012, promotes the growth of renewable energies; incentive new buildings which consume a maximum of 50 kWh/m²/year in primary energy (heating, hot water, lighting and ventilation consumption) and renovations of existing buildings so they do not exceed 80 kWh/m²/year. One of the most interesting topics is the combination of urban compactness (general FAR 3) with the creation of green spaces. More recently, the *Paris's adaptation strategy: towards a more resilient city* (2015) establishes 30 objectives applied in 35 concrete actions, highlighting the importance of information and maintenance of public services, especially during extreme events, for example, the Heatwave Plan that take action from June 1st to August 31st, following Paris local heatwave definition. The plan aims to facilitate access to cooling places, opening parks for 24h a day, creating temporary installation for shading or water amenities aiming mainly active mobility, with pathways linking urban oasis in the city.

The plan incentives standards for constructing buildings adapted to climate change; e.g., in thermal simulations of summer comfort, include a future climate scenario at +3°C to know which building measures to implement to limit interior temperatures higher than 28°C to no more than 50 hours per year ("Haute Qualité Environnementale" efficient level).

One of the objectives include recommendations for buildings and public spaces in urban regulations by progressively adding recommendations, incentives, or requirements to city regulations (city planning documents, construction specifications, etc.). The City of Paris has begun work to identify and remove these barriers where possible. For example, a "greening permit" was created in 2015 to facilitate residents' initiatives to add greenery to public spaces themselves or to remove barriers to installing shades and shutters in Paris, requiring exterior solar protections in public and residential building construction programs.

Finally, for Paris's social housing, there is already an obligation to add greenery to buildings in all new constructions.

In London, UK, *The London Plan*, 2016, includes the Chapter 5: London's response to Climate Change. The GLA developed with the Chartered Institute of Building Services Engineers (CIBSE) guidance for developers to address the risk of overheating in buildings. The guidance allows developers to take a risk-based approach to reducing overheating by providing different future hourly weather data to use in building simulation models. Besides that, the *Climate Change Adaptation by Design*, from TCPA – Town and Country Planning Association, has the aim to communicate the importance of adapting to some degree of inevitable climate change, and to show how adaptation can be integrated into the planning, design and development of new and existing communities.

In the United States, the most significant are the subnational initiatives, in spite of federal government; 20 US states plus Puerto Rico, 135 cities, and 4 counties have been aligned with Paris goals. This group includes states who are members of the *Under2 Memorandum of Understanding* (MOU) and/or the *United States Climate Alliance*, as well as states with official greenhouse gas reduction targets that were at least 85% as strong as the US climate pledge.

New York launches the plan *A stronger, more resilient New York* and the *Rebuild by Design competition – NY,* launched by the U.S. Department of Housing and Urban Development (HUD) in partnership with non-profits and the philanthropic sector, in response to Hurricane Sandy's devastating impact on the eastern U.S. The premise was simple: raise the bar for response, preparedness, and resilience. Driven by innovation and collaboration, the competition became a model to help governments create research-based, collaborative processes that prepare communities and regions for future challenges.

In Brazil, there is an intent of a national adaptation plan, very rough until now, especially regarding cities. In much more detail, there is one plan regarding adaptation strategies for Brazilian coastal cities, detailing adaptation proposals especially the city of Santos, near Sao Paulo, quantifying the impacts of sea-level rise with local data registered since 1945, including also socioeconomic variables (PBMC, 2016).

Regarding the Brazilian context, after 2015, political and economic crises arose. Severe cuts were made in science agencies. Since January 2019, when the new federal government took office, the climate section was eliminated from both the Ministry of the Environment and the Ministry of Foreign Affairs. The government has dismantled several divisions dedicated to climate change and decided to back out of Brazil's offer to host the 25th Conference of the Parties, the United Nation's 2019 climate change conference, which will now be held in Chile in November. The word "climate" has disappeared from the Ministry of Foreign Affairs' administrative structure. Brazil is now threatening to leave the United Nations Paris Agreement, rather than to continue its global leadership role in addressing climate change. Science and its role in policy-making must be strengthened, not reduced and Brazil must keep environmental conservation and sustainability as priorities if it wants solutions that benefit its people (Artaxo, 2019; Escobar, 2019).

3. Sao Paulo Case Study

3.1. Sao Paulo urban and climate context

São Paulo is a sprawling megacity with 39 municipalities. It is the 5th urbanized region in the world with more than 21 million inhabitants, the biggest Latin-American megacity (UN, 2016). Sao Paulo is located at 46.6ºW longitude and 23.5ºS latitude, characterized by a subtropical climate, with mild temperatures, hot and wet summers and milder and drier winters. The overtime data observation reveals a progressive temperature rising: from the measuring start in 1933 there was an increase in annual average temperature of 3ºC. Besides that, future climate scenarios point out an increase in discomfort hours in open spaces and buildings.

Recent studies alert for the increased frequency of extreme events in the city such as heat waves (Batista et al., 2014; Nobre et al., 2010; Marengo, 2006). The overtime data observation reveals the progressive temperature rising: from the measuring start in 1933 there was an increase in annual average temperature of approximately 3ºC and respective relative humidity reduction. There were heat wave events in January and February during the years 2014 and 2015, being the absolute maximum 37,2ºC occurred in October 2014 (IAG, 2017).

In 2016, excepting June, all other months presented monthly average higher than the Normals (1933-1960, 1961-1990) and the climatological mean (1933-2016) since measurements began in the city at the IAG/USP Meteorological Station. In 2016, there were 100 days with temperatures higher than 30ºC (the average is 49 days). In 2015, there were 86 days and in 2014, there were 109 days, being this the warmest year since 1933. Concerning the minimum temperature, in 2017 average values for all months were above the climatological mean (1933-2016) (IAG, 2017).

Sao Paulo is characterised by a heterogeneous urban structure, caused by the rapid growth of the city during the 20th century. High-rises are found everywhere in the city and contrasts with poor informal settlements, spread all over the metropolitan area. In Sao Paulo deforestation has occurred since the early stages of urban development due to illegal and legal allotments, however no updated official monitoring is available. The lack of information about the vegetation dynamics in SPMR can be related both with technical restrictions and with suspicious political and economic interests (Ferreira, 2015).

Besides the urban scale, the Brazilian Panel on Climate Change - PBMC states that the building sector is increasing its energy consumption both in Brazil and all around the world (PBMC, 2016) so that they can respond for a significant carbon dioxide emission share.

According to data from the Brazilian Energy Research Company, energy consumption in buildings is responsible for a significant portion of the energy generated in Brazil: approximately 14% of total energy consumption and 47% of electricity consumption (Brasil, 2014). In the global scenario, buildings account for about 32% of global energy demand from a variety of sources, which has motivated cities worldwide to adopt more rigorous urban and building regulations, as well as more efficient energy consumption policies. In Brazil, unlike countries in higher latitudes, the cooling demand is significantly higher than the heating one, and the energy consumption for air conditioning accounts for approximately 20% of the total in residential buildings and 47% in commercial buildings.

During the heatwave events, the energy demand tends to be even greater. An example is the heatwave that took place in São Paulo in January and February 2014, when there was a 4.9% energy consumption increase during January and 8.6% during February, if compared to the same months in 2013. Great part of it was due to the intensification of the air conditioning use in that period, especially by the residential sector (BRASIL, 2014). Once installed, the equipment will be used whenever there is a temperature increase (Wu et al. 2006), which means that consumption patterns probably will not return to what they used to be previously.

It was verified that, for the São Paulo weather conditions, residential buildings that use traditional construction systems and were built around the 1970's tend to respond reasonably well to the current and projected future climate changes, operating in passive mode and keeping most of the year under comfortable conditions, according to the ASHRAE 55: 2017 (ASHRAE, 2017) adaptive comfort model. The gradual increase of hours in warmer conditions, out of the comfort zone, and the discomfort intensity can be considered unavoidable and it was simulated around 270% discomfort increase in the housing units studied, highlighting the summer period and the heat waves (Alves et al., 2016).

In addition to the traditional residential buildings, there is a large stock of new residential ones in São Paulo, especially built from 2007 to 2014 due to a real estate market boom in the city. Being driven by market issues, the real estate production is remarked by the distance between professional practice and architecture research and it over values the aesthetic while other issues, as functionality and performance, do not play such an important role. Glass façades, less thermal mass and poor natural ventilation design reached wealthy and fancy high-rise residential buildings, which are followed by middle-class buildings, and are spreading very fast.

The city of Sao Paulo has in force three laws for its urban planning and development: The Master Plan (2014), the Zoning Law (2016) and the Building Code (2017) (PMSP, 2019). As recently updated texts, it was expected that they could express the integration of its contents pointing at contemporary urban issues such as managing energy efficiency and providing buildings with quality and comfort to the users. What happens instead are several mismatches between their contents. On the opposite of the worldwide trend, São Paulo city laws have been losing, over the last century and in the update process, almost all the performance construction requirements, which influence the environmental quality of buildings (TSUDA et al., 2018).

4. Methods

In this context, this work envisions a climate adaptation plan for Sao Paulo, initially developed as a starting-point framework, in three scales: metropolitan scale, local scale and building scale.

4.1. Metropolitan scale

Regarding the metropolitan scale, there are already previous results of the impact of the presence of vegetation and its suppression in land surface temperature (LST) in temporal and spatial scales, using the satellite/sensor Aqua-MODIS (passing around 1 p.m. and 1 a.m.), exploring daytime and nighttime effects (FERREIRA, DUARTE, 2018; 2019). Spatial results show LST differences as a function of the presence and type of vegetation at the same time, and temporal results show differences of vegetation suppression from 2002-2017. New developments aiming the adaptation plan could include:

a) besides Aqua-Modis, doing the same readings with Terra-Modis (passing around 10 a.m. and 10 p.m.), one could analyse urban heating/heat release between 10 a.m. and 1 p.m. and between 10 p.m. and 1 p.m., detailing more the urban morphology relations with urban heating phenomena.

b) map priorities for planting trees as a function of surface temperature;

c) adding meteorological simulation of air temperature (u-WRF), current and future climate scenarios could be explored showing the urgency of the proposed measures;

d) adding landscape architecture, planting strategies could be simulated and evaluated (ENVI-met);

e) with LCZ mapping (FERREIRA *et al*., 2017) it is also feasible to explore urban morphology, generating results also for the local scale.

4.2. Local scale

The plan should include the locally measured and simulated green infrastructure, but as greening is not the only answer, benefits of mutual shading of buildings and thermal mass of the built environment will be explored, balancing urban density with climate amenities, in modelling studies using ENVI-met (SHINZATO et al., 2019; GUSSON et al., 2018; SILVA et al. 2018).

Observed data in ongoing studies revels the coexistence of urban nighttime heat island and the urban daytime cool island. Urban morphology plays a dominant role in controlling the co-existence of the UHI and UCI phenomena and urban morphology may be used to control the urban air temperature. When anthropogenic heat is small, a high-rise and high-density city experiences a significant daytime UCI effect; therefore, UCI degree-hours and UHI degree-hours are useful quantification index for urban/rural temperature differences.

4.3. Building scale

After periods of low economic growth in Brazil, which characterized the 1980s and part of the 1990s, economic stability and the rise in average family income created the conditions to supply part of a suppressed demand for thermal comfort, as expressed by the increase of electricity consumption due to the use of air conditioners in the country. The energy consumption for thermal comfort is the fastest growing end-use in Brazil. Considering only the residential sector, the ownership of air conditioners more than doubled from 2005 and 2017, and the demand are expected to increase in a near future. The estimated electricity consumption for air conditioners in the residential sector has more than tripled in the last 12 years.

Future climate scenarios point out an increase in discomfort hours inside buildings (ALVES et al. 2016), including the new stock of residential multifamily buildings, currently under evaluation with TAS/EDSL model. To counteract this, a radical change in building regulations must take place, from the current mere bureaucratic building code towards a design-related environmental driven one, including climate change considerations for the life span of buildings (TSUDA et al, 2018).

5. Final Considerations

Many mitigation measures are well-known and established by local and national governments around the world; on the other hand, adaptation plans with concrete measures are still very few. In spite of the superficial commitment of some federal governments, like ours, science has to work to mobilize subnational levels, with scientists examining the laws, going out of the labs, understand laws, society, finances, etc., putting side by side science and politics. City mayors and other subnational authorities are critical actors in reducing carbon emissions, improve health and increase resilience, as well as to encompass and put in practice (and in force) adaptation plans.

The adaptation plan team must be interdisciplinary (DUARTE et al. 2018). Besides architects, planners, engineers, environmental managers, meteorologists, the team should include social scientists, political scientists, graphic designers (to communicate science for the population, helping visualizing data, transforming numbers in images, infographics) and also lawyers (e.g., in the case of Brazil, to find ways of giving more autonomy to local levels for adaptation measures' implementation, sometimes reacting to the federal government decision).

Adaptation and implementation science is to be developed in a more consistent way. In average, it takes 15 to 20 years until the investment adopted in research is translated into public policies based on evidences. There is an initial local body of knowledge to be implemented, and recent registered climate and energy data tell us there is no more time to start acting.

To conclude, following the IPCC Cities (2018) statement, *"the science we need for the cities we want"*, better informed climate decision-making should be supported by scientific evidences. Regarding the built environment, propositions of design-related adaptation plans have an opportunity to follow the AR6 cycle, aiming the AR7 cycle Special Report on Cities, included in the IPCC agenda for the next years. The focus should be on putting together the cities densification side by side with urban amenities (DUARTE et al., 2016), aligned with UN SDGs, including nature-based solutions - NBS and ecosystem services – ES targeting a more balanced urban ecosystem for the current and future climate.

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Energy & Thermal Comfort Performance Evaluation of Net Zero Energy Building in Hot Dry Climate – A case study

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Abstract:
The paper presents the case study of a Net-Zero Energy Building (NZEB) located within the CEPT University campus, Ahmedabad. It starts with a narration on design and construction and provides an overview of the building envelope characteristics and operational strategies. Custom design and operation of the building management system (BMS) in order to synchronize the electrical consumption and generation using solar PV is described. The paper analyses the energy consumption and generation in NZEB during 24 months of operation (Jan-2017 to Dec-2018). Hourly end use energy consumption and generation data were analyzed to understand the performance of the envelope and electro-mechanical systems. Along with energy consumption analysis, the paper also includes the study of occupant comfort. The occupant comfort data was correlated with the hourly outdoor weather data collected using an automated weather station installed at the NZEB. This paper is an attempt to share the learnings in regard to the design, construction, operation, and maintenance of the NZEB in India.

Keywords: NZEB, Tropical, Thermal Comfort, Environment Monitoring, Building Management System

1. Introduction

India has pledged to increase the energy efficiency of its buildings in India's nationally determined contributions (NDC) submitted to the United Nations Framework Convention on Climate Change (UNFCC). Design and operation of Net Zero Energy Buildings (NZEB) is one of the most effective ways of meeting India's commitments. USAID ECOIII project (Kapoor et al., 2011) identified the barriers on the path of NZEB in India. The key barriers were: limited awareness, nonexistence of policy and programs, lack of market for NZEB, and a high cost of energy efficient (EE) and renewable energy (RE) technologies. USAID PACE – D TA program (PACE-D Technical Assistance Program, 2012) promoted NZEB in India with the formation of an alliance called The NZEBs Alliance. One of the objectives of this alliance was to initiate innovation and research in India to advance the design, construction, and operation practices for NZEB. It identified seven NZEBs in India with insight into each of the projects. One of the NZEB demonstration projects *'Prana'* successfully created awareness about NZEB (Devraj et al., 2018). A study in the context of NZEBs in New Delhi revealed that the relevant constituents for NZEB niche development are present, what lacks is the motivation (Jain et al., 2017). The same study concluded that the policy instruments and strategies for EE and RE are also present but are not integrated as a part of a holistic program. IEA Joint SHC task 40 and Annex 52 extensively documented the various aspects of NZEBs - it documented NZEBs and developed solution tools and guidelines in alignment with building use type and climate context. (Garde and Donn, 2014)

2. Net Zero Energy Building at CEPT University - A case study

CEPT University, Ahmedabad envisaged the construction of NZEB on its campus primarily to house research and development activities of the Centre for Advanced Research in Building Science and Energy (CARBSE). The belief that educating professionals requires practising professionals and academicians to work closely together, firmly underpins CEPT University's pedagogic philosophy. The NZEB site is within the academic and research environment of CEPT University campus, hence it was imperative to demonstrate the design and practice of sustainably built habitat while simultaneously inspiring the next generation of building professionals. The project emphasizes on the creation and dissemination of knowledge pertaining to the fields of energy efficiency and sustainable built environment. The design intent of the NZEB at CEPT was to create varied visual, thermal, and physiological experiences with an objective to sensitize occupants and visitors about the importance of energy efficiency and thermal comfort. It also offers an opportunity to evaluate passive design strategies, active design strategies, and a harmonious combination of these strategies to achieve the targeted comfort levels. This building is designed envisaging it to act as a living laboratory for widening the horizons of building energy performance.

The proponents of the project adopted an integrated design process to demonstrate the symbiotic relationship between architecture, interior architecture, structure, and services.

3. Design process approach

The design phase of the building was laid out to follow an integrated design approach with the support of an integrated team process. A team of international and local experts, owner, building contractor, and probable operators of the building worked together during the design phase. Three design charrettes were conducted involving all the stakeholders. During these design charrettes, the team aimed to evaluate the design for cost, quality-of-life, future flexibility, energy efficiency, overall environmental impact, productivity, creativity, and the ability of the occupants to feel enlivened. Each charrette was conducted over two to three days and was followed by series of online meetings. A total of about 30 such online meetings were conducted over 12 months. An iterative process and exchange of ideas between the master architect, design team, construction team, commissioning team, consultants, with the equipment and material suppliers in tandem, led to the evolution of the building design. Most of the consultants and equipment supplier remained involved in the project even after construction to understand performance of the design.

The design of the comfort systems and energy monitoring systems for the building formed an important demonstration of the collaboration between the academia and the industry, which is not a usual practice in India. The iterative and sequential design process included the following stages of analysis:

(i) Predesign: climate analysis, technical potential energy analysis, site analysis, mutual shading from trees and surrounding buildings
(ii) Conceptual design: passive thermal comfort analysis, building massing/orientation energy analysis, Heating, Ventilation and Air Conditioning (HVAC) system energy and life-cycle analysis
(iii) System development: building envelope optimization, windows design, fenestration shading, daylighting analysis, active system thermal comfort analysis, HVAC sizing and capacity optimization analysis, natural ventilation scheduling, CFD analysis for thermal comfort, renewable energy sources identification, and optimizing energy generation system

(iv) Systems optimization: individual energy conservation measures (ECM) energy analysis, bundled ECM energy analysis.

During the predesign stage, climate analysis was carried out. Additionally, site context analysis was done to account for mutual shading from surrounding buildings/trees. In the same context, the technical potential of various design strategies was studied. The team also acquired energy consumption data of surrounding buildings of similar nature to arrive at a target of yearly energy consumption of NZEB. While arriving at targeted energy consumption, as shown in Figure 1, energy generation potential using Solar PV panels was also considered. This helped the design team to explore various passive and active design strategies while helping downsize the energy demand of the proposed building.

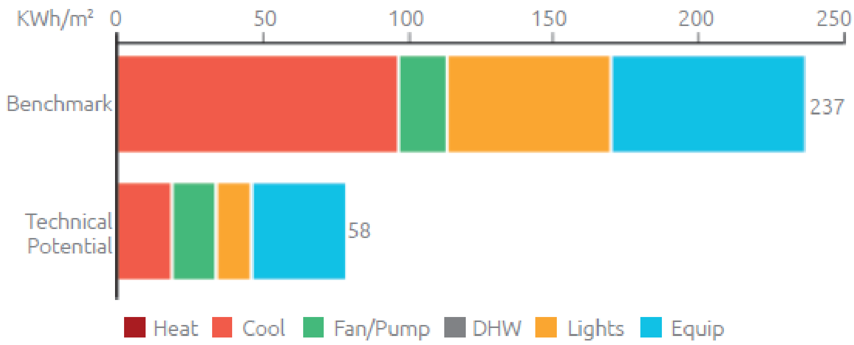

Figure 1. Predesign energy analysis of a benchmark building and technical potential of readily available technologies and design approaches

Ahmedabad has a hot semi-arid climate (Köppen climate classification BSh). There are three main seasons: summer, monsoon, and winter. Apart from the monsoon, the climate remains dry. As shown in Figure 2, the weather is hot throughout the months of March to June - the average summer maximum and minimum temperatures are 43°C and 23°C respectively. From November to February, the average maximum and minimum temperatures are 27°C and 15°C respectively, with an extremely dry climate. Cold northerly winds are responsible for a mild chill in January. The southwest monsoon brings a humid climate from mid-June to mid-September. The average annual rainfall is about 76.0 cm (36.7 inches), but infrequent heavy torrential rains cause the local river Sabarmati to flood. (Vaidya et al., 2015)

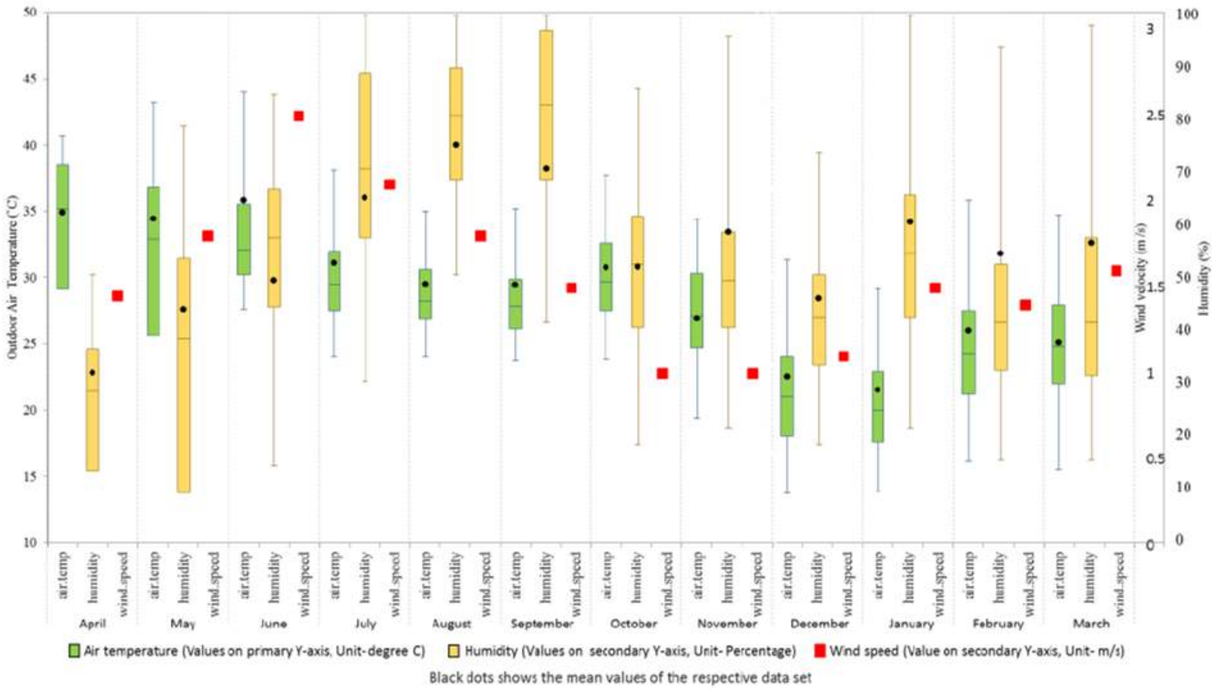

Figure 2. Monthly temperature, relative humidity and wind speed from the weather station at CEPT University campus in Ahmedabad (April 2014 – March 2015)

4. Design description

The final design of the NZEB offers distinct spaces for various functions. The basement houses ‘Thermal Comfort Chamber’ and a seminar room. Two sunken courtyards deliver daylight and ventilation while acting as spill out spaces. South-facing monitor brings daylight inside the seminar room. The basement floor is served by radiant cooling and a dedicated outdoor air system (DOAS). The ground floor accommodates a multipurpose, naturally ventilated space. It also accommodates the HVAC System equipment, electrical panels, and ancillary service equipment. The first and second (mezzanine) floors house the research equipment, working desk spaces, and the Building Management System (BMS). These two floors can be operated in multiple operation modes: (1) Natural ventilation mode (2) Controlled ventilation using the mechanical system – when windows are closed, while mechanical air inlet and exhaust fans are on (3) Active cooling using radiant cooling system and mechanical air management system for fresh air (4) Radiant cooling system with variable refrigerant flow-based cooling. Due to the variety of operation modes, it can be categorized as a ‘mixed-mode’ space.

As shown in Figure 3, the design of NZEB has a 3:1 length to width ratio, with the building’s longer axis oriented from east to west. Fenestration is provided on North and South orientation with appropriate shading to reduce solar heat gain. South facing sloping roof with operable clerestory windows at the top helps in creating stack ventilation as well as providing an appropriate surface to install Solar PV panels. 40% of the conditioned area is below ground level, which reduces the heat gain. Figure 4 shows the indoor and outdoor view of the NZEB.

Figure 3. NZEB floor plans and sections

Figure 4. NZEB outdoor and indoor view.

4.1 Building Envelope Characteristics

The entire envelope including wall, roof, floor, and fenestration has been designed to reduce the heat gains. As shown in Figure 5, the wall assembly with exterior insulation (50mm XPS with U-value of 0.42 W/m^2K) and high thermal mass on the interior (230mm brick wall) provides a near-stable air temperature. Roof assembly with 45mm thick spray foam insulation (U-value of 0.38 W/m^2K) and high SRI cool roof paint (SRI of 103) helps reduce the impact of solar gains. Solar PV panels installed on the inverted beam of sloping roof shields the roof surface from the incident solar radiation. The large cavity between the roof and the solar panels provides efficient heat dissipation. Windows have a uPVC frame and a double-glazed unit (DGU) with low-e glass. Visible Light Transmittance (VLT) of the windows is 39% with Solar Heat Gain Coefficient (SHGC) of 0.29 and U value of 1.8 W/m^{2}K.

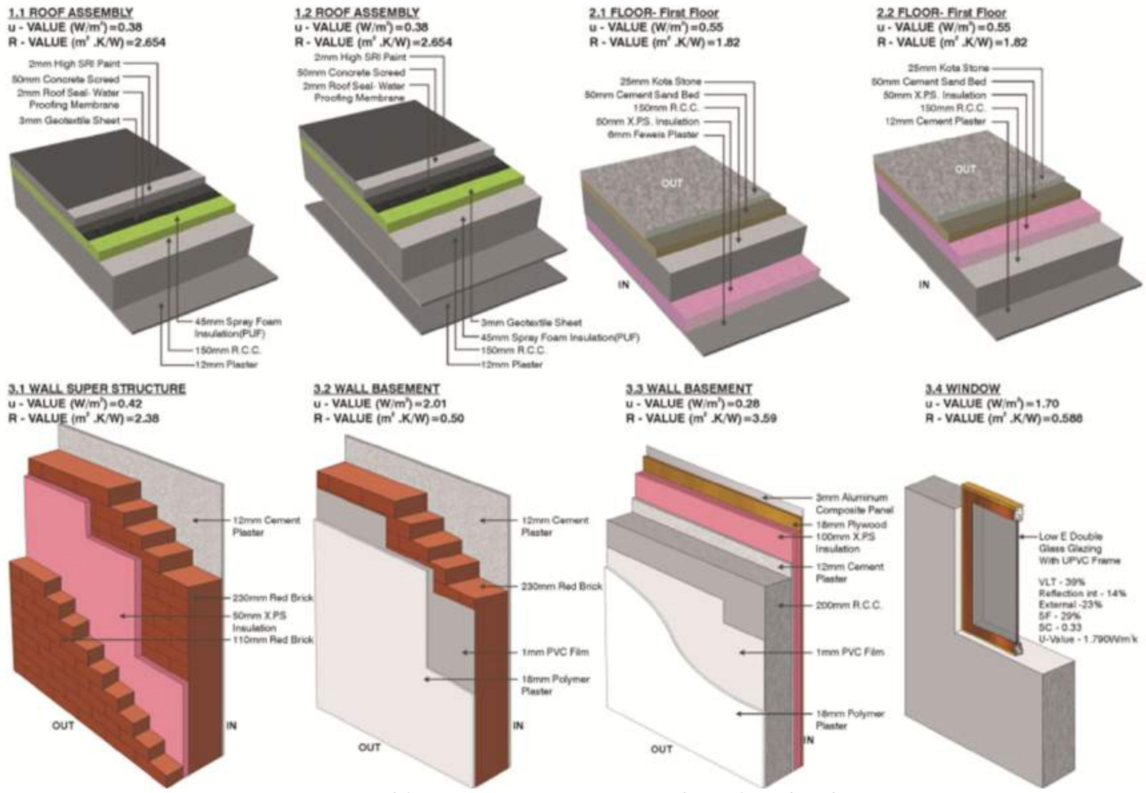

Figure 5. Building Construction Materials and Technologies

4.2 Lighting System Characteristics

The NZEB is designed to maximize daylight inside the building throughout the day/year to ensure minimal dependence on artificial lighting. All lighting fixtures are energy efficient LEDs. Artificial lighting strategy is a combination of ambient and task lighting to provide the required illuminance for all the spaces. Task lights have capabilities for continuous dimming (10-100%) as well as the change in color temperature of light – this gives excellent control to the users to personalize the lighting condition as well as to save electricity. Total connected lighting load of the building is approximately 2200 W (2.7W/m²).

4.3 Air conditioning System Characteristics

The Basement, First, and Second Floor of NZEB are conditioned by radiant ceiling panels installed in the suspended ceiling. Panels of 1200mmx600mm and 600mmx600mm size are made from natural expanded graphite with embedded water pipes. Two variants of the panels have been installed with copper pipe, and polyethylene (PEX) pipes each. High-efficiency air cooled scroll chiller with cooling capacity of 8.2 TR supplies chilled water to the radiant system using a pump with variable speed drive.

A total of eight variable refrigerant flow (VRF) indoor, floor mounted, and wall mounted units have been installed on the first and second floor of the building. These units are served by an 8 TR outdoor unit with coefficient of performance (COP) of 3.8, 4.52, and 6.1 at 100%, 80%, and 50% capacity respectively. This is a supplementary system and is in operation during heavy latent load scenario or heavy internal heat load generation scenario, such as research equipment operation.

The NZEB has silent and high-efficiency fans to supply fresh air as well as to exhaust air for the first and second floor. The fans are positioned to create an artificial draft in the building to be operated in the night ventilation mode or controlled ventilation mode. In addition to these systems, the building incorporates a dedicated outdoor air system (DOAS) system. The DOAS supplements radiant cooling system in the basement for bringing conditioned fresh air during instances of peak cooling period and high latent loads. DOAS has the capacity to recirculate return air and contains variable speed fans, modulating dampers, and airflow stations for accurate control. It supplies $50m^3$/min of airflow and is connected with the supplemental air-conditioning system of Digital Scroll, which measures the heating and cooling capacity for treating the supply air. The Digital Scroll system has a cooling Energy Efficiency Ratio (EER) of 3.89 and COP of 4.1.

4.4 Solar PV System Characteristics

Solar PV system of 30kWp capacity is installed on the south facing sloping roof. It is installed in two parts of 12kWp and 18kWp. Each polycrystalline PV panel of 1975mmx990mm has a rated capacity of 300Wp. The system is connected to the internal grid of CEPT University campus. The system is connected with BMS for data collection and monitoring the performance.

4.5 Electrical and Building Management System Characteristics

The Electrical system is divided into five separate circuits for lighting, HVAC, plug loads, equipment loads, and solar panels, with separate wiring lines for each to allow individual monitoring of each of the components. The research equipment with a higher electrical load in comparison to conventional office-equipment were connected with a 5-ampere plug and a separate circuit. For analysis, all equipment consumption except the loads for Thermal Comfort Chamber (TCC) have been considered a part of space consumption. This system enables efficient sub-metering using smart energy meters with RS485 communication facility for integration with BMS. All plug loads in NZEB are monitored using Smart Power Strips, which provide information for device IDs, usage time, and electricity consumed for each equipment on the desk.

The building incorporates an array of high accuracy sensors and controls for research level of monitoring. It also provides sophistication and flexibility in controlling the systems for conducting various research experiments on building performance optimization. The building is operated in either naturally ventilated mode or air-conditioned mode based on current outdoor weather conditions as well as indoor comfort conditions. In the natural ventilation mode, the active air-conditioning system is to be turned off and all the windows including chimney windows are to be opened to allow the draft to naturally cool the building. When the indoor comfort conditions do not meet the comfort conditions for a specified period, the building is switched to air-conditioned mode. The building operators have the ability to configure various indoor comfort condition algorithms (such as custom adaptive comfort equation or PMV-based algorithm) in the building control system to determine suitable indoor comfort conditions.

In the air-conditioned mode, the primary system (active radiant system) is to be turned on first to maintain indoor thermal comfort conditions. If the primary cooling system is unable to meet the comfort conditions, secondary cooling system (VRV on the first/second floor and DOAS in the basement) is turned on to maintain comfort conditions in the zone. The building incorporates demand-based ventilation controls where fresh air supply is modulated to maintain the appropriate CO_2 level in the zone. All the major HVAC equipment have built-in controllers with a networking capability (Ethernet port) for continuous monitoring and control of the equipment through the BMS network. These networked built-in controllers provide very detailed information on equipment operation, which helps in customizing algorithms to optimize the equipment performance.

Figure 6 shows the conceptual layout of the monitoring and control systems in the building, while Figure 7 shows a screenshot of the BMS.

Monitoring	Integration	Controls	Display
Envelope	Chiller	HVAC	Operation
Environment	HVAC	Lighting	Comfort
Energy	VFD	Plug load	Consumption
Behavior	Photovoltaic	Photovoltaic	Generation
Outdoor		Operation	Historical

Figure 6. Conceptual diagram of the monitoring and control systems

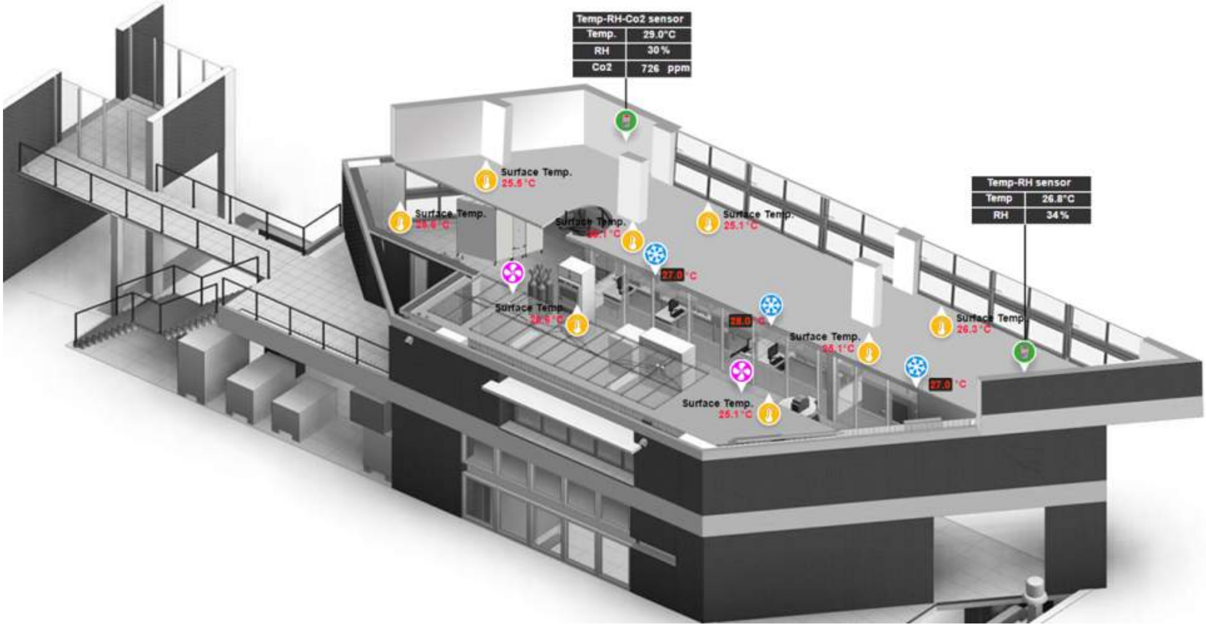

Figure 7. Screenshot of the Building Management System (BMS)

5. Details about monitoring strategies

The NZEB incorporates a three-pronged monitoring approach through (a) environment monitoring, (b) energy monitoring, and (c) thermal comfort monitoring.

5.1 Environment Monitoring

Indoor environment monitoring is carried out using standalone and/or networked sensors and loggers as shown in Figure 8. Parameters such as indoor air temperature, relative humidity, lux level, globe temperature, indoor surface temperatures at strategic positions, and outdoor environmental variables are measured at one-hour intervals. Approximately 50 sensors attached with the logging system comprise of a range of nodes and sensors such as HOBO® data nodes with devices like HOBO® ZW-006, ZW-007, and HOBO U12-12 for the indoor variables. HOBO RX3000 Automatic Weather Station (Onset RX Weather Station, no date) is used for measuring the outdoor variables.

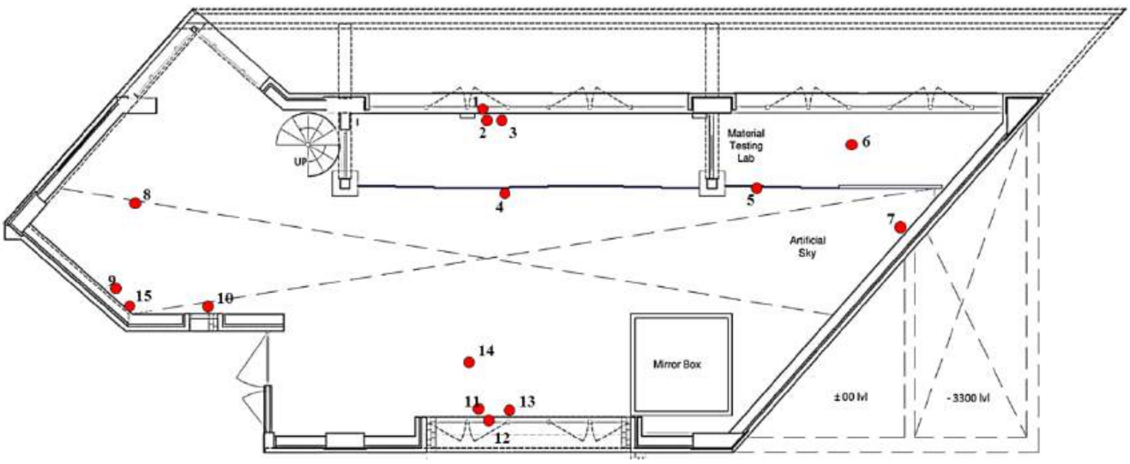

Figure 8. Sensor locations drawing of the first floor

Table 1 provides details of the sensors position and the environmental variables that were measured.

Table 1. Sensor location details

Sensor number	Parameters	Indoor/ Outdoor	Location	Height (mm)	Logger type
1	Surface Temperature	outdoor	Thermal constant analyzer window	1700	HOBO ZW
2	Surface Temperature	indoor	Thermal constant analyzer window	1700	
3	Air Temperature and Relative Humidity	indoor	Thermal constant analyzer window	1500	
4	Air Temperature	indoor	Outside thermal constant analyzer door	2200	
5	Air Temperature	indoor	Outside equipment chamber door	2200	
6	Air Temperature	indoor	Inside equipment chamber near pressure plate	2450	
7	Surface Temperature	indoor	East wall	1800	
8	Air Temperature	indoor	Above guarded hot box	2300	

9	Surface Temperature	indoor	West wall	2050	
10	Air Temperature and Relative Humidity	indoor	Near entry	2800	
11	Surface Temperature	indoor	Work station 5 window	1560	
12	Surface Temperature	outdoor	Work station 5 window	1560	
13	Air Temperature and Relative Humidity	indoor	Near work station 5 window	1580	
14	Air Temperature Relative Humidity Globe Temperature	indoor	Near work station 5	1000	U12-12
15	Air Temperature Relative Humidity Globe Temperature	indoor	Near work station 6	1000	

5.2 Energy Monitoring

The building energy monitoring and control system contains a three-tiered architecture with the tiers of (a) field space, (b) network communication, and (c) station level management tier, as shown in Figure 9.

The field space tier consists of various measurement devices. The BMS controller collects the energy consumption-related parameters such as voltage (V), current (Amp), power factor, and energy (kW or W). Twenty-two EM6400 energy measurement meters (EM6400 Series Meter, no date) located at the ground floor electrical panel perform the task of basic data acquisition. Each energy meter has been assigned to discrete loads. All the energy meters are connected via daisy chain looping before terminating at the BMS controller. The monitoring and communication parameters have been programmed for each energy meter.

The network communication tier is a communication protocol (software) which transfers data between the energy monitoring devices and the BMS computer server from the station level management tier. The transmission network of the building energy monitoring and management system includes two parts: one-part transfers data between the measurement devices and BMS controller. The second part transmits data between the BMS controller (Automated Logic United Technologies, no date) and the BMS computer server.

Station level management tier provides dynamic monitoring and statistical analysis for the building energy data. This tier processes and analyses the building energy consumption data collected by the lower tiers, and then distributes and demonstrates them in a graphical manner.

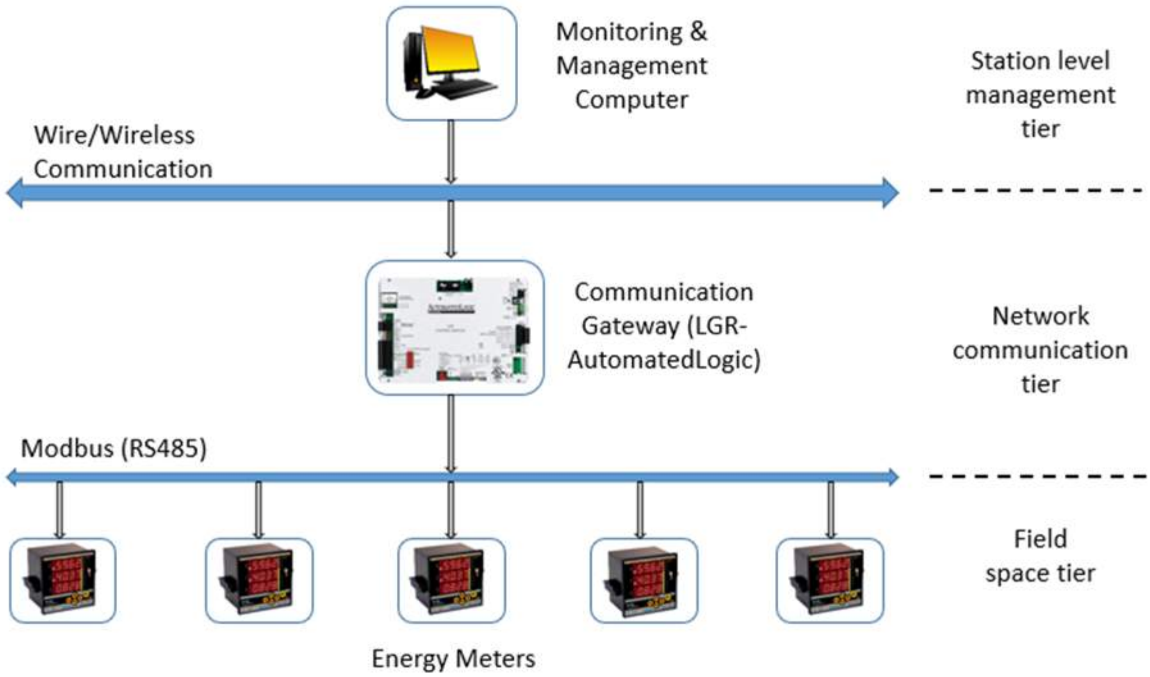

Figure 9. Architecture of the energy monitoring system

5.3 Thermal comfort monitoring

The practice of appropriate strategies to achieve thermal comfort was one of the primary objectives of building the NZEB. The user experience and feedback on the performance of the building is vital to establish the degree of success of the NZEB. As part of the post-occupancy evaluation, building users take surveys (4 times a week) to provide feedback on the thermal environment and air quality. The user feedback allows the facility manager to take informed decisions for fine-tuning building operation to provide satisfactory and healthy workspace and save energy. As an example, based on user surveys, air motion devices had been installed adjacent to the workspaces to provide personalized control over air velocity and thermal comfort.

To map thermal comfort conditions, a routine thermal comfort survey was deployed. Each desk is equipped with globe temperature measurement logger. Each occupant of the building is requested to participate in Thermal Comfort Survey administered four times a week. The surveys are taken on Mondays and Thursdays at 11h00 and 16h00. Online surveys contain questions pertaining to thermal acceptance, thermal sensation, thermal comfort, and preference. Questions also help gain responses regarding the presence of air velocity, the source of air velocity, the status of window operation, clothing, and immediate past activity performed by the occupant.

6. NZEB operational analysis

NZEB operational analysis follows a similar approach to the monitoring approach. Data acquired from various sources are analyzed to understand the: (a) environment performance, (b) energy performance, and (c) thermal performance of NZEB.

6.1 Environment performance

Figure 10 shows the variation of the interior and exterior surface temperatures for the roof and the window on a peak summer day (13th May 2017). The roof and window experienced a thermal damping of 32.9°C and 5.6°C respectively. The window facilitated a thermal time lag of 2 hours, while the roof, owing to its high thermal mass, led to a thermal time lag of 6 hours.

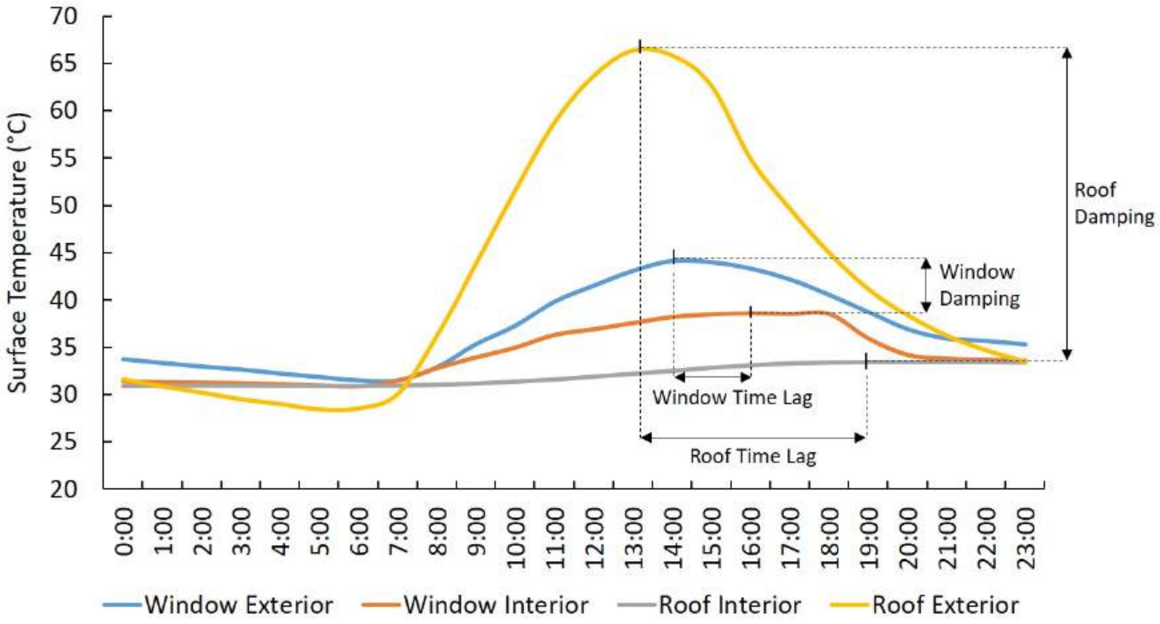

Figure 10. Interior and exterior surface temperatures for the window and roof.

Figure 11 compares the variation of air and surface temperatures for the indoors and outdoors for a typical summer week. The first two days of this week were non-working days, therefore, were observed to have higher indoor surface and air temperatures in comparison to the subsequent working days. The working days necessitated the usage of air cooling devices, thereby reducing the indoor air temperature, as reflected in the figure. This reduction in air temperature led to a significant decrease in indoor surface temperature, making it cooler by over 10°C during the hottest hours of the day. During the non-daylight and non-operational hours, the indoor and outdoor temperatures were observed to attain similar values.

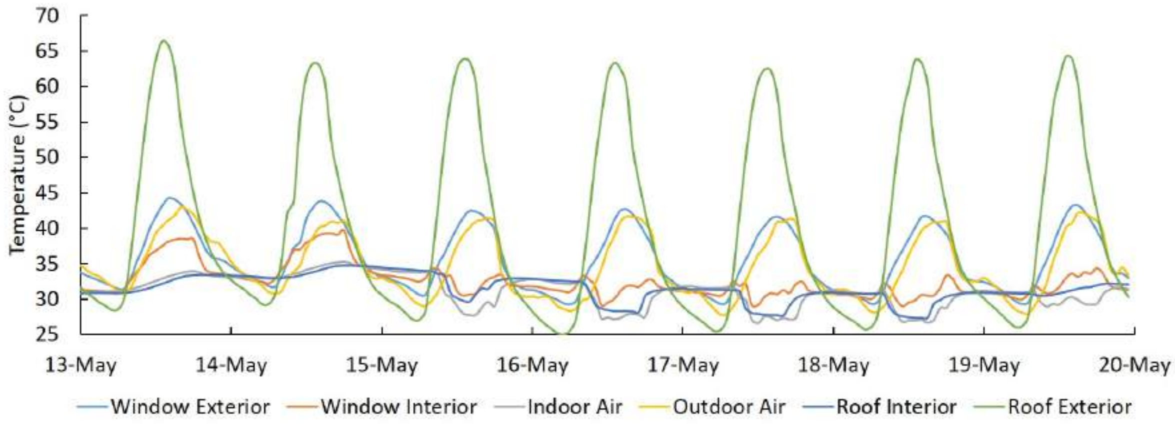

Figure 11. Indoor and outdoor surface and air temperature

6.2 Energy performance

Figure 12 and Figure 13 compare the various environment and energy-related parameters for the typical winter and summer weeks respectively. The hourly average indoor air temperature did not undergo a significant diurnal variation during winter, while the summers experienced a temperature fluctuation of 10°C. The HVAC consumption during winters remained within 5 kWh, while during summer, it was as high as 25 kWh.

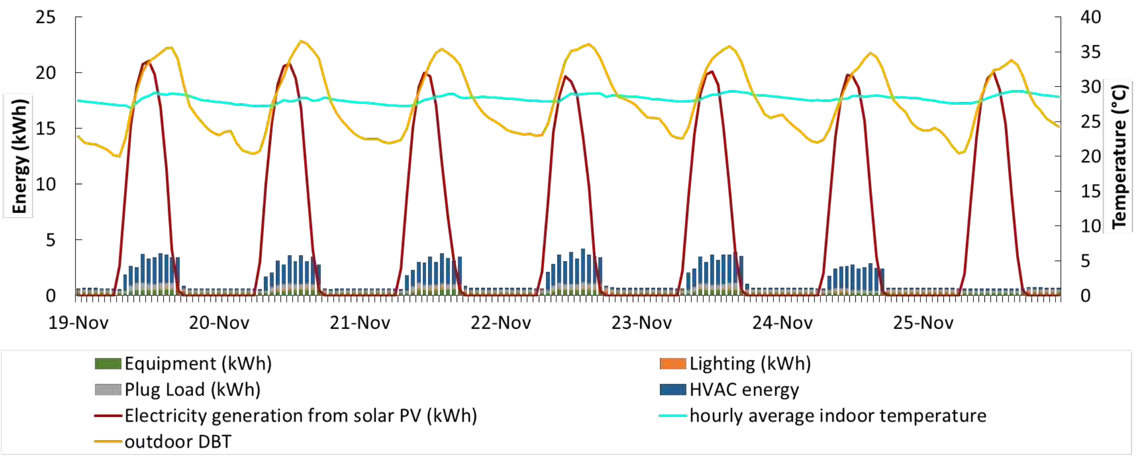

Figure 12. Variation of environmental and energy-related parameters for a typical winter week of 2017

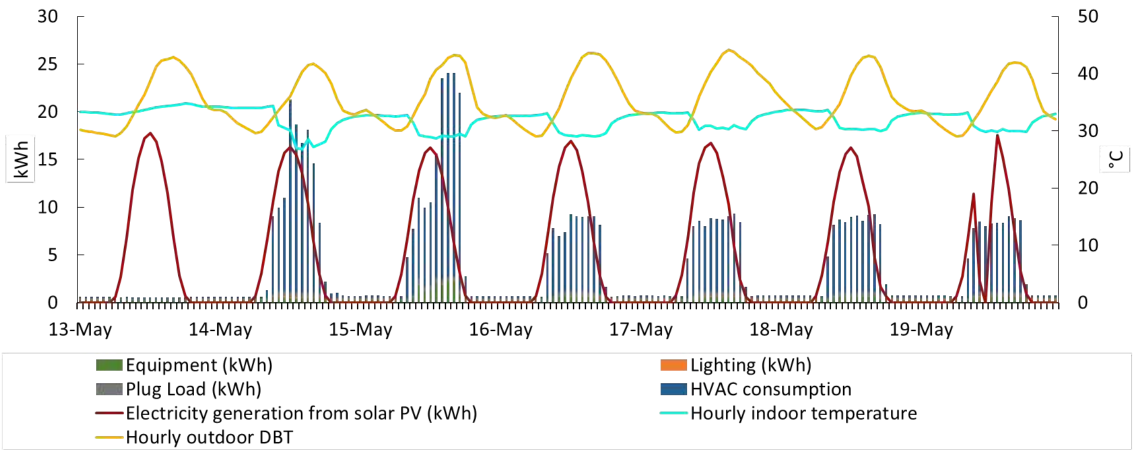

Figure 13. Variation of environmental and energy-related parameters for a typical summer week of 2017

Figure 14 shows the cumulative seasonal and annual electricity generated by solar panels, process consumption and space consumption of the NZEB for two years (2017-

2018). It also shows the share of various cooling and operational components in the space energy consumption. In the figure, 'Electricity generated by solar panels' is the total amount of electrical energy generated by the solar PV assembly, 'Process Consumption' is the total amount of electrical energy consumed by the process load of TCC, and 'Space Consumption' is the total amount of energy used for space cooling, building operation and equipment for testing.

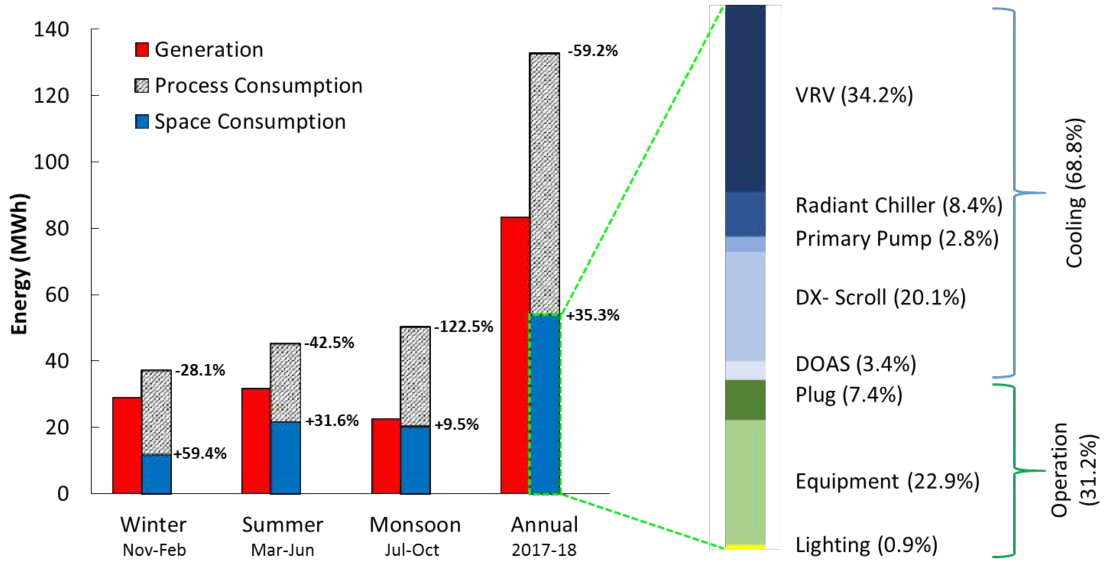

Figure 14. Annual and seasonal energy generation, process consumption, and space consumption for 2017-2018, along with the percentage share of various operation and cooling loads

Considering the seasonal and annual space consumption energy, the building was net energy positive throughout the period of analysis. The building was most energy positive during the winters (59.4%), as the cooling loads were negligible and high radiation coupled with low outdoor temperature allowed the solar panels to operate efficiently. The season of monsoon, due to increased cloud cover, experienced reduced generation, thereby resulting in the least net-positive (9.5%) state. However, if we consider the process consumption (operation of TCC) as a part of the total energy consumption, the building was energy negative by 28.1%, 43.5%, and 122.5% for the seasons of winter, summer, and monsoon respectively. Over the course of two years, the total generation (83.5 MWh) was 35.3% higher than the total space consumption, and 59.2% lower than the cumulative process and space energy consumptions.

Cumulatively, the cooling and operation loads incorporated 68.8% and 31.2% of the annual space energy consumption respectively. VRV (34.2%) and DX-Scroll (20.1%) were the most prominent contributors to the cooling loads, while the permanent testing equipment (22.9%) contributed the most to the operation loads. Active lighting systems (0.9%) were found to contribute the least to the electrical consumption.

The total Energy Performance Index (EPI) of the building for the year 2018 is 25.4 kWh/m^2/year, while in 2017, it was 19.1 kWh/m^2 which indicates a 70% reduction as compared to the benchmark. The EPI of the electricity generated by the solar panels is roughly 52 kWh/m^2. Out of the total EPI, HVAC systems have a major share in energy consumption of almost 70%, while all the other loads are within 30%. The lighting power density (LPD) of the building is 4.7 W/m^2 with lighting EPI of 0.45 kWh/m^2. The plug loads account for only 7.4% with an EPI of 2.49 kWh.

Figure 15 shows a heat-map of the hourly space consumption for the year 2018. The building is daytime operated. However, on some days, 24-hour long isolated streaks are seen in the energy consumption. These are due to the various research-based tests carried out in the building that require the respective equipment to run continuously for prolonged hours. These streaks also account for the cooling required to keep the equipment running without overheating/malfunctioning. The highest energy consumption during the daytime is seen during the peak summer months of April to June, while relatively cooler days of the monsoon and winters observe darker shades (indicating a low energy consumption) in the heat map.

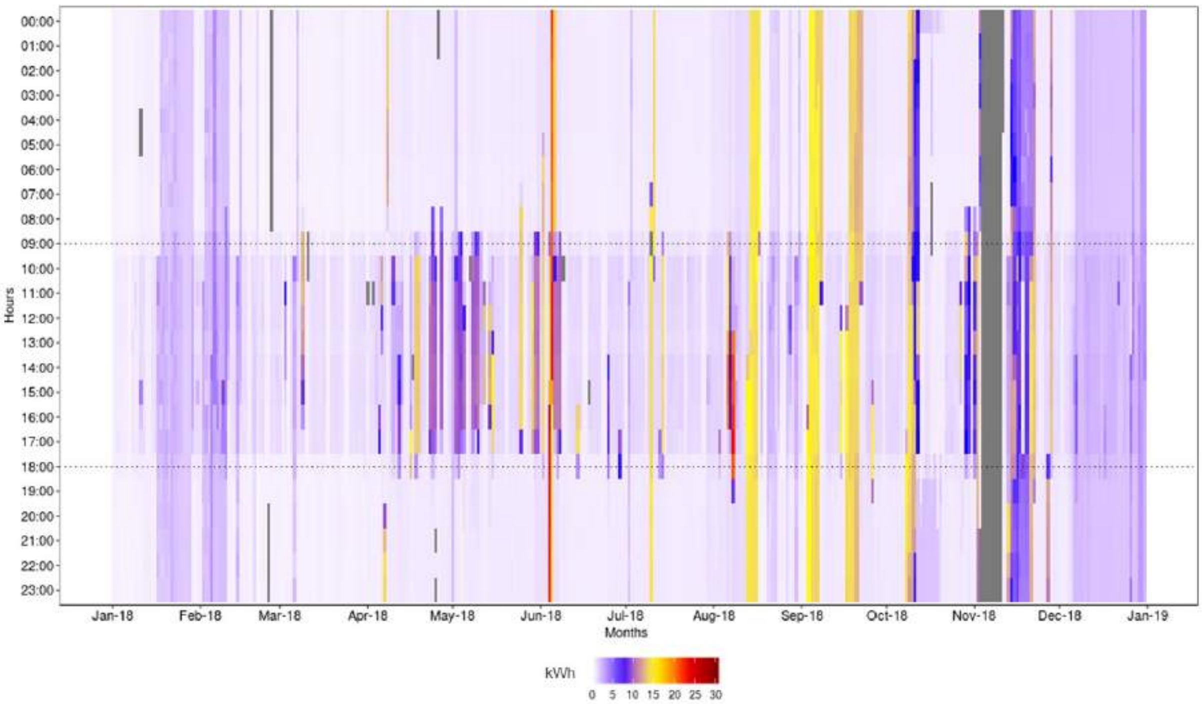

Figure 15. Distribution of hourly space energy consumption for each day of the year 2018

Figure 16 shows the variation of daily space consumption against the daily average outdoor temperature for the three seasons. The daily space consumption shows an exponential increase with the increase in the daily average outdoor temperature. The exponential increase is also visible through the change of seasons from winter to monsoon to summer. The typical space consumption during summers ranged from 100-200 kWh, while during winter, the consumption continually remained under 100 kWh. 3% of the data points exceeding 250kWh daily space consumption were omitted as they represented the few days when the energy-intensive experiments were in progress.

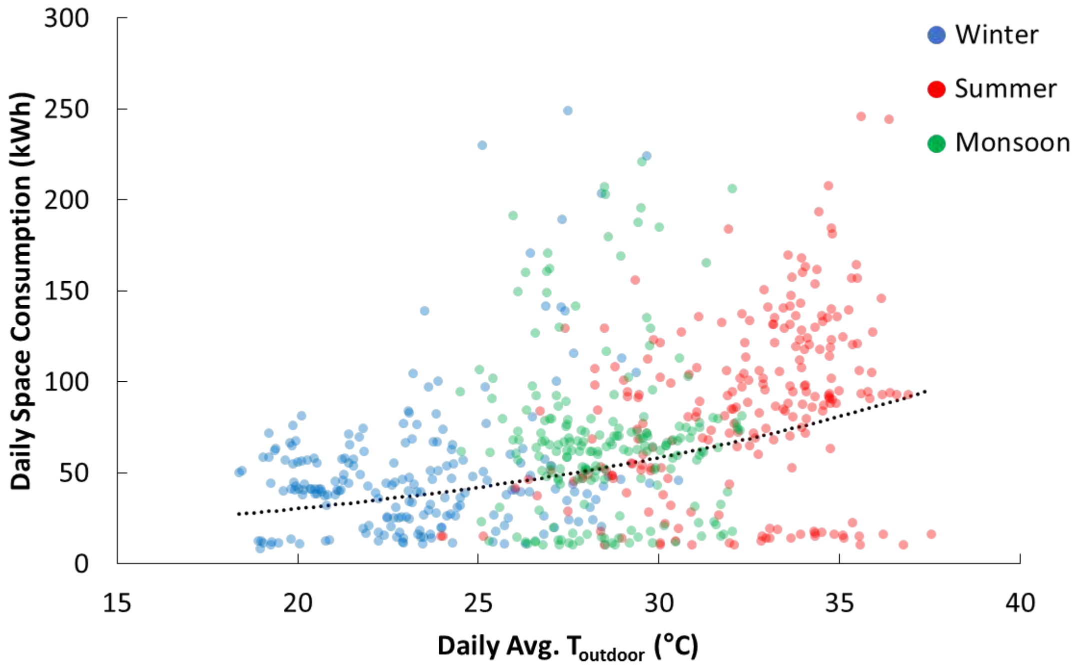

Figure 16. Seasonal variation of total daily space consumption with daily average outdoor temperature for 2017-2018

Two distinct patterns are visible from the graph: the first pattern is the constant low consumption (ranging 0-10 kWh) throughout the year, while the second is the exponential increase in consumption with the outdoor temperature. The low consumption pattern indicates the base load of the building, while the exponential curve shows the base load with the HVAC energy consumption for space cooling. It is seen that the base energy load of the building is around 10kWh per day which is when the HVAC systems are kept off due to favorable outdoor conditions. The base condition is seen for all the seasons when the HVAC systems are kept off. However, it is seen that for daily average temperatures less than 20°C during winters, the HVAC systems are working. These instances account for the days when any ongoing experiment necessitates the operation of HVAC.

Figure 17 shows the hourly variation of indoor ambient temperature with outdoor air temperature in relation to the cooling device used. As per the observations, the use of 'only VRV', 'VRV + Radiant Panel (RP)', and 'only RP' was most common for outdoor thermal fluctuations in the range of 15-45°C, 25-45°, and 25-40°C. The case of 'only RP' was put to use only during non-daylight hours to pre-cool the building before operation, therefore the trends suggest a lower indoor temperature range for the same.

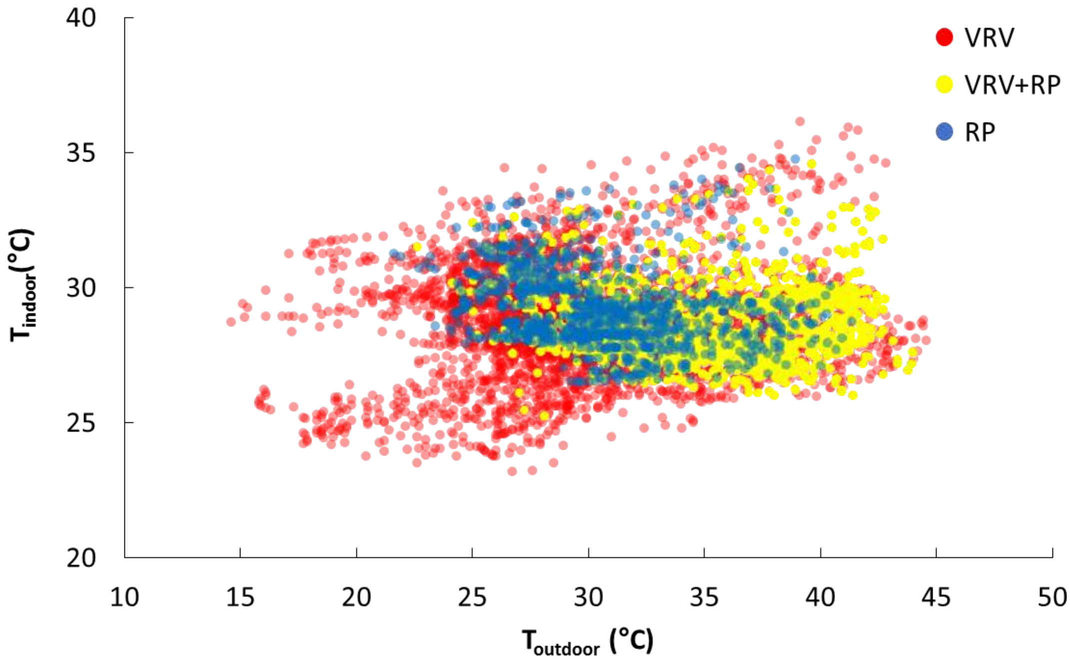

Figure 17. Variation of hourly indoor temperature with hourly outdoor temperature in relation with the operational mode of cooling

RP was only used when the dew point temperature was higher than the supply water temperature as the RP cannot cater to the latent load. For most of the time of the year, VRV was used due to its quick cooling capacity. During the summer months, when the latent load was lower, the RP was used throughout the night to cool the building volume and morning onwards both VRV and RP were used. During the late summer, when the latent loads increased due to the higher humidity content in the outdoor air, VRV was turned on during the day along with the RP. Hence the VRV dehumidified the air due to the condensation occurring at the cooling coil level, while the RP cooled the surface for radiant heat exchange. This combined approach reduced the load on the VRV system.

During instances of peak summer with outdoor temperatures ~45°C, the cooling devices moderated the indoor temperature within 30°C. However, at relatively lower summer outdoor temperatures, some indoor temperature readings were recorded to be beyond 33°C. This can be explained by fact that the cooling devices require some time to bring a noticeable difference in the indoor air temperature – the extreme scatter points at the top indicate the hours when the devices were just turned on during summers. When the outdoor air temperature was between 15-20°C in winters, the VRV was operated at isolated instances in order to keep the indoor air quality in check.

Seasonally, we observe that the cooling EPI of the RP during winters is 0 kWh/m^2, while that of VRV is 1.64 kWh/m^2 (in 2018). In the winter neither RP nor VRV is not required for the space cooling, as the indoor and outdoor air temperatures are already in the comfortable band and the surfaces are naturally cooled by rejecting the heat at night. As mentioned before, during instances of summer days with low latent loads, the RP is turned on. The cooling EPI for RP in summer is 1.60 kWh/m^2 while that of the VRV is 6.59 kWh/m^2.

Figure 18 shows a histogram-plot of the total space consumption and generation for 2017-2018. The X-axis puts the total days into bins of 25 kWh, while the Y-axis shows the number of days. The trend distinctly highlights that the highest number of days had consumption in the range of 0 - 25 kWh, and a generation of 125-150 kWh. It is seen that for the same number of days, generation is much higher than consumption. The frequency of days with higher energy consumption gets decreased while it gets increased for the higher energy consumption. 3% of the data points exceeding 250 kWh bins of energy consumption/generation were omitted for the reason mentioned when describing figure 16.

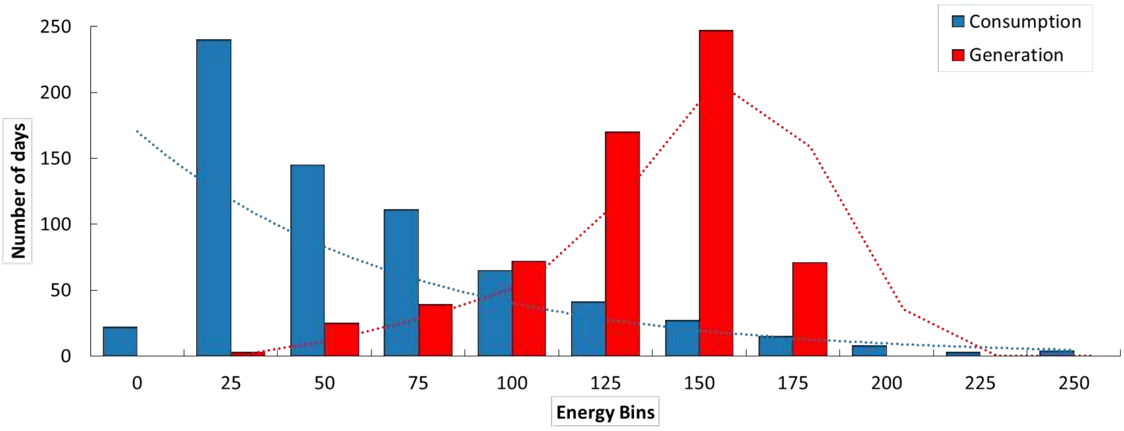

Figure 18. Cumulative number of days plotted against bins of energy consumption/generation for 2017-2018

Figure 19 shows the variation of total daily generation against the ratio of daily averaged outdoor temperature and total outdoor radiation (T_{out}/R). As a physical realization, a low T_{out}/R ratio instance indicates a sunny day with low ambient temperatures. A high T_{out}/R ratio instance, on the other hand, indicates a warm overcast day.

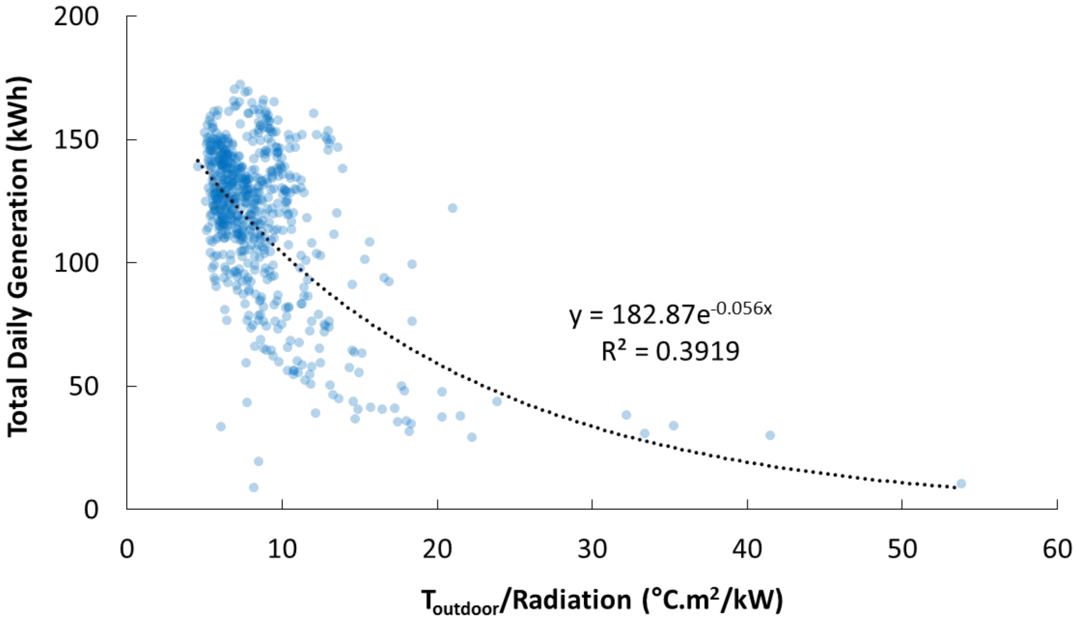

Figure 19. Variation of total daily energy generation with the ratio of daily average outdoor temperature and total daily radiation for 2017-2018

The total daily generation was found to exponentially decrease with the increase of the T_{out}/R ratio. A majority of the daily data points were found to be in the range of 5-10°C.m^2/kW on the X-axis – the total daily generation during these days was dominantly between 80-170 kWh. Days with T_{out}/R ratios higher than 15°C.m^2/kW resulted in a total daily generation of less than 50 kWh.

6.3 Thermal performance

Figure 20 shows the variation of indoor dry bulb temperature against the India Model for Adaptive Comfort (IMAC) band for 80% and 90% acceptability. The indoor temperatures were maintained within the 80% acceptability limit of the IMAC model or around the upper band of the 90% acceptability limit. For most of the time, the indoor temperature was maintained between 26 – 30 °C. Although the indoor air temperature remained close to the upper comfort limit and transgressed the limits at isolated instances, the thermal comfort survey results, as shown in the next section, indicate a high extent of comfort and thermal acceptability.

It must be noted that the temperature recorded by a stand-alone data logger installed at a centrally placed workstation (out of the four sensors and data loggers placed between 20 workstations). (Sama and Lawrence, 2019) further points out that the occupants' comfort vote changes every 0.5°C variation in ambient air temperature, and the data recorded by all the four data loggers was within 0.5°C range for 96% of the data. Thereby validating the decision of choosing a singular logger for analysis.

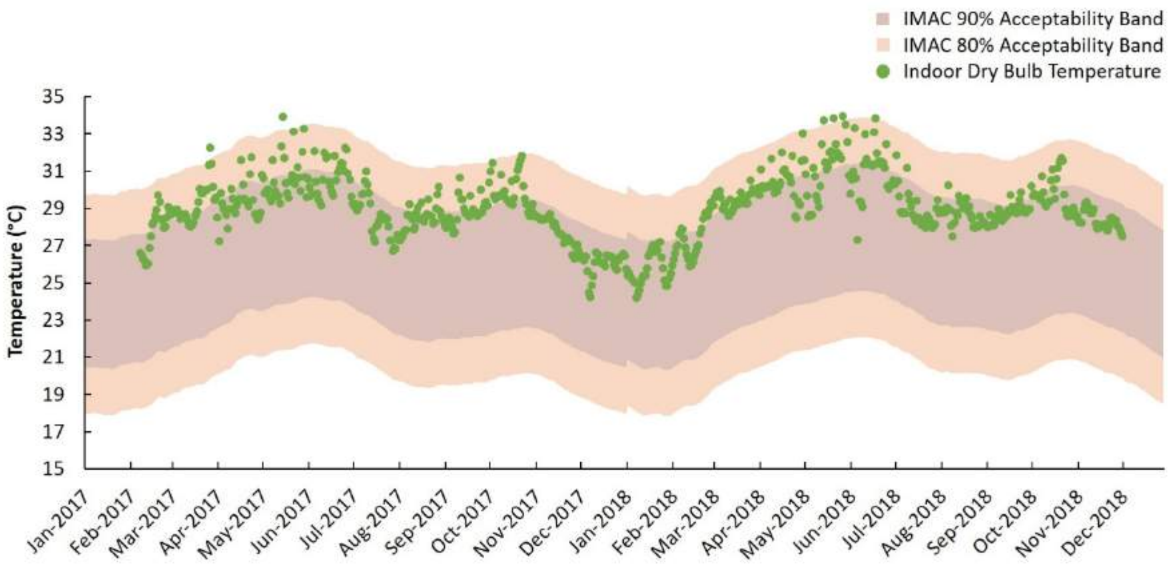

Figure 20. Comparison of indoor dry bulb temperature against IMAC 80% and 90% acceptability limits for 2017 and 2018

Figure 21 shows the occupants' vote on thermal sensation and acceptability against the indoor globe temperature. For the thermal comfort sensation, a 7 point scale was used - where -3 represents 'very cold' and +3 represents 'very hot'. In the figure, each dot represents one survey response. 82% of the occupants voted between -1 and 1 and 72% of the occupants voted between -0.5 and 0.5. At their respective sensation vote, acceptance has been represented with green and red colors. This indicates that the indoor thermal environment is comfortable for more than 80% of the people. However, this does not mean that the rest of the occupants are uncomfortable. The 'Unacceptability' plot indicates another interesting trend – occupants marked their thermal sensation as neutral (i.e. y=0), yet found their thermal environment 'unacceptable' on a significant number of instances. This reflects that occupants did not generally relate the state of 'neutral thermal sensation' with 'thermal acceptability'.

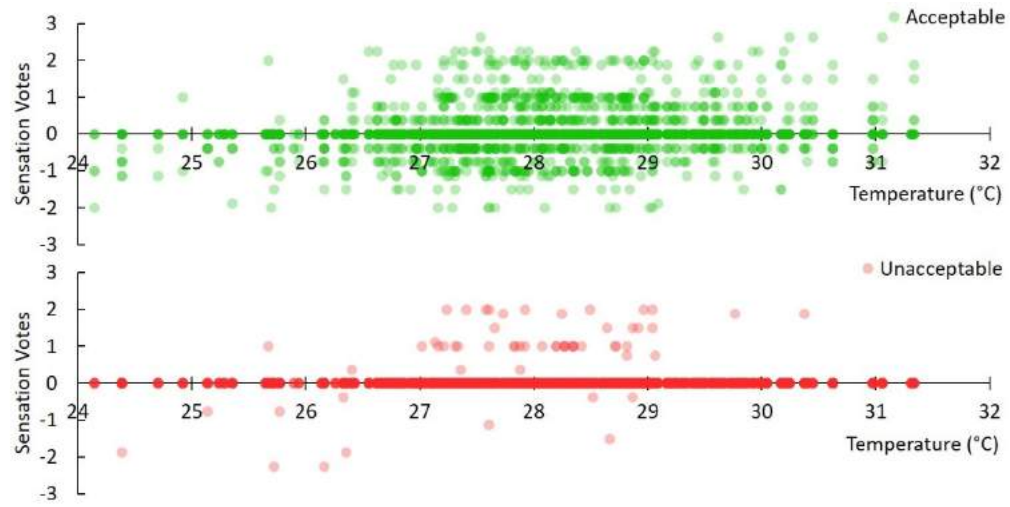

Figure 21. Variation of thermal sensation and acceptability with temperature for 2017-2018

Figure 22 shows the binary thermal comfort responses of occupants against the number of votes and temperature bins. From the thermal comfort surveys, it is found that more than 90% of the occupants were comfortable inside the building all the time.

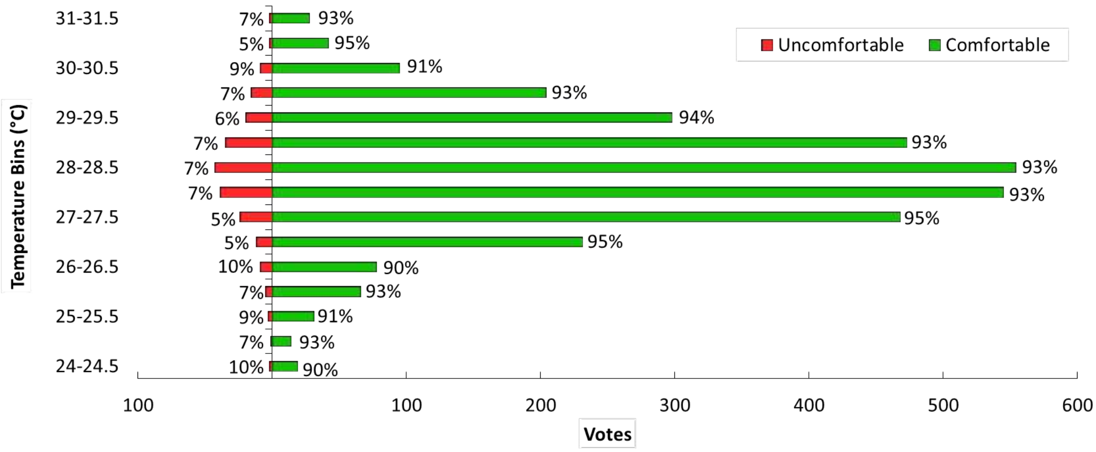

Figure 22. Variation of comfort with temperature during 2017-2018

7. Conclusion

One of the key learnings from the design, construction, and operation of the NZEB at CEPT University was to establish the viability of NZEB with currently available knowledge. At the same time, it also establishes the need to rely on scientific rigor at every stage of building design and operation. The approach to select strategies to achieve energy efficiency first and then be supported by renewable energy could help achieve the NZEB status at a minimal additional cost. Passive design strategies help reduce external and internal heat loads and provide an opportunity to operate the building in the naturally ventilated mode as per the need. Deployment of passive strategies helps reduce the installed capacity of HVAC and lighting system, while reducing energy consumption. Design of building monitoring strategies for indoor environment, end-use energy consumption, energy generation, and thermal comfort needs careful planning. It is very important to allocate financial resources at the occupancy stage for the installation of an environment, energy, and thermal comfort monitoring system and continuous analysis of the monitored data to improve the operation of the building. Maintaining equipment at their optimum performance is essential to achieve the targeted consumption and generation; in fact, it does offer an opportunity to achieve an even higher performance than targeted. Involvement of occupants in the operation of the building also helps achieve the NZEB status; at the same time it helps increase awareness about NZEB. Regular thermal comfort surveys are an effective way of engaging the occupants in the operation of the NZEB. Presence of NZEB within the academic campus further increases the visibility amongst the university students and visitors.

8. Abbreviations

NZEB - Net Zero Energy Building
BMS - Building Management System
Solar PV - Solar Photovoltaics
HVAC - Heating, Ventilation and Air Conditioning
UNFCC - United Nations Framework Convention on Climate Change
EE - Energy Efficient
RE - Renewable Energy
CARBSE - Centre for Advanced Research in Building Science and Energy
CFD - Computational Fluid Dynamics
ECM - Energy Conservation Measures
DOAS - Dedicated Outdoor Air System
XPS - Expanded Polystyrene
U-Value - Thermal Transmittance (W/m2K)
SRI - Solar Reflectance Index
uPVC - Unplasticised Poly Vinyl Chloride
DGU - Double Glazed Unit
VLT - Visible Light Transmittance
PEX – cross-linked Polytehylene
VRF - Variable Refrigerant Flow
TR - Ton of Refrigeration
COP - Coefficient of Performance
EER - Energy Efficiency Ratio
PMV - Predicted Mean Vote
TCC - Thermal Comfort Chamber
EPI - Energy Performance Index
LPD - Lighting Power Density
RP - Radiant Panel
T_{out} - Outdoor Temperature (°C)
R – Total Outdoor Radiation (kW/m^2)
IMAC - India Model for Adaptive Comfort

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Sustainability and "Low-energy" building design in high density urban cities - [Cairo as a case-study]

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Abstract
The rapid increasing of urbanization all over the world, then large and mega cities are growing in number, resulting in increase of: population, pollution, and traffic Complexity. Thus incorporating energy efficiency and sustainable design features into all contemporary buildings has become a high priority for owners, designers, and governments.

The research methodology follows: Literature, Analytical and Comparative/analytical reviews respectively; examines the concept of "low-energy" building, investigates how urban density might affect building energy design in high density cities. Using Cairo as a case-study, the characteristics and factors affecting "low-energy" building design techniques are evaluated. The current energy situation in Egypt is explained and considerations for energy efficiency in high density conditions are discussed.

The research aims to draw-out a frame-work for best strategies and passive design techniques of "low-energy" buildings appropriate for application in dense environments. through using the "Base-case" model vs. "Low-energy" model using "design builder" simulation tool; to compare the impact of applying different strategies: [Orientation- Façade design - glazing materials…]. The research find-out that the "low-energy" designs techniques may reduce energy consumption by about (35:50 % or more). Such results may help designers and owners to make their decisions promoting energy efficiency in: new and retrofit buildings.

Key Words: Sustainability - High density urban cities – "Low-energy" buildings– Passive design

1. Introduction

The vast and rapid increasing of urbanisation all over the world, large and mega cities are growing in number, result in increase of: population, pollution, and traffic Complexity. At present, about 2.5 % of the world's land surface is covered by cities but the people living in them consume 75% of the resources consumed by mankind. The "Ecological footprint" of cities is many times larger than the areas they physically occupy, (Rcreee, 2014).

Sustainability in urban and architecture, Green building, Zero Net Energy (ZNE), and Energy efficient Buildings become popular concepts in the field of urban design, architecture and construction fields. In line with a sustainable development and resilience approaches, it is important for architects and planners to create a healthy, sustainable and resilience built environment, (Naga and Amin, 1996).

Although it is mostly needed and highly economic feasible, the application of these concepts and methodologies in design is not yet at the same level of priority in Egypt, especially Cairo's as one of the most urban dense cities all over the world.

Increasing of energy consumption rates and the accompanied greenhouse gas emissions are considered one of the world's greatest concerns recently. Monitoring the harmful emissions in Egypt, the (CO_2) per capita reached 4.28 ton/year in the latest statistics provided by CAPMAS for the year 2016 rising from 2.93 ton/year in 2008. (CPMAS, 2015), for this reason the building sector represents a large potential for significantly reducing the energy demand and the harmful emissions.

"Low-Energy" buildings in high density urban cites may reduce carbon emissions by (60%) or more, which is translated to (1.65 billion tons) of carbon (EIA, 2017). The Egyptian building stock consumption of electricity increased by 81.2% from 2010 to 2017 in commercial sector, while residential sector consumption increased by 42.8 % (Egypt Ministry of electricity, 2017).

2. Research Problem & Goals

There are two main aspects of the problem:

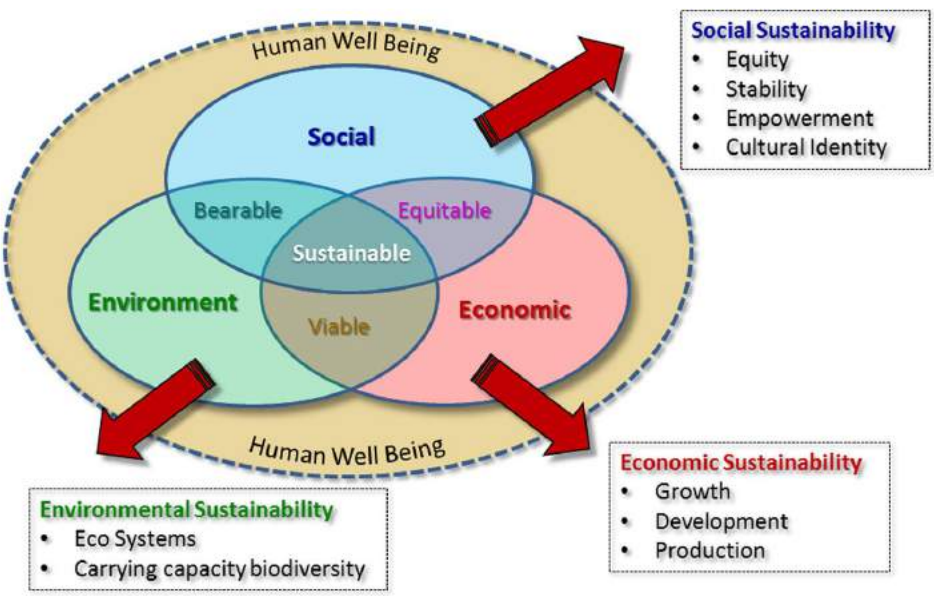
- **First:** Ascending negative impacts [Environmental/Economic] of increased energy consumption; due to the population growth and urban development compared to the energy supply in Egypt, which is mostly generated from fossil fuels.
- **Second**: Inefficient energy [Urban /Architecture] design is considered one of the most reasons for energy loss through the process of reaching thermal comfort of the built environment, which need continuous improvement.

The paper goals are :

- **Draw out:** A proper frame-work and strategy to be helpful in designing "low-energy" buildings in high density urban cities such as Cairo (as a case study).
- **Provide:** A quantitative analysis to get a predictive ratio of energy saving due to follow the previous strategy of "low-energy" building design Vs. Conventional design in Cairo's urban and climatic zone.

3. Sustainability and "Low-Energy" buildings : [Concepts – Importance– Feasibility]

Sustainability; as a major target of building efficiency has three main dimensions: Economic, social and environmental,(Steele,2008), if the three were not considered, the balance would not be achieved, as shown in (Fig.1), Then to reach energy efficient built environment and human well being architects have to compromise the balance of sustainability three dimensions.



(Fig. 1) : Sustainability Dimensions and their impacts on daily human well being systems

"Low-energy" building design is not just the result of applying one or more isolated technologies. Rather, it is an integrated "whole-building design" process that requires advocacy and action on the part of the design team throughout the entire project development process. The "whole-building" approach is easily worth the time and effort, as it can save 30% or more in energy costs over a conventional building designed.

"Low-energy" design does not have to result in increased construction costs. Indeed, one of the key approaches to "low-energy" design is to invest in the building's form and enclosure (e.g., windows, walls) so that the heating, cooling, and lighting loads are reduced, and in turn, smaller, less costly heating, ventilating, and air conditioning (HVAC) are needed.

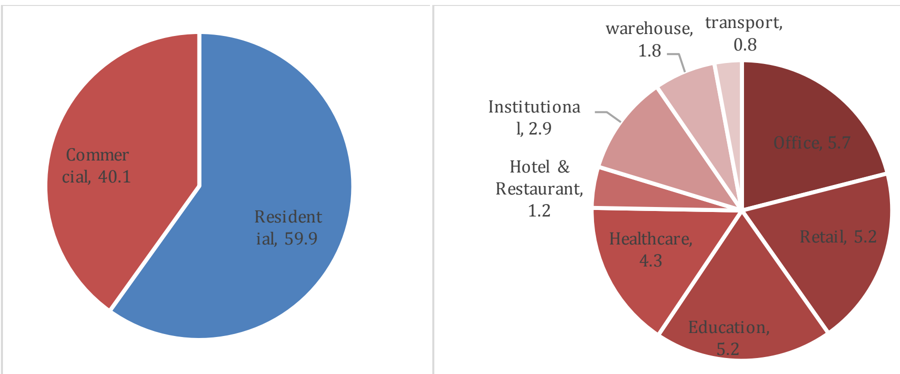
These passive solar design strategies also require that particular attention be paid to building orientation and glazing. Taken together, they form the basis of integrated, whole-building design. Rounding out the "whole-building" picture is the efficient use of mechanical systems, equipment, and controls (Chiras, D. 2009).

By incorporating building-integrated photovoltaic into some conventional building envelopes and materials can be replaced by energy-producing technologies. For example, photovoltaic can be integrated into window, wall, or roof assemblies, and spandrel glass, skylights, and roof become both part of the building skin and a source of power in both: new and retrofit buildings.

4. Energy situation in Egypt

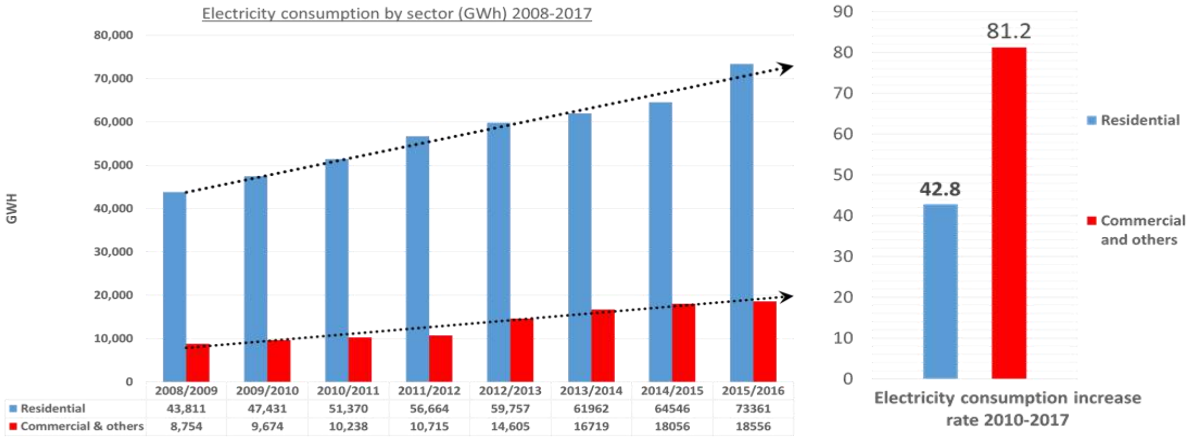
The total energy sold in Egypt for the year 2017 reached 180 terra watt hours with an annual average growth rate of 8.2%, The building sector alone - including all building types contributes around 43% of total energy consumption and one third of greenhouse gas emissions globally, and the numbers are even higher in Egypt, reaching 54% of total energy sold in 2017, (Eehc, 2017).

The building sector consumes 40% of the energy generated on a global scale, while it consumes more than 51.4 % in Egypt according to the annual report of the ministry of electricity,(Fig.2-a), (Eehc, 2017). In other words, both new and the existing buildings represent both the problem and the solution, because if a clear methodology is proposed to convert existing buildings into Low-Energy or Zero-Net Energy buildings (ZNE), then the majority of the urban fabric will be affected.



(Fig. 2-a) commercial Building stock Patterns in Egypt ,2017

Expected growth of energy use in the built environment in the next 20 years is 34%, at an average rate of 1.5%. The residential sector will contribute with 67% of the energy consumption in 2030 and 33% for the non-domestic sector, (Pérez-Lombard et al., 2008).



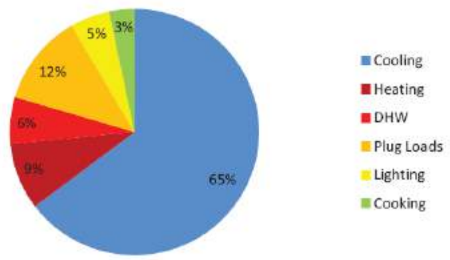
(Fig. 2-b): Electricity consumption in Egypt by sector (Residential vs commercial)- 2008-2017.

Energy consumption in buildings has increased in the last 10 years by almost 95%, and with existing stock that is expected to have a long life, (Figs.2-b&4). Sustainable improvements to buildings should extend to existing buildings as well as new buildings.

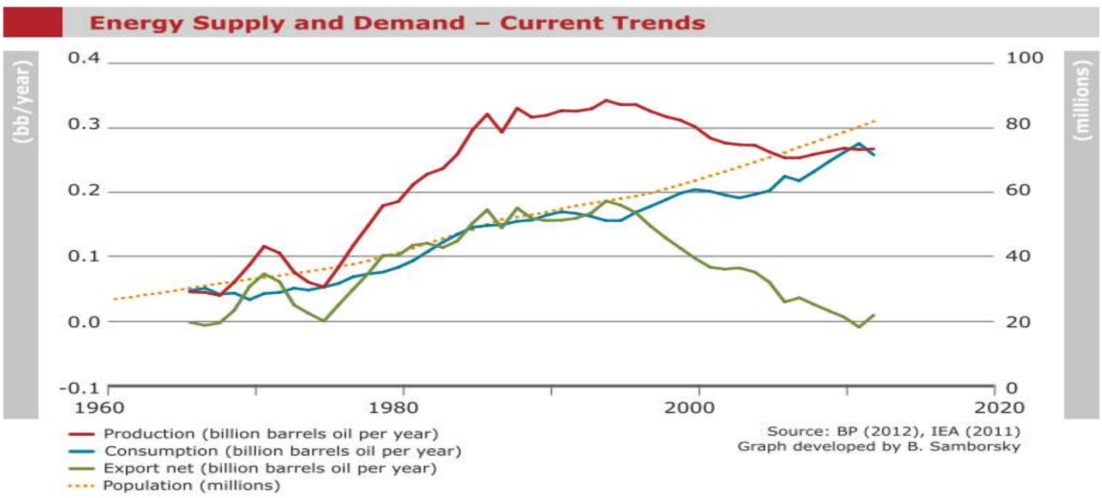
Energy consumption in commercial and office buildings are of the highest compared to other building types; with an annual consumption that ranges between 100 and 1000kWh/m2 depending on geographic location, use, type of office equipment, type of envelope, use of (HVAC) systems and type of lighting (EIA, 2015).

Several factors could reduce the energy consumption in offices and commercial buildings; such as passive design, energy conservation plans, water management systems, controlled lighting systems, use of renewable energy, limited use of active air conditioning system and building envelope improvements.

Fig. (3) Shows the exact breakdown of the energy usage. This shows the importance of solving the thermal comfort aspects and proves that if the building insulation efficiency was enhanced, the energy saving will be significant.



(Fig.3): Energy consumption per household in an urban community in Cairo Eehc. (2017).



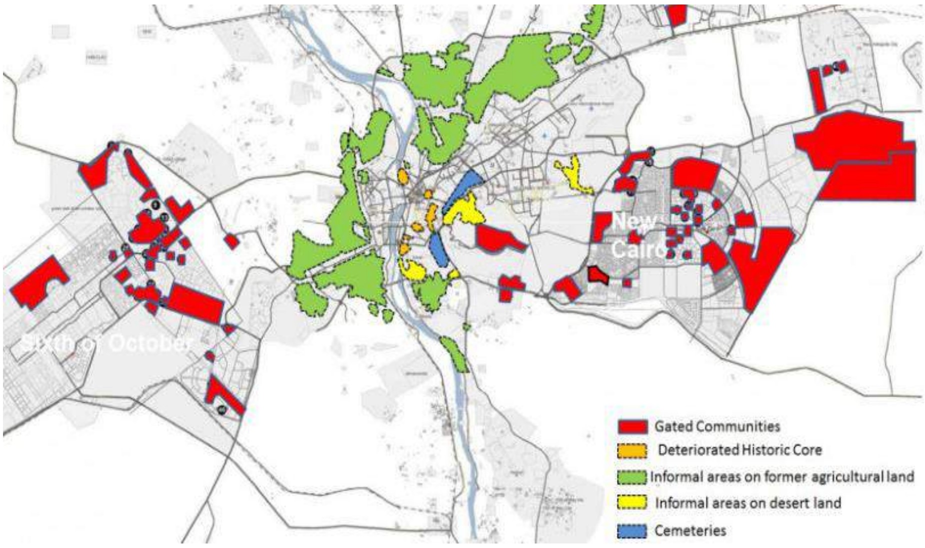
(Fig. 4) : Energy supply and demand and population growth**,** (Rcreee, 2014)

5. Cairo's Urban density growth: [Zones analysis]

Rapid urbanisation in Cairo during the last century has caused a fragmented spatial structure consisting of several small cities shaping the large metropolitan area. These small cities differ spatially, socio-economically as well as culturally from each other (Mekawy & Yousry, 2012, Elisa & Michele, 2013).

A greater Cairo Region (including governorate of Cairo, Giza and Qaliobeya) is well known for its high-density form of development, as shown in (Fig.5). The main urban agglomeration of the Cairo Metropolitan city is 521 km2, and its average density is 397 persons/ Hectar, (World Urban Forum 2017- WUF10).

The annual urban growth rate is about 3.7%. Many development plans since 1982 has been proposed to build new communities and cities around the capital that was defined by a ring road. From such proposals a common idea of laminating growth of the capital and adding new urban corridors in the east and the west is dominating.



(Fig. 5): Location of Greater Cairo (The case-study area): classification according to origin and urban types.

Strategic plans for Cairo 2050 & 2030 are currently prepared. Many projects to improve economy and investments and to enhance transportation are proposed.

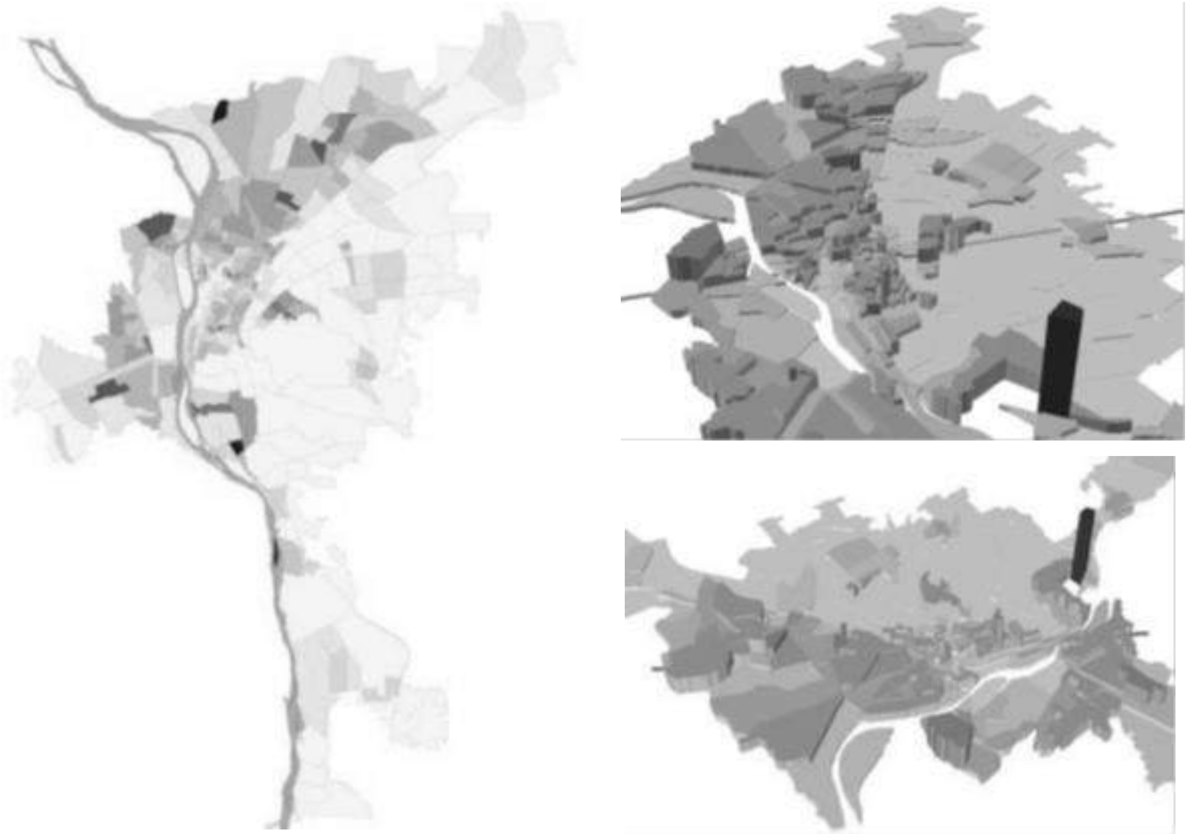
According to the result of Urban Survey 2016/2017 for the main agglomeration of Greater Cairo Region done in the favour of Cairo 2050 project and declared at GOPP publication 2017,(GOPP, 2017), the paper traced the development of population density in all districts s follows:-

By the last 20 years, the rapid extension of Cairo metropolitan involves new locations far from the centre of business district. This has favoured the emergence of sub-centres having a concentration of retailing and commercial activities, mainly aimed at servicing the growing informal settlements on the peripheries the natural growth, (Figures: 6: a, b&c).

The highest population density rates exit in: "Imbaba", "Ain Shams", "Dar El-Salam", and "El-Waily" respectively. Next high density districts like: "Haram", "Shobra El-Khaima", "Marg", and "Omrania" are significantly increasing their density between 1996, 2006, and 2016.

On the other hand very few zones which reflect medium population and urban densities and these are: Old Cairo, Downtown and "Daher" & "Abbasia". These are the central districts of Cairo and which points clearly to the tendency of these districts to accommodate more business uses over their historic and existing residential uses, (Sallhen ,M. and Hassan,G.,2017).

Finally, it was noted that there are several zones with significantly low population density but this is due to the inclusion of wide areas of expansion opportunities and which are also planned but not fully developed and populated such as “15 May”, West NC, “Maadi”, Eastern Expansion desert and “Helwan.



(Fig. 6:a,b & c) : Modeling the Urban Densities Distribution in Greater Cairo,(Sallhen ,M. and Hassan,G.,2017)

6. Impact of Urban density on building Energy demand

The problem of population growth on a limited land basis, the word 'density' is unavoidable, Instead of expanding the boundary, cities often respond to development pressure by setting Targets for increased urban densities. (Burchell and Listokin, 2002).

The result is reflected by the establishment of a high rise cityscape and compact urban settings. The effects of urban density on the total energy demand of a city are complex and conflicting (Givoni, 2004), the following (Table: 1) gives a summary of the positive and negative impacts of urban density.

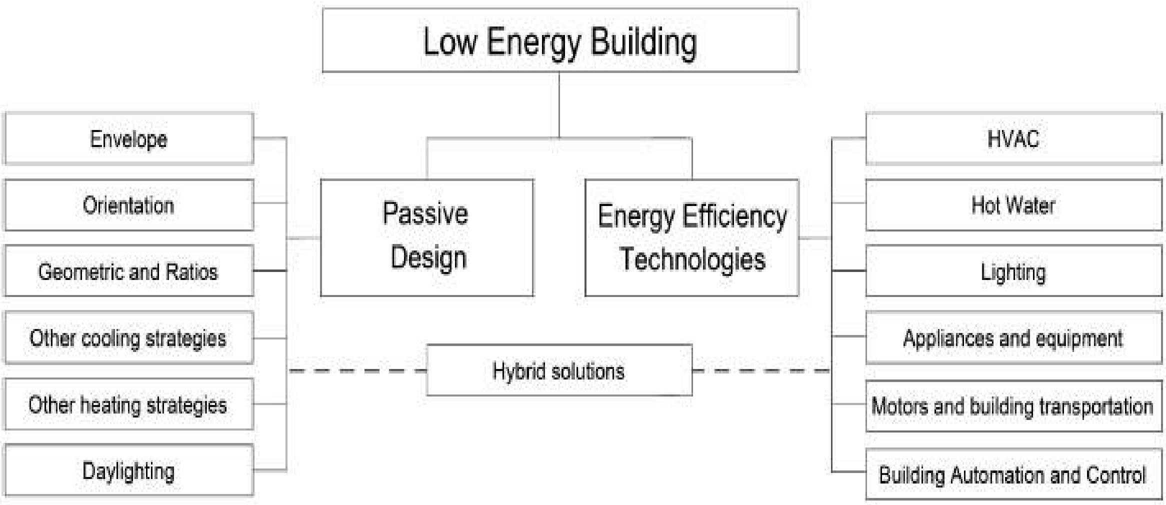
(Table: 1): Positive and Negatives Impacts of Urban density on building energy demand.
(Sam C., 2008 & Author).

Positive Impact	Negative Impact
Transport	**Transport**
▪ Promote public transport and reduce the need for, and length of, trips by private cars.	▪ congestion in urban areas reduces fuel Efficiency of vehicles.
	Vertical Transportation
Infrastructure	▪ High-rise buildings involve lifts, thus increasing the need for electricity for the vertical transportation.
▪ reduce street length needed to Accommodate a given number of	

inhabitants. ▪ shorten the length of infrastructure	**Ventilation** ▪ A concentration of high-rise and large buildings may impede the urban ventilation conditions.
Facilities ▪ such as water supply and sewage lines, Reducing the energy needed for pumping.	**Urban Heat Island** ▪ Heat released and trapped in urban areas may increase the need for air conditioning.
Thermal Performance ▪ Multistory, multiunit buildings could reduce the overall area of the building's envelope and heat loss from the buildings. ▪ Shading among buildings could reduce solar exposure of buildings during the summer period.	**Natural Lighting** ▪ The potential for natural lighting is generally reduced in high-density areas, increasing the need for electric lighting and the load on air conditioning to remove the heat resulting from the electric lighting.
Energy Systems ▪ District cooling and heating system, which is usually more energy efficiency, is more feasible as density is higher.	**Use of Solar Energy** ▪ Roof and exposed areas for collection of solar energy are limited.
Ventilation ▪ A desirable air flow pattern around buildings may be obtained by proper arrangement.	

7. Strategies and design techniques of "Low-Energy" buildings

Energy efficiency should come as a first priority in design, and the success in decreasing the energy consumption to a significant ratio, the renewable energy phase would be simplified to a great extent (George, 2013).



(Fig. :7): Hybrid solutions for low energy buildings (Rodriguez-et al., 2012)

(Fig.7) shows the hybrid solutions of both: the passive design and energy efficiency technologies. The shown solutions can be implemented on the new building design, while the author added a layer of highlight to the solutions that represent the only possible actions for existing or retrofit buildings.

The energy efficiency technologies can be implemented on existing buildings, like installing an effective HVAC system and decreasing the hot water and lighting usage. These technologies are expected to decrease energy consumption to a significant extent.

The passive design applications could not be used for existing buildings, but in this paper the authors are discussing the feasibility of tackling some passive strategies from the existing building perspective (Retrofit), to improve the energy efficiency and sustainable behaviour for such buildings in the high urban density zones of Cairo.

For example, the building envelope could be enhanced by adding some layers to the envelope in order to improve its insulation levels. Then can conclude the general aspects and assumptions for "Low-Energy" buildings design, as shown in (Table: 2).

(Table: 2): General assumptions for "Low-Energy" buildings design. (Sam C., 2008 & Author).

A- Efficiency Use of Energy	**B- Renewable Energy use**
▪ Climate responsiveness of buildings. ▪ Good urban planning and architectural design. ▪ Good housekeeping and design practices. ▪ Passive design and natural ventilation. ▪ Use landscape as a means of thermal control. ▪ Energy efficiency lighting. ▪ Energy efficiency air conditioning. ▪ Energy efficiency household and office appliances. ▪ Heat pumps and energy recovery equipment. ▪ Combined cooling systems. ▪ Fuel cells development.	▪ Wind energy. ▪ Photovoltaics. ▪ Small hydros. ▪ Waste-to-energy. ▪ Biomass energy. ▪ Landfill gas. ▪ Bio-fuels.
C- Reduce Transport Energy	**D- Increase Awareness**
▪ Reduce the need to travel. ▪ Reduce the level of car reliance. ▪ Promote walking and cycling. ▪ Use efficient public mass transit. ▪ Alternative sources of energy and fuels.	▪ Promote awareness and education. ▪ Encourage good practices and environmentally sound technologies. ▪ Overcome institutional and economic barriers. ▪ Stimulate energy efficiency and renewable energy markets.

7.1 Retrofit buildings and "Low-Energy" design techniques

Some literatures provided Positives and negatives study that would assess different alternatives of the possible retrofit actions (for Existing buildings). The paper can summarizes the results of previous strategies of "low-energy" design techniques, as in (table: 3) which discusses the alternatives for glazed facades, where (table: 4) discusses the opaque ones.

(Table: 3): "Low-Energy" building design techniques (with respect to alternatives of glazed facades)

Design Strategy	Positives	Negatives
Additional external glazed façade (DSF)	▪ Reduction of thermal bridges ▪ Preservation of the original building envelope (existing windows and exposed concrete) and its protection. ▪ Potential greenhouse effect to improve the passive energy behavior ▪ Possible integration of solar shading devices.	▪ Potential alteration of the appearance of the building ▪ Need to refurbish also the existing damaged windows ▪ Possible structural problem related to the unknown residual structural resistance of the existing structure (new loads applied)

Additional internal double glazed window	▪ Reduction of thermal bridges (thermal insulation around the new cavity). ▪ Preservation of the existing windows and of the overall external aesthetic aspect of the building. ▪ Potential greenhouse effect to improve the passive energy behavior. ▪ Possible integration of solar shading devices.	▪ Reduction of classrooms net floor area ▪ Need to refurbish also the existing damaged windows ▪ Need to protect and treat the existing façade in exposed concrete.
Replacement of all the windows with new high performance and thermally insulated windows	▪ Minimal aesthetic impact (especially with innovative high performance small section aluminum profile) ▪ No need to refurbish existing windows. ▪ Limited cost if innovative aluminum frame windows are adopted.	▪ Difficult reduction of thermal bridges. ▪ Need to protect and treat the existing façade in exposed concrete ▪ Need to define a position for the solar shading devices.

(Table: 4): "Low-Energy" building design techniques (with respect to alternatives of opaque facades)

Design Strategy	Positives	Negatives
Internal Thermal insulation	▪ Improvement of the internal acoustic ▪ Preservation of the external aspect of the façade. ▪ Easy to realize (no external special scaffoldings due to the complex shape of the building).	▪ Difficulties in thermal bridges resolution. ▪ Need to protect and treat the existing façade in exposed concrete ▪ Reduction of the internal net floor area.
External thermal insulation	▪ Reduction and resolution of most of the thermal bridges. ▪ No reduction of internal net floor area.	▪ Need of "out of shape" scaffoldings with complex geometries. ▪ Change of the external appearance of the building.
Roofs external thermal insulation	▪ Improvement of roofs thermal performances. ▪ No reduction of internal net area. ▪ Reduction and resolution of most of the thermal bridges.	▪ Increase of roof loads. ▪ Need more layering and more cost.

8. Application of "Low-Energy" design techniques on Case-study Retrofit building Model

According to the previous study, the paper suggested to apply some of "Low- Energy" design techniques [as illustrated above in (Tables: 3&4)], on a prototypical design models in one of high urban density studied zones, such as Cairo downtown zone, as follows:-

- **<u>A: "Base-Case" façade Model</u>:** a selected simple existing office building with single conventional glazed curtain wall facade system.
- **<u>B: Retrofit Model</u>:** Retrofit façade for the same "Base-Case" building with three alternative Scenarios, as follows:

- **S-1: Additional External glazed Facade Model:** represents a Ventilated 'Multi-storey' Double Skin Façade (V.DSF) system; consists of simple (inner + outer) single glazed facades.
- **S-2: High performance and thermally insulated colored Glazed façade model:** with high performance reflected colored glazing types.

- **S-3: Orientation for each retrofit facade model:** with respect to each of above scenarios.

Simulation will be done using "Design Builder" tool, thus results from [Retrofit model with different parameters and scenarios] will be compared with "Base-Case" for existing building model. Finally, the paper will compare the energy consumption results for each case with the original "Base-Case" results to get the energy saving ratios.

The climatic zone of study, as in Cairo, Egypt with (latitude 30.1° North and 31.4° East longitudes) - was established by parametric study of thermal and ventilation performance. Climatic conditions of simulation model will follow the Egyptian Energy Code for Commercial buildings, 2009, as shown in (table: 5).

(Table: 5) – Design Climatic Conditions for ' Greater Cairo climate zone',
Ref., [Egyptian Energy Code for Commercial buildings, part: I **I, EECB**- 2009 **]**

City	Location			Winter							Summer			
				Out-door climatic conditions					In-door climatic conditions		Out-door climatic conditions		In-door climatic conditions	
				Dry temperature design values			Moisture temperature design values							
	Longitude (East)	Latitude (North)	Height (m.)	1%	2.5%	5%	99.6%	99%	Degree (C°)	Relative Humidity	Degree (C°)	Relative Humidity (%)	Degree (C°)	Relative Humidity (%)
Cairo	31.4	30.1	74.0	42.1	38	37	26	27	24	50	13.3	70	21	40

8.1 Simulation Models description

The suggested two models are models of an existing and real isolated office building (Cairo centre office building) in downtown zone, (Figures: 8, 9 &10). Simulation models are two identically isolated conventional office buildings (Core & shell type), each one consists of a ground floor plan, seven (7) typical office floors with extended naturally ventilated central core. As illustrated in (Design-Builder) simulation model (Figures: 11, 12) and building data as in (tables: 6: a,b).

(Fig.8) : Cairo's Downtown Studied dense zone , Google earth+, [Accessed,December,2018]


(Figs. 9 & 10) - The "Case –Study" Existing building "Cairo Centre" office building-Downtown - View & Location.

(Table: 6 -a) - Office building Architectural Data, (Author)

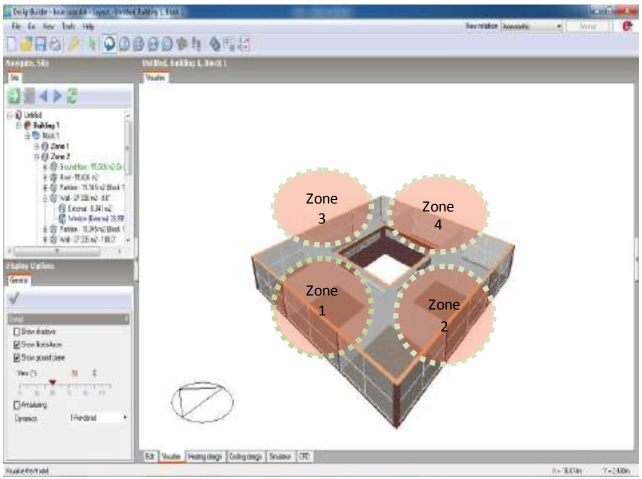
- Building type	Isolated Office building / Core& shell design type (with central ventilated inner core).
- Office Space organization	Open plan - Computerized working cells units
- Occupants rate	**12** persons /100 m2
- Building floors numbers	Ground floor + **(6)** typical floors
- Typical office floor height	**4.0** m (slab to slab) , **3.70** m ~ **3.0** m (clear height)
- Building total height	**(4.0** m X **7** floors**)+2.0** m parapet of façade**= 30.0m**
- Ground floor area	**21.0** mX**21.0** m = **441.00 m2**
- Typical office floor area (Dimensions are suitable for Architectural module+ structural and parking lots design assumptions)	**24.0** m (8.0 m X 3 typical units) X**24.0** m (8.0 m X 3 typical units) = **576.00 m2**
- Ventilation system	- For **"Base-Case" building:** Artificial Mechanical ventilation (Full HVAC) system. - For **V.DSF building:** 'Mixed-Mode' (Hybrid) system all of the year.

(Table: 6- b) - Studied zone data (8.0 m X8.0 m X4.0 m Model, Author**)**

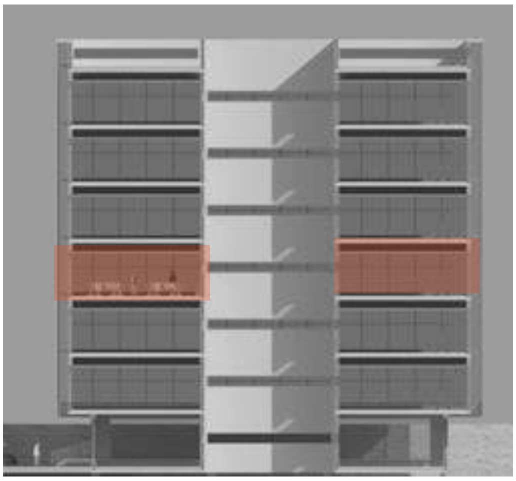
- Office Area of floor plan (For each studied orientation)	8.0 mX 8.0 m = **64.0 m2**
- Office Volume of floor plan	8.0 m X 8.0 m X 3.10m(floor clear height)= **200.0 m3**
-Vertical distance between external skin openings of (V.dsf)	**25.0** m (from first floor to sixth floor)
- External Skin area (V.DSF)	8.0 m X 4.0 m = **32.0 m2**
- Cavity area of each floor plan (Subtracted area of typical floor plan)	8.0 m (width) X (0.30, 0.60, 0.90) m (Cavity depth) = **2.40, 4.80, 7.20 m2** Respectively.
-'Air-Cavity' volume /floor plan	**9.6, 19.2, 28.8 m3** Respectively.

8.2 Simulation Model - [General Assumptions]

- Simulation will be done using of **"Design Builder"** software tool linked to **(Energy Plus)**, which is considered as the most widely used, popular, reliable, and accurate simulation engine among recently thermal and visual simulation tools, as illustrated in (Figures:10,11).



(Fig.10) : "Design Builder" Zonal Simulation Plan of "Base-Case" Model



(Fig.11) : Section of Retrofit Simulation Façade Model

(Author)

- Simulation for both models will be run on "Simplified Model Zone" by dimensions of :(8.0 m width X 8.0 m depth X 4.0 m height floor to floor) for each model, and as for (Double Facade) simulated model will consider the full height of seven floors with continuous 'Air-Cavity', and the tested model zone will be the middle (3rd) floor of the building, to get average simulation results.
- Simulations of both models were based on an extended ten (10) working hour's schedule (weekday from 8:00 a.m. to 6:00 p.m. and two days for week end), but in 'Base-Case' model there is an additional (HVAC) operation two hours called (Set-points) in summer times for adapting the internal thermal comfort in hot days before and after working time.
- (DSF) Air-cavity is naturally ventilated (24 hours) during the whole year through a 'Multi-Storey' façade type. The air flows vertically and diagonally, entering through bottom opening and exiting through top opening on the exterior skin. The internal façade (Skin) windows opening times for internal hybrid (Mixed) ventilation is based on an extended working hour's schedule simultaneously with using (HVAC) operation schedule.
- The analytical study models were simplified in obtaining non-dependent results from other solar orientations. In this way, solar gains from other solar orientations in office zones, and internal heat transmissions were minimized focusing results on each façade orientation.
- Other orientations except tested façade model zones are treated as opaque surfaces, including ground floor. The entire building is 'Mixed-Mode' ventilated (Air-Conditioned as operational schedule, except 'Air-cavity').

8.3 Simulation Parameters Types

Any thermal simulation procedure has two types of Input data which are considered the necessary information to feed the simulation software in order to perform the thermal analysis. It is divided in two groups: the **variable** and the **fixed data parameters**. as illustrated in (table: 7).

(Table:7) - Fixed Thermal 'Inputs' data of the Building - Ref. [Author+ EECB+ ASHRAE]

Parameter	Value	Parameter	Value
Equipment thermal load	**10** W/m2	**Building total height**	28+2= **30**m
Artificial lighting thermal load	**15** W/m2	**Surround zone effect**	**Adiabatic**
Cairo Climate Data-base & Inner space requirements	As: **ASHRAE-55, 2002**	**External Glazing thickness**	**6.00** mm
'Air flow' rate	**Av. 1.00 :1.5**	**Internal Glazing thickness**	**6.00** mm
Ground Solar Reflectance	**0.3**	**External Glazing Factor(s)**	**0.60,0.38**
Occupancy sensible gain	**6.5** W/m2 (As: AHSRAE-55)	**External Skin Glazing U-Value**	**5.70** W/m2c
Occupancy Latent gain	**4.5** W/m2 (As: AHSRAE-55)	**Internal Skin Glazing U-Value**	**5.73** W/m2c
Working time schedule	**(8:0**am**:6:0** pm**)**	**Ground floor**(as Northern wall) **U-Value**	**0.30** W/m2c
Surround building heights	**0.00** m (Acts as isolated building)	**Building Roof U-Value**	**0.25** W/m2c
Tested facade height	**30**m	**Cavity, supporting elements U-Value**	**6.0** W/m2c

8.4 Methodology of Simulation Strategy

All simulations and tests of both two models :(Base-Case and Retrofit) will be run and comparatively analyzed, with respect to the following main two parameters:-

8.4.1 Orientation parameters

By applying simulation for the main four orientations: (N, S, E &West) directions, that for 'Greater Cairo & Delta' climatic zone including all up-dated and approved climatic data inputs with (EECB) such as: (day/night Temperature degrees, Relative humidity percentages, Wind loads/directions, Sun path diagram, Solar Heat-gains, etc....) that for all day and night time and all over the whole year.

8.4.2 Ventilation strategy parameters

By applying simulation for both two models as follows:-

- **For 'Base -Case' Model** (Conventional Curtain wall system):

  This model depends on **Full (HVAC) system** by using of (Chillers of Central air-condition units) for artificial mechanical ventilation supply; according to operational schedule (time-table) for (HVAC) system operation in addition to 'set-points'.

- **For “Low-Energy” design techniques (DSF) Model** ('Multi-storey' Façade type):

  This model depends on two strategies:

a- **'Mixed-Mode'/ (Hybrid) Ventilation strategy** (in day time hours):

This depends on possibility of permitting natural ventilation along specified times of the day and seasonal times, and according to pre-specified schedules for opening the windows of inner facade of (V.DSF) System.

b- 'Night-time' Ventilation Mode (all the year):

In this strategy all 'open-able' windows of the building (including inner skin windows of DSF) will be assumed to be opened in all night times all the year except in 'week-ends'.

8.5 Categories (Groups) of Simulation Parameters

By grouping the Co-related parameters and impacts which can be tested together in the same simulation group test - with respect to the pervious main two parameters (Orientation & Ventilation strategies) for each model, which can be categorized in three groups as follows, and illustrated in **(table: 7)**.

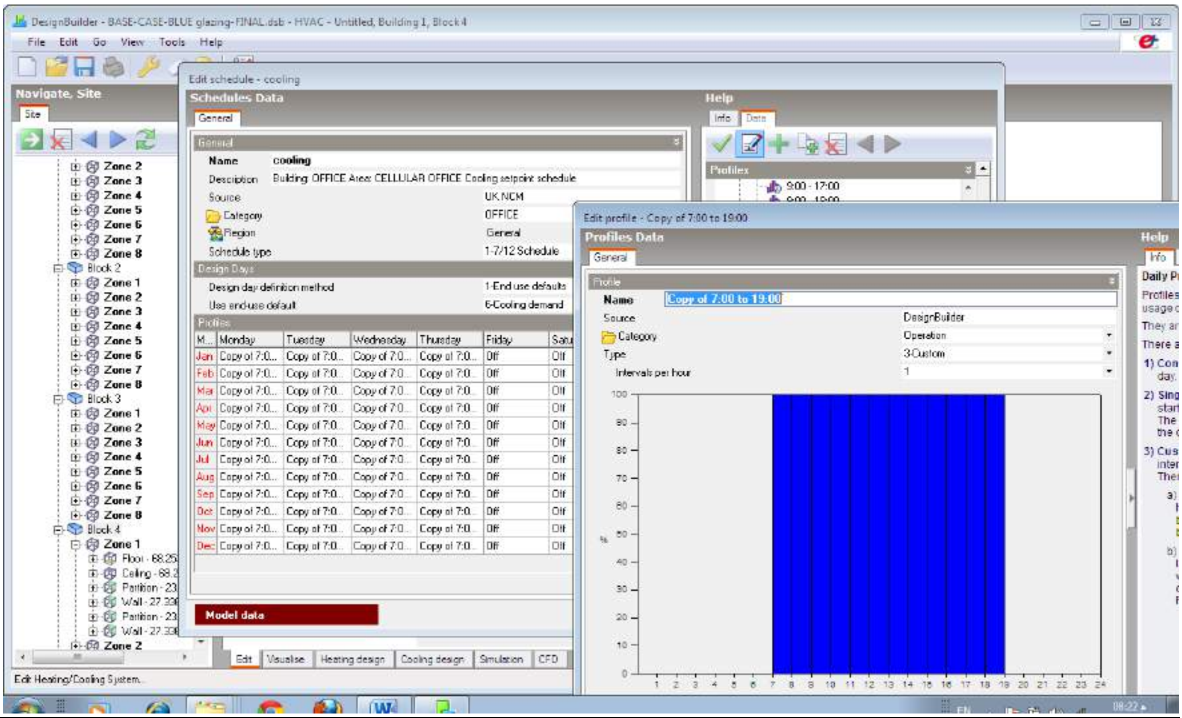
(Table: 7) – General Simulation Conditions For (HPF with DSF type) –(Ref. Author)	For: (X) Façade Orientation
Parameter	**Condition: (Case)**
Group: 2 - 'Air-Cavity' & External Opening Ratio Parameters:	
• **'Air-Cavity' (V.DSF) Type**	'Multi-story Façade.
• **'Air-Cavity' Width(depth)**	- Clear **(30:40 cm)** - Small Type - Clear **(60:70 cm)** - Medium Type - Clear **(100:110 cm)** - Large Type
• **Air-Cavity Outer Skin Openings Type / Ratio**	- From Top + Bottom / **(8%)** - From Top only **/(4%)**
• **Air-Cavity Inner Skin Openings Ratio**	**(20, 30, 40 %)** 'Open-able' as needed Windows (according to orientation)
Group: 1 - Ventilation Strategy Parameters:	
• **Inner Space Ventilation Strategy**	- **'Full Mechanical' Ventilation** as scheduled all the year in working times. - **'Seasonal-Mode' Ventilation** as scheduled all the year in working times. - **'Mixed-Mode' Ventilation** as scheduled all the year in working times.
• **Inner Court Ventilation**	Naturally Ventilated (from basement floor).
• **Night-time Ventilation Schedule**	Naturally Ventilated, From (21:00 p.m. ~ 6:00 a.m.) next day, daily & Five working days except 'Week-Ends'.
• **(HVAC) Ventilation Schedule**	- **From (8:00 ~ 18:00) daily** Five working days except 'Week-Ends' (for Full Mechanical Ventilation). - **According proposed schedule**, with respect to each façade orientation, (for 'Mixed-Mode' Ventilation).
• **Working Times**	**From (8:00 ~ 18:00) daily**& Five working days a week.
Group: 3 - Glazing System & Type Parameters:	

• **External Glazing System**	- (95%), **<u>Green Tempered</u>** Glazing + (6.m.m.) thick. Single Glazing + Inner aluminium frames. - (95%), **<u>Blue Tempered</u>** Glazing + (6.m.m.) thick. Single Glazing + Inner aluminium frames. - (95%), **<u>Green Reflected Tempered</u>** Glazing + (6.m.m.) thick. Single Glazing + Inner aluminium frames. - (95%), **<u>Blue Reflected Tempered</u>** Glazing + (6.m.m.) thick. Single Glazing + Inner aluminium frames.
• **Internal Glazing System**	(90%) Clear Glazing, (% opening ratio) + (6.m.m.) thick. Single Glazing +aluminium frames.

• **Fixed Simulation Parameters inputs** • **Variable Simulation Parameters inputs**

- **Group 1: The impact of Mechanical (HVAC) Ventilation Modes (Ventilation strategies) parameters**

By applying simulation with different mechanical ventilation (HVAC) modes on office space by scheduling the ventilation modes and times along working 'day-time' **(Figure: 12)**, as follows:



(Fig.12) : “Base-Case” and (V.DSF) Ventilation Scheduling -"Design Builder" model settings

- **Group 2: The impact of 'Air-Cavity' width & External Facade Openings Ratio parameters**

By applying simulation for different 'Air-Cavity' widths: **(small = 30:40** cm**, Medium = 60:70** cm**, Large = 100:110** cm.**)** (With the same fixed values for other parameters).

And different External skin (façade) openings ratios with**: only Top opening= (4%)** of its facade total area, and both**: Top + Bottom opening** = **(8%)** - for each case would be tested separately.

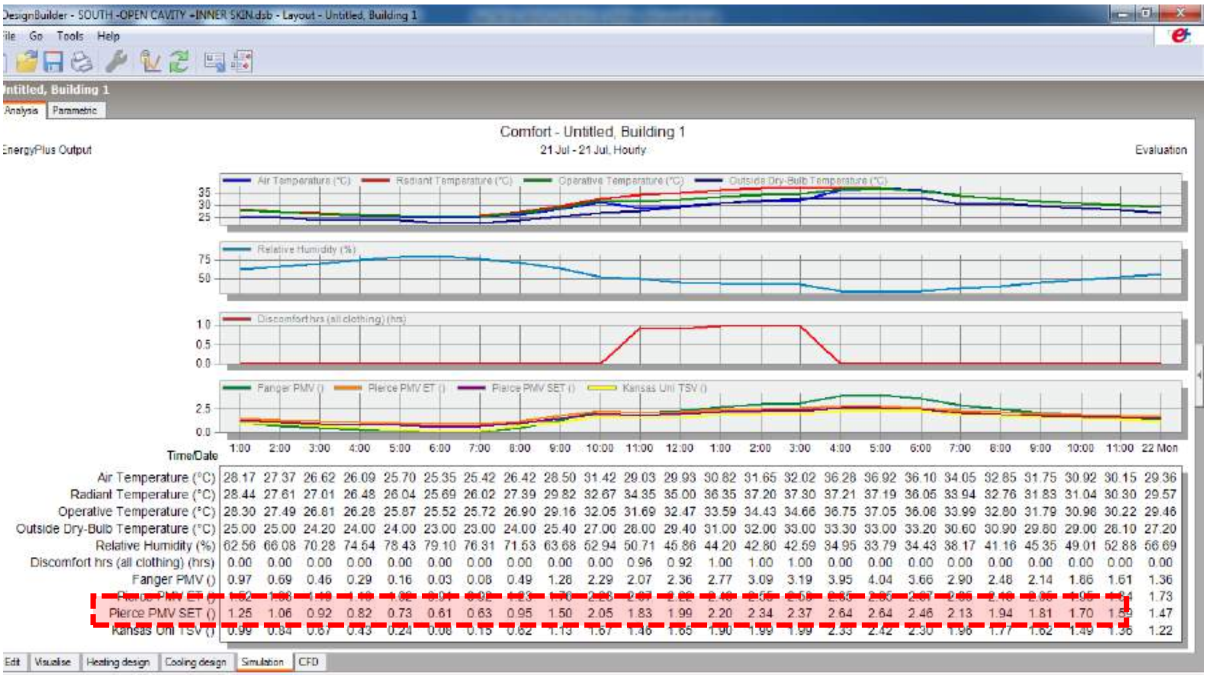
- **Group 3: The Impact of Glazing system and its parameters:** With respect to the 'Air-cavity' width and external façade opening ratio parameters

With different glazing parameters such as: **Types (Clear, Colored: green - blue, reflective: green - blue…)** – Thickness (as most local used and approved types in Egyptian market **(6** mm **in thickness).**

The simulations will be apply on each of the four (4) façades model orientations (clock wise: N, E, S, and W) and default ventilation strategies (Selected from Group: 1 analysis) and with proposed schedule of internal façade correspondent opening ratios.

8.6 Required Simulation Results

Both "Design Builder" soft-ware tool and (Energy Plus) Simulation engine give a wide range of detailed results, as shown in (Figure: 13), but the research will focus on the thermal heat gain Loads and Energy consumption results (due to ventilation), which have a direct, notable and great impact on Economic & Environmental behaviour of the simulated façade models, these results can be classified as their importance as follows:-



(Fig.13) : Cooling loads calculations and (PMV) Check -"Design Builder" simulation outputs

- **Total Energy Consumptions (EC)** (kWh)**:**
  By monthly and annually ratings of total Electricity consumptions due to Ventilation Loads, to calculate the monthly cost of energy consumption according to Local Electricity 'Price-list' for commercial and service buildings type then annual operational cost / saving according to façade alternative.

- **Equivalent Energy Consumptions per façade unit area**(kWh/m2)
  By monthly ratings of Electricity consumptions due to Ventilation Loads divided by façade area of tested zone as follows:

9. Conclusion & Findings

Many cities around the world are facing the problem of increasing urban density and energy demand. Such cities represent a significant source of growth in global energy demand; their energy use, associated environmental impacts, and demand for transport services create Great pressure to our planet. After the previous exploration, analysis, and simulations we can conclude the paper findings as follows:-

9.1 With respect to energy efficient design in high urban density zones:-

- A high density urban area, obtained by a mixture of high and low buildings, could have better ventilation conditions than an area with lower density but with buildings of the same height.
- The use of natural lighting, natural ventilation, and solar energy is also affected by closely spaced or high rise buildings. If not properly planned, energy for electric lighting and mechanical cooling/ventilation may be increased and application of solar energy systems will be greatly limited.
- The denser city models require more careful design in order to maximize energy efficiency and satisfy other social and developmental requirements.
- “Low-energy” design should not be considered in isolation, and in fact, it is a measure which should work in harmony with other environmental objectives.
- Building energy study provides opportunities not only for identifying energy and cost savings, but also for examining indoor and outdoor environment quality.
- From psychological and sociological points of view, high population density and the effect of crowding are interesting topics which have attracted much attention.
- A crowded and stressful urban environment may have unhealthy effects on the occupants, such as air pollution and noise problems. But the level of mobility and traffic speeds will benefit the working and living of the people.
- It should be noted that “density” and “crowding” are not necessarily found together, People who live under crowded conditions may not suffer from being crowded if the built environment has been designed to provide enough personal space and functional open space.

9.2 With respect to application of “Low-Energy” design assumptions and techniques:-

- The application of simulation on External Glazed Facade (DSF) model reduces the total energy consumptions due to both: (HVAC) ventilation & people occupancy by more than (50%: 65%) with respect to correspondent "Base-Case" Façade type.
- Application of ventilated (DSF) type with full (HVAC) ventilation mode only; reduces the total energy consumptions by about (35: 42%).
- The lower energy consumptions of (DSF) orientations in descending arrangement were: [North (N), East (E), South (S), and West (W) respectively.
- "Air-Cavity" width: The larger "Air-Cavity" width, the lower energy consumption (but with little rate in reduction) after (40 cm) width.
- "External Skin" opening ratio: The larger "External Skin" ratio, the lower energy consumption (but with little rate in increasing) due to vanishing of "Stack-effect".
- "Glazing System" type: the more improving of (DSF) Glazing system the lower energy consumption. Ascending by improving: Layers (Single, double, triple), Type (Clear, Colored, Reflected, Coated with 'Low-E', Electrical) and Thickness (4, 6, mm

/pane).As a result of reducing glass (SHGC), U-value, and increasing Light Transmission Values (LT).

- Application of "low-energy" techniques reduced the needed of (HVAC) machines, and their equipment capacities with respect to the needed for the same building with correspondent single skin façade (conventional "Curtain-wall" façade type) as the following ratios:

Façade Orientation	The Reduction Ratio (%) from (HVAC) Equipment Costs Due to application of "Low-Energy" design techniques
(N)	8
(E)	10:13
(S),(W)	32:48

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Modeling natural ventilation in commercial buildings using data-driven methods

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Abstract: This work summarizes findings from the long-term research on modeling occupants' interactions with operable windows in commercial buildings. For that purpose, the monitoring data from two commercial buildings located in Germany with natural and mixed mode ventilations were analysed and suitable machine learning modeling approaches were investigated. In particular, three research questions were addressed. Firstly, the conventional machine learning was explored for developing the occupant-wise calibrated occupant behaviour (OB) models. Secondly, large scale data were used to develop a deep learning-based model that was tuned on a building level. Eventually, the predictive model for natural ventilation was developed for the application in model predictive control (MPC) in real-time building automation systems (BAS). The results showed, that both the random forest algorithm and the deep neural network could model imbalanced OB data with a satisfying accuracy.

Keywords: occupant behaviour, natural ventilation, deep learning, random forest

1. Introduction

OB was identified as one of the main drivers that impacts the energy consumption in commercial buildings (Wagner et al. (2017), Azar et al. (2014), Hong et al. (2015)). In particular in case of European buildings, the OB in terms of window openings was identified to have a significant impact on the thermal gains and losses (Fabi et al. (2012)). Therefore, realistic representation of natural ventilation is necessary to model the overall energy consumption. However, the reliable modeling of natural ventilation becomes challenging in case of mixed mode buildings, since the occupants' actions that were driven by from thermal/physiological needs or behavioural habits may result in a set of different actions such as turning on/off mechanical ventilation, adjusting thermostats or opening the windows.

Motivated by the impact of occupants' on the energy consumption in buildings (Hoes et al., (2009)), this paper addresses the modeling of window opening-related OB in commercial buildings. For that purpose, an extensive literature review was conducted and data-driven OB models in buildings were developed.

The remaining document is organized as follows: the existing studies on data-driven OB modeling were summarized in section 2. For readability reasons, all used abbreviations are listed out in Table 1. Section 3 described the research workflow and the core ideas behind the conducted OB modeling for its' inclusion in building performance simulation (BPS) and BAS. The results and model comparisons are presented in section 4. The key findings are elaborated and summarized in section 5. Eventually, the outlook and the future challenges are presented in section 6.

Table 1. List of used abbreviations.

ACC	accuracy	MPC	model predictive control
BAS	building automation system	OB	occupant behavior
BPS	building performance simulation	PGM	probabilistic graphical models
ERC	energy research center	SVMs	support vector machines
HMM	hidden Markov model	TNR	true negative rate
k-NN	k-nearest neighbor	TPR	true positive rate

2. Related research

Although data-driven methods and machine learning have already been the focus of research of a number of studies for OB modeling, there is little research available on their application for natural ventilation and window opening modeling. As a result, the findings from the previous studies on general OB and occupancy modeling were reviewed, and an overview of the existing applications is presented in Table 2. Based on these, a set of suitable data-driven methods was identified, namely decision trees, support vector machines (SVMs), probabilistic graphical models (PGMs), neural networks and statistical methods.

Table 2. Overview of the existing studies that applied machine learning approaches for modeling the OB in buildings. The studies were grouped based on the used modeling algorithms.

study	decision trees	SVMs	PGM	neural networks	further methods	statistical methods
Andersen et al. (2013)						X
Basnayake et al. (2015)					fuzzy logic	
D'Oca and Hong (2014)					clustering	
D'Oca and Hong (2015)	X					
Dobbs and Hencey (2014)			X			
Dodier et al. (2006)			X			
Dong and Andrews (2009)			X			
Dong and Lam (2014)			X			
Hailemariam et al. (2011)	X					
Khosrowpour et al. (2016)		X				
Liang et al. (2016)	X					
Liao et al. (2012)			X			
Li and Dong (2017)		X	X	X		
Li and Dong (2017a)			X			
Li and Dong (2018)		X	X	X		
Peng et al. (2017)					K-NN	
Peng et al. (2018)					clustering	
Reinhart (2004)						X
Richardson et al. (2008)			X			
Ryu and Moon (2016)	X		X			
Wang et al. (2005)						X
Wang et al. (2018)				X		
Yu et al. (2011)	X					
Zhao et al. (2014)	X		X			

Decision trees were applied by multiple studies for modeling the occupancy in commercial buildings (Liang et al., (2016), D'Oca and Hong (2015), Candanedo and Feldheim (2016)). Their results pointed out, that decision trees could realistically reconstruct the occupancy patterns, while keeping the model complexity low, compared to alternative modeling methods such as neural networks.

As an alternative to decision trees, PGMs were also applied to model the occupancy (Tijani et al., (2015), Li and Dong (2017)), as well as energy consumption (Li et al., (2016) and Sokol et al., 2017). Additionally, Tijani et al. (2015) pointed out that the PGM could be used to describe the causality of the occupants' actions, in a manner similar to humans' reasoning.

SVMs are a class of machine learning algorithms that learn to extract a pattern behind input features (Magoulès and Zhao (2016)) that result in deterministic, convex problem formulation (Boyd and Vandenberghe (2004)). The idea behind the SVMs is to maximize the margin between the data points that belong to different classes (Magoulès and Zhao (2016)). SVMs found application for modeling the occupancy in commercial (Li and Dong, (2018)) and residential buildings (Li and Dong (2017a)). The pointed out, that the SVMs could predict the occupancy patterns in residential and commercial buildings with similar performance in terms of accuracy, when compared to Hidden Markov Models (HMM) and neural networks.

Additionally, alternative methods such as fuzzy logic, neural networks, and K-nearest neighbour (K-NN) were explored for applications such as occupancy identification, HVAC control and occupants grouping (Basnayake et al. (2015), D'Oca and Hong (2014), Peng et al. (2017), Peng et al. (2018), Wang et al. (2018)).

3. Method Overview

The overview of the research steps is presented in Figure 1. An extensive literature research was conducted and the existing data-driven approaches for modeling the OB in buildings were summarized. Based on the findings from the latter, the key challenges regarding the OB modeling were identified. These included the "data imbalance" of OB data and the models' scalability with the increased number of occupants.

Once the latter modeling challenges were detected, suitable data driven methods to address these problems were explored. For that purpose, two sets of experiments were conducted. The first batch of experiments included the research on the applicability of conventional machine learning algorithms for modeling the human actions in buildings. In the scope of second batch of experiments, deep learning methods were applied to model the occupants' interactions with windows in commercial buildings. Here, the main goal was to develop an OB model, that could model a wide range of occupants without the need for occupant-wise model calibration.

Eventually, the set of developed models for human building interactions were tested for their practical potential. The practical applications of the OB models included the BAS and BPS. However, in cases of BAS and BPS different implementation problems needed to be tackled, and a non-unique modeling objective should be fulfilled. Namely, BAS require a real-time capable model, that could deliver the prediction of the future actions. In case of OB modeling for the incorporation in BAS, the models could benefit from the time-series properties of continuous data streams in building control.

Hence, the reliable reproduction of such high resolution time-series of indoor climate in BPS environment may be unfeasible, even in case of well calibrated building physics models. On the other side, the OB model for the BPS application could result in a lower model complexity, since in the BPS settings the OB should be identified, instead of predicted for the future time steps. Due to these diverging requirements for BAS and BPS, two separate modeling approaches were proposed. Here, in case of BPS a model that identified the OB was formulated, while the potential of time-series modeling of OB was explored for the application in BAS.

Eventually, the OB identification- and prediction performance was qualitatively and quantitatively analysed and compared to the baseline model. The baseline model was defined as a logistic regression that used indoor- and outdoor temperature as model inputs. This choice was made based on the findings of previous studies, that were accepted as the established modeling approach in the research community (Rijal et al., (2008), Haldi and Robinson, (2009)).

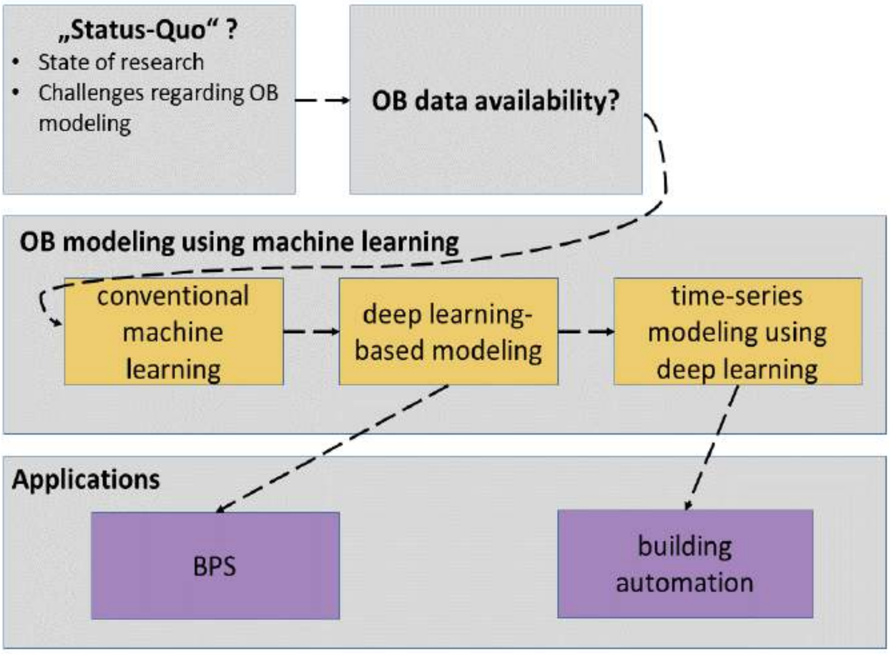

Figure 1. Overview of the conducted research on data-driven OB modeling.

3.1. Used data

The models were developed using the long term monitoring data from two commercial buildings located in Frankfurt and Aachen, Germany. In the first building, namely "KfW Ostarkade", monitoring data were collected in naturally ventilated single- and two-person offices (Kleber et Wagner, (2006)). The monitoried variables include the weather on site, indoor climate and occupant-related features, such as window states, occupancy and position of sun protection. The second building, namely "E.ON ERC" is an research centre with single and double offices, located in Aachen, Germany. The mixed-mode ventilation is available in all offices that were available in the data set. The used monitoring data set consisted of weather data from the nearby weather station, indoor climate and OB in terms of occupancy and the window openings. For additional information on monitoring data, the reader is referred to Fütterer and Constantin (2014) and Markovic et al. (2018).

3.2. OB modeling for BPS

Occupant-wise modeling using conventional machine learning

Initially, traditional machine learning methods were applied to model the window opening states in commercial buildings. The core idea was, to develop a modeling approach, that was capable to learn window opening behavior and resulting window states, based on input variables that were defined using domain engineering knowledge. Additionally, the models' complexity was aimed to remain low, in order to make the occupant-wise model adaptability computationally feasible. Therefore, window opening models using SVMs and random forest classification were investigated (Markovic et al., (2017)). For that purpose, the window states were defined as a binary classification problem, based on 11 input features, while the particular attention was put on achieving an optimal accuracy for the imbalanced data.

Building-wise modeling using deep learning

A deep learning driven OB model was developed to predict the window states, where the focus was put on model scalability for a large number of occupants that were not seen during training procedure. Based on previously conducted occupant segmentation (Markovic et al., (2018)), the model was trained using data from 3 single- or two-people offices, while it was evaluated using data from additional 49 offices. The model development included research of the impact of the neural networks' architecture and hyperparameters on the predictive performance and learning capacity. For further technical details, the reader is referred to Markovic et al. 2018, while the developed model is publicly available in the form of a Git repository[1].

3.3. OB modeling for BAS

Based on the findings from machine learning- and deep learning driven window opening modeling, a window opening model for the inclusion in BAS was developed. For further technical details and research steps, the reader is referred to Markovic et al., (2019). The model used minute-wise indoor climate measurements over the previous 60 minutes, in order to make the prediction of the future occupants' actions and resulting window states on the time horizon of 10 minutes in the future.

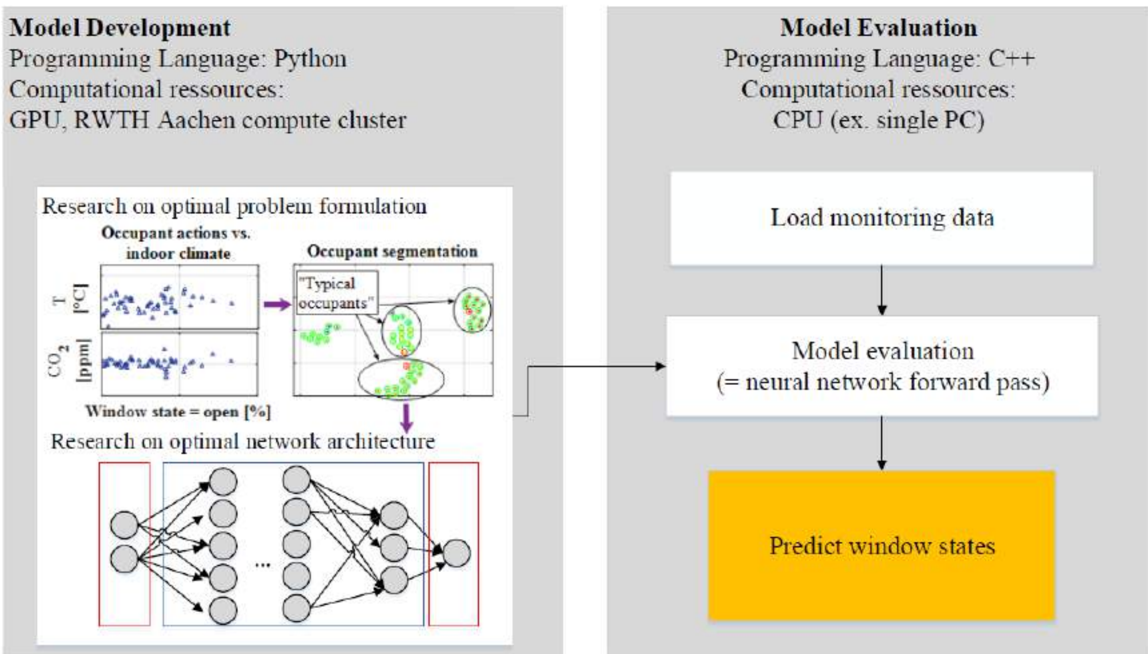

Figure 2. Computational setting for the research on OB modeling (left side) and the OB model's inclusion in real time BAS (right side).

[1] https://git.rwth-aachen.de/romana.markovic/window_opening

An overview of the models' implementation is presented in Figure 2. The model was developed using large-scale computations that were hosted at the Compute Cluster at the RWTH Aachen University (Figure 2, left side). Similarly to the model described in section 3.2, the development included research on an optimal problem formulation and the impact of network architecture on modeling the time-series of OB. Eventually, the trained model was exported for the implementation in real-time BAS. Therefore, the monitoring data were loaded for the online model evaluation. These monitoring values were used for the prediction of the future window states, which were defined as an input for the model predictive HVAC control (MPC).

4. Results

The predictive performance on the evaluation set was summarized using absolute metrics as previously introduced by Markovic et al., (2017). They consisted of accuracy (ACC), true positive rate (TPR), true negative rate (TNR) and F1-score. For additional information on the used evaluation protocol, the reader is referred to Markovic et al., (2017) and Markovic et at., (2018).

4.1. OB modeling for BPS: Occupant-wise model calibration

The performance of the occupant-wise OB modeling using conventional machine learning was compared to the baseline model and the results are summarized in Table 3. The results pointed out, that the proposed methods could handle data imbalance better, when compared to the two-variable logistic regression. As a result, the proposed methods correctly identified approximately 65 % of the opened windows correctly on the data set used in the original study (Markovic et. al, (2017)). In the scope of evaluation using an independent data set (E.ON ERC data), SVMs and random forest could identify 30 % and 48 %, respectively.

Table 3. Summary of the model evaluation results. The model originally developed using KfW Ostarkade data set was evaluated using the E.ON ERC data set. Additionally, the results were compared to recalibrated two-variables logistic regression that was defined the be the baseline model.

Method	KfW Ostarkade				E.ON ERC			
	ACC [-]	TPR [-]	TNR [-]	F1 [-]	ACC [-]	TPR [-]	TNR [-]	F1 [-]
SVMs	0.83	0.64	0.87	0.78	0.92	0.3	0.96	0.72
random Forest	0.89	0.65	0.94	0.82	0.94	0.48	0.96	0.77
logistic regression	0.77	0.27	0.92	0.69	0.94	0.24	0.98	0.72

4.2. OB modeling for BPS: Building-wise model calibration

The results of the building-wise model calibration using a deep learning model are presented in Table 4. The results obtained from the original study (Markovic et al., 2018) are expanded and compared to the results obtained by the calibrated baseline model, namely, two-variable logistic regression. The results showed, that the deep learning model classified 89 % and 73 % of the window states correctly on the two used data sets. In case of the logistic regression classification, the accuracy ranged between 93 % and 74 %. Resultantly, the performance of the logistic regression was in the similar range, when compared to the building-wise calibrated deep learning model, in case of a naturally ventilated building (KfW Ostarkade). Hence, in case of the mixed mode building, namely E.ON Energy Research Center (in further text referred as E.ON ERC), the logistic regression could not reliably identify the opened window states.

Table 4. Model comparison results. The results of the deep learning modeling from Markovic et al., (2018) were summarized and compared to the two-variable logistic regression.

method	E.ON ERC				KfW Ostarkade			
	ACC	TPR	TNR	F1	ACC	TPR	TNR	F1
	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]
deep learning method	0.89	0.52	0.92	0.65	0.73	0.76	0.71	0.74
logistic regression (baseline model)	0.93	0	1	0	0.74	0.6	0.82	0.67

4.3. OB modeling for BAS

In case of the application in BAS, the modeling target was shifted from current time-step, to predicting the window states ten minutes in future, which corresponded to time-horizon of ten time-steps. The evaluation results are analysed (Markovic et al., (2019)) and the key performance metrics are summarized in Table 5. The results showed, that 88 % of the window states could be correctly predicted ten time-steps in future, while 37 % of the correct window states could be correctly identified.

Table 5. Predictive performance of the time-series based model for the application in BAS.

	E.ON ERC			
	ACC	TPR	TNR	F1
	[-]	[-]	[-]	[-]
Time-series for OB prediction	0.88	0.37	0.92	0.51

5. Discussion

The performance of occupant-wise OB models was researched for classification models that were identified as suitable based on the current applications in the fields of applied machine learning. Additionally, the models' choice was made based on the specific requirements of modeling the OB data, namely, data imbalance and the need for representing occupant' diversity. The modeling results showed, that the machine learning approaches outperformed the baseline models on both data sets.

In the scope of the second batch of experiments, a building-wise calibrated window opening model was developed using deep learning methods. In the scope of this study, the performance on two independent data sets was presented and compared to the building-wise calibrated baseline model. In case of the mixed-mode ventilation, the deep learning model outperformed the baseline model by a large margin. Hence, in case of the evaluation using a data set where 30% of the input features were missing, namely KfW Ostarkade, the performance of the data driven model was in the same range as the baseline model.

Eventually, the potential of model predictive natural ventilation modeling for the inclusion in BAS for HVAC control was investigated. The results showed, that 88 % of the future window states could be correctly predicted, while 37 % of the opened windows could be predicted and used as the input for MPC.

This long term study focused on modeling the OB in continental climate. The used long term monitoring data were collected in Frankfurt and Aachen in Germany. Thus, the gained knowledge and the proposed modeling formalism would be beneficial for predictive models in case of extreme climate conditions. In particular, the OB models' for the extreme climate must address the data imbalance, in order to correctly predict the occupants' actions as the rare events. The data imbalance of occupants' actions was already investigated in the scope of this study, and the gained knowledge could be beneficial as the starting point for the model formulation in case of extreme climates. Secondly, a suitable modeling approach should be proposed to represent the occupants' diversity under unusual weather conditions. It would be interesting to evaluate the potential of proposed modeling approaches in case of extremely hot or humid climate conditions. In these cases, the proposed modeling approaches may be applied for predicting the alternative OB, including but not restricted to the use of air conditioning or ventilation. These scientifically important questions are still open, and they should be addressed in future research.

6. Conclusion and Outlook

This works presented the findings of the long-term research on modeling the OB in terms of natural ventilation. The study proposed OB modeling using machine learning and deep learning methods that are novel in the field of human centered buildings. The findings of the data-driven machine learning modeling could be used as a supporting tool to the experts in fields of occupant cantered building automation and architectural design. In particular, the application of novel machine learning approaches could be beneficial in cases where the application of the conventional research methods from the latter fields is not feasible due to the large amount of occupants' data or where the causalities of the occupants' actions are still not defined by the domain knowledge.

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A paradigm shift in comfort design for Singapore

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Abstract: In Singapore, where low temperature air conditioning represents the well-established standard, leaving this conventional path and introducing a high comfort design with higher room air settings in combination with breeze and excellent fresh air supply is almost precluded by the system and poses a challenge to clients and design teams. Today, there are few buildings designed on purpose with this Hybrid System Design for Adaptive Comfort. Adaptive Comfort concepts deliver the same comfort but with lower reliance on mechanical systems. Combined with Hybrid System Design, the ventilation and cooling systems can be substantially downsized, reducing investment cost as well as substantially reducing energy demand for ventilation and space cooling. This paper is about the design verification of a Hybrid System Design, on the example of a student hub space at a university building in Singapore. To address typical questions during a design process arising from this new design approach, the performance of a conventional air conditioning system is systematically compared to the performance of a Hybrid System Design using dynamical thermal simulation. Relevant comfort parameters are compared on an hourly time base with additional focus on space humidity. Challenging basic design assumptions from client's brief and schematic architectural design, the path to a high comfort – low tech – low energy design is made transparent to inform client and design team.

Keywords: SET, PMV, Adaptive Comfort, Tropical Comfort, Singapore

1. Why challenge conventional air conditioning design in the tropics?

The global community is searching for realistic options to reduce the use of fossil fuels. The vastly growing building sector will be one of the major concerns in the next 25 years. Between 2010-2030, 84 billion m² of new and rebuilt buildings will be constructed in cities worldwide. That is the equivalent to the rebuilding of the entire US building stock three and a half times over. Nearly 60% of global development will occur in Asia, about 9% in Latin America, and most of these new buildings will be constructed in tropical, warm and humid climates (McKinsey, 2015). In maintaining the type of indoor conditions, we have learned to universally expect, buildings require massive energy inputs. The way we define comfort plays a significant role in this. What if we challenge this definition? Are the conventional targets to cool and condition spaces the only way to achieve thermal comfort?

There is plenty of evidence that unlocking MEP design from very tight comfort envelopes is key to improving thermal comfort and reducing systems and energy demand. Many technical papers and reports highlight the energy saving potential of increased set point temperatures.

Going beyond that and designing for higher indoor temperatures and humidity levels in combination with elevated air speed requires that the design options are evaluated, and performance is verified with dynamical thermal simulation (Kessling et al, 2017).

1.1. Hybrid System Design: high comfort – low tech – low energy

The concept of Hybrid System Design combines excellent supply of tempered fresh air with fans that elevate air speed to satisfy thermal comfort requirements. The fresh air rates are designed for good indoor air quality (IAQ) and to keep carbon dioxide (generated by occupants) and other air pollutant levels low. With rising indoor temperatures, the occupants can elevate the air speed at their location as per their personal preferences. Typically, the air speed can range from a low breeze (0.3 m/s) to a slightly noticeable airflow (1 m/s).

1.2. The design process for Hybrid System Design with Adaptive Comfort

In conventional HVAC design cooling loads are evaluated to guarantee that these maximum indoor air temperatures and humidity levels are never exceeded. This is simple and widespread, there are many computer design tools available which directly evaluate the internal and external cooling loads and proposed system design. Many of them perform a cooling load evaluation for a single maximum design point. The complex question of thermal comfort is reduced to a temperature and humidity set point.

When designing for Adaptive Comfort, six environmental and personal parameters, air temperature (Tair), mean radiant temperature (MRT), relative humidity (RH), average elevated air speed (v), clothing factor (clo) and metabolic rate (met), are considered. This requires that the building design be evaluated with dynamic simulation tools and adaptive models be applied to verify comfort. The design focus is shifted from air temperatures (or operative temperatures) to more comprehensive comfort parameters: Predicted Mean Vote for elevated air speed (PMVeas) and Standard Effective Temperature (SET). The greater set of parameters introduces greater complexity but offers more opportunities to create comfortable conditions.

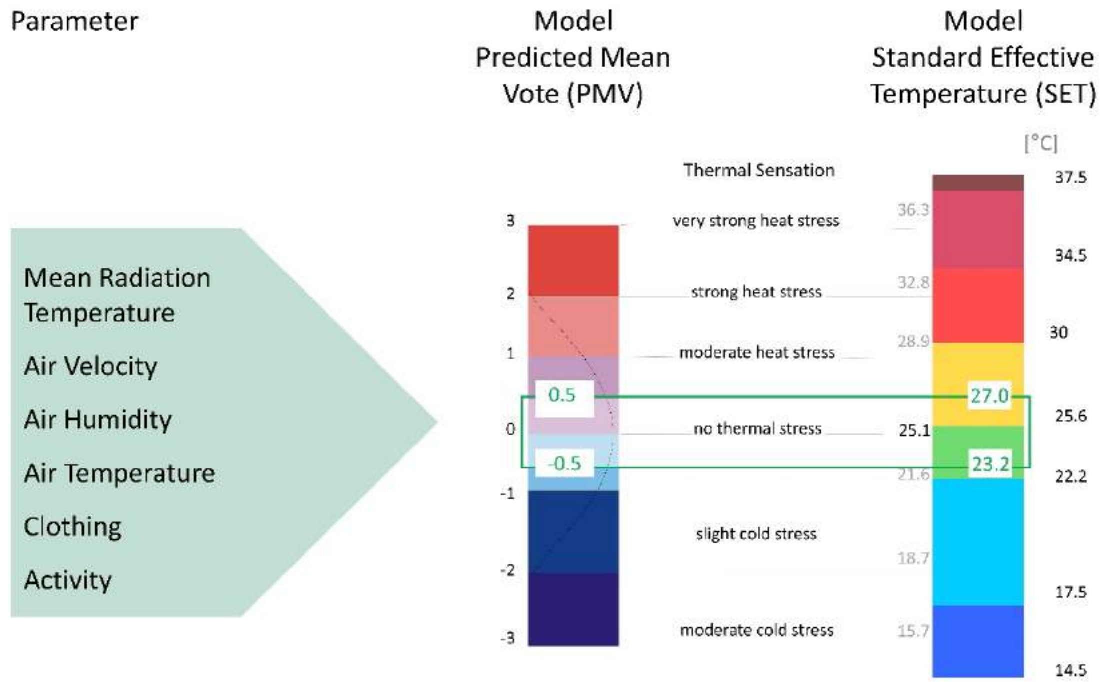


Figure 1. Six environmental and personal parameters are considered in advanced thermal comfort models. The green box indicates compliance with ASHRAE standard 55: +/- 0.5 PMV, which is equivalent with 90% of the occupants being satisfied with their thermal environment. In the context of tropical environments (rh = 70%, v =0.7 m/s, met= 1.1, clo= 0.5) this is equivalent to a range 23.2 to 27.0 °C SET.

Adaptive Comfort models, developed based on extensive field studies across the world, describe the cooling effect of breeze (Humphreys et al. 2016). With ASHRAE Standard 55-2013, Appendix G, Addendum d, a procedure and simulation code for evaluating the cooling effect of elevated air speed with the thermal comfort Parameters PMVeas and SET is available (ASHRAE 55, 2013). The code and a methodology to evaluate a design for Adaptive Comfort was implemented in the TRNSYS 18 building simulation package (TRNSYS 18, 2017).

The authors are aware that the terms Adaptive Comfort and Hybrid System Design need further clarification and might stretch their conventional meaning. In practice, within projects, this is partly intended to initiate a discussion with clients and design team to lay the grounds for an informed discussion about re-thinking comfort. We use these terms in the absence of better ones.

2. Design evaluation for a student hub in Singapore.

In the following the design evaluation for a student hub for a new university in Singapore is presented. Purpose and scope is to show how client and his MEP team as well as the architects can be informed on design alternatives to conventional air conditioning.

The first set of studies (section 3) is dedicated to questions of thermal comfort and indoor air humidity. With conventional air conditioning design issues such as sick building syndrome, cold draft, low comfort because of low temperatures, mold, noise, etc. are typical complaints in buildings, including university buildings. Reasons, underlaying most of these complaints, are reduced with Hybrid System Design. Even though the client and his MEP team raised concerns including:

- what is the indoor air quality in terms of CO2 level?
- what is the thermal comfort if temperatures are raised?
- what is the indoor relative humidity and how can mold be prevented?
- what are the consequences for system design addressing mold risk?

A second set of evaluations (section 4) is targeting to highlight design options to improve passive and active design of the building and system including the questions:

- what are the consequences for system design if state of the art assumptions for appliances and artificial light are considered?
- what are the consequences for system design if the thermal quality of the envelope is improved?

For all comparisons only the system design: Full AC or Adaptive Comfort has been different. All other assumptions such as outdoor supply air ratio, passive design of the building and internal loads have been similar.

Table 1. Initial design criteria for space, loads and envelope

area	21m x 13m = 272m²
room height	4.5m
occupancy	42 people (6.5m²/person)
	Mo.–Fr. 8:00 – 23:00 (schedule)
electrical gains	10W/m² (light)
	16W/m² (104 W/person)
window wall ratio	0.16
window	single, u-value 5.5W/m²K, film, g-value 0.45
overhang	as per architect’s facade design
opaque walls	u-value 3 W/m²K
side walls	internal (light), adiabatic
floor cover	stone
infiltration	0.1 1/h when system in operation

	0.3 1/h when system off

2.1. Methodology of design verification

To address the questions during a design process arising from this new design approach the performance of a conventional air conditioning system (Full AC) is systematically compared to the performance of a Hybrid System Design (Adaptive Comfort) using dynamical thermal simulation.

The space is conditioned with the cooling effect of the tempered supply air and with an additional cooling system in case of higher cooling loads. This could be a fan coil unit in the space or a return air system. The approach with a return air system design was considered as per preference of the clients MEP team. For the different load options, the size of the return air systems are evaluated to compensate the remaining cooling loads considering the passive building qualities and internal loads.

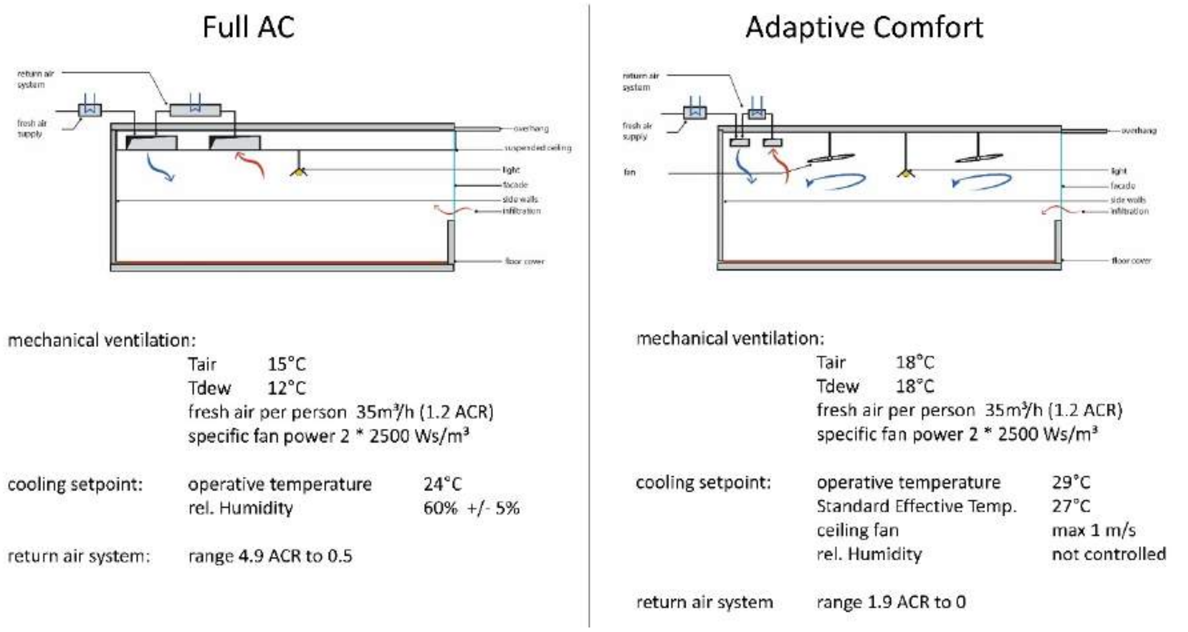
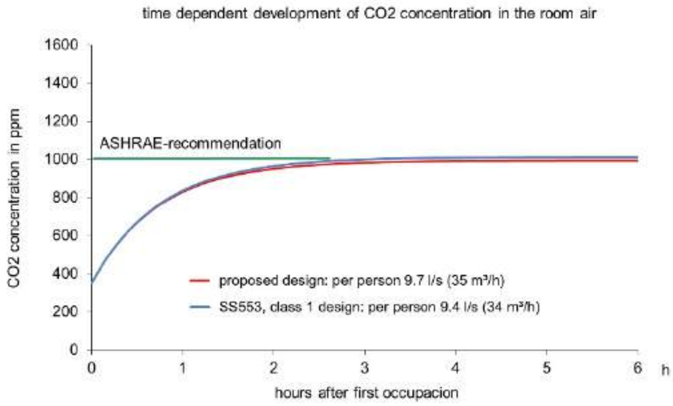


Figure 2. Design settings for the VAC design, left AC design, right Adaptive Comfort design.

For the conventional Full AC system, the cooling set point is 24 °C operative temperature. For the Adaptive Comfort system cooling set point is 27 °C SET. The comfort effect of ceiling fans is evaluated with an algorithm identifying optimal air speed in a range of 0 to max 1m/s (Kessling et al 2017).

2.2. What is indoor air quality in terms of CO2 levels?

The concept of Hybrid System Design is to create an excellent fresh air supply and to maximize the cooling effect of the tempered supply air (Franke et al 2014, Kessling at al 2017). The fresh air rates typically range from 18 cfm (30 m³/h) up to 27 cfm (45 m³/h). Supply air is typically tempered to 18 or 20 °C and dew point with no further controlled dehumidification. According to the Singaporean code of practice SS 553, class 1, the outdoor supply air for the student hub shall be in the range of 34 m³/h and person keeping the indoor CO2 level during occupancy in the range of maximal 1000 ppm as recommended by ASHRAE for good IAQ (see Figure 3). For all studied options the same outdoor air rate is established.



Design criteria for fresh air supply according Singapore code of practice SS553, class 1, for office type common areas:

specific fresh air supply per area:	0.6 l/sm²
specific fresh air supply per person:	5.5 l/sm²
density of occupancy according brief:	6.5 m²/person

resulting outdoor fresh air: 9.4 l/s person ~ 34 m³/h person

Figure 3. Development of indoor CO2 level for proposed outdoor air supply rate.

3. Analysis of thermal comfort and humidity conditions

Relevant comfort parameters are compared on an hourly time scale. In the following the results for conventional Full AC design are shown on the left side to be directly comparted to results for Adaptive Comfort given on the right side. Both systems create comfort but in different ways.

With the basic façade design walls and windows have high radiant temperatures. With the Full AC design the air temperatures need to range low with 20 to 21 °C to compensate high MRT and to create operative temperatures of max 24 °C. Air temperatures always need to be lower than outside air temperatures (see Figure 4).

With Adaptive Comfort design air temperatures range around 26 °C. With breeze (technically: elevated air speed, EAS) the SET is lower than the air and the operative temperatures. As air temperatures are closer to outside air temperatures heat losses are reduced. This would also allow to open the windows for natural ventilation when outside conditions allow. Because indoor and outdoor temperatures are close the risk of mold is considered to be lower as is case of combining natural ventilation with full AC.

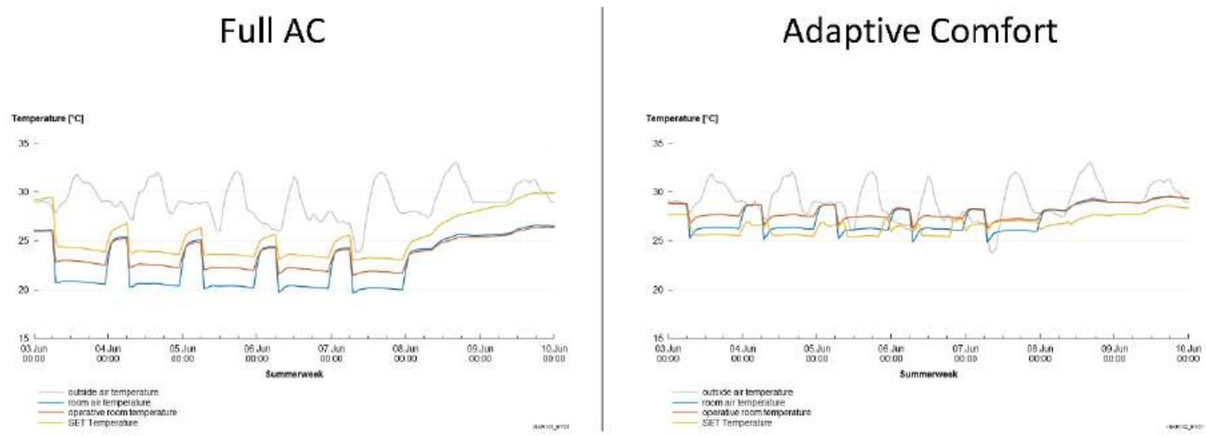


Figure 4. Comparison of temperatures. Both systems create comfort but in different ways.

3.1. What are the effects on thermal comfort if temperatures are raised?

With the Full AC design operative temperatures range up to 24 °C, SET ranges from 22 to about 25 °C. With the Adaptive Comfort design SET ranges from 25 to 27 °C and operative temperatures range up to 29 °C. Both systems provide excellent comfort.

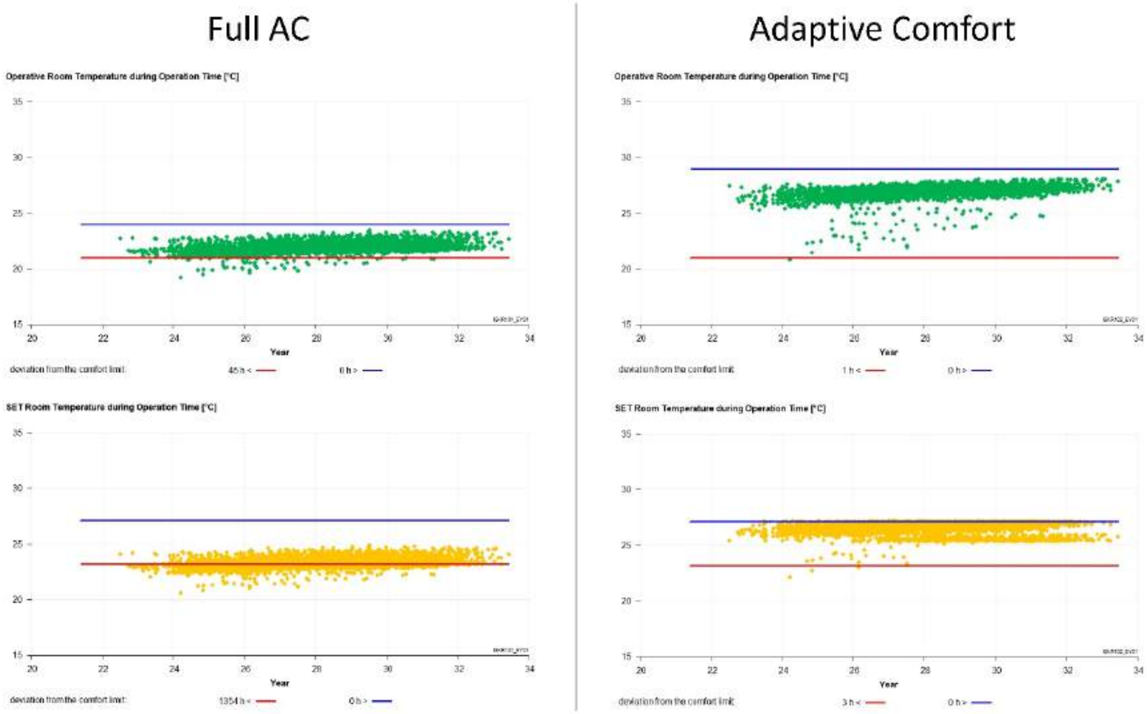


Figure 5. Comparison of operative and SET temperatures.
Both systems create excellent comfort during occupation hours.

3.2. What is the indoor relative humidity and how can mold be prevented?

Even though problems with mold are typically an issue of overly cooled spaces and lesser reported of spaces which operate at higher temperatures the MEP designer insisted in verifying indoor air humidity in greater detail. For air conditioned spaces, Singapore code of practice is prescribing indoor relative humidity shall be below 65% RH during occupation. There are no limits for off hours when systems might be turned off. In Singapore, humidity loads origin from people and infiltration. Humidity is removed from the room with the cooled and dehumidified supply air. With the lower temperatures in the Full AC system supply air has to be dehumidified to lower humidity (12 °C dew point). With the Adaptive Comfort design supply air is cooled and dehumidified to 18 or 20 °C air temperature and dew point (see setpoints in Figure 2). Humidity in the space is not controlled. Both systems operate in slight positive pressure to reduce infiltration.

The study (see Figure 6) unveiled that Full AC design, when mech. systems are in operation the relative humidity (RH) is within the design range < 65 %. When mechanical systems are shut down, the RH is increased due to infiltration up to nearly 100%. This is mostly because thermal mass is keeping the room air cold. About 3386 h are with RH > 65%, 2651 h with RH >= 75%, and about 870 hours with RH > 90%.

With the Adaptive Comfort design when mech systems are in operation the RH is ranging up to 75 %. When mechanical systems are shut down, also the RH is increased due to infiltration. Because the thermal masses are not cooled that much, ranges of RH and risk of mold are reduced because of higher indoor air temperatures. The RH is ranging up to 85% with about 2235 hours with 75 % =< RH < 85%. There are no hours with RH > 90%.

This analysis clearly underpins that risk of mold is increased at afterhours rather than at hours of operation with a higher probability with Full AC design as hours of high RH are substantially increased.

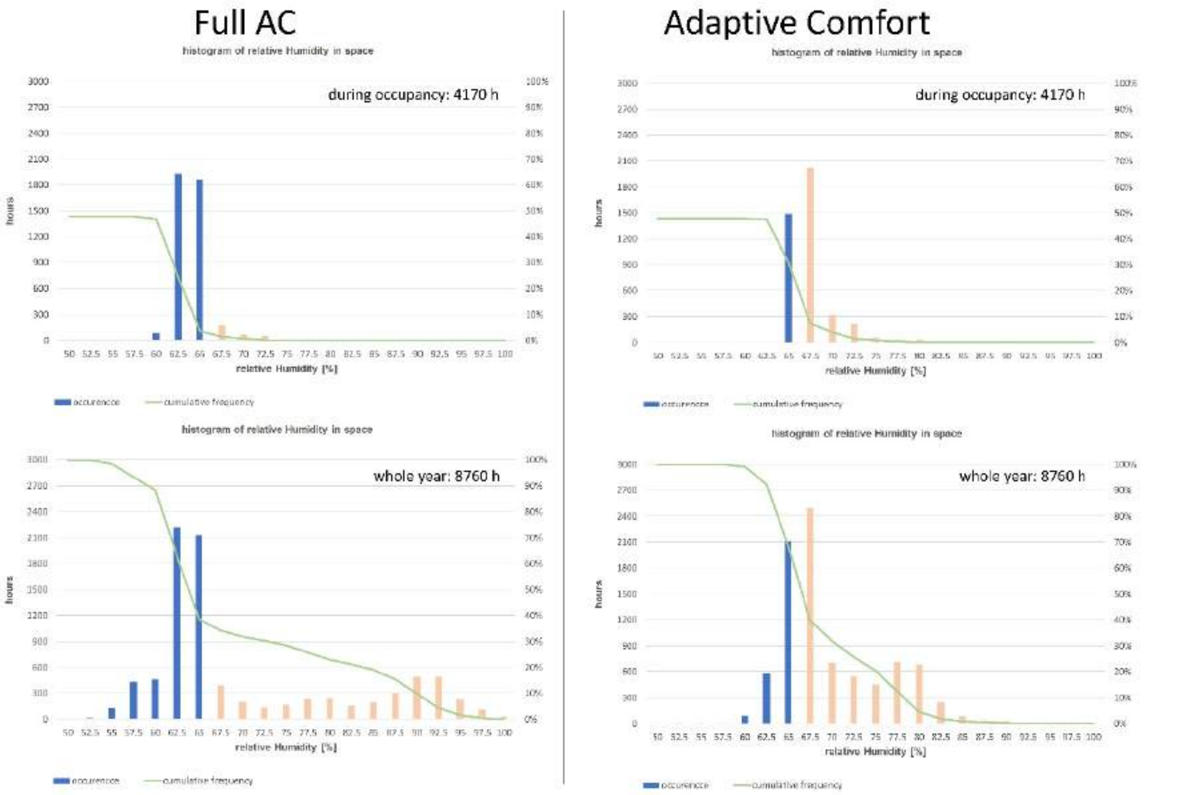


Figure 6. Statics of humidity at occupation and off hours.

4. Optimization of the energy design

The initial architectural design proposal and assumptions given in the design brief have been challenged to identify options for an improved design. The studied scenarios include:

S1) Reference: standard operation of VAC systems only during working hours. Design assumptions reflect the initial ETTV specifications and façade design as well as internal given loads for AC design criteria. This scenario was used for the initial study of thermal comfort parameters and humidity.

S2) S1 + reduced internal gains, with state the art artificial light and electrical equipment loads

S3) S2 + realistic schedule of occupancy, improved façade ETTV quality and VAV system. This scenario represents a state-of-the-art design.

Even though none of the scenarios 2 and 3 represent a unique technical innovation, the integral design and analysis is supporting to engage all stakeholders into the design. The client will learn about the consequences of a design brief which, supposedly is suggesting design parameters e.g. for internal loads for artificial light and laptops playing on the safe side, will increase cooling systems, investment cost and future energy demand. Architects and MEP designers can identify holistic façade strategies which better satisfy code of practice as well as comfort and energy design. Highlighting by dynamical load analysis, façade parameters which limit the design and shall be improved, can drive sustainable design decisions.

For all scenarios the thermal comfort was well satisfied and is similar, to what is discussed in section 3. These results are not presented here. The scenarios are compared in terms of peak cooling capacity [W/m²], sizing of required return air system in return changes per hour to deliver the cooling of the space [ACR] and Energy Use Intensity (EUI) in [kWh/m²y]. The evaluated EUI includes cooling energy and electrical energy of user, artificial light and auxiliary electrical energy for mechanical ventilation and is given per net area of the space.

4.1. State of the art assumptions for internal loads

State-of-the-art design need to anticipate future improvement of energy demand for artificial light, appliances and especially in IT design. Given the occupancy density of 6.5 m² per person and design criteria for internal gains of 16 W/m² the per person electrical load for equipment is about 104 W. The total permanent equipment loads in the Student space would add up to 4.3 kW. Assumptions for artificial light with 10 W/m² are outdated. Both is rated as very high.

Modern lap tops have an average load of about 40 W max. This equals an internal load of about 6 W/m². State-of-the-art LED lighting (500 lx) is available at 5 W/m². For innovative high comfort - low energy design realistic load assumptions are proposed.

Further to that anticipating typical schedules of occupancy, the energy demand and electrical load calculation will be more realistic and at the same time the peak load will be identified with dynamical cooling load analysis.

4.2. Improved façade design

The initial architectural design proposal had a very low Window to Wall Ratio (WWR). This was driven to satisfy the local code of practice and the Envelope Thermal Transfer Value (ETTV) but would not address a good daylight design and autonomy. The integral design process unveiled several options for improvement, but this study does not form part of this paper.

With improved heat protection the thermal comfort is improved, and the air conditioning loads are significantly reduced. With state-of-the-art high selective double glazing risk of condensation is significantly reduced, u-value of glazing is reduced (improved) to 30%, while the g-values remain similar and the daylight transmittance is increased. The u-value of the opaque façade elements can be reduced to 0.6 W/m²K (20% or initial value) by simple means. With improved façade parameters also the WWR ratio can be increased and the daylight autonomy can be increased significantly without compromising the ETTV score.

Table 2. Initial and improved façade parameters

Parameter	Basic (S1 and S2)	Improved (S3)
WWR	0.16	0.16
window	single glazing u-value 5.5 W/m²K g-value 0.45 daylight ~50%	double glazing with high selective coating u-value 1.6 W/m²K g-value 0.40 daylight ~70%
opaque walls	u-value 3 W/m²K	u-value 0.6 W/m²K
ETTV	48.2 W/m²	21.9 W/m²

4.3. Cooling Capacity and the size of the return air system

With reduced internal loads (S2) and improved façade (S3) the peak cooling capacity significantly drops down (see Figure 7). For the improved scenario (S3) a maximal cooling capacity of 120 W/m² would be required with the Full AC system. With an Adaptive Comfort design the required cooling capacity of 70 W/m² would be completely covered by the cooling potential of the tempered supplied fresh air.

So for an optimized scenario no additional cooling system would be required. This has substantial impact on the design. As indoor air temperatures are allowed to rise, return air systems with heat recovery become less efficient and less relevant in tropical and subtropical climates with the ultimate consequence that mechanical systems can be simplified and reduced to supply air systems only. So even with highly efficient latent and sensible heat recovery systems the energy savings are low and easily outweighed by auxiliary energy demand for fan operation (PLEA 2016). At the same time, with only supply-air systems in place, there is a significant impact on investment cost and on architecture: no false ceiling for eventual return air systems of fan coil units, higher space volume etc.

4.4. Electrical Use Intensity

With optimizing the load and building, the EUI significantly is dropping down to 108 kWh/m²y for the Full AC design and 74 kWh/m²y for the Adaptive Comfort design. Both numbers are rated as excellent for a high densely occupied student hub with 15 hours of occupation, 5 days a week. This is equal to 3900 hours of operation per year and about 60 % longer operation compared to typical office use with 9 hours per day.

The energy reductions achieved with the Adaptive Comfort design of about 32% savings are beyond savings which are possible with increasing chiller efficiency or other technical innovations. The energy and system savings go without compromising thermal comfort, emphasizing the importance of re-defining strategies for comfort leaving traditional paths of conventional air condition design.

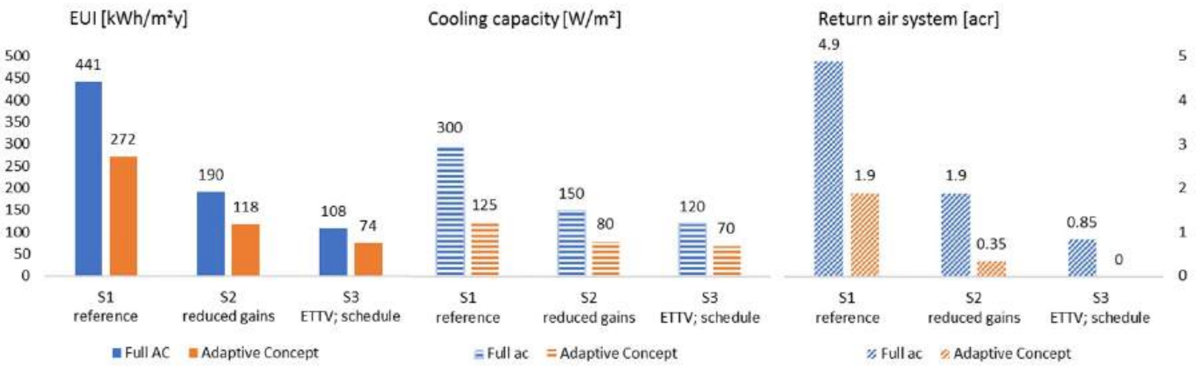


Figure 7. EUI capacity, cooling capacity and sizing of return air system for scenario 1 to 3.

5. A Net Zero School of Design at National University of Singapore

For the new School of Design at the National University of Singapore (NUS) the presented strategy to optimize the comfort and building design was consequently applied. The client wanted to become the new school a role model for tropical architecture and a showcase for Adaptive Comfort design to reach out to the next generation of architects being educated at NUS. With a gross floor area of 8,500 m², the five-story building will accommodate labs, design studios and workshops for the schools of architecture and interior, landscape and product design (Kessling et al 2016).

Awarded to Serie Multiply Architects, London and Singapore trough an international design competition the design started in 2013. Architects of record, structure and MEP is delivered by Surbana, Singapore. The contractor is Kajima, Singapore. The School was opened and occupied by NUS in January 2019 and detailed feedback on user satisfaction and comfort as well as verified energy measurements are expected soon.

"Preliminary results of subjective surveys completed by occupants show high levels of user acceptance of the environmental conditions offered by the building. The building is designed to be climate responsive with net-zero energy consumption featuring a range of sustainable design features and more than 1200 solar photovoltaic panels on its rooftop. SDE4 exceeds standards of health and wellbeing creating new avenues for delivering comfort in the tropics, embracing an innovative hybrid cooling system, that supplies rooms with 100% fresh pre-cooled air, albeit at higher temperatures and humidity levels than in a conventional system, and augments this with an elevated air speed by ceiling fans. This cool circulating air creates a comfortable condition in a high energy-efficient system. Therefore, the architecture becomes an agent of systemic enhancement—not just to do less harm, but to do systemic good—by making the discussion of design fundamentally public." (Lee 2019).

Figure 8. Image of the new Net Zero Energy School of Design at the National University of Singapore. The building is designed with Adaptive Comfort and supposedly the first of its kind in Asia. Image: Transsolar.

The design process was organized in a series of charrettes to create a faculty building that serves the various programs while remaining comfortable and energy efficient. Besides introducing the concept of Hybrid System Design and Adaptive Comfort, a strong emphasis was given: to improve the efficiency of chillers, reduce pressure drops in ventilation systems, utilize efficient artificial light and controls, verify load assumptions and allowances and to optimize the building design and envelope for natural cross ventilation, excellent ETTV and maximal daylight autonomy but low solar gains.

"During this process, the building has demystified the general perception of spatial quality, comfort, and cost for sustainable buildings. SDE4 changes the argument that green buildings cost more, as it has limited, or no extra cost compared to similar, industry-standard models." (Lee 2019). As a result, the optimized faculty building will be a Net Zero Energy Building, supposedly the first of its kind in Asia.

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Energy retrofit for buildings in Iraq: Insulation Parametric Study

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Abstract: The target of this research is to investigate the potential of reducing energy demand for residential buildings in Iraq. In this article the effect of thermal insulation for exterior walls and roofs in existing buildings is tested. Characteristics of typical existing buildings were chosen based on the online survey conducted in 2014 by the author.

To test the different scenarios, a 3D model was constructed and simulated using TRNSYS. Parameters such as HVAC, thermal storage capacity, shading, infiltration rates, and temperature settings are defined here as constants. In the reference building scenario, the building has no insulation. 8 more scenarios related to wall insulation were tested (4 with interior and 4 with exterior insulation). For the roof 8 further scenarios were tested as well.

The results show that insulation the roof results in energy saving up to 31%; however, using only 6 cm of insulation proved to be the optimal solution, with savings up to 27% compared to 31% when 18 cm insulation was used. The effect of wall insulation was lower. With savings up to 14% using 18 cm external wall insulation and 11% with 6 cm insulation. In roof and walls, exterior insulation performed slightly better than interior insulation.

Keywords: Energy retrofits, hot-arid climates, thermal insulation, TRNSYS-simulation

1. Introduction

Iraq faces an everlasting electricity crisis since 2003. According to the annual report of the ministry of electricity, the power supply did not exceed 54% of the demand in 2017, and the residential buildings are responsible for 61% of the electricity consumption in the same year (Ministry of Electricity- Iraq, 2018). The aim of this research is to reduce energy demand in existing residential buildings in Iraq. In a search for the most cost-effective way, the research compares different wall and roof insulation scenarios. Other building parameters such as, thermal heat capacity, heating and cooling systems, indoor design temperatures, infiltration rates and shading are investigated in other research papers.

Several studies dealing with the optimum insulation parameters in hot climates have been conducted. Samuel Dominguez et al. investigated the energy reduction for social housing buildings in Spain (Domínguez et al., 2012). Other similar studies were also conducted in other warm climates of Jordan, Dubai and Turkey (Jaber and Ajib, 2011), (Friess et al., 2012), (Bektas Ekici et al., 2012). Less studies were conducted in hot-arid climates generally and in Iraq especially. with most of the studies either focusing on building components or neglecting the economic values. Mahdi and Khadom defined the economical optimum insulation thickness by calculation the annual cooling savings by calculation the U-Value and annual heat flux in different climates in Iraq (Mahdi and Khadom, 2015). The author published earlier research on the topic but that research concentrated on new buildings (Dietrich et al., 2014).

2. Methodology

2.1. TRNSYS Simulation

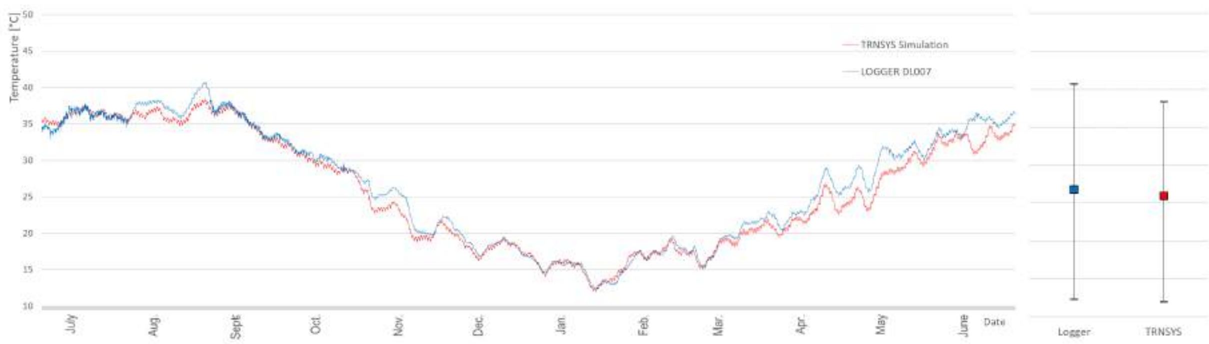
The different scenarios are tested by means of thermal simulation using TRNSYS (short for TRansient SYstem Simulation program). Like other simulation tools, TRNSYS has been validated according to the methods defined by the international energy agency. The "Task 32" describes the model for simulating solar energy (Heimrath and Haller, 2007). The model was used by the author to check the results and to learn how to use the program.

Further tests were performed by comparing the simulations with real time measurements of buildings in Baghdad, to check how accurate are the results in extreme hot climates. Table 1 lists the parameters for a room in residential building in Baghdad, this room was chosen to demonstrate the thermal behavior for a whole year in a non-occupied, free-running room without the uncertainties related to occupancy hours and air conditioning hours especially with the irregular, yet often electricity blackouts.

Table 1: Building parameters used in validation model

Building component	Material / Value
External wall	plaster + 24cm brick + cement plaster
Tie beam/ parapet	plaster + 24cm concrete + cement plaster
Floor	20cm concrete slab + 6cm screed /floor finishing
Roof	Concrete slab + 6cm thermos-stone + av. 8cm sand + cement tiles
Window	single glazed with steel frame
HVAC	None (free-running)

Despite all the uncertainties related to weather data, building material, internal heat flows from other rooms, there was a good agreement between the measured indoor temperatures and the simulation results with a root-mean-square-deviation of 4,23°C as can be seen in Figure 1 (Rashid et al., 2016).



2.2. Typical building

In the online survey conducted by the author on residential buildings in Iraq, participants provided the information for the typical residential buildings in Iraq. A two-storey single-family house for 4 inhabitants with net floor area of 120 m² and construction materials as listed in Table 2 below was defined as the reference building in the simulation (Rashid et al., 2016). Information such as air conditioning, occupancy hours, and the internal gains are also defined based on the survey results. Inputs from Iraqi building code for cooling are used to define Material properties, and interior design temperatures.

Table 2: Parameters of reference building (typical residential building)

Parameter	Value / Type
Housing type	single-family house
Net-floor-area	120-150m²
Total habitable rooms	6
Surface-area-to-volume-ratio	50-55%
Exterior walls	24 cm brick construction (no insulation)
Roof / floors	20 cm reinforced concrete (no insulation)
Windows	single glazing with iron frames
HVAC*	Heat pump (COP 3.0)

* not modelled in TRNSYS simulation

3. Simulation model

A single room with comparable proportions to the typical residential building is used as a reference building. Figure 2 shows the 3D model of the building used in the simulation. The model consists of 3 storeys with 15 identical rooms measuring 4mx5mx3m each. Results of the south-oriented room in the middle of the second floor are compared. The room has a surface-area-to-volume ratio of 53% which is close to a typical single-family house in Baghdad with 120²m net floor area. Using a single room has the advantage of reducing the calculation time while taking the thermal mass of the interior walls into consideration. The different parameters used in the simulation model are discussed in the next sections.

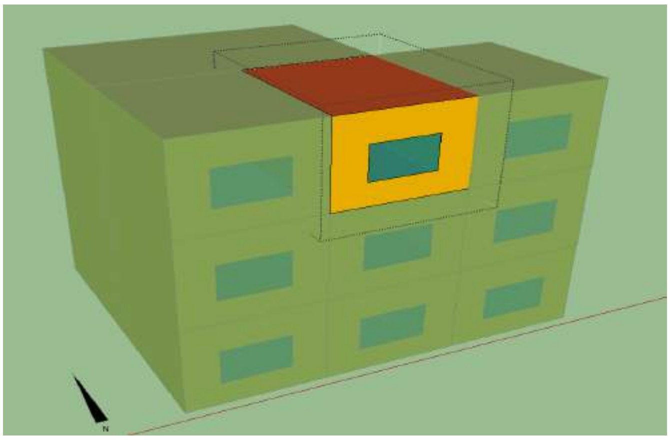


Figure 2: a sketch of the 3D model for the test building used in the simulation

3.1. Climate data

The climate dataset for Baghdad was used in the simulation as a representative for the whole country. further studies will include the simulation in other cities to represent all the climate zones of Iraq. Interpolated climate data form Autodesk green building studio was more accurate when compared to Meteonorm data (Rashid et al., 2016). Consequently, a TMY2 file was generated from the climate data to be used in the simulation.

Table 3: Weather data for the simulation model

Location	Baghdad (Iraq) 33° 20´ N, 44° 23´ E
Time zone	GMT +3
Source of data	Autodest(R) Green building studio
File type	TMY2

3.2. Heating and cooling

For all the rooms in the simulation model, similar parameters were selected. The fixed parameters were; heating, cooling, ventilation, infiltration, occupancy and internal gains. For heating and cooling, the heating and cooling energy demands are the results of the TRNSYS simulation. No heating and cooling system was defined in the simulation program; however, it is assumed that a heat pump with a coefficient of Performance of 3.0 is used (Rashid et al., 2016). The indoor design temperature is defined according to the Iraqi building code with 21°C during winter and 24°C during summer (MoCH Iraq, 2015).

3.3. occupancy and internal gains

Based on the results of the online survey, internal gains from occupants and electrical equipment are defined in all scenarios. The average daily profile of internal gains from electrical appliances is shown in Figure 3. A total of 4 persons was set to be living in the building with the occupancy ranging between 2 and 4 (Rashid et al., 2016). The metabolic rate was calculated with an average of 1met or 58.2 W/m² (ISO, 2006). Approximately 100W was calculated as internal gains from each occupant assuming a surface area of 1.7m²/person. The defined profile is the same for the whole year with no differentiation between the seasons or week days.

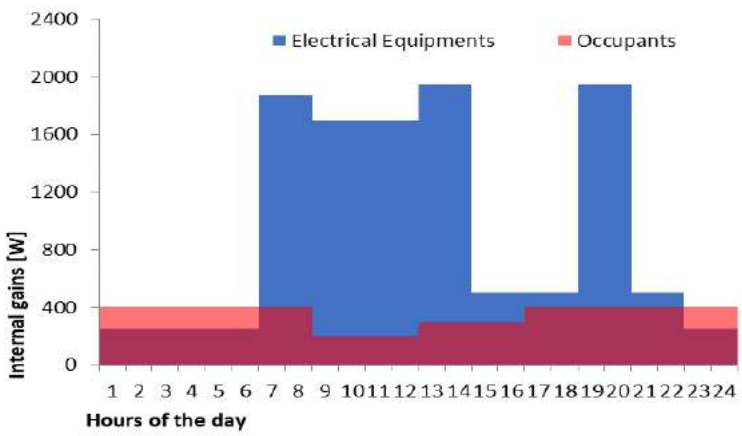


Figure 3: Daily profile of gains from electrical appliances in typical residential buildings in Iraq

3.4. Construction material

The reference building has 24cm brick walls with concrete roof and ground floor as the online survey results suggest (Rashid et al., 2016). The constructions of building components were defined according to the common practice. The thermal properties of different materials are listed in Table 4 as described in the Iraqi building code for cooling (MoCH Iraq, 2015).

Table 4: thermal properties of construction materials defined in Iraqi building code 404-2

Material	Conductivity	Capacity	Density
Normal concrete	1.85	1000	2400
Reinforced concrete	2.10	1000	2500
Brick	0.60	840	1790
Sand	0.33	800	1520
Screed	1.40	1000	2000
Tiles	1.60	1000	2450
Plaster (cast)	0.42	750	1200
Roof tiles	1.10	1000	2100

3.5. Windows and shading

A south-oriented 2.4m² window is modelled for each room (20% glazing of the façade). According to the online survey, 68% of the housing units have single-glazed windows with Iron frame (Rashid et al., 2016). The window used in the simulation model has a U-Value of 5.7 W/m²K for the glazing and an overall U-Value of 6.0 W/m²K (MoCH Iraq, 2015). It is not common to use solar blinds in Iraq (Rashid et al., 2016). The simulation model does not include any solar shading device.

3.6. Infiltration and ventilation rates

In a field study conducted in 2017, the infiltration rate for single-glazed windows with iron frame was calculated using the crack method. It is found to be $0.17h^{-1}$ (Rashid et al., 2018). The minimum ventilation rate of 7.5 l/s/person defined by the Iraqi building code are set in the building model as well (MoCH Iraq, 2015).

4. Thermal insulation scenarios

Apart from the reference building construction, a total of 18 other scenarios of wall and roof insulation were tested. The insulation used in the simulation is polystyrene with 0.035 W/mK thermal conductivity and neglected thermal mass. The effect of insulating the ground floor was neglected for two main reasons; first, because it is labour and cost intensive, in the second place, because the energy transferred to the ground are negligible as the average ground surface temperature stays within the moderate range.

4.1. Wall insulation

External and internal thermal insulation for the walls were tested. With insulation thickness ranging between 4 and 18 cm. In total, 8 scenarios for wall insulation were tested with 4 insulation thicknesses as exterior or interior insulation. The insulation parameters of the different wall scenarios are listed in Table 5.

Table 5: parameters of the wall insulation scenarios

Scenario	**Exterior wall insulation**	**Interior wall insulation**
EW_O04	4cm	-
EW_O06	6cm	-
EW_O12	12cm	-
EW_O18	18cm	-
EW_I04	-	4cm
EW_I06	-	6cm
EW_I12	-	12cm
EW_I18	-	18cm

4.2. Roof insulation

The variations of roof insulation were similar to those of the wall insulation. 4 scenarios with external roof insulation and 4 others with internal roof insulation. The insulation thickness also ranged between 4 and 18 cm. The different scenarios and thicknesses are listed in Table 6.

Table 6: parameters of the roof insulation scenarios

Scenario	**Exterior roof insulation**	**Interior roof insulation**
RF_O04	4cm	-
RF_O06	6cm	-
RF_O12	12cm	-
RF_O18	18cm	-
RF_I04	-	4cm
RF_I06	-	6cm
RF_I12	-	12cm
RF_I18	-	18cm

4.3. Wall and roof combination

two further scenarios with a combination of both wall and roof external insulation were tested. Only wall and roof insulation with thicknesses 4 and 6 cm were tested here as can be seen in Table 7.

Table 7: Parameters of the external wall and roof insulation scenarios

Scenario	**Exterior roof insulation**	**Interior roof insulation**
EW+RF_O04	4cm	4cm
EW+RF_O06	6cm	6cm

5. Results and Discussion

5.1. Energy demand

The annual heating and cooling demands for the reference building was first calculated. 294.884 kWh/m²a of energy is needed to cover the cooling and heating demand, almost 89% of the energy demand is needed during the cooling season, whereas the heating demand represents only 11%. Different scenarios were compared to the reference building. Up 31% reduction of total energy demand for heating and cooling could be achieved using 18cm thermal insulation for the roof. When exterior wall insulation was used, the reduction was between 10% and 14%. When the wall insulation is combined with roof insulation, 36% reduction was achieved even with only 6cm of insulation. Energy demands of the different simulation scenarios are displayed in Figure 4.

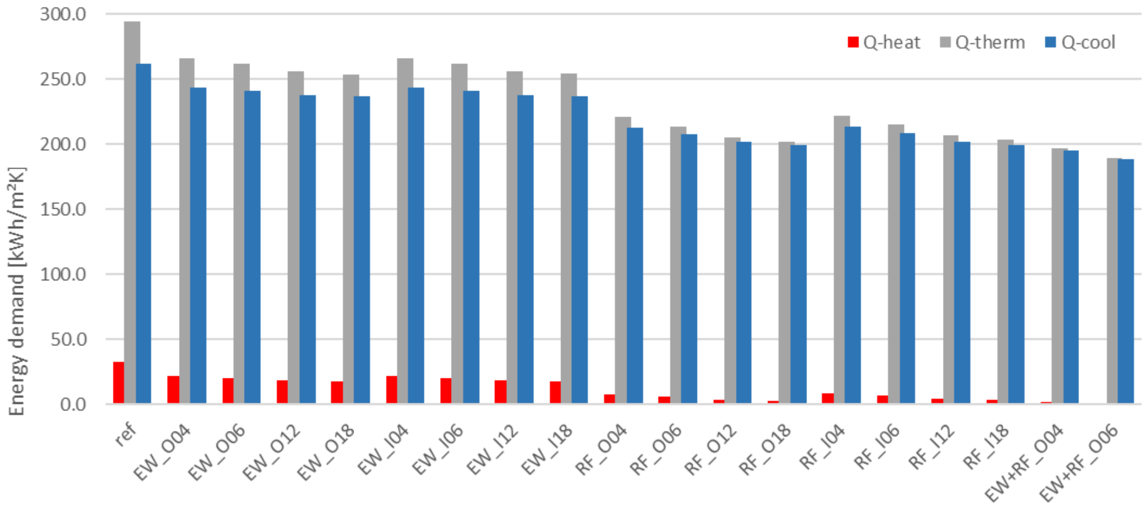


Figure 4: comparison of the heating, cooling and total energy demands for the different insulation scenarios

the simulation results show that the building performs slightly better with external wall and roof insulation than with internal insulation, although the difference is negligible, it is recommended to use the external insulation to reduce the thermal stress on the building envelope and reduce the effect of thermal bridges.

As shown in Figure 5, the correlation between insulation thickness and energy savings is not linear, the reduction in energy demand achieved by using 18 cm of insulation is slightly higher than those achieved when 12 cm insulation was used. Using insulation with a thickness up to 6 cm appears to be the optimal solution in terms of energy savings.

Figure 5 also shows a much higher potential of energy saving when the insulation is used on the roof rather than the walls. The difference can be explained by the greater area of the roof which is more than double the area of the exterior wall in the 3D model. When we look at the energy demand reduction per square meter of insulation, the roof insulation still performs slightly better than wall insulation, giving us an indicator for the most relevant building components in building insulation.

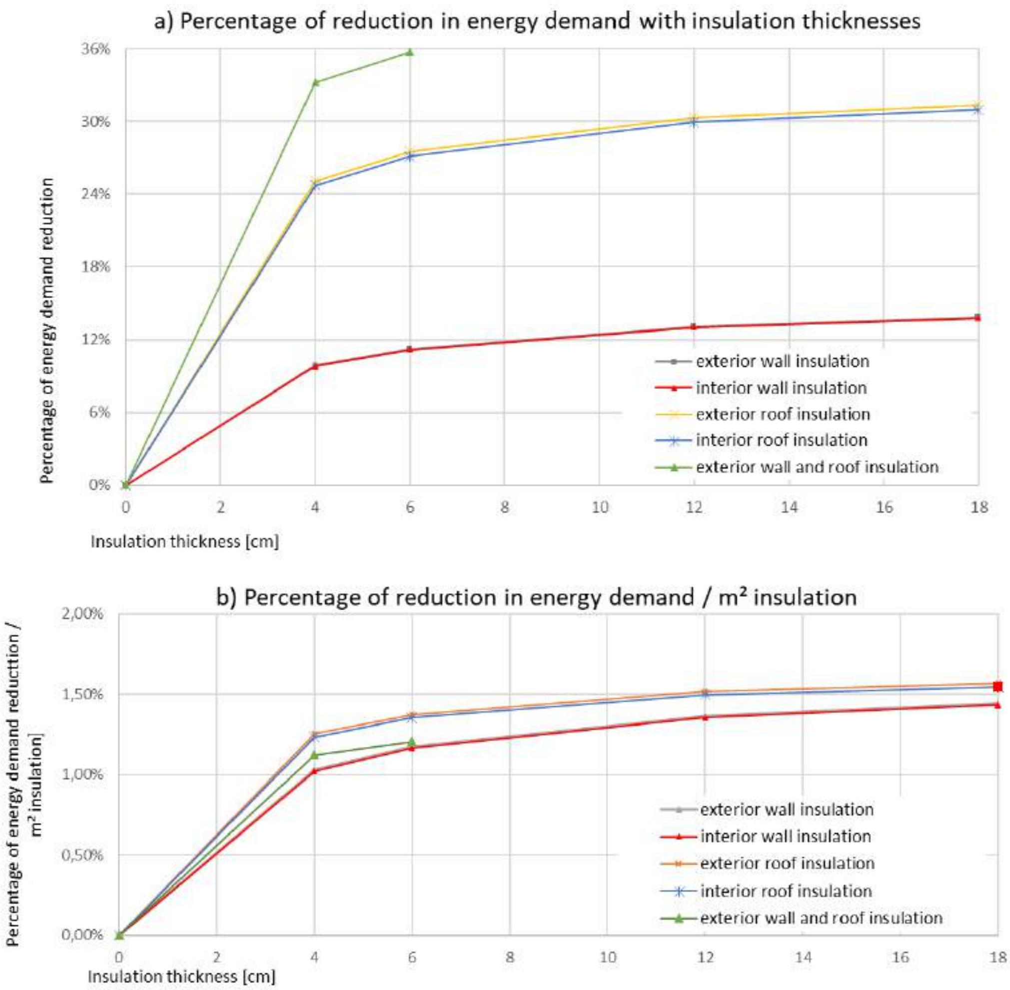


Figure 5: Correlation between insulation thickness and reduction of energy demand
a) for the whole building
b) for each m² of insulation

5.2. Energy and investment costs

The economical aspect of using additional thermal insulation was also tested. In Iraq, a new progressive tariff for electricity was in introduced in 2017 (Ministry of Electricity- Iraq, 2018). the total electricity consumption for the different scenarios was is the sum of the electricity demand for electrical appliances which is assumed to be the same for all the months with monthly energy demand for heating and cooling.

The total investment in building insulation was calculated according to the prices found in one of Iraq's most widely used online marketplaces. The cost for insulating the roof with roof works costs generally less than the exterior wall insulation with façade works (Rashid, 2019). The total costs for different scenarios are listed in Table 8.

Table 8: Average costs for wall and roof insulation for a single-family house in Iraq

Scenario	Insulation thickness [cm]	Insulation material cost [1000IQD/m²]	Facade works cost [1000IQD/m²]	Roof works cost [1000IQD/m²]	Wall area [m²]	Roof area [m²]	total investment [1000IQD]
EW_O04	4.00	6	100	-	40	-	4,240
EW_O06	6.00	9	100	-	40	-	4,360
EW_O12	12.00	18	100	-	40	-	4,720
EW_O18	18.00	27	100	-	40	-	5,080
EW_I04	4.00	6	50	-	40	-	2,240
EW_I06	6.00	9	50	-	40	-	2,360
EW_I12	12.00	18	50	-	40	-	2,720
EW_I18	18.00	27	50	-	40	-	3,080
RF_O04	4.00	6	-	50	-	60	3,360
RF_O06	6.00	9	-	50	-	60	3,540
RF_O12	12.00	18	-	50	-	60	4,080
RF_O18	18.00	27	-	50	-	60	4,620
RF_I04	4.00	6	-	50	-	60	3,360
RF_I06	6.00	9	-	50	-	60	3,540
RF_I12	12.00	18	-	50	-	60	4,080
RF_I18	18.00	27	-	50	-	60	4,620
EW+RF_O04	4.00	6	100	50	40	60	7,600
EW+RF_O06	6.00	9	100	50	40	60	7,900

The savings of energy costs when the buildings are insulated could reach up to 342,000 ID/a (254€/a). When these savings are counted against the total investment of the insulation, it shows that the scenario with 4cm interior wall insulation is the most cost-effective scenario with 9 years payback period as can be seen in Figure 6 below.

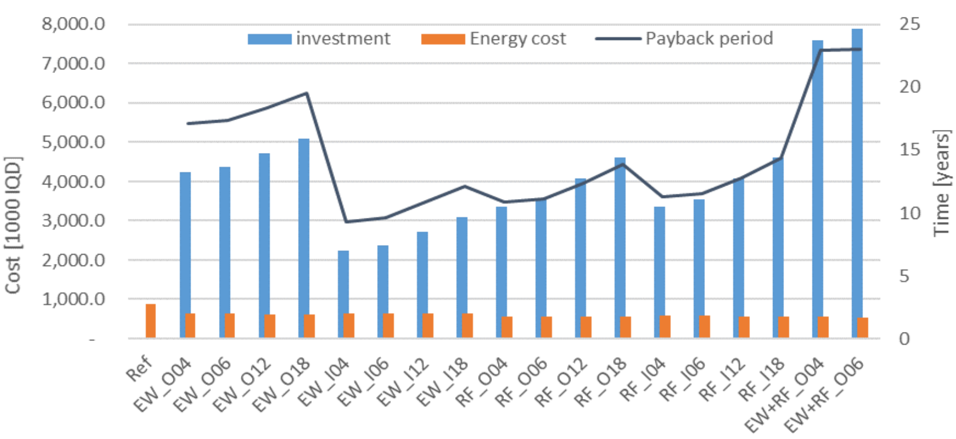


Figure 6: Investment, energy costs and Payback periods for the different scenarios

6. Conclusion

The simulation results show the potential of energy savings in heating and cooling energy demand. with cooling energy demand up to eight times higher than heating demand, more investigation is needed for measures to reduce the cooling demand such as the effect of external shading. Alongside shading, research dealing with new buildings' thermal mass, HVAC, thermal comfort and set temperatures is underway.

The results do not present the building retrofit using thermal insulation as an economically attractive solution; However, they still show the most reasonable variation of insulation and the possibility of combining different solutions. Further investigations dealing with hygrothermal behaviour of different insulation types, the effect of thermal bridges, and the environmental impact of insulation are important points to increase the accuracy and applicability of this study's results.

Using thermal insulation helps achieving thermal comfort with less energy consumption. Although the comfort temperatures defined in the Iraqi building code do not take the adaptive approach into account, similar indoor design temperatures are defined in other hot regions like Saudi Arabia (Saudi Building Code National Committee, 2018). In a related research, it is found that by using the adaptive thermal comfort approach, higher energy savings could be reached.

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Thermal Comfort and Energy Use of Affordable Housing in Ahmedabad, India

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Abstract: 'Housing for all – 2022', a large-scale housing initiative was launched in 2015 by the Indian government for providing quality affordable housing to the lower economic segment by the year 2022. Occupant thermal comfort is one of the significant aspects of liveability and applies to affordable housing as well. These houses have low energy consumption as of now, however as incomes and comfort expectations increase, energy use and related costs in this segment are expected to surge.

So far, comfort field studies in affordable houses in India remains a subject largely neglected. This paper reports findings of the thermal comfort conditions and energy use of 20 houses in three affordable housing developments located in Ahmedabad, India during winter season (November end - March beginning). The analysis discusses results from data collected using three methods - Long-term monitoring of household energy use and indoor environment parameters of temperature and relative humidity, instantaneous measurements of thermal comfort conditions and right-here-right-now thermal comfort surveys. It is observed that average daily energy use ranges from 0.5 - 6.75 kWh and is dependent on appliance ownership and occupant behaviour and is base load driven in these houses. 65% of the occupants reported being comfortable in their thermal environment during the survey period. The conclusions from this study will be of meaning to various stakeholders in the affordable housing segment.

Keywords: Affordable houses, Thermal comfort, Energy monitoring, Environmental monitoring

1. Introduction

India is the third largest economy in the world (IMF's World Economic Outlook Database, April 2018). The Indian residential sector is responsible for 22% of the current electricity use and is expected to represent 39% of the country's total electricity demand by 2047. This is a projected ten-fold increase - from 175 TWh in 2012 to 1,840 TWh by 2047 (NITI Aayog, 2015). Residential energy consumption comprises of energy from various sources such as electricity supplied by grid, biomass, electricity generated from renewable sources and unauthorized access to electricity. The discussion here is on consumption of electricity supplied by distribution company.

'Housing for all – 2022', a housing initiative was launched by the government of India in 2015 with an objective of providing affordable and quality housing to the people of economically weaker sections (EWS) and the low-income group (LIG) by the year 2022. The state of Gujarat has a projected housing demand of 776,000 by 2022, out of which 43,000 have already been constructed and 62,000 are under development (Ministry of Housing & Urban Poverty Alleviation Government GoI, 2018). Ahmedabad, situated in Gujarat, was one of the cities chosen for the implementation in Gujarat. Confederation of Real Estate Developers Association of India (CREDAI) is working in conjunction with the government to build 203,000 affordable houses in the city. Ahmedabad Municipal Corporation (AMC) and Ahmedabad Urban Development Authority (AUDA) are also working towards providing affordable houses to the urban poor in the state (Pradhan Mantri Awas Yojana Ahmedabad).

The annual report for FY 2014-15 by the Ministry of Housing and Urban Poverty Alleviation (MHUPA) estimates that India has a housing shortage of 18.54 million units of which 96% is in the EWS and LIG segments. Each house is around 30-60m^2 and will add to the at least 360 million m^2 of built-up area.

The entire ecosystem of affordable housing development faces a lot of challenges like land availability, financing, approvals, relocation and employment of people amongst others (AEEE, 2018). Incorporating energy efficiency in this segment of the housing to provide thermal comfort is likely to be an additional challenge - with additional costs and compliances for energy efficient design and construction. However, if business as usual development continues, it will lead to locking in a large amount of inefficient housing, with high costs of maintenance. Building thermally comfortable housing is also important from a resilience perspective. Urban poor are most vulnerable to climate change impacts such as increased temperature and urban heat island effects due to their lack of access to proper housing and common services. Building climate-resilient housing will reduce these vulnerabilities from both a health and energy perspective (ACCCRN, 2013). Also, there is a need for affordable developments to be comfortable for better living conditions and health of the occupants. A considerable portion of the income of these residents goes into meeting basic living costs, so it is difficult to do additional expenditure on health and comfort measures. And, to be able to provide quality affordable housing, it is important to gain more perspective of the existing scenario. This large-scale construction of affordable housing provides an opportunity to assess and build housing that also focuses on providing thermal comfort, hence minimizing future energy use, in line with India's climate change targets (AEEE, 2018).

A study on the occupant and household characteristics along with energy use load curves helps give an insight into the seasonal and daily usage patterns and potential for savings. Additionally, studying occupant thermal comfort helps assess the liveability of these affordable houses in terms of thermal comfort as perceived by the occupants and if the energy use is impacted in trying to attain the desired comfort levels. The purpose of the study is to analyse energy use load curves and various determinants driving it along with thermal comfort study of twenty affordable houses in three projects in Ahmedabad. One of the projects is an in-situ rehabilitation of existing slum dwellers through public-private participation and the other two are affordable housing developments in partnership with developers.

Studies on energy consumption in residential segment have generally focused on high- and mid-income targeted buildings, often ignoring affordable housing with the assumption that they don't have considerable effect on national energy because of low level of energy use. This, however, may no longer be true in future due to large scale development of housing in this segment (Prayas, 2017). This new construction could form a significant portion of energy use in the country.

The operational energy use in the residential sector is primarily to maintain comfort by space cooling/heating, lighting, running household equipment and appliances. This energy is used during the entire lifecycle of the project; however, it is less in the affordable housing sector due to a limited number of appliances and lighting. Commonly used appliances include ceiling fans, lights, refrigerators, televisions, evaporative coolers and hot water geysers.

The study is being conducted for Mahila Housing Trust (MHT) organization under the iNumber project to collect, analyse and use this data to provide local inputs in city level planning efforts. It will help inform the various agencies involved in the affordable housing segment. It will also help educate the occupants on their energy usage and on various determinants influencing their energy use and thermal comfort.

The scope is limited to investigating the selected twenty houses for a period of one year and the results presented in this paper are preliminary and limited to the winter month study. Also, energy consumption monitoring is being done at the house level and not at the building level or appliance level. This is because building utility energy use is not the focus of the study and low density of appliances in these affordable houses makes it easier to understand the key energy-using appliances. As the study period is limited to the winter season, occupant discomfort and comparatively high energy used to offset it, which is usually experienced in the summer months, cannot be investigated and hence, an understanding of annual pattern and variations cannot be gained from the preliminary results.

2. Literature Review

The literature review was carried out on existing research conducted in similar fields and the reviewed studies are limited to those focusing on residential energy use, thermal comfort field surveys in naturally ventilated dwellings, and energy and environmental monitoring. This helped gain an understanding of methods and results from previous studies and helped establish the significance of such a study.

2.1 Residential energy use

Energy audits in residences are done to understand daily and seasonal variation in energy consumption, to give recommendations without much or no investment and help establish trends which might help in the future prediction of energy use (Kumar et al, 2015). The strategy of metering and sub-metering of the houses and co-relating energy consumption to simultaneous recording of temperature is also understood through such studies (Hatch & Rashed-Ali, 2016).

Peak load, idle consumption and energy use of the house are determined by various factors such as external conditions (e.g., location and weather), physical characteristics of the dwelling, appliance and electronics stock, and a number of occupants (Kavousian et al, 2013). Another study on residential energy use discusses the energy use in Dutch dwellings being determined by the number and use of appliances and lights (direct determinants), floor area and presence of occupants, and household and economic characteristics (indirect determinants), and establishes correlations of energy use with all the variables (Bedir et al, 2013). A few of these were investigated in our study.

Current appliance and energy use trends were reviewed through the literature. As reported by the Ministry of Power, 100% of the households are electrified in the state of Gujarat (Saubhagya Dashboard, 2017) and average annual energy use per electrified house is 1079 kWh in India (WEC, 2014). While in Gujarat, average household energy use is 800-900kWh (Khosla, 2017). A study on the impact of LED bulb programme in the country says that the number of LED bulbs bought per low-income household is three. Average lighting energy usage in LIG households is for 5.5hrs and 85% of these are used between peak hours (6-10 pm). The LED penetration is widespread with at least one LED used in 90% of the houses (Chunekar et al, 2017). A study shows that fans are the most commonly owned appliances followed by televisions and refrigerators (Khosla & Bhardwaj, 2017). Another study indicates that ceiling fans and refrigerators dominate house level energy use followed by lighting and hot water (EDS, 2011). Currently, the households primarily rely on fans to enhance thermal comfort, with a limited presence of air-coolers. However, if this sector shifts to air-conditioning in future with a rise in income and thermal comfort expectations, the energy use will escalate considerably (AEEE, 2018).

The significance of various determinants in residential energy use in the country, such as a number of occupants, size of the house, household wealth, appliance availability and use and temperature, have been identified in studies to develop a residential forecasting model and for the smart grid to enable smart grid technologies. 100% of houses are reported to own fans, 80% have at least one TV and 60% have access to refrigerators (Fuchs et al, 2015). Apart from climate conditions and building characteristics, type of lighting, appliance penetration, the efficiency of appliances and behavioural tendencies also determine overall energy use. While surveys are low cost and help gain insight into appliance ownership and usage pattern, they do not result in the completely accurate dataset. A study of load curves of households would help energy distribution companies understand supply-demand and future consumption projections better and appliance manufacturers understand product performance (Khosla, 2017).

A study on residential energy consumption concludes that 60% of the urban houses consume less than 100 units per month and lights, AC, fans, air-coolers, refrigerators, televisions, and water-heaters account for about 90% of the total consumption. 82% of urban houses own a TV and 43% own refrigerators. Households' use of appliances depends on several factors such as income, climate and typical behavioural tendencies. The appliance ownership increases exponentially with the increase in expenditure of households and then hits a plateau. There is a need to collect more information regarding people's energy consumption through more localised surveys (Chunekar et al, 2016).

2.2 Residential thermal comfort

The methodology followed in developing the ASHRAE adaptive thermal comfort model – RP884 (Dear, Brager, & Cooper, 2016) and Indian model for Adaptive comfort (Manu et al, 2016) have been reviewed to understand the methodology for residential thermal comfort field studies and results. The data analysis and result presentation methods were also understood.

The results from a study on thermal comfort in rural households in India report that PMV of the households ranged between −0.85 to 0.69 (winter) and PPD was 5-20% for ASHRAE 55(2017) and was comfortable as per 80% acceptability limits. It was found that thermal comfort sensation was slightly cool to neutral during winter in this study (Ravindra et al, 2019).

A field study in residential apartments in Hyderabad, India concludes that thermal sensation correlates strongly with outdoor temperature (r = 0.61). The occupants feel comfortable in a wide range of humidity (17- 78%). Also, PMV mostly exaggerates the actual sensation. It discusses the adaption of the occupants in varying thermal conditions through various behavioural control actions such as clothing, metabolism and operation of windows, fans, air coolers, and ACs. The study concludes that the proportion of open windows increase as the indoors become warmer. It was highest at 70% when indoor globe temperature (T_g) was between 32°C and 34°C. The proportion of fans had a strong correlation with T_g. It was found about 84% fans were in use when T_g was at 35–40°C. 80% of the subjects were comfortable when the indoor temperature was between 26.0 °C and 32.5 °C. A significant variation between thermal regulating appliance ownership and actual usage was found (Indraganti, 2010a).

Another study in mixed mode buildings, occupants in naturally ventilated (NV) zone voted to be comfortable 80% of the time when the indoor temperature was less than 33°C.

Air speed at humidity above 50% in the NV zone is quite high around 1 m/s indicating at occupant tendency of using fans at high humidity. When the indoor temperature was between 30-35°C, occupants voted to be “neutral” or “slightly warm” in 73% of the observations. Out of these, 84% were comfortable (Honnekeri et al, 2014).

A study on adaptive thermal comfort comments on the flexibility of occupants towards variations in the outdoor environmental conditions. It concludes that subjects are comfortable up to 32°C at still air condition (0 m/s - 0.2 m/s) and up to 35°C at higher speed (up to 1.5 m/s) in NV buildings in the composite climate of India. This is because increased air movement aids comfort by high convective heat transfer and higher evaporation rate of sweat. Votes on the comfort side are greater in number due to the adaptive measures by the occupants (Kumar et al, 2016).

A study (Nicol, 2004) in NV mode in hot humid climate comments on the limitations of the PMV model in predicting actual comfort temperatures. The study suggests that increased air movement helps widen the comfort band while increased humidity reduces it.

Based on a literature review, a research gap in thermal comfort studies in the affordable housing sector was revealed. It is, therefore, necessary to investigate this and to add to the knowledge on thermal comfort of occupants in affordable housing.

3. Methods

3.1 Overview

The research study comprises of a field study of twenty houses in three affordable housing developments in the city of Ahmedabad. Ahmedabad lies in western India, in the state of Gujarat and experiences a hot and dry climate. Table 1 shows a detailed description of Ahmedabad weather conditions.

Table 1 - Ahmedabad weather description

Latitude	23.03°N		
Longitude	72.58°E		
Altitude	53 metres above mean sea level		
Air temperature	Minimum – 10 °C	Mean - 28°C	Maximum - 45 °C
Seasonal mean air Temperature	Summer (March to June) - 32°C	Monsoon (July -October) - 29°C	Winter (Nov to Feb) - 22°C
Mean relative humidity	Summer (March to June) - 45%	Monsoon (July -October) – 71%	Winter (Nov to Feb) - 52%
Average annual rainfall	782mm		

Three buildings shown in Figure 1 are selected by MHT from the various affordable housing schemes in the city governed by practical reasons such as the willingness of the society members to participate and a minimum of one year of occupancy. All constructions are new and occupied for not more than five years. Also, the twenty houses in the three projects represent available configurations, orientations, and floor levels. The buildings were named as S1-3 and houses as S1H1, S2H2, S3H3 and onwards. The surveyed buildings are all naturally ventilated, and occupants have control over the operation of doors, windows, fans and so on. The data collection involved walk-through visits of the projects, procurement of drawings, energy bills, demographic and building details, making visual observations and taking of photographs, energy metering, continuous logging of environmental variables of temperature and RH, right-here-right-now thermal comfort surveys accompanied by simultaneous measurements of indoor environmental variables.

Figure 1 - Details of case studies

The overall size for the survey study is 239 respondents to assess occupant comfort in the winter season (November end – March beginning) based on which the results are presented. The sample size includes residents occupying the houses for at least 4-5 years who are acclimatized to the climate. The age and gender of the sample size have been shown in Table 2 and Table 3.

Table 2 - Survey respondents' age

Age	Number of respondents
Below 20	25
20-30	74
30-40	75
40-50	33
Above 50	31

Table 3 - Survey respondents' gender

Gender	Number of respondents
Male	67
Female	170

The occupants were interviewed to understand thermal comfort perception, satisfaction, and preference along with their behaviour and characteristics. Each house had three to six occupants. At least one member from each house was interviewed with a structured questionnaire form during each survey set. Surveys were repeated after every 15 days between 12 noon to 6 pm. Interview of residential occupants was carried out using the modified survey questionnaire from addenda to ASHRAE Standard 55, 2010 - Thermal Environment Point-in-time survey questionnaire. In the comfort studies, for clothing values of Indian attire, the study by Rawal et al, 2016 was referred. The metabolic rates are derived from standard checklists provided in ASHRAE Standard 55. The conduct was as per class II of ASHRAE also used in RP884 field studies.

3.2 Data Collection

3.2.1 Initial briefing and data collection

Firstly, the location, orientation and floor position of all twenty houses are identified from the architectural layouts of the buildings. Also, energy bills are collected to understand energy consumption and metering equipment requirement. A walk-through visit to all three sites is done to get an overview of the buildings to brief the occupants about the purpose of study and show instruments (energy meters and loggers) to be installed in their houses and about the surveys. This information is conveyed in the language of their understanding i.e. Hindi / Gujarati and any queries and concerns of the occupants are addressed. Tentative location for installation of energy meters and loggers is identified during these visits. A one-time data collection (Table 4) of the houses and occupant details will be gathered.

Table 4-Pre-field study datasheet – Houses

House ID	Block No.	Flat No.	Floor	Number of family members							Flat type	Electrical appliance
				Name of the owner	Living since	0-18 years	18 - 40 years	>40 years	Male	Female		

3.2.2 Installation of monitoring equipment

One energy meter was installed in each house due to single-phase power supply and to monitor energy use at a more granular level (15-minute interval) than that obtained from monthly energy bills. The location for energy meter installation was decided inside the house for equipment safety. With the help of an electrician, energy meters were installed in each house enclosed in a meter box for safety reasons. These were mounted at a suitable height to avoid tampering but accessible for ease of data extraction.

Two HOBO U-12 data loggers were installed in each house, in two different orientations. These were wall mounted at an accessible height for ease of data extraction after every 15-day time interval - one in the living room and another in the bedroom, away from direct sources of heat radiation such as windows, refrigerator, gas stove etc. The houses were all 1BHK apartments (30 – 40 m^2) and hence, two loggers were found enough to monitor the conditions in regularly occupied spaces in the house. The battery and functioning of the loggers were checked before installation to avoid data loss issues in the future.

The logging interval for both energy meters and data loggers was set at 15 minutes.

3.2.3 Thermal comfort survey design

A structured survey questionnaire was developed and administered in an interview format with each unique response recorded on a smartphone. The questions are also translated in a language of occupants' understanding i.e. Hindi/Gujarati.

The Questionnaire included the following parameters:

- Occupants' age, gender, weight and height
- Occupants' sensation, acceptability and preference on ASHRAE 7-point thermal sensation scale, the perception of air movement
- Occupants' comfort response and the reason for discomfort, if any
- Types of clothing the subject is wearing during the one-hour period of survey activity the occupant were engaged in prior to the survey
- Type of behavioural control adopted by the occupant to achieve comfort

3.2.4 Survey deployment

The occupants at each site were pre-informed about visits. Apart from the survey form, a datasheet (Table 5) was prepared to note the measurements and observations. Information on the number, type and wattages of lights and household appliances was gathered. A laptop installed with HOBOware and ConfigView was carried to the site and data was extracted and stored as per the unique device code and date assigned to it. HOBOware helps to extract data and is a graphing and analysis software for HOBO data loggers. ConfigView is a tool to help extract and visualize what are the actual values of energy being used.

Table 5 - Measurement and observation data sheet

Occupant Unique code	Date-Time	Gender	Season	Sky condition	Status of fan	Distance from fan	Status of windows	Distance from windows	Dry Bulb Temperature (°C)	Relative Humidity (%)	Air Velocity Along x-axis(m/s)	Air Velocity Along y-axis (m/s)	Globe Temperature (°C)	
		Male/Female	Winter/Summer/Monsoon	Clear/Cloudy	On/Off		Open/Closed/Partially open						Indoor	Outdoor

3.2.5 Instruments used

The instruments are shown in Table 6 aided the field study.

Table 6 - Instruments used

Measurement Instrument				
	Onset HOBO U-12 Temperature/RH/Light/External Data Logger	Velocicalc Multi-Function Ventilation Meter 9565 and Thermoanemometer Straight Probe 960	Extech HT30: Heat Stress WBGT (Wet Bulb Globe Temperature) Meter	Secure Liberty 100 energy meter
Measurement range	**Temperature:** -20° to 70°C (-4° to 158°F) **RH:** 5% to 95% RH	**Air velocity:** 0 to 9,999 ft/min (0 to 50 m/s) **Temperature:** 0 to 200°F (-18 to 93°C)	**Black globe temperature:** 32 to 176°F (0 to 80°C)	**Voltage:** 57.7 V (100V) - 240 V (415 V) AC 3 phase 4 wire (3 phase 3 wire) **Current:** Available 1-2A and 5-10 A in single variant (field configurable)
Accuracy	**Temperature:** ± 0.35°C from 0° to 50°C (± 0.63°F from 32° to 122°F) **RH:** ± 2.5% from 10% to 90% RH typical, to a maximum of ±3.5%, below 10% and above 90% ±5% typical	**Air velocity:** ±3% of reading or ±3 ft/min (±0.015 m/s), whichever is greater. **Temperature:** ±0.5°F (±0.3°C)	**Black globe temperature:** ±4°F/2°C	**Accuracy class:** 0.2s, 0.5s, 1.0 **Main frequency:** 50/60Hz with ±5%
Purpose	*For continuous measurement and logging of dry bulb temperature and relative humidity in houses.*	*For instantaneous measurement of air velocity, temperature and relative humidity in a thermal comfort survey study.*	*For measurement of indoor and outdoor globe temperatures in a thermal comfort survey study.*	*For continuous measurement and logging of energy use of houses.*

4. Results and Discussions

4.1 Residential energy use

The energy use of the twenty houses in three societies was investigated over the period of four months along with other occupant and household characteristics such as size of house, building construction and envelope, house demographics such as occupant number, gender, age group, employment and economic status, occupancy schedule and appliance ownership, appliance usage behaviour and indoor-outdoor environment (temperature and RH).

Figure 2 shows the indoor air temperatures logged at every 15 minutes in the house in relation to the energy use, also metered at an interval of 15mins, over the entire study period (Nov 20 - Mar 05).

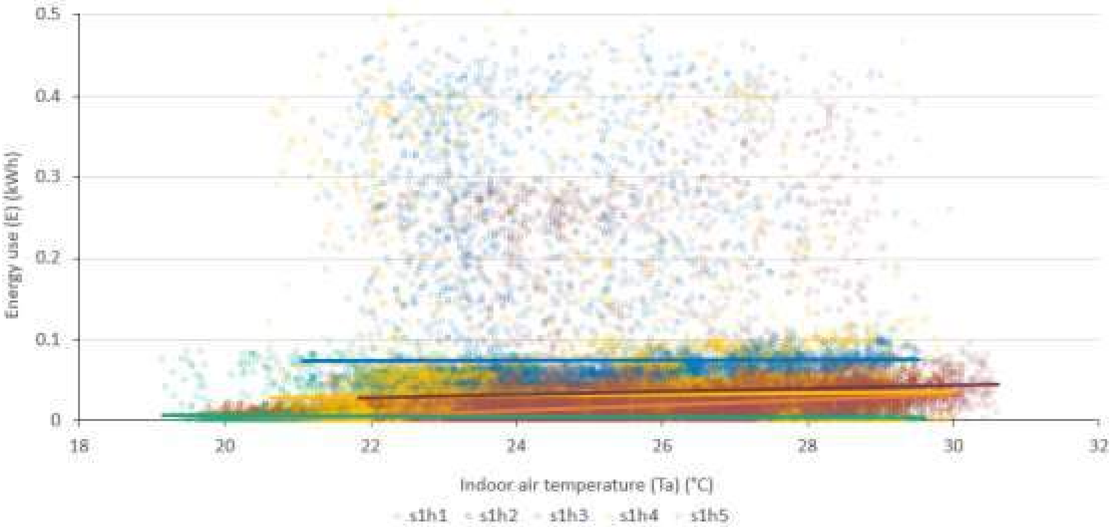

Figure 2 - Energy use in relation to indoor air temperature - Society 1

Table 7 - Statistical data - Figure 2

Society 1	S1H1	S1H2	S1H3	S1H4	S1H5
Linear equation	E = 0.0002Ta + 0.0688	E = 0.001 Ta + 0.0182	E = -0.0003 Ta + 0.0134	E = 0.0034 Ta - 0.0685	E = 0.002 Ta - 0.0145
R^2	3E-05	0.0007	0.004	0.3695	0.0037
p-value	0.0473	0	2.123E-24	0.05	0.000790
N	2522	2522	2522	2522	2522

It is observed that there is a very weak correlation of energy use to indoor temperatures in the affordable housing segment as per the R-square values of the linear regression. Also, the p-value is less than 0.05 indicating a reliability of this correlation. It is seen that the energy use of the occupants did not vary considerable over the study period (Nov 20-Mar 05). Similar trend was observed in S2 and S3.

In 14 houses, energy use is found to strongly correlate to the connected load as observed in *Figure* . The R^2 value of linear regression is significant (0.7) and p-value is observed to be less than 0.05. This indicates that there is significant potential for energy savings by replacing appliances of old technology with new energy efficient appliances. However, it also indicates that with increased incomes and hence, purchasing power, the connected load of the houses can be expected to rise, and as a result the energy use in affordable houses can be expected to surge.

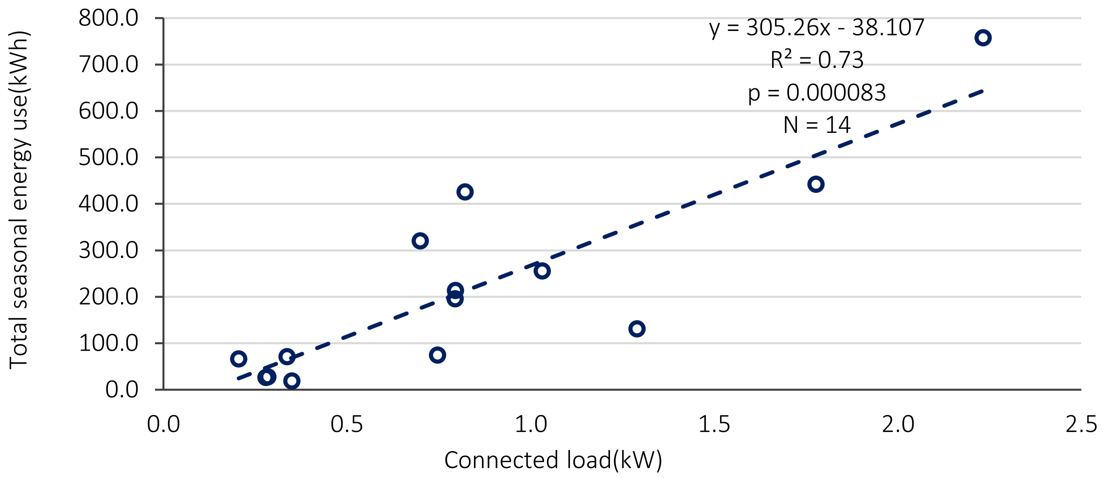

Figure 3 – Total seasonal energy in relation to total connected load of the house.

Figure shows the percentage of houses as per seasonal energy use ranges. It is observed that the total energy use in 45% of the surveyed affordable houses is less than 100kWh. 20% of houses have energy use ranging from 200-500kWh and only one house (5%) is found to have energy use between 700-800kWh.

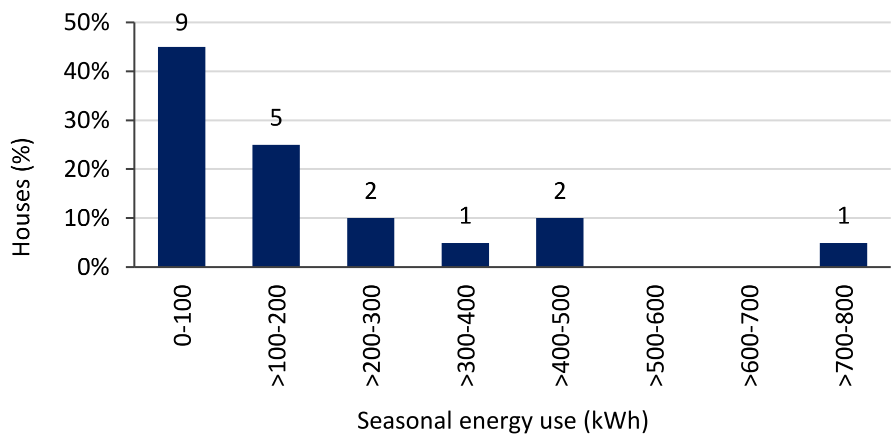

Figure 4 – Percentage of houses with range of seasonal energy use

4.2 Residential appliance penetration

Figure 5 shows the appliance penetration in the houses surveyed. It is observed that lights and fans are present in all houses with at least one LED fixture in each house. The TV is the most dominated household appliance present in 90% of the houses. Refrigerators, mixer grinders and air coolers are found in 70%, 45% and 30% houses respectively.

Occupants prioritise owning fans over coolers and ACs as an adaptive measure for achieving thermal comfort. Old technology - high energy consuming light fixtures, TVs and refrigerators have still not been completely replaced with energy efficient options available in affordable housing.

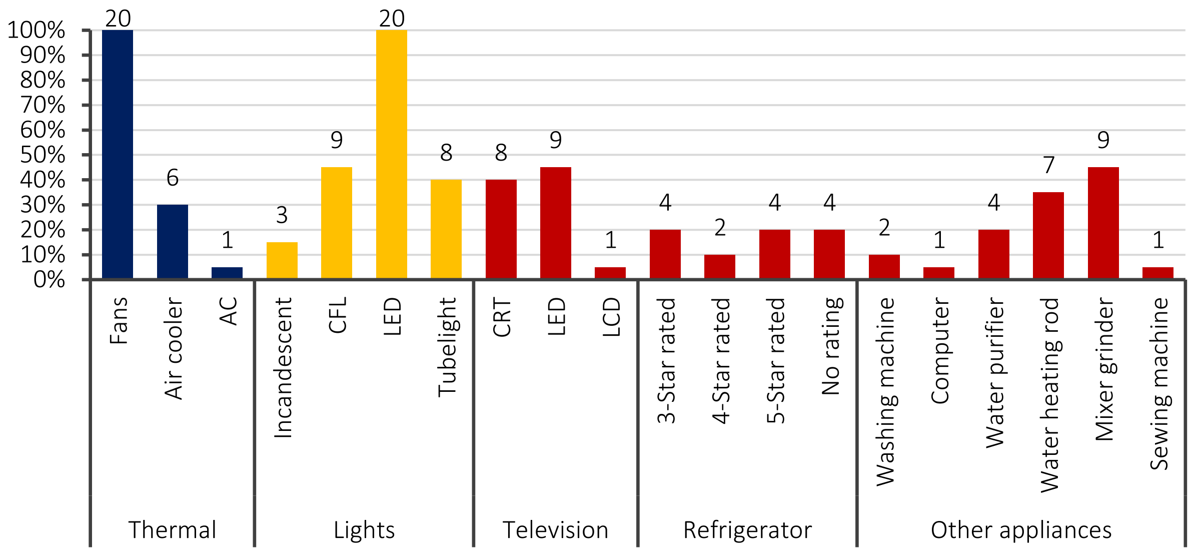

Figure 5 - Appliance penetration in affordable housing

4.3 Physical environment measurements

During the survey days, the outdoor temperature varied from 22.4°C to 37.1°C while RH varied from 20.4% to 46.9%. During the field study, the physical measurements of environment variables was carried out. Outdoor weather data was obtained from weather station of CARBSE at CEPT University, Ahmedabad. Table 7 shows the statistical analysis of variation in outdoor and indoor variables observed during this time.

Table 8 - Indoor and outdoor environmental parameters

Description	Temperature		RH		Indoor air velocity	Globe temperature	
	Indoor	Outdoor	Indoor	Outdoor		Indoor	Outdoor
Average	27.3	29.2	38.9	32.3	0.3	26.2	35.1
Std. Deviation	2.2	3.5	6.8	6.2	0.3	2.5	5.7
Max	32.0	37.1	54.6	46.9	2.0	31.2	45.0
Min	22.4	22.4	20.8	20.4	0.0	22.3	22.0

4.4 Personal variable – clothing and activity

The clothing values include chair insulation of 0.15clo, which is added for all occupants occupying an upholstered seating. It is observed that 70% of the female respondents were in the Indian ensemble of Sari (Figure 6). Women's clothing insulation (Mean – 0.68, min – 0.33, max – 1.56, SD – 0.16) was slightly higher than that of men (Mean – 0.56, min – 0.32 max – 1.08, SD – 0.15). Not all respondents were wearing footwear and only 6% wore socks.

Figure 2 shows the variation of occupant clothing and their corresponding operative temperature. It is observed that the occupants do not rely much on achieving comfort by modifying their clothing. The slope of regression shows only a slight decrease in clothing insulation with increase in temperature for both male and female occupants.

Figure 6 - Occupant clothing

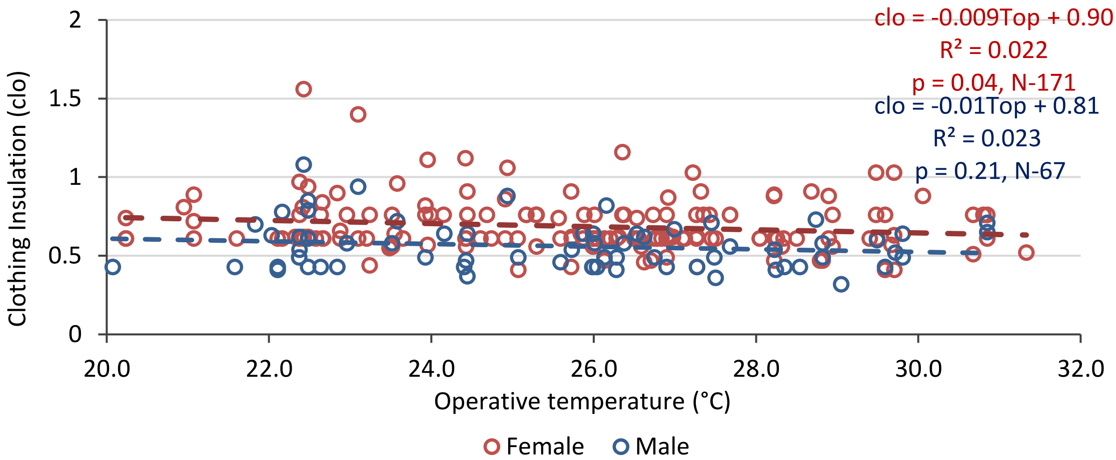

Figure 2 - Impact of clothing insulation on thermal comfort sensation votes

The metabolic activities ranged from sleeping (0.7) to house cleaning (2.0) during the survey. Table 9 shows descriptive statistics of occupant clothing and metabolic activities.

Table 9 - Occupant clothing values and metabolic rates

Description	Clothing value	Metabolic rate
Average	0.65	1.29
Std. Deviation	0.17	0.52
Max	1.56	2.00
Min	0.32	0.70

4.5 Subjective thermal variables

The enquiries from survey questionnaire regarding occupant characteristics helped establish a relation between their comfort responses. Figure 8 categorises the thermal sensation votes as per occupant age group. It is observed that highest neutral sensation responses were recorded in 20-40 age group while, >40, the 'Slightly cool' thermal sensation response dominated. It can be inferred that older people felt colder as compared to the younger occupants under similar thermal conditions.

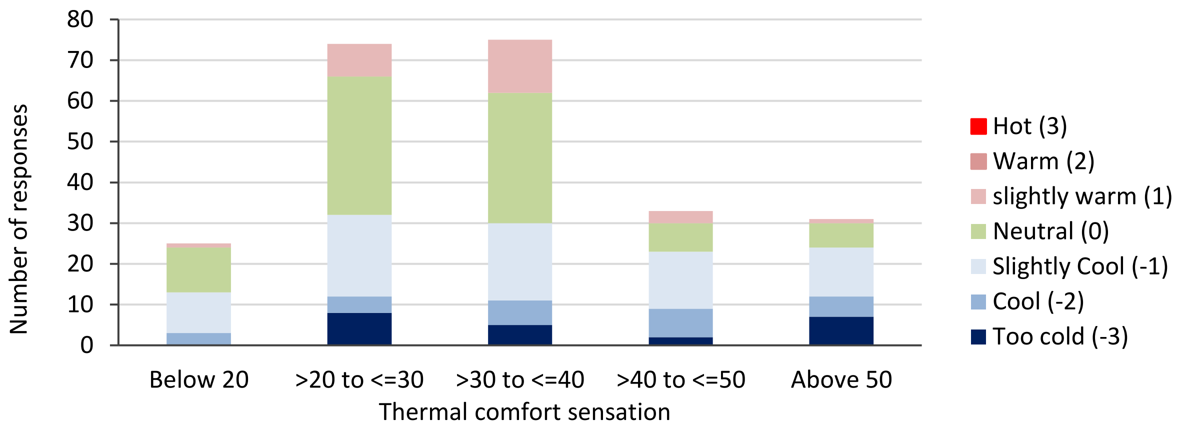

Figure 8 -Thermal sensation vote corresponding to occupant age

Figure 9 shows the preference of the occupants to their thermal environment. It is observed that 63% of the occupants do not desire any change and 27% would prefer a warmer environment. Only 10% occupants preferred a cooler environment. Occupants started preferring cooler environment at temperatures greater than 26°C. In the winter season, the majority do not desire any change hence, the possibility of adoption of measures to achieve comfort are minimal. With, increasing temperatures, occupants desire cooler environment and hence might use more thermal appliances such as fans, coolers and ACs.

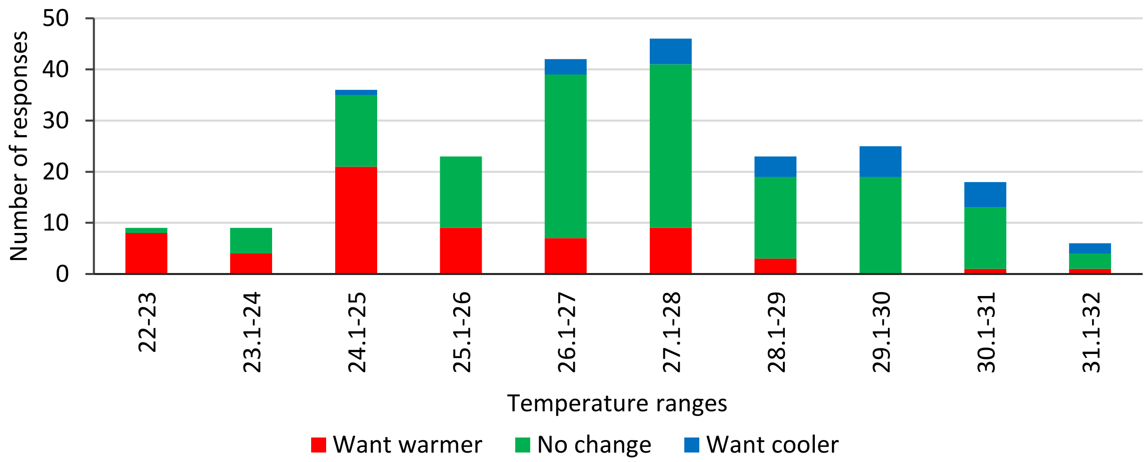

Figure 3 - Thermal preference corresponding to indoor operative temperatures

Figure 10 shows the acceptability of the occupants to their thermal environment. It is observed that 59% of the occupants found the environment acceptable and 29% found it unacceptable. The temperature range of 26-28°C was comfortable to maximum occupants. This acceptance of the occupants towards high temperatures (27.1-32°C) could be due to their acclimatization and behavioural controls adopted.

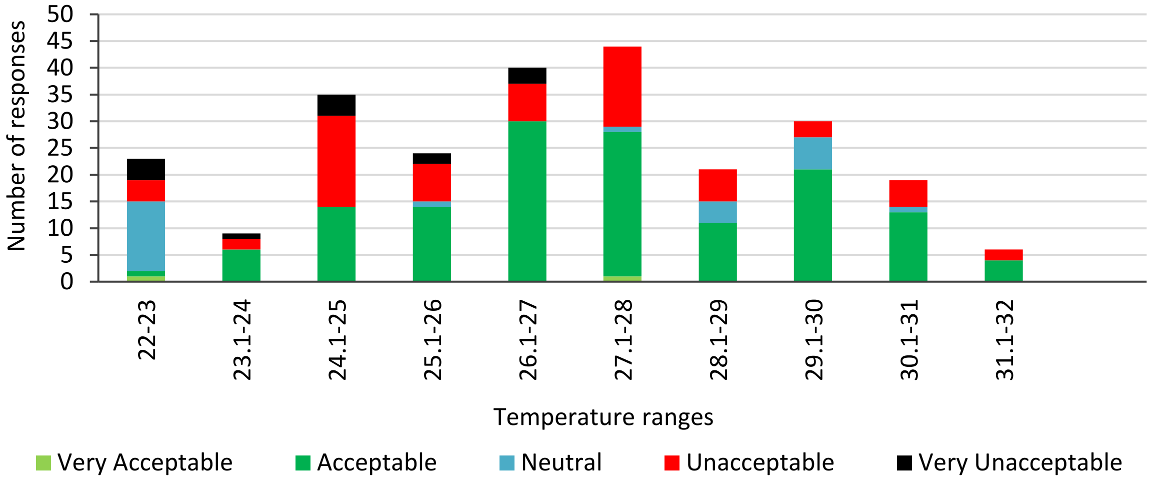

Figure 4 -Thermal acceptability corresponding to occupant age

4.6 Adaptive measures

Figure 5 shows the various adaptive measures adopted by the occupants in these houses to achieve greater thermal comfort. The occupants actively used fan control to maintain thermal comfort. They kept fans off during the months of November and December while, they preferred to keep fans on during February and March. The occupants whose houses had curtains, used them actively all through. Windows and doors were kept open during Nov-Jan while kept them shut as temperatures rose in Feb-March. During discussions, it was revealed that occupants preferred to move out of houses to sit in sunlight spaces to feel warm during cold weather. So, this measure was later included in the questionnaire. The occupants also said that even in summers, they prefer to get out and sleep on building terrace as the RCC walls lose heat during night time causing discomfort. The occupants did not adopt measures such as use of air conditioner, portable heater/fan/air coolers at all during the study period.

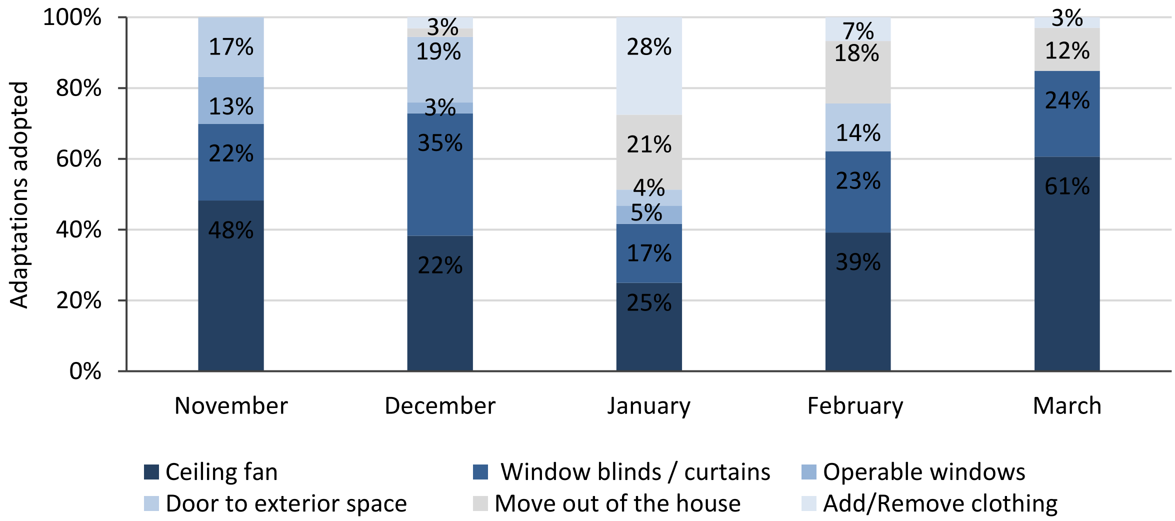

Figure 5 – Percentage preference of adaptive measures adopted by the occupants

4.7 Comparison of actual mean votes and predicted mean votes

A linear regression of both actual mean votes and predicted mean vote has been done against respective operative temperatures as seen in Figure 12.

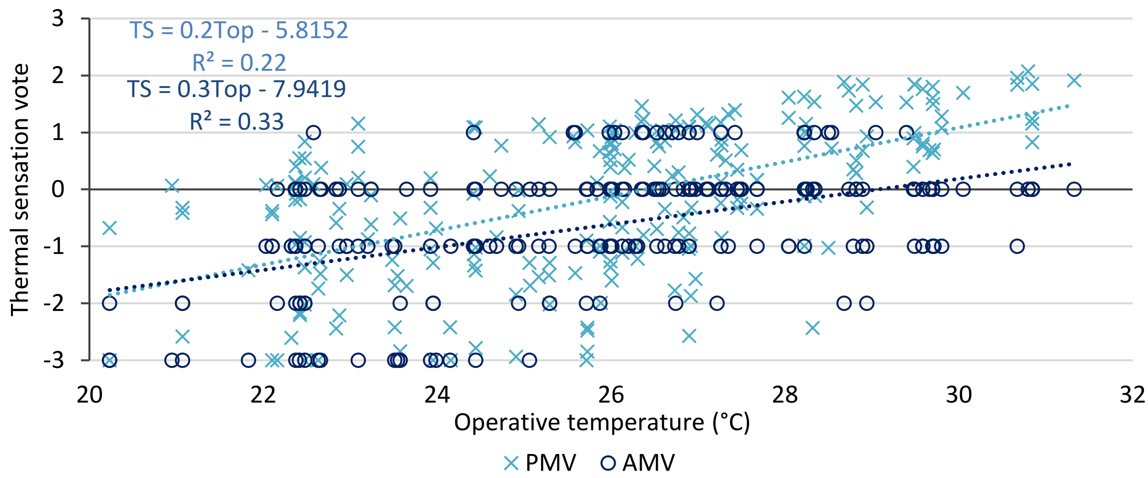

Figure 6 - Comparison of actual mean votes and predicted mean votes

It is observed that the slope of predicated sensation is greater than that of observed sensation responses. Over prediction is observed in PMV as compared to actual responses.

4.8 Adaptive comfort – ASHRAE Adaptive thermal comfort model and NBC - India model for adaptive comfort (IMAC)

The 90% acceptability comfort bands of both ASHRAE and NBC-IMAC have been plotted to see how many data points of operative temperature are comfortable as per both the comfort models. The lines indicate the comfort bands and each point represents a value of operative temperature and actual comfort vote in Figure 13.

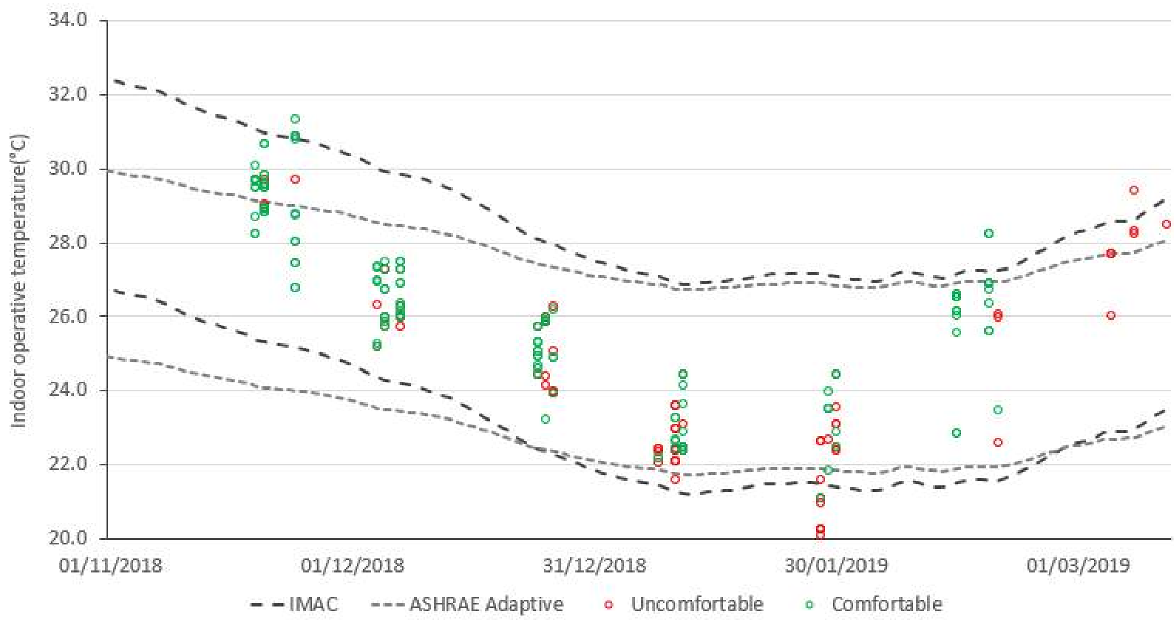

Figure 7 - Comfortable hours as per ASHRAE adaptive comfort and NBC - Indian model of adaptive comfort

As seen in Figure 7, 11% of the operative temperature values are uncomfortable as per ASHRAE while, it is only 4% in the case of IMAC. The range for ASHRAE comfort band is 5°C and IMAC is 5.7°C which shows the wider range of adaptability the Indian comfort model. The actual comfort responses at their respective operative temperature have also been indicated in the above figure. It is observed that 35% of the occupants reported discomfort and 65% reported being comfortable. Out of these occupants' feeling uncomfortable, 62%

responded with temperature (high (8%) and low (92%)) as main reason for their discomfort, 15% due to unacceptable air velocity (50% each - high/low) and 23% found both temperature and air velocity dissatisfactory.

5. Conclusions

As per the findings of the study, the mean hourly energy use is not related to mean outdoor temperature and indoor operative temperature. It is predicted to relate to appliance ownership and occupant behaviour in affordable housing. The energy use is found to be base load driven. Older technology energy guzzling variants are still being used in such housing due to affordability reasons. In the instance of their replacement in future with energy efficient versions, the connected loads can be brought down. We recommend policies and regulations offering financial incentives aimed at improving the efficiency of the appliance stock. Replacement of certain end uses such as refrigerators, water heating rods, TVs and lights provides great potential for reducing energy consumption. Provision of community utilities such as solar water heaters is one such solution.

As per the observations from a thermal comfort field study in winter, the occupants adopt control measures which do not increase energy use such as adding clothing insulation, turning off fans, closing doors and windows. Also, the occupants currently do not own space heaters, and this indicates the minimal possibility of purchasing heaters in future. Air coolers, however, have a presence in the houses. This indicates an increased presence of air coolers and ACs in high summer temperatures when fans are insufficient to provide thermal comfort. So, subsidies can be provided on low energy cooling solutions to reduce future connected loads.

6. Acknowledgements

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The influence of the improved Saudi system of houses' setbacks on indoor comfort conditions

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Abstract: The high levels of energy consumed for cooling purposes in the Gulf region highlight the importance of satisfying thermal comfort demands passively or at least reducing the gap towards that. Recently, the Saudi Ministry of Municipal and Rural Affairs improved the houses' setbacks regulations. These improvements increase the built-up area to 70% of the property's area and allow reducing the previously required setbacks by up to 100% of no more than two sides. This paper, up to the authors' knowledge, is the first attempt to investigate the influence of the improved Saudi system of houses' setbacks on the cooling loads and internal thermal comfort conditions. Implementing Design-Builder software, 50% and 0% of setbacks cases were applied to a villa in Riyadh. These cases were investigated in Muscat considering the climatic, social, and cultural similarities of the Gulf region. The corresponding reductions in the cooling loads during summer were around 6.3% and 21.6% in Riyadh and almost 12.3% and 15.1% in Muscat. The predicted mean votes of the base cases and the investigated cases fell in the (slightly warm) category. Exploring the influence of other cases allowed by the system is recommended in Riyadh and other cities in the Gulf region.

Keywords: Saudi system of houses' setbacks, cooling loads, thermal comfort, Riyadh, Muscat

1. Introduction

The demands of indoor thermal comfort are a considerable energy consumer (Nematchoua, Tchinda and Orosa, 2014; Yang, Yan and Lam, 2014) especially in extreme climate regions like the Arabian Gulf countries. For instance, Abu Dhabi, the capital city of the UAE, has one of the highest energy consumption levels globally (Giusti and Almoosawi, 2017). In Saudi Arabia, around 80% of the annual electricity production is consumed by the construction sector. Roughly half of this amount is used in residential buildings where air conditioning consumes almost 70% of the total electric consumption (Saudi Electricity Company, 2014; SEEC, 2018). Likewise, it is estimated that air conditioning consumption exceeds 70% of the electric energy consumed by buildings in Oman (Zurigat *et al.*, 2003). Indeed, air conditioning systems are integrated into all buildings' types in the Gulf region (Qader, 2009). Surveying a sample of residential buildings in Oman revealed that air conditioning units were installed in all bedrooms and in more than 60% of living rooms, kitchens, and guest rooms (Majid *et al.*, 2014). Another survey conducted in Muscat, the capital city of Oman, found that the operation of air conditioning units extended between 20 and 24 hours daily during summer (Al-Gharibi, 2016).

These levels of energy consumption emphasise the necessity of integrating energy saving techniques in buildings. Such techniques were integrated into the traditional domestic architecture of the Gulf region. Examples include courtyards, windcatchers, thermal mass, compacted form, and mashrabiya. Yet, the majority of modern buildings lack such vernacular techniques. There may be reasons for this shift in architecture. For instance, using traditional construction materials like mud and timber may not be practical today. Yet, it should be mentioned that the discovery of oil and natural gas in the Gulf region has contributed to this shift, if not generated it. These discoveries transformed the Gulf countries politically, economically, and culturally. These transformations were expressed in an astonishing speed of construction where international styles of architecture were widely applied in the modern cities that replaced the typical small settlements of the Gulf (Al-Hathloul and Edadan, 1993). Importing such styles was mainly owing to inviting foreigner architects to work in the Gulf (Katodrytis, 2015) and because traditional architecture for the local people at that time was related with poverty (Abedi and Soltanzadeh, 2014). Indeed, "until recently, westernisation was interpreted as the only form of modernisation in the Gulf" unfortunately (Katodrytis, 2015, p. 125). However, it should be mentioned that the Sultanate of Oman was perhaps the only Gulf country that has a different opinion on this "importing issue" (Ragette, 2012) and a quick comparison of its buildings with those of the other countries in the Gulf confirms this opinion.

Nowadays, there are attempts to adapt architecture to the extreme climatic conditions of the Gulf region by façade layering (Katodrytis, 2015) for instance. However, these attempts are more convenient for commercial and governmental buildings. In the residential sector, the concept of a detached house (villa) is still dominant. This concept was borrowed from the western world where a need for shedding rainwater was necessary (Ragette, 2012). Obviously, such purpose is not necessary for the Arabic region and almost contradicting with the demand for shading. The practice of importing architecture is generally still continued in the Gulf region perhaps because of the complexity and difficulty associated with the attempts of "upgrading" the traditional Gulf architecture to cope with the modern life requirements. It is not a problem of discontinuity in developing the local architecture alone; rather, there may be a need to invent new techniques to cope with the climate change and to gain the social acceptance (Al-Khatri and Gadi, 2015).

Recently, the Saudi Ministry of Municipal and Rural Affairs (MOMRA) adopted some improvements in the system of residential buildings' regulations. These improvements can be considered as a modified resemble of the compacted form of the traditional Gulf towns as demonstrated in Figure 1. Applied on the ground floor only, the new system increases the built-up area to 70% of the property's total area instead of 60% that was allowed by the previous system as illustrated in Figure 2. In addition, it is now allowed to reduce the previously required setbacks by up to 100% of no more than two sides of the house. The previously required setback on the main facade, which is at least one-fifth of the street width, is still required by the new system.

(a)

(b)

Figure 1. Compacted traditional settlements: (a) Najd, Saudi Arabia (photo by Aasem Alabdullatief), (b) Nizwa, Oman (Traub and El-Shahat, 2008)

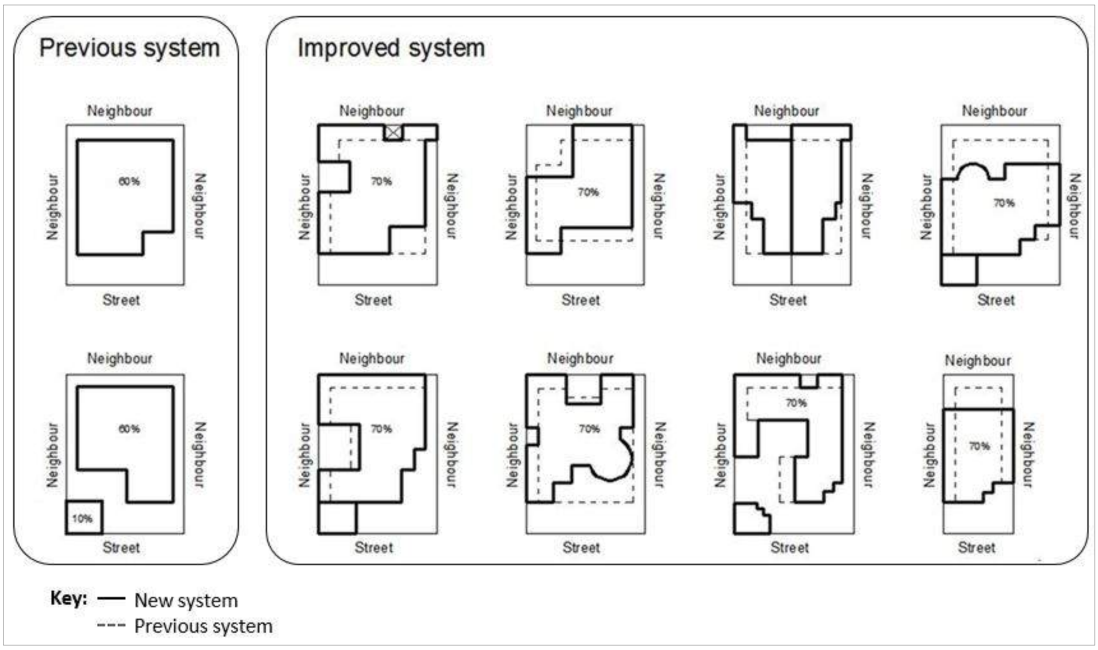

Figure 2. Illustrative examples on applying the improved system of houses' setbacks [Reproduced from (MOMRA, 2018)]

Although this system was developed in response to social and economic demands, there some concerns associated with its application regarding daylight access, natural ventilation, and sound transmittance. The system accounts for this by restricting the setbacks' reduction by maintaining the access to adequate levels of daylight and natural ventilation, which is mostly achieved by courtyards, skylights, or lightwells as requested by the system (MOMRA, 2018). Moreover, it is expected that applying the new version of the Saudi building code will reduce sound transmittance considerably. This is because the minimum thermal resistance of walls permitted by the code is 2.9 m^2K/W achieved by two layers of concrete blocks with 10 cm polystyrene insulation layer (SBCNC, 2018). Considering that thermal resistance is positively related to thickness, it is obvious that the new code will positively contribute towards decreasing sound transmittance. Yet it should be mentioned that the code is currently applied in the governmental buildings only and will be applied in the residential sector by 2020.

Considering the exaggerated real estate prices, the usefulness of the new system is confirmed as it allows for greater use of the property land. It is expected that these improvements will positively contribute towards enhancing the life quality of the users who would apply the system. Eventually, this will serve the crucial goals that the Saudi government has launched recently under a program called VISION 2030. This paper investigates the influence of the compacted form on indoor comfort conditions by applying two cases of those allowed by the system.

2. Methodology

2.1. The climatic conditions

The Gulf region is located within a hot desert climate (BWh) according to the Koppen-Geiger climate classification. This type of climate is characterised by its low precipitation levels and mean annual temperature that is equal to or greater than 18 °C (Kottek *et al.*, 2006). Two seasons are distinguished in this type of climate, which are a hot season and a relatively cooler season. The maximum air temperature in the former can reach up to around 45 °C during day time and to almost 25 °C during night time. In the latter season, the maximum temperature falls in the ranges of 20-30 °C and 10-20 °C approximately during day and night respectively. The levels of relative humidity are generally below 40% with the exception of the maritime regions where it is normally within 90% (Konya and Vandenberg, 2011).

The investigated cities in this paper are Riyadh and Muscat that are the capital cities of Saudi Arabia and the Sultanate of Oman respectively. Figure 3 presents the mean levels of precipitation, mean minimum and maximum air temperatures, and morning and afternoon levels of relative humidity of both cities. The hot season extends between April and October, including both, in Riyadh and between April and November, including both, in Muscat. In this season, the mean maximum temperature in Riyadh fluctuates between 32 °C in April and 42 °C in June, July, and August. The maximum levels of morning and evening relative humidity are around 64% and 34% both occurring in April. The corresponding minimum levels are 33% roughly in July and 19% approximately in both July and August. In Muscat, the mean maximum temperature during the hot season ranges between 30 °C in November and 38 °C in June. The morning relative humidity fluctuates between almost 58% and 82% in May and August respectively, whereas the corresponding levels of evening relative humidity are almost 60% and 80% in May and August respectively. As demonstrated, the precipitation levels are noticeably low with a maximum of around 25 mm during April in Riyadh and almost 28 mm during January in Muscat.

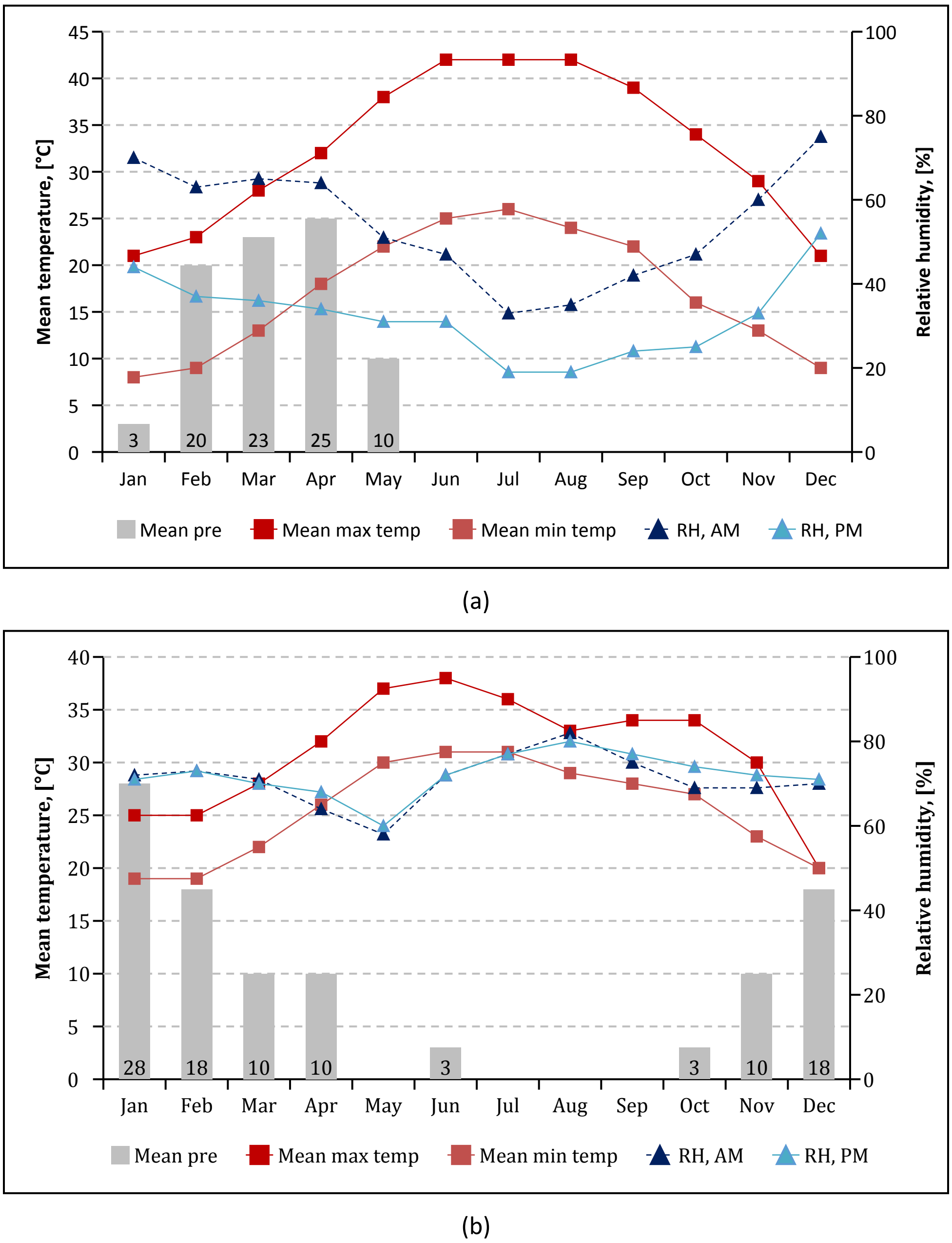

Figure 3. Climatic conditions of: (a) Riyadh and (b) Muscat [reproduced from (BBC, 2015a, 2015b)

2.2. The investigated villas

Three villas in Riyadh city were selected for the investigation reported in this paper. Each villa has an approximate area of 700 m². They are located on a north-south axis as demonstrated in Figure 4. They were built between 1992 and 1998 with no distinctive architectural features as noted from Figure 5. Their eastern and western facades view parallel streets that have a width of around 10-15 m. Besides, a mosque and two schools are located close to the villas. The outdoor ground cover of the three villas is terrazzo tiles. It may worth mentioning that villa (A) is surrounded by trees of more than 5 m height and villa (C) has an outdoor swimming pool.

Figure 4. The selected villas (Google Earth Pro image)

Figure 5. A photo of villa (A) (photo by Aasem Alabdullatief)

2.3. Specifications of the developed model

To explore the impact of the improved Saudi system of houses' setbacks on the required cooling load in summer, a model of the selected villas was developed using Design-Builder software. The actual monthly readings of electricity consumption of villa (A) for 2017 were obtained to validate the base model as explained in the following section. The characteristics of the constructed base model are summarised in Table 1.

Table 1. Characteristics of the base case model of villa (A)

Characteristics	Description of the base case model
Location	Riyadh (24°42’43.0” N, 46°46’37.0”)
Orientation	70° North east
Plan shape	Rectangular
Number of floor	2
Floor to floor height	2.6 m
Occupied floor area	452 m^2
Floor dimension	14 x 15 m
Window area	15% of the gross wall area
Window type	Typical double glazing – PYR B Clear 3 mm
Exterior walls	2 mm paint plaster + 7 mm cement plaster + 100 mm concrete blocks + 50 mm extruded polystyrene + 120 mm concrete blocks + 5 mm cement plaster + 2 mm inner paint plaster
Roof	10 mm outer tiles + 30 mm cement layer + 4 mm asphalt roll + 100 mm light concrete + 50 mm extruded polystyrene + 250 mm slap concrete + 2 mm paint plaster
Floors	7 mm tiles + 30 mm cement layer + 250 mm slap concrete
Infiltration	0.85 ACH
Occupancy Density	0.019 person/m^2
Lighting power density	5 W/m^2
Thermostat Setting	22-26 °C

After applying the necessary adjustments, two cases of those allowed by the improved setback system were selected for investigation. These cases are 50% and 0% of setback and they were applied on one side of villa (A) during the summer season. Considering the similarity in the climatic, social, and cultural conditions in the Gulf region, the model was simulated, without any change in its specifications, in Muscat city with the aim of exploring the performance of the proposed changes in the villas under a maritime Gulf region. The cooling loads of the base cases were compared with the required cooling loads of the relevant setbacks. The mechanical cooling system was assumed on by default during the investigation period and was turn off only when the temperature falls below a set-point of

22 °C. Besides, the predicted mean votes before and after applying the investigated cases of setbacks were compared.

2.4. Model validation

The actual monthly amounts of electricity consumption of villa (A) for the year of 2017 were obtained to validate the base model. The actual and simulated consumption amounts are demonstrated in Figure 6. The simulated consumption amounts followed the expected pattern as they increased gradually during summer and decreased during winter. However, there is no clear pattern for their relationship with the actual consumption amounts. For instance, the former amounts were higher in all months except July, September, October, and November. Besides, the difference in consumption amount is not constant; the differences in January and February are not comparable with those of May and June for instance.

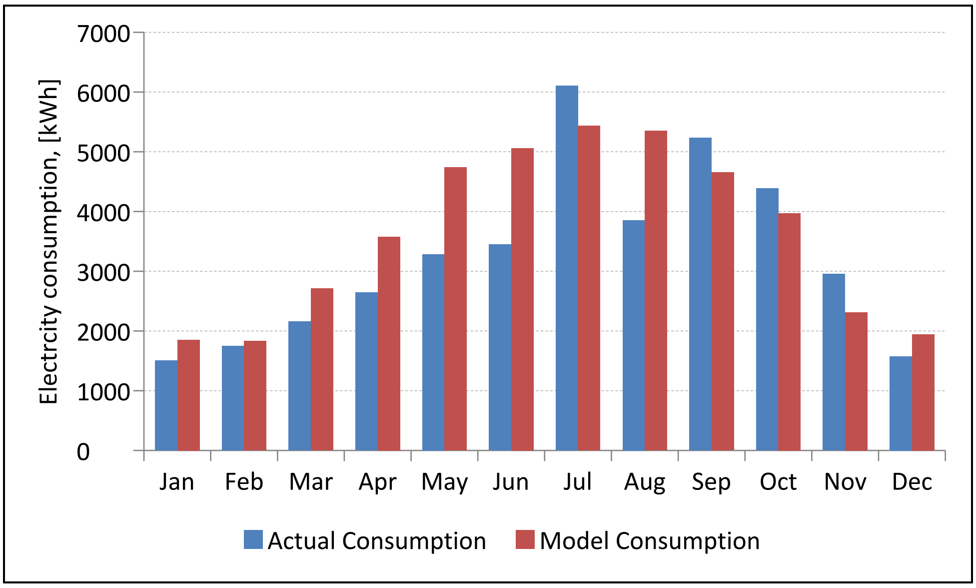

Figure 6. The actual and simulated monthly pattern of electricity consumption of villa (A)

For further investigations, the monthly and annual differences in consumption were calculated as displayed in Table 2. The satisfactory and acceptable limits of differences between the actual and simulated models are summarised in Table 3. Comparing the two tables reveals that the model consumption levels exceeded the acceptable limits in April, May, June, and August. It is worth mentioning that Table 3 levels are recommended for commercial buildings. Higher levels should be expected in residential buildings due to the different and hard to expect patterns of electricity consumption in houses. Indeed, the investigated villa showed unexpected levels of consumption during the summer months. In particular, there was an unexpected decrease in August compared with July and September. A reasonable justification may be spending some days of these months outside the villa considering that summer months coincide with the holidays' season. The annual difference in consumption is within the acceptable level and, indeed, is very close to the satisfactory level. Therefore, it is possible to consider the model validity taking into account that it was built on the most possible similarity to the actual villa details in a matter of form, dimensions, and envelope materials.

Table 2. Comparison of the monthly electricity consumption of villa (A) with the model consumption

Month	Actual Consumptions, [kWh]	Model Consumptions, [kWh]	Differences, [%]
January	1506	1853	23.0
February	1748	1831	4.7
March	2157	2712	25.7
April	2642	3578	35.4
May	3286	4739	44.2
June	3451	5061	46.7
July	6105	5436	-11.0
August	3855	5351	38.8
September	5232	4655	-11.0
October	4388	3972	-9.5
November	2953	2314	-21.6
December	1577	1945	23.3
Total	38900	43447	11.7

Table 3. Satisfactory and acceptable levels of the actual and simulated consumption differences for commercial buildings [reproduced from (Kaplan & Canner, 1992 in Rahman et al., 2008)]

	Daily	Monthly	Annual
Satisfactory	15%	5%	10%
Acceptable	25%-35%	15%-25%	25%

3. Results and Discussion

The influence of the improved Saudi system of houses' setbacks on the cooling loads in summer was investigated by simulating the selected villas in Design-Builder software. The investigation was applied in both Riyadh and Muscat cities representing hot dry and hot humid climates respectively. The required cooling loads of the base case model in these cities were estimated at 24,571 kWh and 38,875 kWh respectively. The corresponding predicted mean votes as estimated by the software were 1.0 and 0.8.

As demonstrated in Figure 7, applying the improved system of setbacks had a positive influence on the required cooling load during summer in both cities. Considering the 50%

setback cases, the reduction in the cooling loads were estimated at 6.3% and 12.3% in Riyadh and Muscat cities respectively. The corresponding percentages of 0% setback cases were 21.6% and 15.1% approximately. Further reductions are expected if the suggested setback cases were applied on more than one side. Yet, applying 100% setback on one side seems to be promising in Riyadh considering the resulted reduction. Considering Muscat city, the cooling loads' reduction increased comparatively slightly in Muscat perhaps due to its humid nature besides to its mountainous nature. Indeed, the basaltic formations of the city absorb heat during day time and release it during night time (Ragette, 2012).

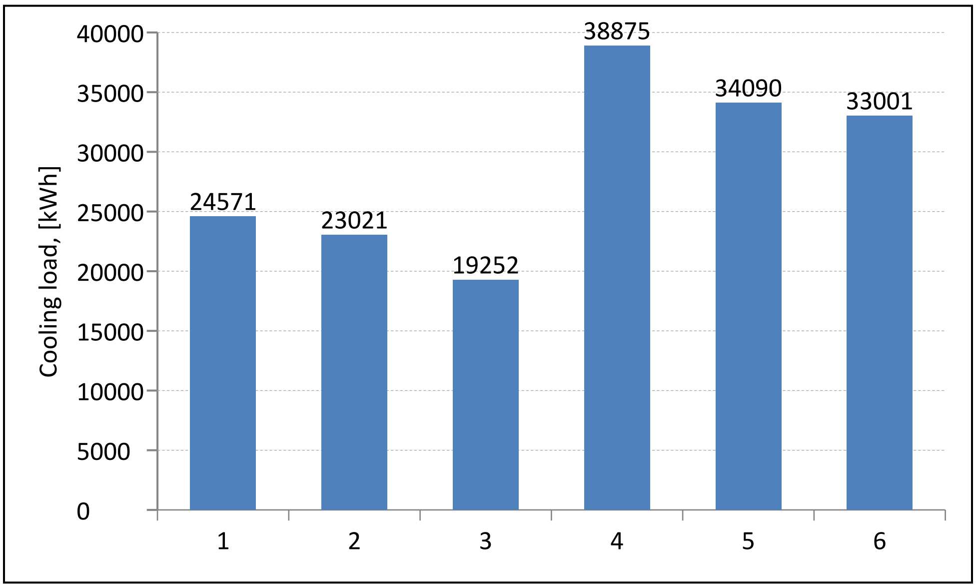

Figure 7. The cooling loads of the base cases and investigated cases in Riyadh and Muscat cities

Considering the thermal comfort conditions, Figure 8 presents the predicted mean votes (PMV). As demonstrated, there was a marginal decrease in the predicted mean votes. The votes of the investigated cases were still in (slightly warm) category similar to the base cases' votes. Yet, it is worth mentioning that the PMV of 0% setback case in Muscat was close to the edge between (slightly warm) and (neutral).

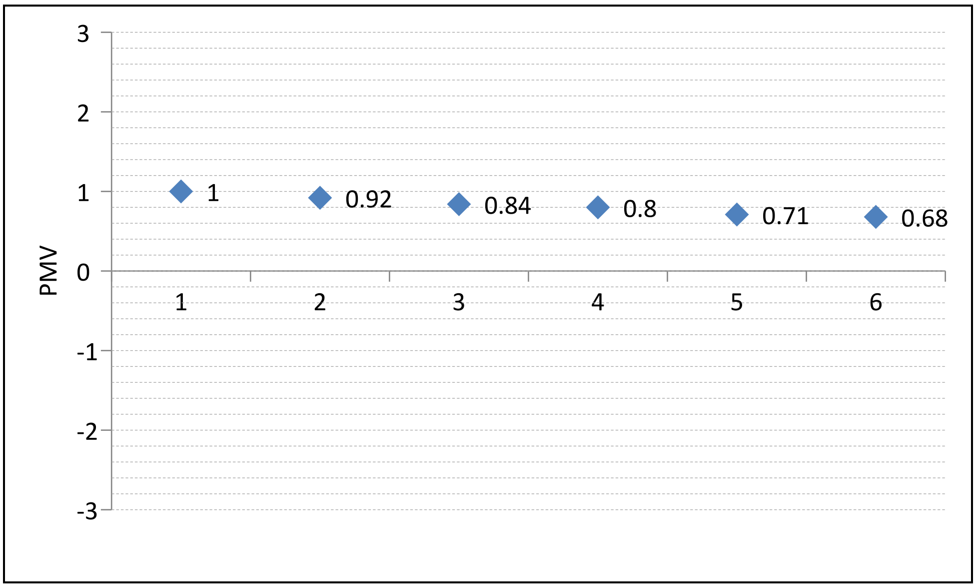

Figure 8. PMV in the base cases and investigated cases in Riyadh and Muscat cities

Applying the improved system of setbacks has a positive influence on decreasing the cooling loads and improving the thermal comfort conditions. The improvement increases with the decrease in the setback percentage in both cities; yet, Muscat has a slower rate. A similar observation was noted in (Al-Khatri and Gadi, 2015).

4. Conclusion

The regulation of Saudi houses' setbacks was improved recently. Accordingly, the total built-up area can reach a maximum of 70% of the property area and the setbacks are decreased by up to 100% of no more than two sides of the house. This system resembles the compacted forms of traditional domestic architecture in the Gulf region. The influence of this system on the required cooling loads during summer was investigated in Riyadh and Muscat cities. Two cases of 50% and 0% setbacks were applied and the cooling loads and PMV were compared with the base cases. A maximum reduction of around 21.6% in the cooling loads was achieved in Riyadh applying the 0% setback. The reductions in Muscat were lower due to its climatic conditions and mountainous nature. The predicted mean votes of both the base cases and the investigated cases fell in the (slightly warm) category. Further investigations exploring the allowable cases by the system are recommended in Riyadh to identify the optimum percentages of setbacks for each case. Explorations in other cities in the Gulf are recommended considering the climatic, social, and cultural similarities. Finally, it is worth mentioning that using accurate weather files is positively linked to the accuracy of the simulated model predictions.

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Evaluating the effect on thermal comfort and energy use of applying the Passivhaus standard to a dwelling in a hot humid climate – a case study in Jakarta, Indonesia

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Abstract: Houses built in tropical countries will experience hot and humid climatic conditions, with high levels of moisture. Together with moisture builds up by occupants' activity, ventilation for such housing will lead to very high levels of indoor relative humidity. The use of air conditioning to cool rooms and reduce relative humidity in dwellings is an energy-intensive approach but it is also energy-inefficient as the conditioned air is lost through the building envelope via ventilation and air infiltration. The German Passivhaus standard's approach in tropical housing might be effective in preserving stable interior temperatures, nevertheless special attention is needed to the removal of excess moisture.
The objective of this research was to investigate the thermal comfort and energy-saving implications of applying Passivhaus principles to existing urban row houses in Jakarta, Indonesia. The goal was to achieve the lowest possible carbon emission building whilst maintaining a comfortable and healthy environment. The software model of the existing dwelling was built in IES software and was checked against field measurements of air temperature and relative humidity made in the house. Parametric modelling involved gradually improving insulation levels and air-tightness in the house until the Passivhaus standards were reached. Analyses of the results enabled the optimum insulation and air-tightness settings to be determined for minimizing cooling and dehumidification energy use in the air-conditioning system.

Keywords: Passivhaus, hot and humid climate, thermal comfort, low-carbon and low-energy cooling

1. Introduction

Indonesia is Located between 6°08′ N–11°15′ S and 94°45′–141°05′ E. According to World Map of the Köppen-Geiger climate classification, Indonesia is included in the Af category, that is equatorial rainforest with fully humid zone (Kottek et al., 2006). The climate in Indonesia is generally hot and humid, with a relatively small variation of temperature throughout the year. Most of the Indonesian regions experience rainfall between 1000 and 4000 mm/year, with average and maximum outdoor temperature are 26 °C and 37 °C, respectively, while the average relative humidity ranged between 73% and 100% (Santy et al., 2017).

Population growth and a need for housing have contributed greatly to uncontrolled urban sprawl around the peripheries of Indonesia's major cities (Rahadi et al., 2015). Jakarta, the capital of Indonesia, has a high demand for dwellings. The housing developments are growing mostly into the satellite city by developing new towns. These new towns mainly consist of low density, single-family houses, and exclusive residential areas for middle- and upper-income groups (Firman, 2004). The thermal performance of these houses tends to make them unsuitable for the effective use of air conditioning (AC). With houses not airtight and poorly insulated, residents tend to lower the air-conditioning temperature setting to achieve their comfort level, resulting in inefficient use of air-conditioning. The monthly average use of electricity consumption households was between 300-400kWh (Santy et al., 2016). The application of simple passive cooling measures, such as glazing, shading, insulation, and natural ventilation, to these dwellings can reduce the cooling loads by up to 43% (Omer, 2008). Design principles that use natural ventilation to reduce the dependence of the cooling devices to achieved comfortable condition will provide enough fresh air in the building to keep the occupants healthy. At the same time, this fresh external air will introduce more moisture in to a house during the hot season, which is likely to increase the indoor relative humidity level.

This paper presents the application of the German Passivhaus standard to reduce domestic energy use whilst creating thermal comfort in housing built in the tropical climate of Indonesia. Analysis was done by investigating the typical housing characteristic, building performance (in this case are temperature and relative humidity), and energy consumption. The research then continued by applying the German Passivhaus standard to Indonesian dwellings in order to study the building performance and energy consumption. Passivhaus might be able to suppress the energy consumption, especially for cooling energy needs.

1.1. Adaptive Thermal Comfort

The significance of indoor thermal comfort valuation and measurement is not only associated with achieving thermal satisfaction, but also to control energy usage and improving indoor air quality (Nicol and Humphreys, 2002). The current Indonesian national standard indicates that comfort temperature is 25°C ± 1 °C and relative humidity 60% ± 10% (SNI, 2000). This number is lower than the result from researchers who has researched the comfort temperature for people in Depok area (Jakarta satellite town). The finding was a comfort temperature of 27.6°C (Santy et al., 2016).

The ASHRAE Adaptive Comfort Model was developed from a global database that separated buildings into those that had mechanical system and naturally ventilated buildings (NV). Thermal comfort standards recognize that comfort depends on context. People living with air-conditioned spaces expect homogeneity and cool temperatures, while people who live in naturally ventilated buildings are used to thermal diversity. Their thermal perceptions are likely to extend over a wider range of temperatures than are currently reflected in the old ASHRAE Standard 55 comfort zone (de Dear and Brager, 2002a). The results of this adaptive comfort standard (ACS) are shown in Figure 1.

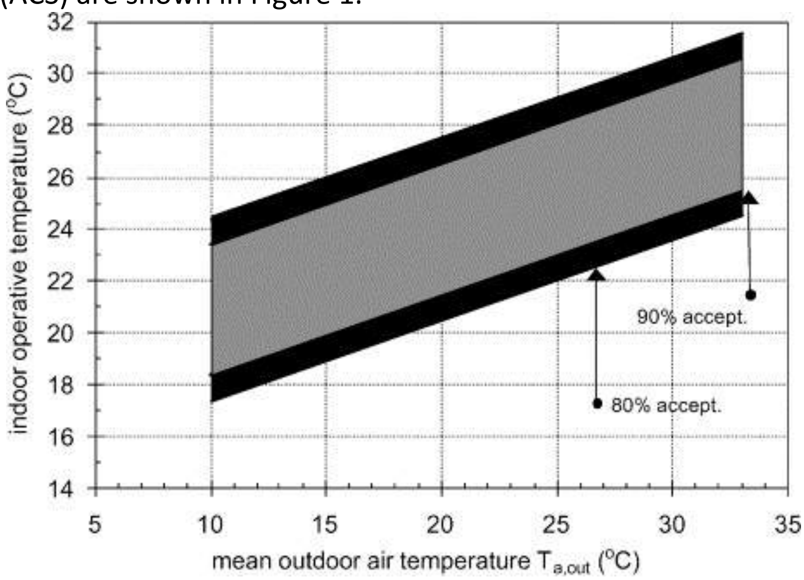

Figure 1 – Proposed adaptive comfort standard (ACS) for ASHRAE Standard 55, applicable for naturally ventilated buildings (de Dear and Brager, 2002b).

The important finding on the ASHRAE adaptive comfort standard study was the difficulty of creating generalization for areas that have mean outdoor temperatures above 23°C. The research indicated that buildings in this zone are unable to maintain thermal comfort, even as defined by the ACS model, for many hours of the day. These uncomfortable buildings came from various regions of Pakistan, Australia, Greece, Singapore, Indonesia, and Thailand (de Dear and Brager, 2002b). This is consistent with the research by Karyono, who found that there are some climatic differences between cities in the lowland and highland in Indonesia, which could lead to the difference on the people's comfort temperature due to physical adaptation (Karyono, 2018).

1.2. Passivhaus standard

The Passivhaus standard was established as a building concept for residential buildings in Germany. It has the main purpose to deliver excellent cost-effectiveness, especially in the case of new buildings. The German Passivhaus standard, which was originally developed to reduce winter heat losses from north European buildings, is based on the concept of an air-tight envelope. The general criteria of Passivhaus can be seen in Figure 2 (Passivhaus Institute, 2016). The achievement of the initial projects that had very low energy consumption and high thermal comfort levels, has encouraged the spread of the Passivhaus standard to other countries in Europe. The Passivhaus Institute indicate that Passivhaus certified buildings have spread throughout the world. In the database of Passivhaus compiled by iHPA, Passivhaus Institute and Affiliates, there have been thousands of single detached family houses registered as Passivhaus in the several countries, but there are none in Indonesia (Passivhaus Dienstleistung, n.d.).

			Criteria[1]			Alternative Criteria[2]
Heating						
Heating demand	[kWh/(m²a)]	≤	15			-
Heating load[3]	[W/m²]	≤	-			10
Cooling						
Cooling + dehumidification demand	[kWh/(m²a)]	≤	15 + dehumidification contribution[4]			variable limit value[5]
Cooling load[6]	[W/m²]	≤	-			10
Airtightness						
Pressurization test result n_{50}	[1/h]	≤	0.6			
Renewable Primary Energy (PER)[7]			Classic	Plus	Premium	
PER demand[8]	[kWh/(m²a)]	≤	60	45	30	±15 kWh/(m²a) deviation from criteria...
Renewable energy generation[9] (with reference to projected building footprint)	[kWh/(m²a)]	≥	-	60	120	...with compensation of the above deviation by different amount of generation

Figure 2 – Passivhaus Criteria

Passivhaus buildings achieve thermal comfort by passive measures, such as high levels of insulation, excellent airtightness, good indoor air quality and minimum thermal bridges, supported by a whole house mechanical ventilation system with highly efficient heat recovery (BRE, 2017). Applying the Passivhaus building standard can preserve stable interior temperatures, but in tropical climates with high temperature and high humidity, its airtight envelope might hinder the removal of excess moisture. The Passivhaus standard application must accurately consider moisture balances and the attendant latent loads on the building with a hot and humid climate.

The cooling strategy used in the Passivhaus house built in Louisiana, southern USA, with a high humidity climate, is by using Energy Recovery Ventilators (ERV). Unlike straight heat exchangers, which are commonly used for Passivhaus building in Central Europe, ERV transfers water vapour, which prevents the air from drying out in winter months, and removes outdoor humidity during summer months (MacDonald, 2010). ERV systems transfer moisture from the incoming humid air to the outgoing stale indoor air that is being vented to the outside, making the internal humid air that produced by equipment and building user are remain inside.

2. Research methodology

This paper discusses the development of a Passivhaus standard for housing built in Indonesia that work for both thermal comfort and energy efficiency. IES is a commercially available dynamic thermal simulation software. It was used to analyze the building performance of an Indonesian dwelling by creating a building model using information such as: building materials, cooling systems, lights and appliances, and presupposed occupancy schedule from the selected house. A row or terraced house was chosen because this style forms the majority of the existing urban housing stock (Badan Pusat Statistic, 2018). The chosen house is shown in Figure 3. The selected house's area lied between 50m^2 to 69m^2 floor area, since this is the most prevalent size for housing in Jakarta Metropolitan Region (Sigalingging et al., 2017). A Jakarta weather file was acquired through the climate-modelling software Meteonorm (Meteotest, 2018). The empirical validation of the model designed by the IES software was determined by comparing the computer simulation results with field experiment data from a target house. This validated model was than used to explore the effects on the indoor environment when applying the Passivhaus standard to the row house, to study the energy needed to achieve thermal comfort.

2.1. Case Study Data and monitoring result

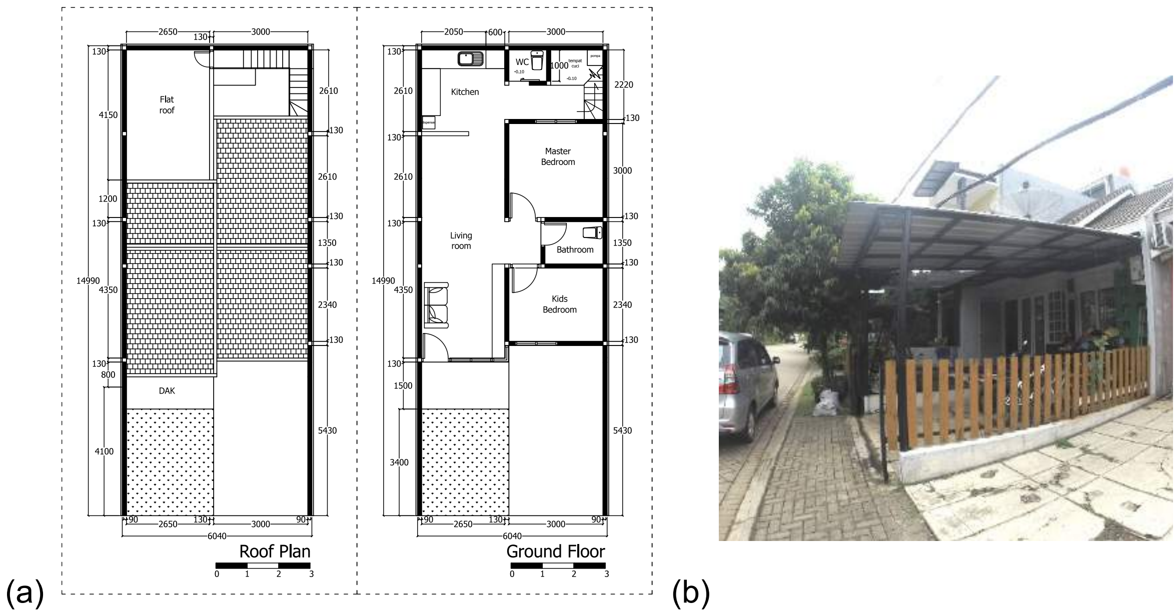

Figure 3 – The case study row house (a) floor plans, (b) exterior view

The house's walls are made of low brick and bricks; the floor material was dominated by ceramics; roof material are tiles, and the ceiling material is gypsum. The house measures 6 m x 10 m with a total floor area of 55m^2, with a floor-to-ceiling height of 2.85m. The building is oriented towards north and is not insulated. The windows material is clear glass with awning on the internal side which gives more privacy to the residences.

House monitoring was done over two periods that represented two different seasons in Indonesia: January – February for the rainy season and September – November for the hot dry season. Loggers were used to monitor the air temperature and relative humidity of two main activity locations in the selected row house (master bedroom and living room (Fig. 4)). Loggers were also used to monitor the outside air temperature and relative humidity, which were used later to validate the computer model. Two types of loggers that were used in this monitoring - Tinytag data loggers and Rotronic data loggers.

Figure 4 – Logger location in master bedroom, Living area & outdoor area

2.2. IES VE 2018 software Validation

The whole house was modelled in three dimensions using IES VE software with the data obtained from field observations. The building shape is based on the plan provided by the home owner, building materials are from data based on the contractor's specification, and the occupant activity schedule was gained from field observations. Measured data were used on the empirical validation of the IES VE 2018 model. The building simulation air temperature and relative humidity results will be compared with measured data. To be able to make a comparison, the modelled house was simulated in the same period as the monitoring time period. The building elements used to build the base model in IES VE 2018 can be seen in Table 1.

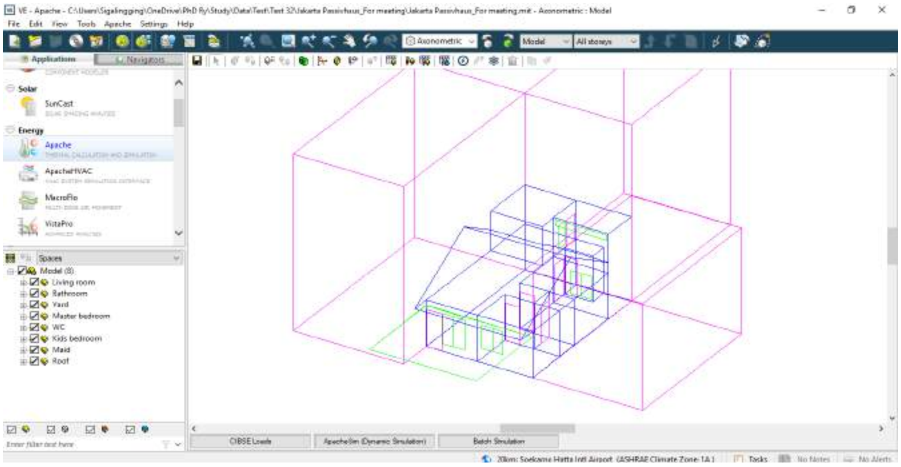

Figure 5 – IES software view

Table 1 – Factors Building elements

Building Element	Constructional layers
External and internal walls	25 mm thick cement plaster + 100 mm thick clay brick + 25 mm thick cement plaster
Party wall	25 mm thick cement plaster + 100 mm thick clay brick + 25 mm thick cement plaster
Floor	8 mm thick ceramic tile + 22 mm thick cement screed + 100 mm thick concrete slab + soil layer
Window	6 mm thick single layer glass
Ceiling	6 mm thick gypsum board
Pitched roof	20 mm thick roof tile + 25 mm thick timber batten
2nd floor slab	22 mm thick cement screed + 100 mm thick concrete slab + 20 mm thick cement plaster

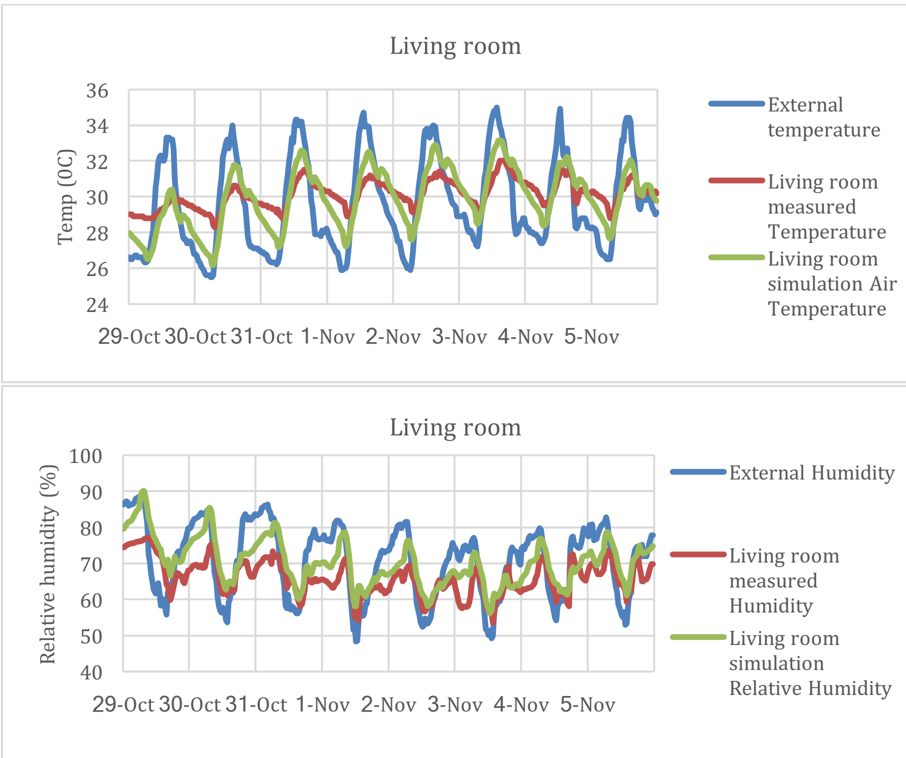

Figure 6 – Measurements and simulation data comparison on Living room

The simulation result from the modelled house in IES VE software was then compared with measured data; the graphs can be seen in Figure 6 and Figure 7. The two main rooms discussed here are the living room and the master bedroom. The living room graph shows that the IES simulation demonstrated the identical fluctuations to the measured data, both for air temperature and relative humidity. From the graphs the air temperature differences were less than 3^{0}C, and the relative humidity differences were less than 10%. The bedroom area indicated similar results, where the air temperature of the modelled house had the same fluctuations as the measured data with only a few hours during the day showing 1^{0}C differences.

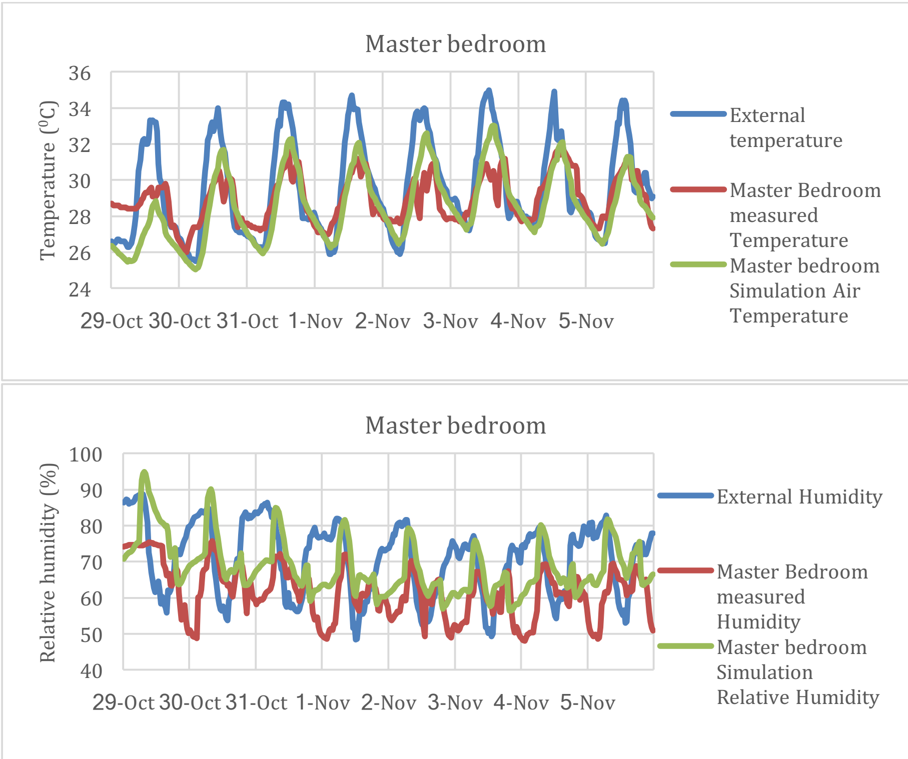

Figure 7 – Measurements and simulation data comparison on master bedroom

A more detailed inspection (Figure 8 and Figure 9) shows that the simulation temperature and relative humidity temperature has relatively the same fluctuation but with slightly differences in the few hours during the day. These differences in the living room and master bedroom results were possibly happening due to logger accuracy and software simulation accuracy. The differences were also possible from the actual sky coverage and wind speed data that were not captured on the site measurements. Other possible reasons for the temperature and humidity differences are from occupant activity that were based on typical behaviours whereas the actual conditions might be slightly different from day to day.

From this validation exercise, it could be seen that the IES VE 2018 software could be used to model the selected house. The validation process indicated that the result produced relatively similar outcomes compared with the field measurement data. The simulation results of the built model in IES VE software shows that the results were satisfactory in displaying the same trend as the measured data.

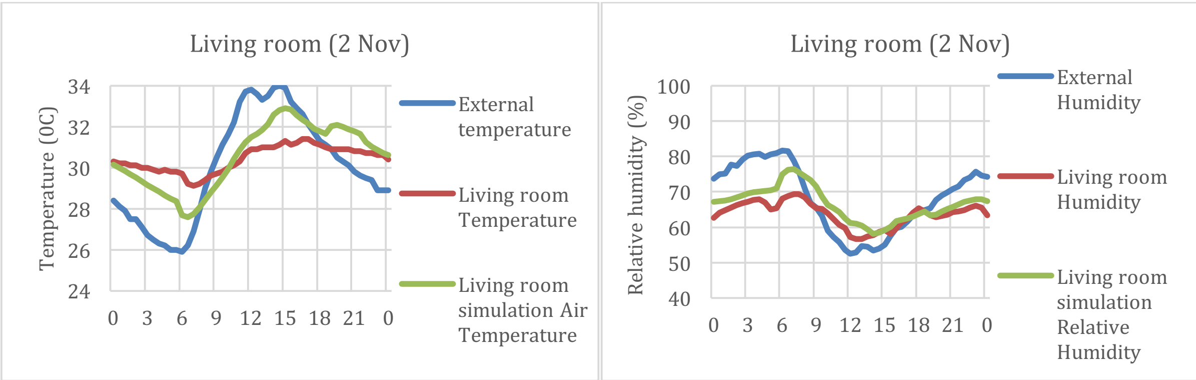

Figure 8 – One day comparison of measurements and simulation data on living room

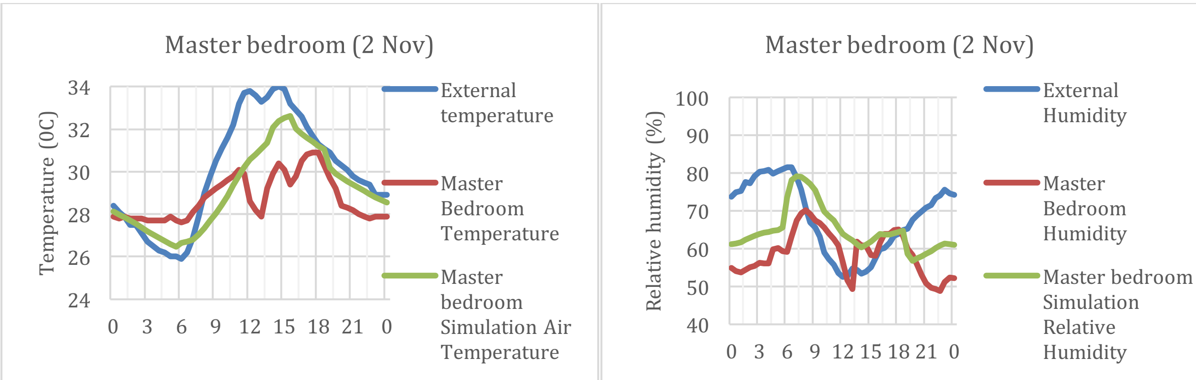

Figure 9 – One day comparison of measurements and simulation data on master bedroom

2.3. Evaluating Indicator

The adjustment and calibration process were conducted in accordance with the specifications of the standard ASHRAE 14-2002 (ASHRAE, 2002). The statistic MBE represents the mean ratio of relative error between two values, as shown in Equation (1), while CV/RMSE represents the average deviation between an actual value and a predicted value as shown in Equation (3). CV/RMSE values are used to assess the differences in the simulated and observed hourly data, to evaluate the prediction accuracy of the simulation result. ASHRAE Guideline 14 defines the acceptable limits for calibration to hourly data as within ±10% MBE and≤30% CVRMSE(hourly) measured at a utilities level (ASHRAE, 2002).

$$MBE = \frac{\sum_{i=1}^{N_S}(y_i - \hat{y}_i)}{\sum_{i=1}^{N_S} y_i} \qquad (1)$$

$$\hat{Y}_S = \frac{\sum_{i=1}^{N_S} y_i}{N_S} \qquad (2)$$

$$\text{CVRMSE}_{(S)} = \frac{\sqrt{\sum_{i=1}^{N_S} \frac{(y_i - \hat{y}_i)^2}{N_S}}}{\hat{Y}_S} \qquad (3)$$

where:

- y_i : Recorded data
- $\hat{y}_i$: Simulated data
- $\hat{Y}_S$: Sample mean for recorded data
- N_S : Sample size

The evaluation results of the statistical error analysis data for the mean hourly error of measured data versus simulation result are listed in Table 2. The calculation were done for one week period. From the table it can be seen that the results of the simulation comfortably meet the acceptance criteria. The living room's relative humidity and temperature MBE percentage are very low. The relative humidity in the master bedroom was slightly above the limit, but the temperature MBE percentage was below -1% for the master bedroom. For all measured elements the CVRMSE percentage was below the acceptable limit.

Table 2 – Statistical error data for the mean hourly error of measured data versus simulation result

Measured element	**MBE (%)**	**CVRMSE (%)**
Living room relative humidity	-5.9	7.5
Living room Temperature	0.3	3.1
Master Bedroom relative humidity	-10.9	14.0
Master Bedroom Temperature	-0.5	3.6

3. Application of Passivhaus standard into modelled house

Using the validated modelled house in IES VE 2018, the Passivhaus standard was applied to the selected house. By applying Passivhaus strategies in to the modelled house, the building performance was observed. When one or more Passivhaus criteria were applied to the same building layout, shape, occupancy schedule, and climate data, the effect of Passivhaus standards on the modelled house were explored. This study analysed the effects when the Passivhaus model used air conditioning (AC) and dehumidifiers for cooling and dehumidification to try and achieve thermal comfort for the occupants. The cooling load will be studied through numerical simulation using the IES VE 2018 software program. Both scenarios (existing and Passivhaus dwelling) used the same HVAC system (AC and dehumidifier). In both simulations, AC and dehumidifier was ducted into the living room, master bedroom, and children's bedroom. Table 3 indicates the material used in the building to correspond to the Passivhaus concept. This Passivhaus model was then used to explore the effects on the indoor environment to study how much energy was needed to bring comfort to the house.

Table 3 – Passivhaus building elements

Building Element	**Constructional layers**
External and internal walls	25 mm thick cement plaster + 100 mm thick clay brick + 100 mm XPS Extruded Polystyrene + 25 mm thick cement plaster
Party wall	25 mm thick cement plaster + 100 mm thick clay brick + 100 mm XPS Extruded Polystyrene + 25 mm thick cement plaster
Floor	8 mm thick ceramic tile + 22 mm thick cement screed + 100 mm thick concrete slab + Urea Formaldehyde Foam + soil layer
Window	6 mm thick double layer glass
Ceiling	6 mm thick gypsum board
Pitched roof	20 mm thick roof tile + 25 mm thick timber batten + 100 mm MW Glass Wool (rolls)

4. Comparing the simulation results

The simulation results from the Passivhaus application to the Jakarta house can be seen in Figure 10 and Figure 11. The results show that the Passivhaus building model had air temperatures that were typically 2^0C lower than simulation results for the original house, although the temperatures of both scenarios were still above 28^0C. However, both the Passivhaus model and original house simulation results suggest relative humidities that were 60%.

Sequentially implementing Passivhaus requirements in to the housing model revealed some interesting results. By applying all the Passivhaus requirement, but without the floor insulation, the simulation showed a significant energy saving. Air temperatures for the Passivhaus application exclusive of floor insulation are shown in Figures 10 and 11. They indicate that removing floor insulation created lower temperatures in the living room and master bedroom that were maintained below 26^0C for the selected time period. Applying Passivhaus without floor insulation also created stable relative humidity levels below 60 %.

For the simulation, the AC was set to meet the adaptive comfort temperature for a tropical climate, which is 27.6^0C. With the ground temperature based in the simulation validation set around 5^0C lower than outdoor temperature, for the selected period there was more than 75% of the time when the ground temperatures were below the adaptive comfort level (Figure 12). This situation meant that the floor could act as a sink for the heat in the house.

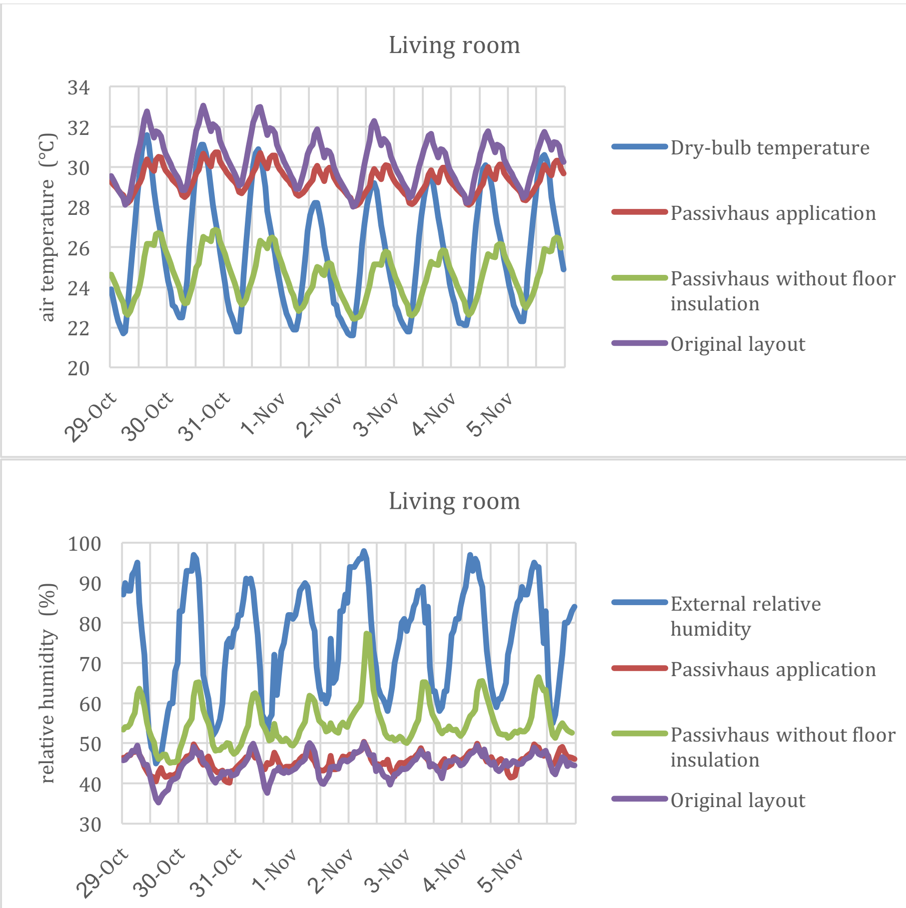

Figure 10 – Hourly air temperatures comparison in living room for Passivhaus approaches and original layout.

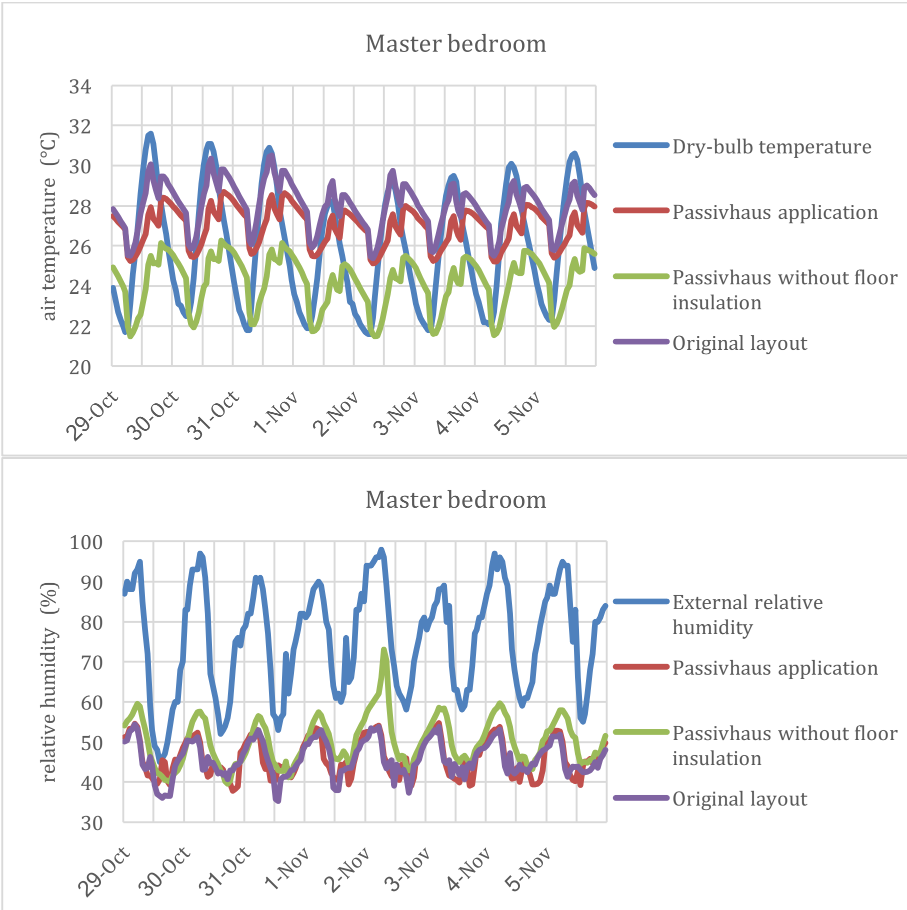

Figure 11 – Hourly air temperatures comparison in master bedroom for Passivhaus approaches and original layout.

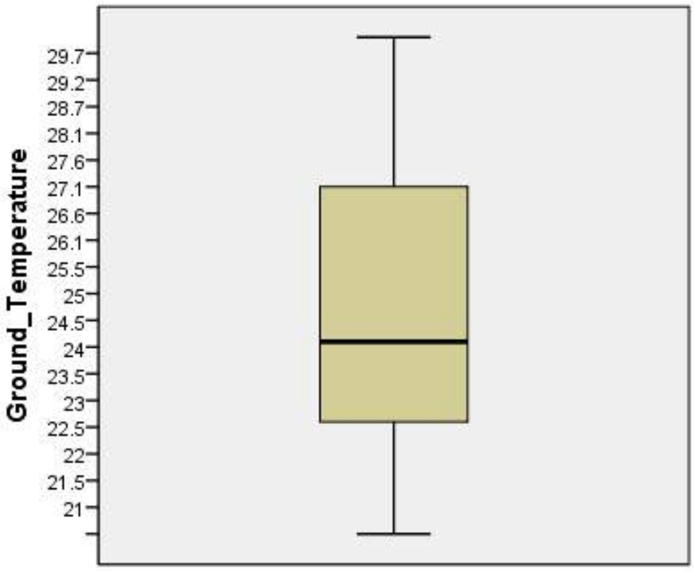

Figure 12 – Box plot of ground temperature during the one-week period.

All the scenario energy consumptions were then investigated, to test how the building performance was related to the energy used. The IES simulation results reveal that annual cooling energy used in the building was 11.41 MWh for the house in its original layout, 10.89 MWh for the house if using the full Passivhaus standard and 8.61 MWh if using Passivhaus but without floor insulation. This modelling results show that the building model that applied Passivhaus concepts but excluded floor insulation had the lowest air temperatures and had relative humidities within the comfort range. This scenario also has the lowest energy consumption compare to the other scenarios (Figure 13).

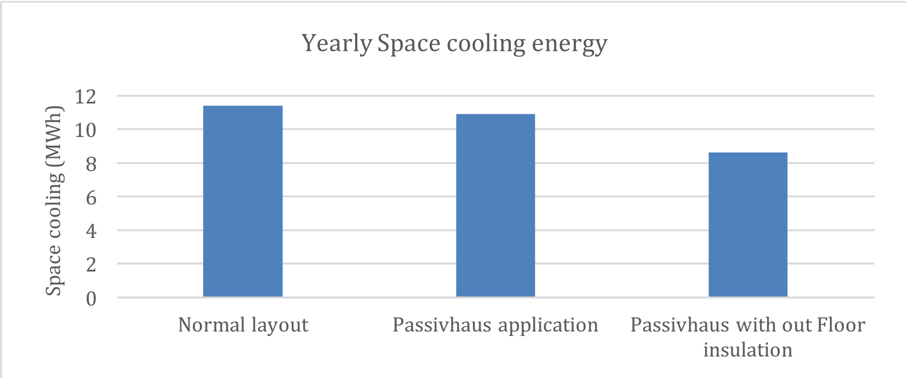

Figure 13 – Yearly space cooling comparison.

5. Conclusions

One building has been chosen to study the impact of applying the Passivhaus standard to a typical tropical climate dwelling in the Jakarta Metropolitan Region. Site measurements were carried out to validate the model of the house using IES VE 2018 software. The validated model was then used to study the effect of applying the Passivhaus standard by incrementally applying Passivhaus requirements into the building. Using the same building layout, shape, HVAC system, occupancy schedule, and climate data, the results showed that applying the Passivhaus standard can lower the building temperature and relative humidity to the comfort level with lower energy usage. However, the better performance was found if the Passivhaus application was used without floor insulation. But, the research has also found that to achieve comfort levels for temperature and relative humidity requires high amounts of energy, even though the number is reduced with Passivhaus applications.

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Applications of Evaporative Cooling for Thermal Comfort

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Abstract: Evaporative cooling (EC) is seeing increasing attention as a low-energy method to increase thermal comfort in hot climates. Although EC can reduce air temperatures using the latent heat of water, the accompanying rise in humidity and the limited achievable temperature drop may discourage adoption of EC systems. Here, a short review of common EC system types and the basic physics of EC applied in thermal comfort models are presented. Some current research on EC and thermal comfort is reviewed for the purpose of sparking discussion of EC in the context of thermal comfort.

Keywords: evaporation, mist, cooling, thermal comfort

1. Background

Evaporative cooling (EC) is a low-energy method that takes advantage of the latent heat of evaporation of water to cool air. Although EC can reduce air temperatures using the latent heat of water, the accompanying rise in humidity and the limited achievable temperature drop present challenges in evaluating EC in the context of thermal comfort. Direct measurement of cooled air may encounter errors due to sensor wetting. Comfort surveys are often based on relatively short term exposure times, which may lead to over-estimation of coolness.

1.1. Physics of Evaporative Cooling

Water evaporating in air takes heat from the air to provide the energy for the phase change from liquid water into vapour. This exchange reduces the temperature of the air. The latent heat of evaporation is provided by the sensible heat lost from the air. The net change in energy is zero, thus some call evaporation cooling (EC) a form of “free cooling”. EC can be extremely energy efficient.

There are limitations to EC. First, a supply of clean water is needed. As water is introduced into an air stream, any contaminants within the water can also become airborne. Of special concern is the potential for deadly *legionella* bacteria to be inhaled into the lungs. Regular cleaning and maintenance are essential, similar to cooling towers.

Second, the cooling effect is limited. The affected air cools and is humidified along a constant-enthalpy line on the psychrometric chart, with the ultimate limit as saturated moist air at the wet bulb temperature. EC potential can be described in terms of the wet bulb depression (the difference between dry and wet bulb temperatures) as the maximum possible air temperature reduction. The final condition depending on the ratio of air to evaporated water. EC systems for comfort in hot climates are generally not designed to reach this saturation limit, as it would be uncomfortable, prevent sweat evaporation, and promote wetting of surrounding surfaces and clothing.

When the supply water temperature is greater than the wet bulb temperature, a small amount of sensible heat is added to the air, however this is insignificant compared to the latent heat of evaporation. If a 50°C water supply is used for EC when the wet bulb temperature is 20°C, the sensible heat gain is about 5% of the total latent heat of evaporation.

Low humidity improves potential temperature drops (the wet bulb depression is larger) and cooling capacity (more water can evaporate per unit of air). Relatively high temperatures in a given climate (at the daily high temperature, during heat waves, in urban heat islands) are generally accompanied by lower relative humidity. Thus EC potential is best when heat stress is typically worst. The hotter a given climate gets, the more effective an evaporation cooling system can become. As climate change and heat islands yield hotter extremes, installed EC systems can become more effective rather than less as with mechanical vapour-compression air-conditioning systems.

1.2. Evaporative Cooling Techniques

Many techniques to make use of the cooling effect of evaporation have been developed. The tendency of bodies of water to be cooler than the surrounding air has long been exploited by bathers seeking relief from heat. Fountains yield pools of water near the wet bulb temperature, which cools bathers and air through conduction and convection and provides radiant cooling. Windcatchers combined with a *qanat*, an underground water channel, to yield EC have been used in desert climates for millennia as an early form of building cooling. In the Japanese tradition of *uchimizu*, people sprinkle water over hot ground surfaces in the afternoon to reduce its temperature.

EC can be classified into "indirect" and "direct" techniques. Indirect techniques typically use evaporation to cool supply air via a heat exchanger, such that the EC air does not mix with the supply air. Supply air temperature is reduced but absolute humidity in unchanged. In terms of thermal comfort, the indirect evaporation technique is little different from standard air-conditioning techniques, though the limited temperature drop and inability to dehumidify must be taken into consideration.

Direct techniques mix supply air with evaporating water, reducing temperature, but increasing humidity. These effects have opposite influences on thermal comfort in hot environments. Further, the humidification and potential to saturate supply air tends to limit EC to use in open or well-ventilated spaces. Direct EC techniques generally share the following pros and cons;

Pros:

- Low energy cost compared to standard vapour-compression air-conditioning.
- No special refrigerants needed.
- Less complex than standard HVAC equipment. Easier maintenance.

Cons:

- Cooling effect (temperature drop) limited to wet bulb depression.
- Strict maintenance and cleaning required to reduce risk of *legionella*, mould, etc.
- Increased humidity can promote corrosion, mould.
- Some system components need regular replacement.

Indirect-direct evaporative cooling (IDEC) can achieve supply air temperatures lower than the ambient wet bulb temperature by pre-cooling inlet air with indirect EC, then using direct EC. Using multiple steps and heat exchangers, the theoretical limit of IDEC cooling is to the dew point temperature of the initial ambient air.

Common direct EC systems are described below with their particular pros and cons.

1.2.1. Evaporative Coolers

Also known as "swamp coolers" or "desert coolers", evaporative coolers blow outdoor air through a wetted media such as mesh or wood wool into the cooled space. A water pump supplies water to the top of the media, which has a large surface area to promote evaporation. Gravity pulls water down to wet the media. Some of the water evaporates into the air, but much flows to the bottom of the unit, where it is collected and recirculated to the top. Makeup water is required to replace that lost in evaporation, often governed by a simple float valve. The energy inputs are to the mechanical fan and to the pump which circulates the water. Power consumption is typically much lower than vapour-compression air conditioners of similar capacity. Pros and cons particular to evaporative coolers include;

Pros:

- Very simple. Mechanically-inclined person can install, maintain, or even build.
- No high-pressure fittings needed.
- Low electric current draw, suitable when electric supply is limited.

Cons:

- High humidity inside unit promotes corrosion of the unit and supply air ducts.
- Media must be replaced regularly.
- Risk of not only for mould, bacteria, etc. but also insects. Much higher risk if not properly maintained.

1.2.2. Mist sprays

A key to increasing EC efficiency is increasing the surface area of water in contact with air. Breaking down the water into small droplets greatly increases the surface area for evaporation. While 1 litre of water in a 1mm shallow pool has $1m^2$ of surface area, a spray of 1 litre of 10µm droplets has a total surface area of $600{,}000m^2$.

"Mist" is defined as a collection of airborne water droplets of 100µm diameter or less (Lefebvre and McDonell, 2017). Mist droplet diameter distributions are often described in terms of average diameter. The Sauter mean diameter is the ratio of the volume of all droplets to the surface area of all droplets, often abbreviated SMD or d_{32}. SMD is often used in comparing mists for EC purposes as the evaporation rate of the mist as a whole is better correlated to SMD than a simple arithmetic average size, as smaller drops far outnumber larger drops. Mist droplet evaporation time is proportional to the square of the diameter and inverse linear proportion with the wet bulb depression. Knowing the droplet evaporation time and airflow of the target environment aids in configuring the mist EC system to prevent wetting.

There are several types of equipment used to produce mist. Hydraulic spray nozzles are supplied with pressurized water from a pump. Higher pressure creates smaller droplets. At pressures around 5MPa, the SMD ranges from 20~100 microns. Simple systems using only tap water or hand pump pressure tend to produce relatively large droplets (over 500 microns, similar to light rain) and can cause uncomfortable wetting. Pneumatic spray nozzles (AKA "atomizers") use pressurized air to break up a stream of water into droplets. It is possible to create SMD of less than 10 microns, but the energy cost is higher than hydraulic sprays due to the need for a constant stream of pressurized air. Rotating plates use centrifugal acceleration to break a stream of water into droplets and "fling" them into the air. A wide range of droplet diameters are possible. Vibrating plates and ultrasonic transducers can produce extremely fine mists of SMD under 10 microns without need for pumps, but the mist produced per unit can be quite small compared to spray nozzles. The EC effect of a commercially available ultrasonic mist fan may even be smaller than the waste heat produced by the fan motor. Ultrasonic transducers tend to be used for indoor humidification due to their simplicity, low energy use and low flow rates that reduce the fear of completely saturating the air.

Pros and cons particular to mist sprays produced by pressurized nozzles include;

Pros:

- Low energy cost compared to mechanical air conditioning.
- No makeup water or water recycling. Total evaporation of all water used is possible.
- Slight wetting of people is possible, providing extra cooling.
- Visible. Those who desire more cooling can easily find and approach the mist.

Cons:

- Airborne droplets at sizes that are easily inhaled deep into the lungs, *legionella* countermeasures extremely important. Reluctance to adopt the system for this reason.
- Possible wetting of surrounding surfaces, people. Possible slipping hazard.
- Mist is easily scattered away by light breezes.

1.2.3. EC fans

The cooling effect of a fan can be improved by adding an EC system such as a mist spray to reduce the temperature of the blown air. The circulation of air by the fan also promotes evaporation of any surfaces that become wet and prevents a local build up of humidity near the spray nozzles. Oscillating fans can further improve air mixing and reduce humidity build up. It is possible that oscillating fans may be perceived as more comfortable than a steady stream of air. The repeated cycle of sudden temperature drops as the EC blown air passes would be a repeated temperature gradient stimulus.

1.3. Evaporation Cooling and Thermal Comfort

In hot conditions, an increase in humidity typically reduces thermal comfort. A common concern raised on EC is whether the increase in humidity cancels out the reduction in temperature. As EC is largely an adiabatic process, the temperature and humidity changes are predictable for any mixture ratio of air and water if there is complete evaporation.

In the constant-enthalpy process of water evaporation into air, absolute humidity increases by about 0.41g/kg(DA) per 1°C drop in temperature, or an increase in vapour pressure of about 63Pa. Feeding this into the ASHRAE 55 two-node model of heat exchange for the human body, we can predict the net change in heat flux of the human body exposed to EC. Two-node models calculate the thermal balance based on 6 routes of heat exchange as per the heat balance equation;

in which *M* is the rate of metabolic heat production, *W* is the rate of mechanical work, *C* and *R* are the sensible heat loss from the skin by convection and radiation, E_{sk} is the total evaporative heat loss from the skin, C_{res} and E_{res} are the rate of heat loss from respiration by convection and evaporation, and *S* is the rate of heat storage into the body.

We use the two-node model to compare EC with a comparable level of standard AC, a fan without cooling, a fan with standard AC, a fan with EC and a base case with no cooling. We take a hot summer day (T_a = 38°C, *RH* = 40%) as the base condition, and calculate the change in all terms of the heat flux as per ASHRAE 55 for a 3°C reduction in air temperature using EC, with the accompanying 1.25g/kg' increase in absolute humidity, *x*. The radiant temperature is taken as the initial air temperature and left unchanged, assuming EC does not affect radiant temperature. Air speed is taken as nearly still (v = 0.15m/s), metabolic rate as resting (1.0 met) and clothing insulation as light summer wear (0.4 clo).

For the standard AC case, we use a 3°C reduction in air temperature and no change in absolute humidity. For the fan case, a 1.0 m/s air velocity is applied with no other changes from the base case. For the fan with standard AC, the above two conditions are applied together. For the fan with EC, the 1m/s air velocity is added to the EC conditions above.

The breakdown of heat exchanges are shown in Table 1. Note that in this model, positive fluxes represent cooling of the body. The model calculates heat fluxes and changes in body temperature in 1-minute steps over 60 minutes to a near steady-state. The results shown are from the first iteration at 1 minute, and the last iteration at 60 minutes. Also included in the table are the projected values of skin temperature (T_{sk}), core temperature (T_{cr}), skin wettedness (w) as well as Standard Effective Temperature (SET) and Predicted Mean Vote (PMV).

Table 1. Change in thermal balance for various cooling strategies according to ASHRAE 55 two-node model.

	Base case		Standard AC		Fan		AC + Fan		EC		EC + Fan	
Time (min)	1	60	1	60	1	60	1	60	1	60	1	60
T_a (°C)	38.0	38.0	35.0	35.0	38.0	38.0	35.0	35.0	35.0	35.0	35.0	35.0
T_r (°C)	38.0	38.0	38.0	38.0	38.0	38.0	38.0	38.0	38.0	38.0	38.0	38.0
RH (%)	40.0	40.0	47.1	47.1	40.0	40.0	47.1	47.1	50.6	50.6	50.6	50.6
x (g/kg')	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	18.0	18.0	18.0	18.0
v (m/s)	0.15	0.15	0.15	0.15	1.00	1.00	1.00	1.00	0.15	0.15	1.00	1.00
C (W/m²)	-9.4	-3.9	-0.8	4.6	-20.8	-8.8	-1.7	9.4	-0.8	4.6	-1.7	9.5
R (W/m²)	-14.0	-5.8	-16.1	-8.1	-11.4	-4.8	-15.9	-9.8	-16.1	-8.1	-15.9	-9.8
E_{res} (W/m²)	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.0	3.0	3.0	3.0
C_{res} (W/m²)	-0.3	-0.3	-0.1	-0.1	-0.3	-0.3	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
E_{sk} (W/m²)	6.0	63.4	6.0	57.2	10.7	67.4	10.6	54.4	5.6	57.4	9.8	54.5
Sum (W/m²)	**-14.5**	**56.6**	**-7.7**	**56.8**	**-18.6**	**56.7**	**-3.8**	**57.2**	**-8.3**	**56.8**	**-4.7**	**57.1**
T_{sk} (°C)	34.0	36.2	33.9	36.1	34.0	36.2	33.9	36.0	33.9	36.1	33.9	36.0
T_{cr} (°C)	36.5	36.9	36.5	36.9	36.5	36.9	36.5	36.8	36.5	36.9	36.5	36.9
w	0.06	0.50	0.06	0.46	0.06	0.30	0.06	0.25	0.06	0.48	0.06	0.26
SET	N/A	35.9	N/A	35.1	N/A	32.5	N/A	31.1	N/A	35.6	N/A	31.4
PMV	N/A	4.68	N/A	4.05	N/A	3.08	N/A	2.26	N/A	4.11	N/A	2.34

Overall there is a small but insignificant reduction in cooling effectiveness of EC compared to standard AC. There is a wide difference in total heat fluxes at 1 minute elapsed time. The total heat flux of the EC and "EC + Fan" cases are slightly worse than the AC and "AC + Fan" cases, by about 0.6W/m² and 0.9W/m² respectively. However, compared to the initial base "do nothing" case of 14.5W/m² of net heating, this is fairly small. After 60 minutes, the body model reaches a near steady state and there is little difference in heat flux and core temperature among all cases. The net cooling of EC cases is not significantly different from standard AC. Skin wittedness is slightly (up to 0.02) higher in the EC cases than the AC cases. The SET value for EC alone is significantly closer to the base case than AC alone. When combined with a fan, the 0.3°C difference becomes relatively small. PMV values are based on environment conditions, not the body response, so the result is presented as the 60-minute column. SET values are calculated only for the 60-minute case.

2. Evaporative Cooling in Practice

There is much current research on the topic of EC including surveys of people exposed to evaporative cooling, especially in the extreme heat of summer. Evaporation is swift in dry climates, allowing for greater temperature drops and more cooling. However, evaporative cooling is seeing success in sub-tropical and even tropical environments.

A difficulty in evaluating EC is the problem of measuring the air temperature drop near EC equipment (mist sprays, wetted media) is the possibility that sensors will be wetted and thus function as imperfect wet-bulb thermometers (Miura et al, 2008). Assuming such readings are dry-bulb temperatures would lead to over-estimation of the cooling effect. Measuring downstream of a mist EC spray where the mist has completely evaporated avoids this problem, but the dry-bulb temperature inside the mist is desired to build a useful model for thermal comfort effects. If a CFD simulation of the mist and cooled air matches the downstream dry sensors, or bucket tests collecting unevaporated mist mass within the mist cloud, it could be assumed the simulated dry bulb temperatures inside the mist reflect reality to some extent (Farnham, 2009). Ultrasonic anemometers have been used by Kohno and Narita (2012) to attempt measurement of the dry-bulb temperature inside mist by taking advantage of the relationship between the speed of sound and air density, which is dependent on temperature and humidity. Sound virtual temperature readings were higher than the temperatures taken by thermocouples inside the mist, indicating the thermocouples were showing temperatures lower than the actual dry-bulb temperature. Further work was needed to account for the unknown humidity. They propose a combination with infrared humidity sensors to compensate.

Nakai et al (2009) used mist of 20 micron SMD as a supplement to spot air-conditioning (AC) in a machine factory. The factory had an 8.5m high ceiling and was ventilated at 2 ach. Spot AC alone was compared to spot AC with mist at 2 air velocity settings. At 1.5m height, air temperature with mist was 1~3°C cooler than AC alone, relative humidity increased 10~25% and SET* was 1~2°C lower depending on the air velocity setting. Surveys showed about 20% of workers experienced a 1-step improvement in thermal comfort (7-step scale) and overall comfort (5-step scale) but a 1-step higher feeling of humidity (5-step scale). Optimization for the site could yield much less energy demand on the spot AC system while maintaining comfort by using mist as a booster.

Mist EC is often deployed in large semi-enclosed spaces, where natural ventilation can help prevent a build up of humidity. Suzuki et al. (2011) arrayed mist nozzles well-inside, just-inside or just outside a 2.7m high piloti (pier) area under a building which channelled the air flow as a wind tunnel. On hot summer days (34~36°C) temperatures in the space dropped by about 1~5°C, in roughly inverse proportion to the wind speed and depending on nozzle position, with just-outside yielding the worst result due to varying wind direction there.

Misaka et al. (2011) deployed mist EC in a large semi-enclosed exhibition pavilion in the humid climate of Shanghai. Experiments in a 5m-high, 800m^2 piloti space on hot, humid summer days of 33~35°C and 50-60%RH yielded average temperature drops of 2°C and average humidity increase of 15% (but reaching a maximum of 90% near the nozzles), while SET* dropped by 1~2°C on average.

Furumoto et al. (2016) deployed mist EC over a summer at a train station concourse and ticket gates area, while conducting extensive surveys not only of comfort, but the riders' opinions of mist EC in contrast to standard AC or natural ventilation. The misted area had average drops in SET* of 0.5~1.5°C over the 2 months of the study. In overall satisfaction, mist EC only slightly outranked AC and natural ventilation, but on the point of aesthetics, mist EC was highest at 63% positive vs. 41% for AC. The study also compared the responses of those who noticed the mist was operating vs. those who did not (Interestingly, 59% of those surveyed did not know the mist was operating.) Those who noticed the mist were half as likely to vote at +3(very hot) on the 7-level thermal scale while also tending to wish the mist cooling effect was even stronger. Those who did not notice the mist were twice as likely to vote "uncomfortable" on a 7-level scale. This could indicate that perception of mist affects thermal comfort votes.

Kohno et al. (2013) combined mist EC with various types of sunshades for outdoor comfort. Test subjects sat in each zones with different types of sunshade for 5 minutes each and completed comfort surveys with and without mist EC. In direct sunlight without shade, mist EC yielded little effect. Responses of "uncomfortable" were 81% without mist and 80% with it. However, when shaded, "comfortable" votes greatly increased, reaching over 90% in some cases. With more transparent shades tending to have lower comfort responses without mist, roughly the same as the fraction of sunlight blocked. However, with mist even the least-shaded case (10% of sunlight blocked, 7% comfort without mist) increased to 63% comfortable.

Hirayama and Sato (2015) published a report on their measurements of radiant cooling effect on the thermal environment in an outdoor cool spot that uses EC louvres (a 2m tall wall of many long, thin concave metal slats with water dripping from the top layer down, roughly resembling window blinds). The louvre temperature was often 10°C lower than ambient air, while air passing through the slats was about 2.5°C cooler. The space combining wet pavement and near the EC louvres was consistently 10-20oC lower MRT than a neighbouring parking area. No comfort surveys were done.

Miyasaka et al. (2018) performed comfort surveys for the "Zero Energy Cool Tree" system. A wooden platform and sunshade with a central column in a tree-shape with mist spray nozzles equipped in the sunshade creates a cool space with wooden benches for relaxing. The air temperature at the benches was about 0.5 – 2.0°C cooler than ambient. The best-rated part of the system is that the benches are typically 4-6°C cooler than ambient. Where 25% of subjects felt the space was pleasant on non-cooled benches, over 50% rated the experience pleasant after sitting on the cooled benches.

Misaka and Narita (2018) evaluated EC mist spraying as a form of artificial sweat. Mist was sprayed onto a heated copper plate as an analogue to human skin. Further, human subjects were evaluated in a 20 minute exposure either to outdoor sun, or a shaded area with a mist fan. By monitoring short and long wave thermal radiation, air temperature, etc. the researcher determined the mist creates an additional 3 – 7W/m^2 of cooling as an added source of artificial sweat.

3. Discussion topics

Although there are more and more studies of EC, the proportion in which has subjects have been surveyed for thermal comfort is quite small. A common point is that many studies are of comfort in outdoor environments, and EC exposure time tends to be quite short, usually less than 30 minutes, often much shorter. The influence of thermal history and sudden temperature gradients likely may lead to over-evaluation of the coolness. There is much research to be done on EC in the context of thermal comfort.

Some concepts for discussion include:

- What is the target for use of EC? Is it for outdoor comfort or indoor comfort?
- What is the time span for EC exposure? Is it for short-term use over spans of minutes or for hours? How should experimenters account for this, knowing that short term exposures might lead to over-evaluation? On the other hand, if EC use is for short term, are short-term exposures and survey results really "over-evaluation"?
- EC seems to be a cooling "multiplier". Fan cooling becomes stronger. Shaded areas become more pleasant. While EC alone may have little or no significant effect.
- How do we prevent the problems of *legionella* and other hazards presented by EC systems, especially if they become far more widespread and not under supervision of professionals?
- How do we better account for the "artificial sweat" effect of contact evaporation from mist EC systems? Can physiological models be adjusted to handle this?

EC has great potential to improve thermal comfort in extreme heat, especially considering that it becomes more efficient and effective as temperatures increase. The special consideration. Hopefully, this brief summary presents a few of the special concern and unique uses of EC for thermal comfort.

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Dry Mist Systems and its impact on Thermal Comfort for the Tropics

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Abstract: This abstract should be a maximum of 200 words. Font Calibri, 10 point, normal, fully justified, single space.

Tropical countries, like Singapore, are hot and humid throughout the year. Coupled with the Urban Heat Island effect from rapid urbanisation, Singapore has seen a long-term increase in annual average temperatures over the years. One solution is the use of misting systems that tap on the principle of latent heat of vaporisation to provide cooling. This paper specifically addresses the use of "Dry Mist" systems, where the sprays are of ultra-fine droplet size and do not cause a wet sensation upon contact, thus the name "Dry Mist".

These systems have typically been employed in temperate countries, like Japan, and has not been widely employed in Singapore due to the seeming low potential for cooling in humid countries. However, such systems can still be effective during hot afternoons, where the wet bulb depression can go between 5-7oC. Thus, the use of Dry Mist and its impact on human thermal comfort is worth studying.

Due to the impact on skin temperature and wetness, the Standard Effective Temperature (SET*) has typically been used to represent the change in thermal comfort from Dry Mists. However, these values are assumed from the human metabolic rate and are typically used for sweating on the human skin. Thus, its appropriateness as a suitable comfort index may be questionable. Another possible comfort index is the mean skin temperature, but the measurement process is tedious and intrusive as it involves placing equipment on at least 10 parts of the human body. Many studies have tried using thermal mannequins to cover this gap, but this paper hopes to address this issue by testing if thermal comfort from misting can be simplified to just a few variables that are easy to measure. All variables tested will be analysed statistically and the variables with the highest impacts will be chosen.

Keywords: Dry mist; Evaporative Cooling; Water droplet; Thermal Comfort; Tropics

1. Introduction

Tropical countries, like Singapore, are hot and humid throughout the year. Located just above the equator, the average temperature in Singapore goes between 25 and 31°C, and Relative Humidity (RH) typically ranges between 70-80% (GuideMeSingapore, n.d.). The landscape in Singapore has changed drastically due to urbanization and is now filled with many tall buildings. There is a rampant use of air-conditioning units to provide thermal comfort especially in commercial buildings, and the urban heat island (UHI) effect was deemed to be about 4.01°C (Wong & Yu, Study of green areas and urban heat island in a tropical city, 2005). Furthermore, the yearly mean temperature has been increasing at a rate of 0.25°C per decade (NEA Singapore, 2012) and there is an urgent need to derive alternative solutions to combat these rising temperatures, especially in naturally ventilated environments.

Evaporative cooling systems have been considered good alternatives to traditional HVAC systems due to the lower energy consumption, and to the fact that they do not using refrigerants which are damaging to the environment (Wong & Chong, 2010). Such systems have been proven to be hygienic if properly and regularly maintained (Esen & Tuna, 2015) and are also capable of attenuating solar radiation (Dombrovsky, Solovjov,

& Webb, 2011). These systems are more effective in cooling than water bodies because evaporation can still take place in humid environments (Haeussermann, et al., 2007). Such systems have been used in different cooling applications like farms (Haeussermann, et al., 2007); aerosol reactors (Fisenko, Wang, Lenggoro, & Okyuama, 2006); Wind Towers (Saffari & Hosseina, 2009); water evaporative walls (Naticchia, D'Orazio, Carbonari, & Persico, 2010); roofing systems (Cuce & Riffat, 2016); and evaporative cooling pads (Liao & Chiu, 2002).

One evaporative cooling system specifically is the 'Dry Mist' system, which refers to systems which produce ultra-small water droplets that evaporative very quickly, and do not leave a wet sensation on the human skin upon contact. These can be produced through high pressure water or air, and through ultrasonic means (Nijdam, Starner, & Langrish, 2004). Traditional 'Wet Mist' systems are disadvantageous because only a fraction of the water evaporates, and the remaining liquid produces a wet sensation upon contact, lowering the cooling performance (Belarbi, Ghiaus, & Allard, 2006). The effects of the Dry Mist can be accentuated through buoyancy and wind (Hunt & Linden, 1999); droplet velocities (Hou, Tao, Huai, & Guo, 2012); higher pressures (Husted, Petersson, Lund, & Holmstedt, 2009); spray angles (Li, Cader, Schwarzkopf, Okamoto, & Ramaprian, 2006) and wet bulb depression (Zheng, Ichinose, & Wong, 2018). Till date, such systems have been studied for thermal comfort in Japan (Farnham, et al., 2016; Yoon, Yamada, & Okumiya, 2008) and these systems use single flow high pressure water only.

The use of Dry Mist systems for thermal comfort in a tropical country like Singapore has not been studied, especially for two-flow systems using both high pressure water and air. This is important since Singaporeans are exposed constantly to high temperature and humidity and may have different thermal adaptations in that they are more tolerant to heat stress (Yang, Wong, & Jusuf, 2013). However, one key concern is the tediousness and difficulty in having accurate skin temperature measurements from occupants as they are often intrusive and require many measurement points. Thus, Computational Fluid Dynamics (CFD) models that are tested and validated can provide a solution to this. Thus, this study will first include the conduct of a field experiment to determine thermal comfort among Singaporeans using Dry Mists. Subsequently in the future, a CFD model will be developed based on inputs from a prior study (Zheng, Ichinose, & Wong, 2018) and validated against this field experiment to provide skin temperature values.

2. Methodology

2.1. Experimental Space

The field experiment is conducted in a University Campus in Singapore and located on the 3rd level of the building which is roughly 45m elevation above sea level. The space is semi-enclosed, where it is bounded by walls on the north and east end but exposed on the south and west end. In addition, a white gazebo tent, measuring 3m by 3m and 2.5m tall, is set up to provide shade for the participants. Thus, participants are not exposed to any direct solar radiation during the entire procedure. Two people undertake the experiment at one time while seated down, and they each have a stool placed in front of them to hold the experiment instruments. Instrumentation details will be explained later. The schematic of the layout is shown in Figure 1.

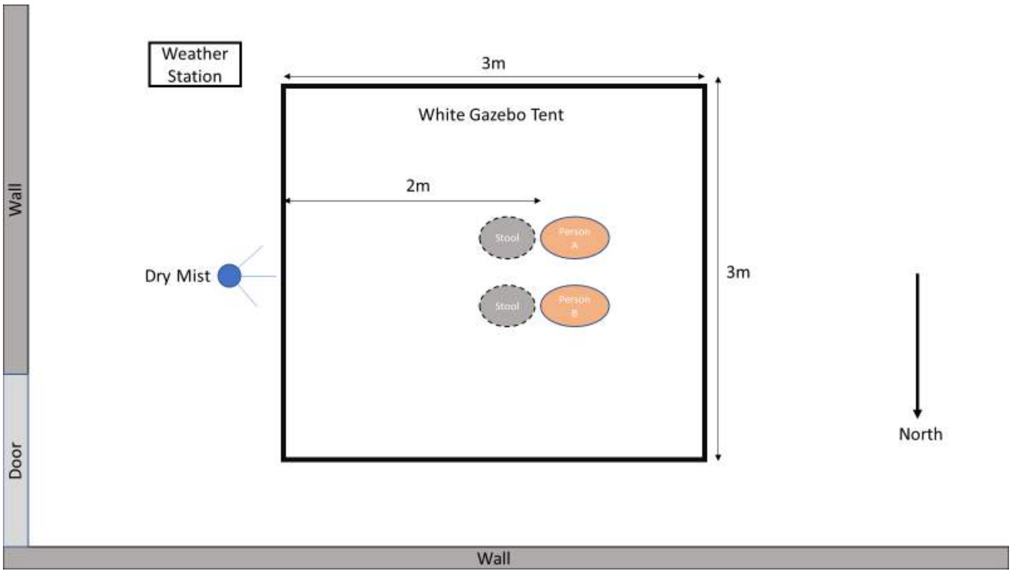


Figure 1 Experimental set-up location

2.2. Dry Mist System

The Dry Mist system includes a small fogger secured onto a stand to provide the appropriate height and are attached to an air compressor on one end, and to a direct water tap on another end. As seen in Figure 2, this system works by releasing two high pressure air jets at an angle, which then collide with a water jet in order to break up the water into very fine droplets. Regulating valves are built in the system to change the air and water pressure. As pressure increases, water droplets are released at higher sheet velocities, higher water mass flow rates and the increased turbulence also produces smaller droplet sizes. The performance data of the system is shown in Table 1.

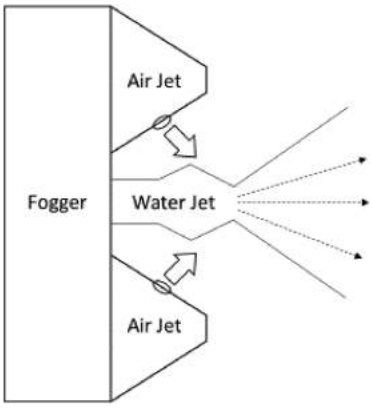


Figure 2 Operation of fogger

Table 1 Performance date of Dry Mist Fogger

Air Capacity (litres per minute)			Water flow rate (litres per hour)		
2.5 bar	3 bar	4 bar	2.5 bar	3 bar	4 bar
30	35	45	0.9	1	1.1

The droplet sizes from the system are measured using a Particle Image Velocimetry (PIV) system containing 2 high-power lasers, a camera, computer and a synchroniser.

The lasers are categorized as Class 4 lasers, and their function is to provide illumination of the flow so that images or videos can be captured by the camera. The camera used is a Model 630057 PowerViewTM Plus 2MP PIV camera system and comes with a default 28mm F/2.8 Af Nikkor lens. The lens is interchangeable for different application needs. Namely, the 28mm is used to study a whole-field flow for measuring the spray angle, spray coverage amidst other things. Another lens, with focal width of 105mm, is used in this study for the study of droplet sizes at a micro level, since the images are more zoomed-in and the pixel pitch is appropriate. For this purpose, a Sigma 105mm DG Macro lens was used for this study. The Synchronizer is used to ensure each component is employed in the right timing sequence. This is crucial, since the images are captured at fractions of a second apart, and the camera shutter speed needs to be able to capture these images. Finally, the 'Insight' software, which comes with the PIV system, is used to analyse the captured images, and the software can compute the flow field parameters.

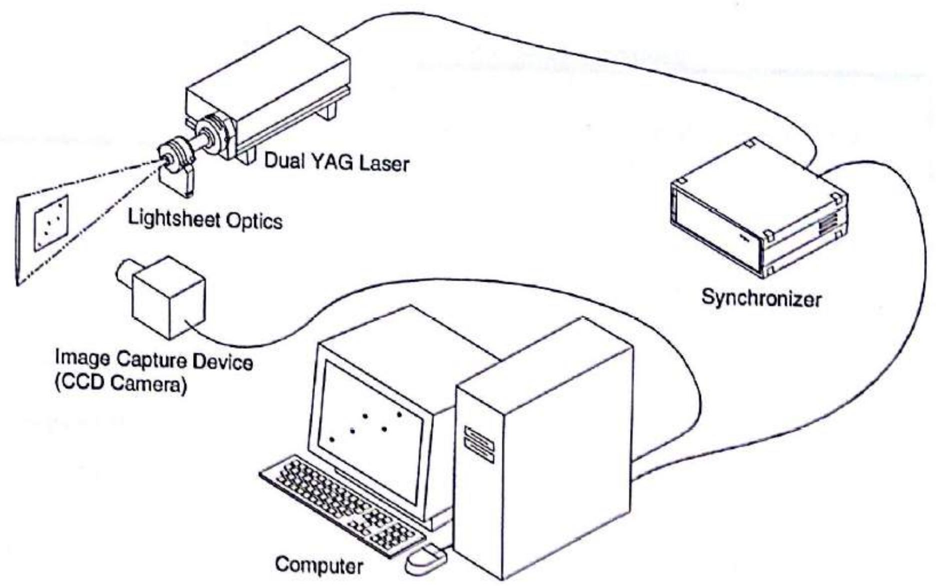


Figure 3 Overview of PIV system

Figure 4 Process of capturing droplet flow field

Due to the random nature of particle flow field and particle collision and breakup, many images must be captured, processed and analysed to get a more accurate measurement of the droplet size distribution. Thus, 100 images are captured for each perpendicular and parallel direction, totalling 200 images and more than 650,000 droplet particles. The raw images are in TIFF type image files and these will be imported into the open-source ImageJ software created by the US National Institute of Health (NIH) for thresholding and processing. Figure 5 shows an example of a processed image file using the software and Figure 6 shows the Histogram of particle frequencies.

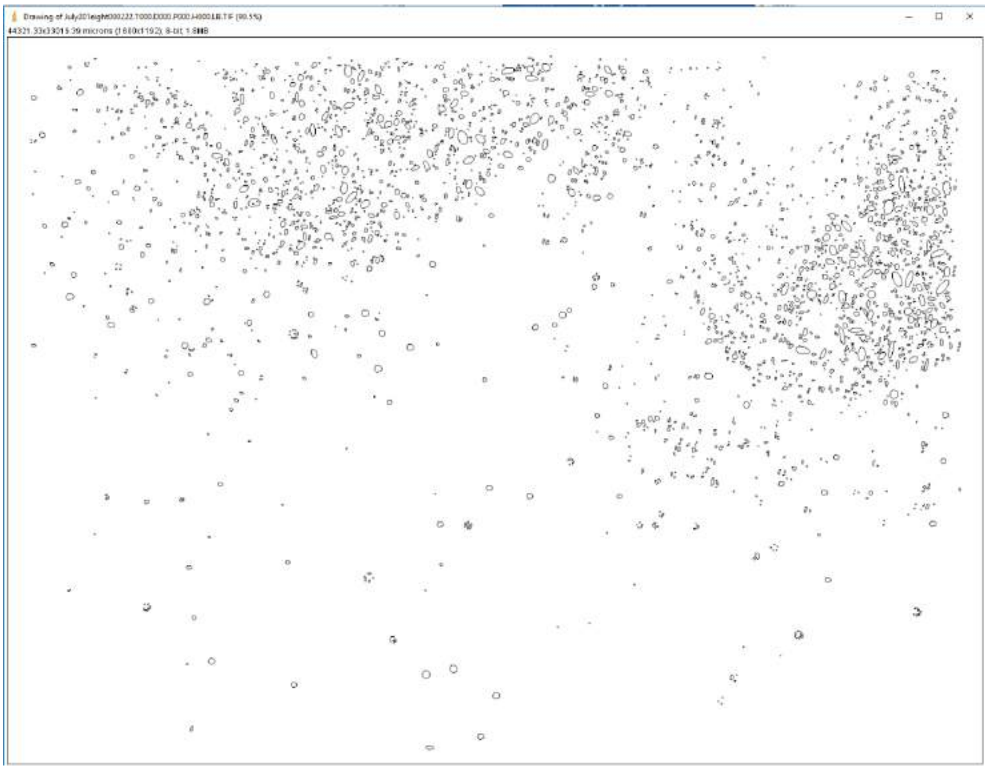


Figure 5 Example of processed image file using ImageJ software

Droplet sizes are typically represented using the Rosin-Rammler distribution and this requires one single mean diameter to characterize the droplet size. The distribution function assumes an exponential relationship between the droplet diameter, d, and the mass fraction of droplets with diameter greater than d, Yd:

Where,

mean diameter

n = spread parameter

Since the distribution will be used as an input for the CFD model in the future, the mean diameter value can be obtained via calculation, where it is the value of d at which (ANSYS Inc., 2009). The distribution is input into a MATLAB tool published previously (Brezani & Zelenak, 2010) and the Rosin-Rammler diagram can be plotted. From Figure 7, the mean diameter can be estimated via the black horizontal line, and $\bar{d}$ is estimated to be around 90 microns. The key distribution parameters are shown in Table 2 and will be used as input for the CFD model.

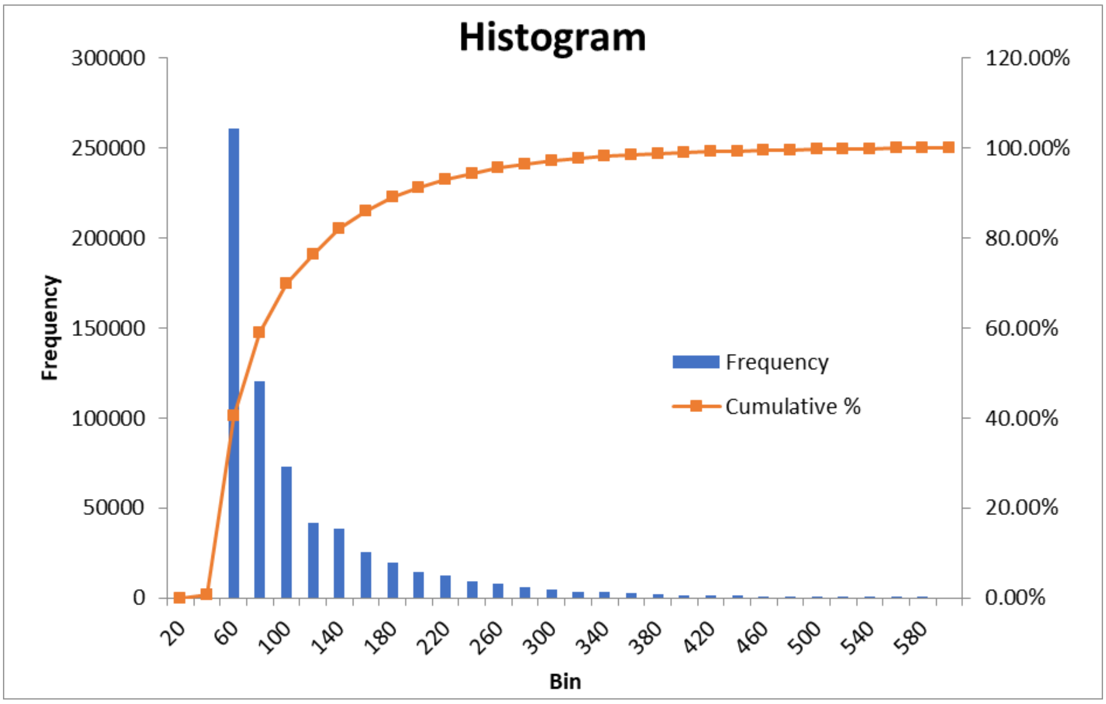


Figure 6 Histogram of particle frequency and cumulative percentage

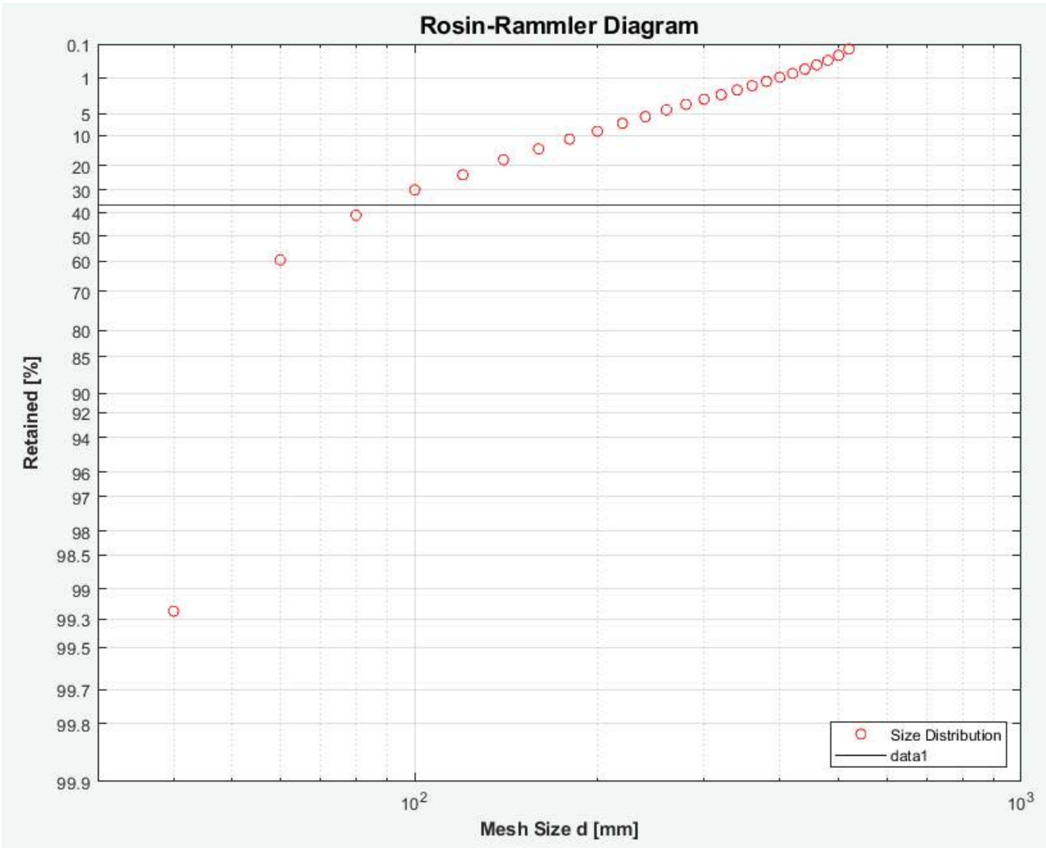


Figure 7 Rosin-Rammler Distribution Diagram

Table 2 Key distribution parameters

Parameter	Value
Mean	90 µm
Min	31.2 µm
Max	563.49 µm
Spread	2.68

2.3. Instrumentation

All measurements taken are at the frequency of one second. The globe thermometer used is based on a previous study and is made of a 40mm ping pong ball coated in flat grey paint. A HOBO thermocouple wire is placed at its centre and the globe thermometers are placed such that there is no overshadowing effect from the surrounding. The measured variables and equipment used are shown in Table 3.

Table 3 Equipment used for variable measurement

Variable	Equipment	Measurement range	Accuracy
Air temperature (Ambient)	HOBO 12-bit Temp/RH Smart Sensor THB-M002	-40°C to 75°C 0-100% RH	+/- 0.21°C from 0° to 50°C +/- 2.5% from 10% to 90% RH
Air Temperature (Localized)	HOBO Pro V2 U23-001	-40° to 70°C 0-100% RH	±0.21°C from 0° to 50°C ±2.5% from 10% to 90% RH
Globe temperature	HOBO Thermocouple Data Logger, U12-014 with Type-T Copper-Constantan thermocouple sensors and 40 mm diameter ping pong ball	−200 °C to 100 °C	±1.5 °C
Wind speed	Wind Speed Smart Sensor WSB-M003	0 to 76 m/s	±1.1m/s or ±4% of reading whichever is greater
Solar Irradiance	Solar Radiation Smart Sensor HOBO M003 with HOBO H21 Micro Station	0 to 1280 W/m^2	±10 W/m2 or ±5%, whichever is greater in sunlight
Skin Temperature	Multi-purpose non-contact infrared thermometer	Body 32 – 42.9^{o}C	±0.2^{o}C for 36.0 – 39^{o}C

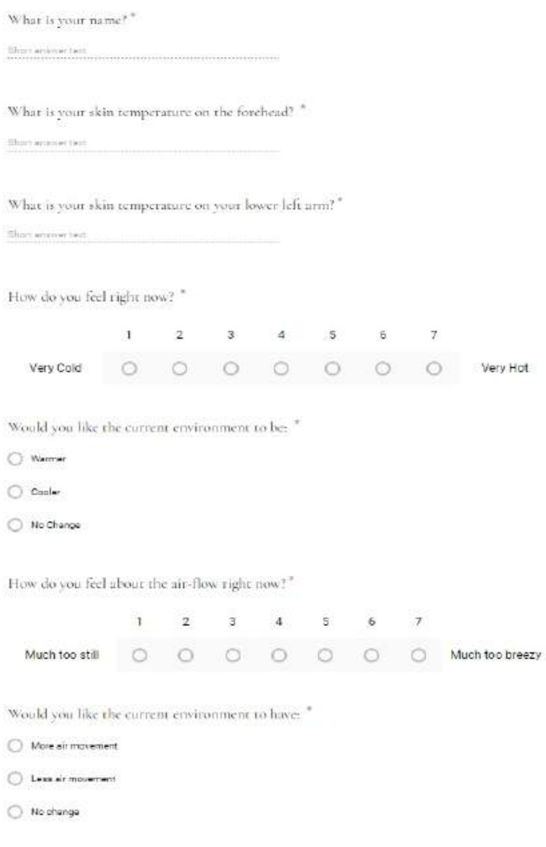
2.4. Experimental Measurements

The thermal comfort survey is conducted for twenty Singaporeans aged between 20-30 years old. Foreigners are not included in the study since the purpose is to study the thermal adaptation of locals. The study was conducted over 3 days in the afternoon, during November period. Like shown in Figure 1, two people participate at any one time and each time slot takes roughly 30 minutes. The time slot is broken down into three 10-minute periods where participants first sit under the tent with no mist, then the mist is switched on, and switched off for the last period. Participants are asked to fill in the comfort survey using a Google Form at the end of every 10-minute period, for a total of three surveys per participant. Questions asked in the survey are shown in Figure 8.

The participants are asked to help one another measure the skin temperatures on their foreheads and lower left arm using the infrared thermometer. Participants are briefed that the thermometer should be placed 5cm away and the surveyor checks that each measurement is conducted properly with appropriate distance and at the right locations. If the values turn out to be significantly different across the three measurements, then the participants are asked to retake the measurements until the values are more consistent.

To evaluate the reliability of the Infrared thermometer, a circle was drawn on the skin of the lower left arm and temperature measurements were taken within the circle. Reliability addresses the issue of an instrument's ability to reproduce a result (Burnham, McKinley, & Vincent, 2006). Measurements are taken at alternating sequences between the lower left arm and the centre of the forehead, at 10 second intervals, until 20 measurements per location were taken. A Test-Retest Reliability check was conducted using SPSS software, and the coefficient showed perfect correlation where the skin temperatures varied no more than 0.2°C.

In addition, participants are requested to fill in a 'personal data' form which records the types of clothing which they wear. These data are used to calculate the 'clo' values used for calculation of SET* later in the study. Since Singapore has a summer-like weather condition through the year, most participants turned up in a t-shirt, shorts and slippers, which translates to a clo value of 0.36. There are 5 participants who wore long pants and covered shoes, and their clo values are calculated to be 0.57; and 2 other participants wore t-shirt and shorts but with covered shoes and their clo values are 0.41.


What is your name? *

What is your skin temperature on the forehead? *

What is your skin temperature on your lower left arm? *

How do you feel right now? *

Very Cold 1 2 3 4 5 6 7 Very Hot

Would you like the current environment to be: *

Warmer

Cooler

No Change

How do you feel about the air-flow right now? *

Much too still 1 2 3 4 5 6 7 Much too breezy

Would you like the current environment to have: *

More air movement

Less air movement

No change

While the thermal comfort surveys are being conducted, climatic variables are also being measured in the area immediately in front of the participants. These variables include the globe temperature, air temperature, RH and solar irradiance. At the same time, a weather station measures the ambient air temperature, RH, wind speed and solar irradiance. All variables are recorded at per-second intervals.

3. Experimental Results

3.1. Climatic Variables

The experiment was conducted over a 3-day period, and the climatic conditions varied among different days. Worthy to note is that temperatures on the 2nd day are lower, and the RH is higher than other days, as seen in Figure 9. This is because the day was cloudy, and it started drizzling during the evening after the experiments were conducted. The other days are more typical of hot afternoons in Singapore, with temperatures about 32^{o}C and RH between 60-70%. Furthermore, wind profiles are important since the water droplets are very small in mass and heavily influenced by ambient wind flow. The profiles can be seen in Figure 10, and it is noted that Day 3 was more windy than usual, with velocities between 2-3m/s. Velocities on other days were 1m/s or less, which is more typical of weathers in Singapore.

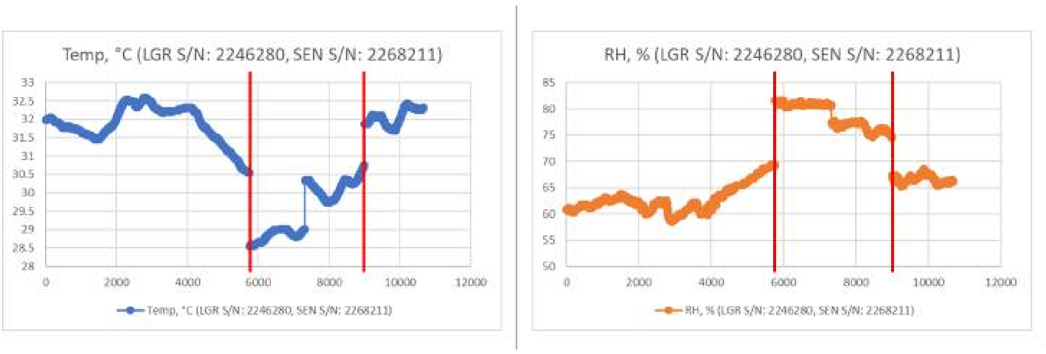


Figure 9 Temperature and RH profiles over 3-day experiment period

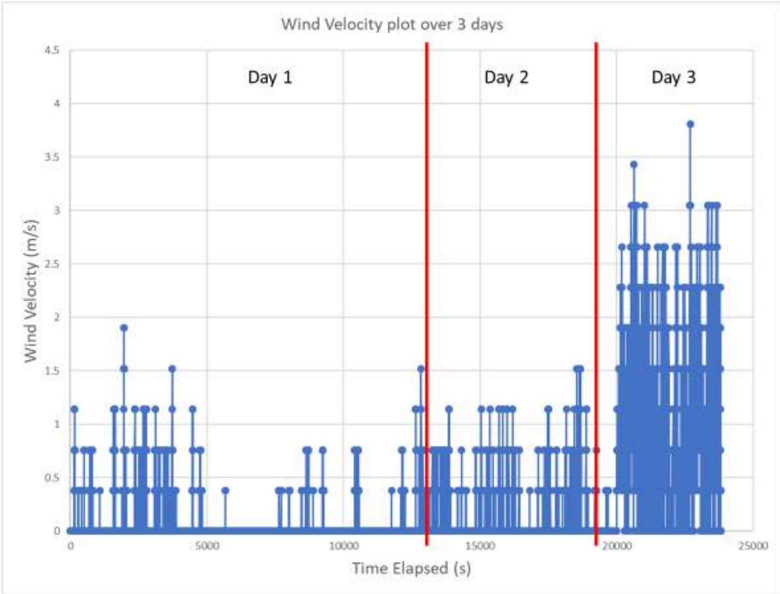


Figure 10 Wind profile for 3-day period

After the Dry Mist is switched on, it is expected that temperatures around the participants will drop if there is no strong influence from wind, and the RH will also increase. The amount of cooling depends largely on the wet bulb depression. The impacts of the Dry Mist are seen in Figure 11, where the T-type temperatures which are measured from the globe thermometers shows a 2°C decrease at its maximum. Different sets of equipment are placed in front of each participant, which explains the blue and grey lines. This decrease in temperatures is accompanied by a roughly 10% increase in RH, as shown in the orange and brown lines and the RH reaches 80-85%. The period of Dry Mist operation is demarcated by the red dotted lines.

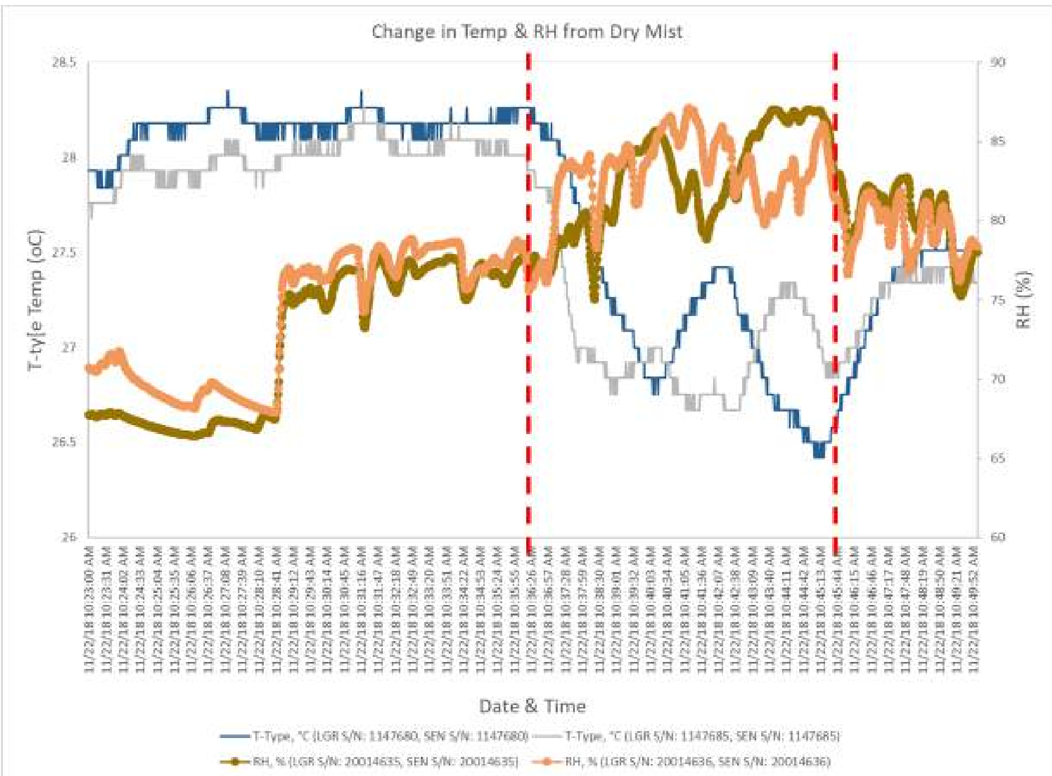


Figure 11 Impacts of Dry Mist on Temp & RH

Figure 11 shows the change in temperature during a non-windy day, and the contrast can be seen in Figure 12. Figure 12 shows the wind conditions on the 3rd day where there are continual stronger winds, with its velocities shown by green line. The blue and grey lines show the T-type temperatures from both participant positions. The three mist operation periods are marked by the red dotted lines and the reduction in air temperatures are not visibly significant. This is simply due to the strong winds that direct the mist away from the participants' direction and the cooling effect is not captured. In the first time period in the morning, there are lesser winds and the reduction in temperature is about 1^{o}C. This reduction in temperature is relatively less because the air is humid that day at about 80% RH.

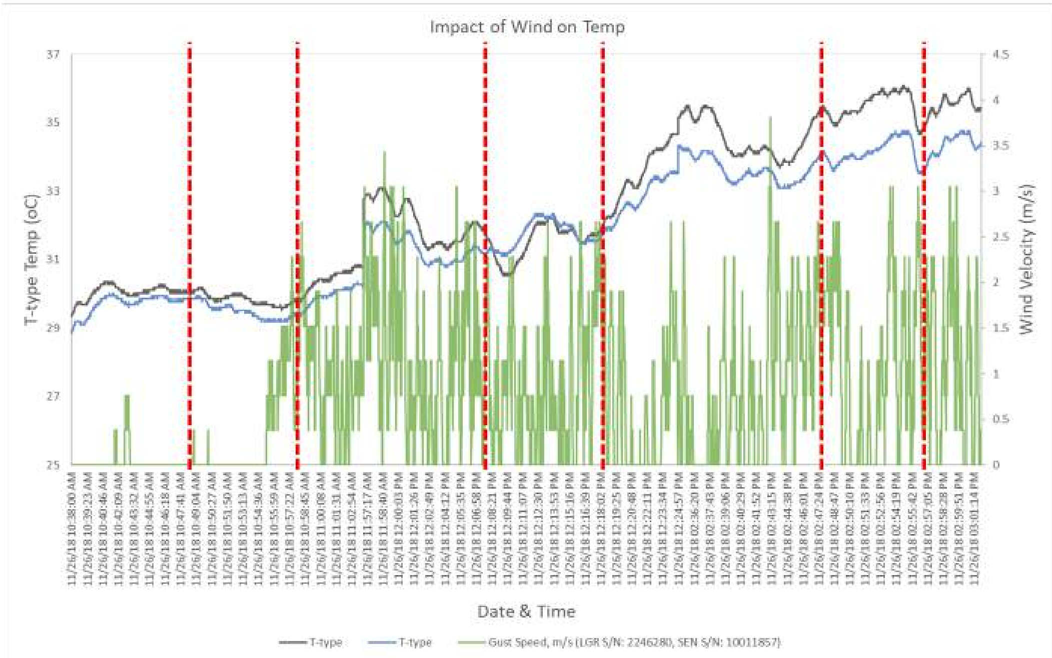


Figure 12 Impact of strong winds on temperature drop

3.2. Human Thermal Comfort

As mentioned above, the participants are surveyed on their perception of thermal comfort and thermal sensation based on a 7-point scale and the results are shown in the Bubble-plot Diagram in Figure 13. Thermal comfort is defined by ASHRAE as the condition of mind that expresses satisfaction with the thermal environment, whether it is comfortable or uncomfortable. Thermal sensation is a conscious feeling that grades the thermal environment whether it is hot or cold.

The figure is broken down into two parts to show the contrast between before and after the mist is turned on (left), and between after the mist is stopped and resting for 10 minutes after that (right). The size of the bubbles determines the number of participants who answered that value. Thus, a bigger bubble would mean more participants. The impacts of the Dry Mist are visibly seen from the shift from blue to orange bubbles, as people feel less hot in sensation and cooler in thermal comfort, albeit only shifting 1 point on the comfort scale, and roughly 2 points on the sensation scale. The change is evident especially by observing the large sized bubbles. After the mist is switched off and participants have rested for 10 minutes, their thermal sensation and comfort goes back to almost the same as before the mist is turned on – feeling warm and hot. This is shown by the shift of the larger bubbles from orange to grey colours, where thermal comfort and sensation are mostly around 1 or 2 on the scale.

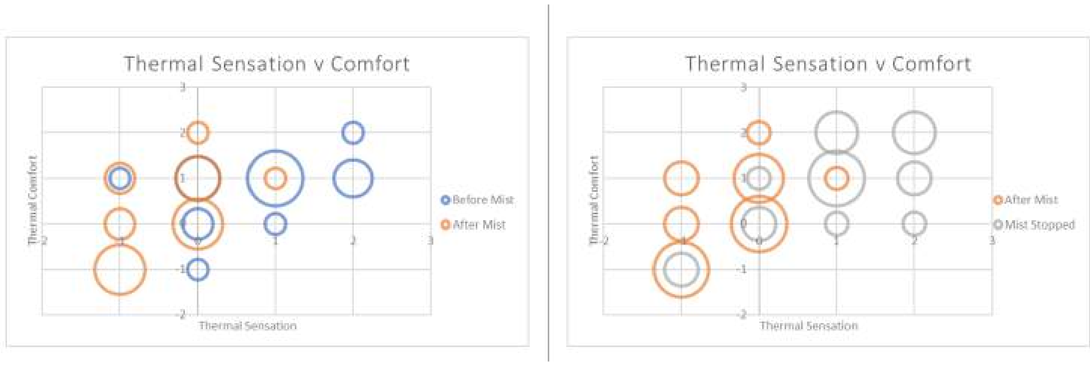


Figure 13 Thermal Sensation and its impact on Thermal Comfort

Participants are also surveyed on how wet they feel their skin is, and how pleasant they feel about that wettedness. The results are shown in Figure 14 to represent the change after mist is turned on, and after the rest period. Expectedly, there is a slight increase in skin wettedness since the Dry Mist is directly sprayed at them. However, participants' perception towards the increase in wetness shows a visible increase in pleasantness, with most participants finding it pleasant, above the neutral perception. 10 minutes after the mist is switched off, participants felt their skin was drier, but the pleasantness also decreased slightly.

Figure 14 Skin Wettedness and its pleasantness

Questions were also asked about how the participants felt about the wind flow, whether is it too breezy or still, and whether they felt the air was humid or dry. The results are shown in Figure 15. The contrast in airflow from the Dry Mist is evident, as the graph shifts right from blue to orange, representing stronger airflows. However, participants did not feel a drastic change in air humidity despite the direct spray from the mist. The seeming lack of change in air humidity is also seen after the mist is stopped and participants have rested for 10 minutes. What is different though, is that the airflow is expectedly lower, and participants find the air more still.

Figure 15 Perception of airflow and air humidity

The relationship between Thermal Comfort and Thermal Sensation are expectedly correlated, with a Spearman correlation of 0.516 as calculated using SPSS software. This relationship is shown in Figure 16. This means that the hotter the sensation, the warmer the participants feel. Worthy to note is that looking at the best fit line where TSV is zero, thermal comfort is still slightly warm at 0.5. This means that even when participants feel neither hot nor cold, they are at a comfortably warm level.

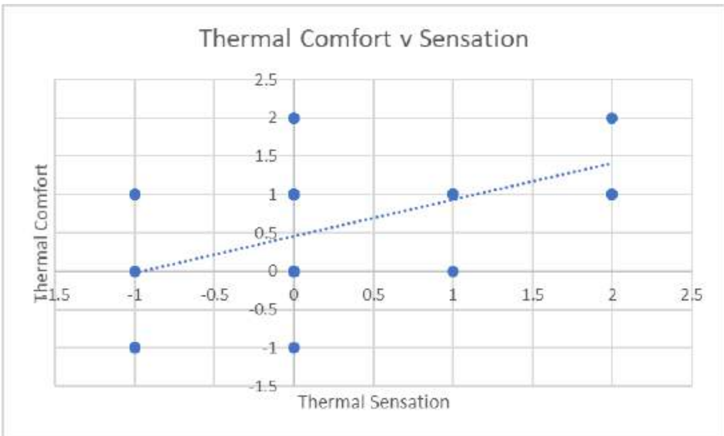


Figure 16 Relationship between Thermal Comfort and Sensation

Participant skin temperatures are taken on the forehead and lower left arm by using an infrared thermometer. The temperatures for the forehead are shown in Figure 17, while temperatures for lower left arm are shown in Figure 18. It must first be noted that the skin temperature does not decrease by a large margin even with the mist turned on for 10 minutes, averaging a reduction of about 0.1°C for both areas. The difference is more significant, however, after the mist is turned off. Forehead skin temperatures increase by about 0.1°C, and an average of 0.2-0.3°C on the lower left arm.

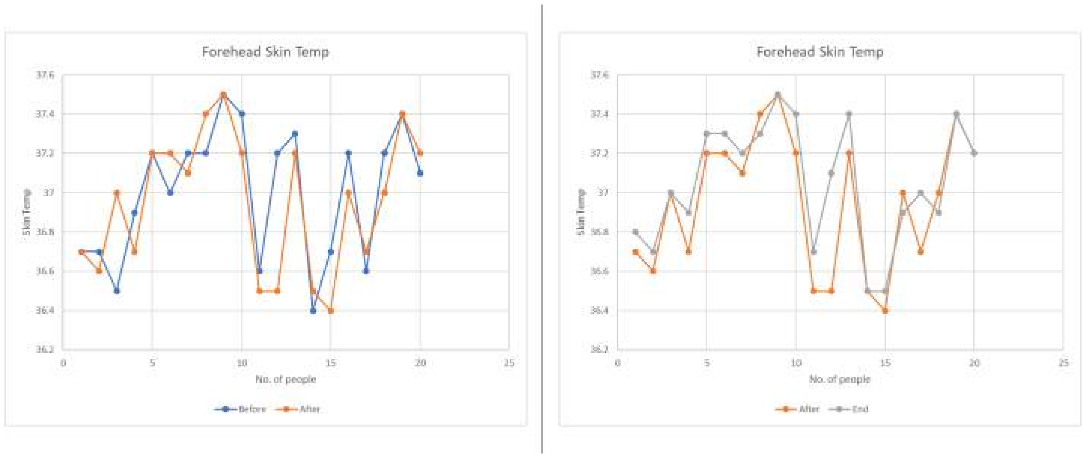


Figure 17 Forehead skin temperature changes among the participants

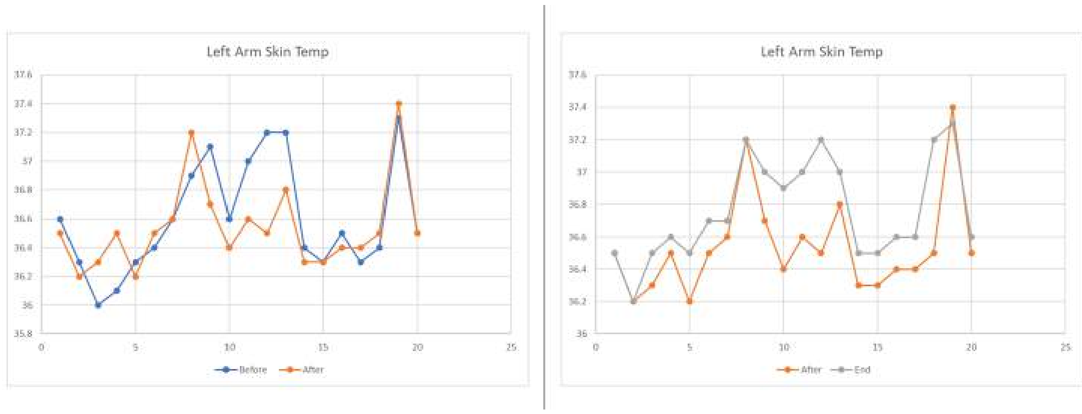


Figure 18 Left arm skin temperature changes among participants

4. Results Discussion

4.1. Thermal Sensation and Comfort

As can be seen from Figures 11-18, the Dry Mist system is able to provide cooling, while increasing the air humidity and the wind velocity. However, participants' thermal sensation and comfort are dependent on many other factors like their thermal adaptation and skin temperatures and it is necessary to study what exactly are key contributing factors. For the purpose of this study, the 2-node Pierce model is considered, to derive the Standard Effective Temperature (SET*) and quantify the changes in air temperature, RH and wind velocity. The calculation is conducted using the CBE Thermal Comfort Tool (Hoyt, et al., 2017). The changes are calculated 10 minutes apart from before and after the mist is turned on, and all changes in the variables are tabulated in Table 3.

Table 4 Changes in all variables from before/after mist is turned on

SET* Change (Wind) (°C)	SET* Change (°C)	Forehead Change (°C)	Left Arm Change (°C)	Airflow	Air Humidity	Skin Wet	Wet Feeling	TSV Change	TC Change
-4	-1.1	0	-0.1	0	0	1	-1	0	-1
-3.5	-0.6	-0.1	-0.1	0	-2	1	2	0	-1
-2.6	0.3	0.5	0.3	0	1	1	3	0	1

-2.4	0.5	-0.2	0.4	2	1	1	1	0	-2
-3	0	0	-0.1	1	1	0	3	-2	-1
-3.1	-0.1	0.2	0.1	3	-1	1	1	0	0
-2.6	0.5	-0.1	0	3	0	0	2	-2	0
-3.4	-0.3	0.2	0.3	3	-2	2	1	-1	0
-3.5	-0.8	0	-0.4	0	0	0	1	-2	-2
-3.4	-0.8	-0.2	-0.2	0	0	0	1	-2	0
-4.2	-1.6	-0.1	-0.4	3	0	0	3	-2	-1
-3.9	-1.1	-0.7	-0.7	0	0	0	1	-3	0
-3.9	-1.2	-0.1	-0.4	-1	-1	2	2	-1	-3
-4	-1.1	0.1	-0.1	0	-1	0	1	-1	-2
-3.5	-0.4	-0.3	0	1	0	0	1	-1	-1
-3.5	-0.5	-0.2	-0.1	3	0	0	1	0	0
-4.9	1.3	0.1	0.1	0	0	1	1	-1	-1
-6	0.3	-0.2	0.1	1	1	1	0	-1	-1
-6	-0.2	0	0.1	1	-1	-1	-1	-1	1
-5.5	-0.3	0.1	0	3	1	0	2	-2	1

It should be noted here the two different SET* values are calculated – one with no wind velocity, and one with 0.38m/s wind velocity induced from the mist. This is to hopefully segregate the change in Thermal sensation from the mist alone, not including induced wind draft. Worthy to note is that skin temperatures changes are not major, with all changes within 1 °C or less. A few conclusions can be drawn from these results. Firstly, the change in Thermal Comfort (TC) and Thermal Sensation Vote (TSV) has no seeming correlation, as shown in Figure 19, where the correlation value is only -0.0689, meaning that the change in TSV contributes only about 7% to the change in TC. There are likely other contributing factors to thermal comfort. Thus, this paper will focus on TSV and TC as two separate dependent variables.

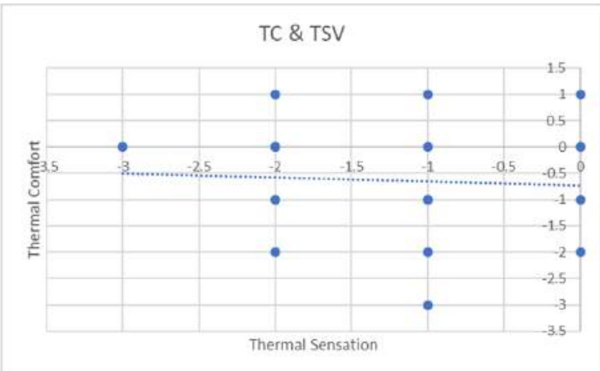


Figure 19 Change in Thermal Comfort vs in Thermal Sensation

To quantify the change in TSV and TC, it is necessary to study the impacts from different variables and this is done by studying individual correlations and conducting a multiple linear regression, using the highest correlated variables. Each variable and their correlation values are calculated in SPSS statistical software and tabulated in Table 4. Since the TSV and TC are ordinal variables, the Spearman Rank Order Correlation Coefficient was chosen, since it is a non-parametric measure. Ultimately, five variables are chosen for TSV change, namely 'SET* (No Wind), Forehead, Left Arm, Skin Wetness and Wet Feeling'. Three variables are chosen for TC change, namely 'SET* (No Wind), Left Arm and Airflow).

Table 5 Correlation values against TSV and TC

TSV Change	Variable	Correlation Value	TC Change	Variable	Correlation Value
	SET*(No Wind)	0.216		SET*(No Wind)	0.282
	SET* (Wind)	0.182		SET* (Wind)	0.033
	Forehead	0.215		Forehead	0.229
	Left Arm	0.517		Left Arm	0.309
	Skin Wetness	0.548		Skin Wetness	-0.275
	Wet Feeling	-0.237		Wet Feeling	0.02
	Air Flow	-0.02		Air Flow	0.410
	Air Humidity	-0.183		Air Humidity	0..077

Ordinal regression is conducted using SPSS to analyse the results and predict the ordinal dependent variable (TSV & TC), given the chosen independent variables. The typical multiple linear regression cannot be conducted in this case, since the variables are ordinal in nature and are not normally distributed. However, two assumptions were carefully considered before implementing this model. Firstly, no multicollinearity is ensured, where there may be two or more independent variables that are highly correlated with each other. The only two variables in this case are the SET* values with and without wind, but SET* with wind is not considered for this analysis. Further, the ordinal regression model assumes that there are proportional odds where each independent variable has an identical effect at each cumulative split of the ordinal dependent variable. This can be tested and shown in the output tables 5 & 6 below.

The top portion of the tables shown Model Fitting information, which helps us determine whether the model improves our ability to predict the outcome by comparing a baseline (Intercept-only) model against the model with all variables included. The statistically significant chi-square statistic (0.002) indicates that there is a significant improvement. Next, the Goodness-of-Fit table shows the Pearson's Chi-square statistic for the model and are intended to show if the observed data are consistent with the fitted model. From the significance, it may suggest that the model does not fit very well, and this could be due to the small sample size. However, other measures of association must be consulted, and these are shown in the Pseudo R-Squared values. For ordinal regression models, three approximations are required to sufficiently explain the proportion of variance in the outcome. These are Pseudo values because they look like R-squared being on a similar scale with higher values indicating a better model fit, but they cannot be interpreted in the same way as linear regressions. As seen from Table 5, the Pseudo R-Squared values are relatively high, and this means that the 5 chosen variables can explain to a large extent (Nagelkerke: 82.4%) the change in TSV.

Table 6 SPSS Ordinal Regression Output for TSV

Model Fitting Information				
Model	-2 Log Likelihood	Chi-Square	df	Sig.
Intercept Only	49.584			
Final	21.446	28.139	10	0.002
Goodness-of-Fit				
	Chi-Square	df	Sig.	
Pearson	108.505	47	0	
Deviance	21.446	47	1	
Pseudo R-Square				
Cox and Snell	0.755			
Nagelkerke	0.824			
McFadden	0.567			

The model for TC likewise shows a statistically significant result as seen from the p-value in obtaining Chi-square statistic. However, the model is not as good a fit compared to TSV as can be seen from the significance from the 'Goodness-of-fit' ($p>0.05$). The Pseudo R-Squared values are significantly high, and may explain that the 3 chosen variables – SET*, left arm skin temperature and Airflow – can explain to a large extent the variance in Thermal Comfort.

Table 7 SPSS Ordinal Regression Output for TC)

Model Fitting Information				
Model	-2 Log Likelihood	Chi-Square	df	Sig.
Intercept Only	56.516			
Final	0	56.516	6	0
Goodness-of-Fit				
	Chi-Square	df	Sig.	
Pearson	45.303	66	0.976	
Deviance	39.019	66	0.997	
Pseudo R-Square				
Cox and Snell	0.941			
Nagelkerke	0.996			
McFadden	0.976			

4.2. Comparison with local data

Outdoor thermal comfort has previously been studied extensively in Singapore (Yang, Wong, & Jusuf, 2013), although the study was not a field experiment in that no variables were deliberately changed. This study differs since the Dry Mist is administered to change Thermal Comfort among participants. Thermal neutrality was previously determined to be 28.7°C operative temperature and 80% acceptable range was 26.3 – 31.1 °C. However, Operative temperature may not be a suitable index to quantify cooling effects from Dry Mist since it does not consider skin wetness and cooling from skin.

A similar approach is adopted to analyse the relationship between mean TSV (MTSV) and SET*, by dividing SET* into different data bins that are 0.5°C apart. The MTSV was then weighted with the number of participants in the corresponding bin. The results are shown in Figure 20, and no meaningful conclusions can be drawn since there is no clear pattern. This agrees with the findings of this study, since Table 4 shows that the correlation between TSV and SET* is only about 21.6% and cannot account for majority of the variances in TSV.

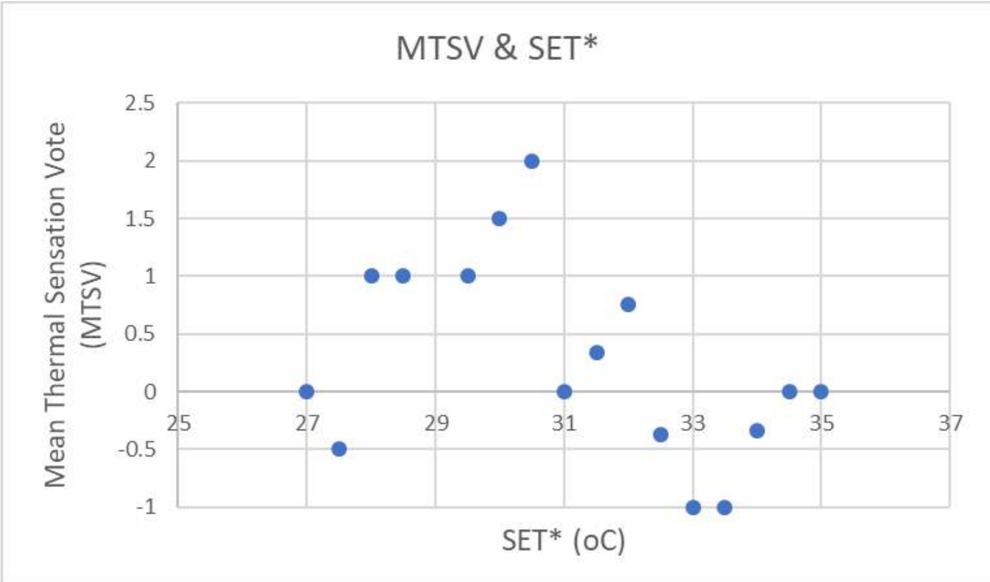


*Figure 20 Mean Thermal Sensation Vote based on SET**

Another attempt was made at how the MTSV changes against the Left arm skin temperature, since there is a higher correlation, and the results are shown in Figure 21. The graph shows a much clearer pattern, that as the skin temperature rises, MTSV rises. The linear relationship, with a Spearman correlation of 0.587, was found to be:

$$MTSV = 0.7098\ T_{leftarm} - 25.815 \qquad R^2 = 0.587$$

Using the above equation, the neutral left arm temperature can be found by solving for MTSV to be zero, and the neutral left arm skin temperature was 36.37°C. Assuming the acceptable range to be 80%, it translates to +- 0.85 on the ASHRAE scale, and this corresponds to a left arm skin temperature of between 35.17°C and 37.57°C (ISO, 2005).

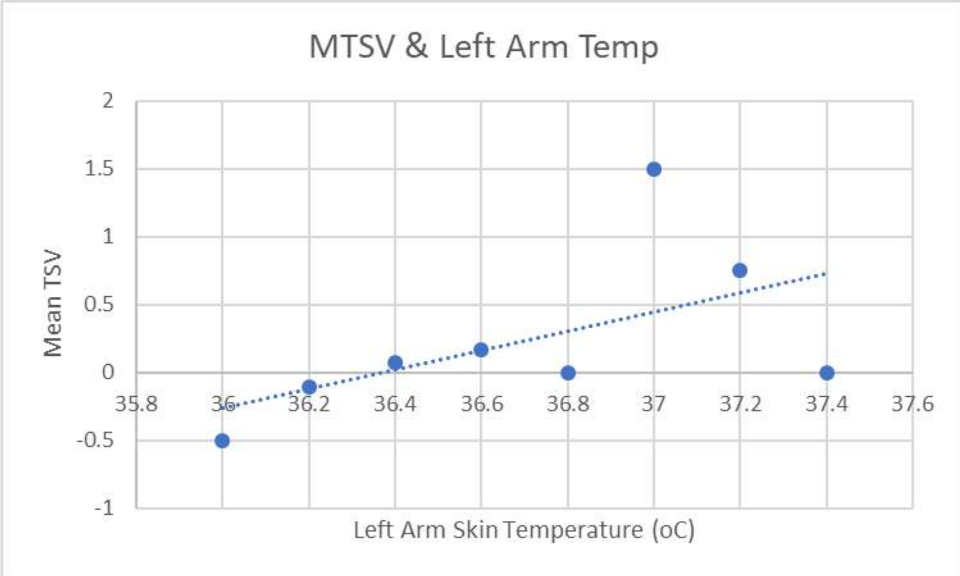


Figure 21 Mean Thermal Sensation Vote based on Left Arm Skin Temperature

5. Conclusion

There are a few conclusions we can draw from this study, about how to effectively employ the use of the Dry Mist system and achieve optimal thermal sensation and comfort among occupants. Firstly, since the Dry Mist provides localized cooling only in the area of coverage, it is not recommended to use the system when there is high ambient wind velocity, since the droplets will get carried away and the cooling effects will take place at unintended locations as seen in Figure 12. This agrees with another paper in Japan, which recommends that the system be switched off when wind velocities reach 3m/s or more (Yoon, Yamada, & Okumiya, 2008). Another key result as seen from Figures 14 & 15, is that despite a slight increase in skin wetness perception by participants, there is also a greater increase in the pleasantness of this wetness. This agrees with another paper where the wetness was also rated as pleasant by most participants (Farnham, Emura, & Mizuno, 2015). Furthermore, the increase in skin wetness perception is accompanied by no change in air humidity perception, and this may highlight the heightened tolerance for humid air in Singapore.

Another key finding is that the SET* plays a smaller role in determining thermal sensation than skin temperature. This means that the placement of the Dry Mist system is important for maximum exposure to human skin. This must consider the spray distance, coverage and pressure of operation, like highlighted in a previous study (Zheng, Ichinose, & Wong, 2018). It is easier for maximal exposure when the participants are seated down like in this study, but more care must be taken when participants are asked to stand. Finally, the air flow perception from participants contribute significantly to their thermal comfort perception but this is not so for thermal sensation. Although the misting system already induces increased air velocities from its high-pressure air and induced downdraft from cooling, urban planners can consider coupling the system with a fan to increase thermal comfort further.

Since it has been established that skin temperatures play a huge role in thermal sensation and comfort for participants using Dry Mist, future studies can consider using computational tools like CFD to model the change in skin temperatures across the human body. Also, the authors acknowledge that the sample size is relatively small, and the results should be referenced with caution. Further studies will seek to expand the sample size to increase the reliability of the results.

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"Performance Evaluation of Indirect-Direct Evaporative Cooling System In Hot & Dry Climate"

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Abstract: The commercial and residential sector demands high cooling requirement, which is mostly achieved by using conventional cooling systems like split ACs, chillers or VRF. These systems currently produce 100 MT of CO_2 per annum and hence contribute significantly to carbon emissions. To mitigate such environmental impacts, using low energy cooling systems like an indirect-direct evaporative cooling system (IDEC) is an energy efficient alternative as it uses energy only for pumping water and blowing air.

This study evaluates the cooling performance of IDECs. The wet bulb effectiveness (WBE %) was calculated from the hourly measured values of air temperature (T_a °C) and relative humidity (RH %). These parameters were measured at inlet and supply air. Energy consumption of the IDEC, air blower fan, and water pump were monitored every hour. Thermal comfort surveys were conducted to establish a relation between the effectiveness of IDECs, the cooling energy consumption and degree of occupants' comfort. ΔT_a of 5- 6 °C and saturation deficit of as 30-35% was observed. During August-October WBE varied from 55-83% with an energy consumption range of 29-30 kWh. Whereas, for November-December, WBE varied from 41-67% with energy consumption range of 23-28 kWh.

Keywords: Indirect-direct evaporative cooling system, IDEC effectiveness, low energy cooling (LEC), energy consumption, thermal comfort

Table 1: Nomenclature

Sr. No	Variable	Symbol	Unit
1	Wet Bulb effectiveness (WBE)	ε_1	%
2	Dew point effectiveness (DPE)	ε_2	%
3	Outdoor air-dry bulb temperature	T_1	°C
4	Outdoor air wet bulb temperature	$T_{1'}$	°C
5	Outdoor air dew point temperature	$T_{1''}$	°C
6	Supply air dry bulb temperature	T_2	°C
7	Volume flow rate	$\dot{V}$	m^3/s
8	Mass flow rate	$\dot{m}$	kg/s
9	Specific heat of air (1.006)	C_p	kJ/kg.K
10	Density of air (1.225)	ρ_{air}	kg/m^3
11	Outdoor humidity ratio of air	X_1	$kg_{\text{of water}}/kg_{\text{of dry air}}$
12	Supply humidity ratio of air	X_2	$kg_{\text{of water}}/kg_{\text{of dry air}}$
13	Cooling capacity of system	Q_c	kW
14	Specific water consumption	SWC	$kg_{\text{of water}}$ /kWh
15	Water consumption	WC	kg/hr

1. Introduction

India, with a population of nearly 1.2 billion, is the world's third largest greenhouse gas (GHG) emitter. It has pledged to reduce carbon emission per unit of gross domestic product ('emission intensity') up to 35% by 2030 from the 2005 level (Chen, 2017).

Commercial building space accounts for 33% of the total built space and is increasing at a rate of 8%–10% annually (Kaja, 2017). HVAC systems contribute to 31% of the energy used by commercial buildings in India (Tathagat. et al, 2014). Due to higher demand, the required air- conditioner capacity in India is also growing at a rate of 20% per year (Phadke, Abhyankar, & Shah, 2013).

Cooling is intimately associated with human health, well-being, and productivity. The need to ensure thermal comfort for all and access to cooling across the populace is even more important considering the tropical climate of India. A large part of the country's cooling requirements across sectors is met using conventional air conditioning systems (Altvater, 2012). These use a vapor-compression cycle containing a refrigerant as a working fluid which has a high Global Warming Potential (GWP). This practice has not changed fundamentally in nearly 100 years. (Goetzler, Guernsey, Young, Fuhrman, & Abdelaziz, 2016).

These systems use a typical mechanical vapor compression cycle (MVC) containing a refrigerant as working fluid. These refrigerants having high GWP are listed for phase-out/phase-down under the Montreal Protocol to which India is a party. Technology like IDECs reduces direct climate impact through the elimination of refrigerants altogether.

Evaporative coolers have been commercialized for some time, yet, they have only achieved limited market penetration, even in hot and dry climates. Residential and industrial air cooler market for direct evaporative cooler (DEC), indirect evaporative cooler (IEC) and indirect-direct evaporative cooler (IDEC) is growing with a compounded annual growth rate (CAGR) of approximately 20% and 8% respectively which is comparable to CAGR of 25% for variable refrigerant flow (VRF) (India Air Cooler Market Outlook, 2021), (The Indian HVAC&R Growth Story, 2018).

This low adoption rate, especially in the industrial sector, is indicative of several significant technical barriers that evaporative cooling has in operation and practice. Some of them are low effectiveness in adverse ambient conditions, low applicability during humid conditions, increased on-site water consumption and low thermal comfort.

To overcome these barriers, a field testing in a variety of conditions is required to understand its performance throughout the year, quantify water consumption, and identify potential maintenance problems (Goetzler, Zogg, Young, & Caitlin, 2014).

Specifically, this research determines the WBE of the IDECs for providing thermal comfort in various seasons in hot and dry climatic conditions. The amount of energy and water consumption for providing thermal comfort is also determined.

2. Literature review

Conventional MVC system is commercially dominant as they are stable for providing heating and or cooling for the buildings despite having high GWP (Vakiloroaya, Samali, Fakhar, & Pishghadam, 2014) (Amer, Boukhanouf, & Ibrahim, 2015).

In contrast, evaporative cooling systems are more environmentally friendly as they use water as the working fluid to cool air through evaporation (ASHRAE Handbook, 2007). Also, these systems consume less energy and their performance improves as wet bulb depression and RH deficit increases (Duan, Zhan, Zhang, Mustafa, & Zhao, 2012). Because of this fact, such systems have a wide application in hot & dry climates (Datta, Sahgal, Subrahmaniyam, Dhingra, & Kishore, 1987).

The existing evaporative cooling systems can be classified into three main categories: DEC, IEC and IDEC (Duan, 2011). Here, we will understand the working of IDEC in detail. An IDEC system utilizes a heat exchanger in which one side is a wet-air passage and the other side is a dry-air passage as shown in Figure 1. All of the air entering the equipment is outdoor air. The outdoor air enters the dry side of the heat exchanger at point A, exchanges heat with the wet side air and exits the heat exchanger at point B without changing its humidity as shown in Figure 2. A portion of the air at point B is delivered to the building as the supply air, while the rest of the air is directed through the wet-side of the heat exchanger. On the wet-side, the air stream increases in enthalpy as it absorbs heat from the dry-side air and evaporates water from the water supply (Pistochini, Modera, & Power, 2011).

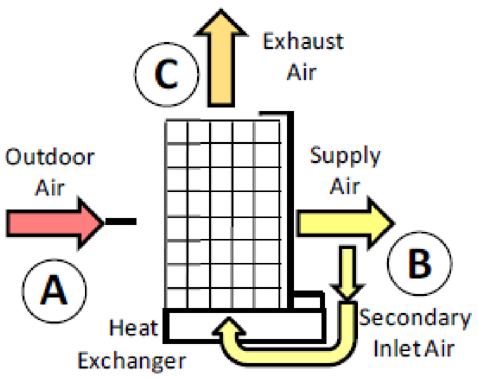

Figure 1: Schematic of IDEC system supplying air (Pistochini et al., 2011)

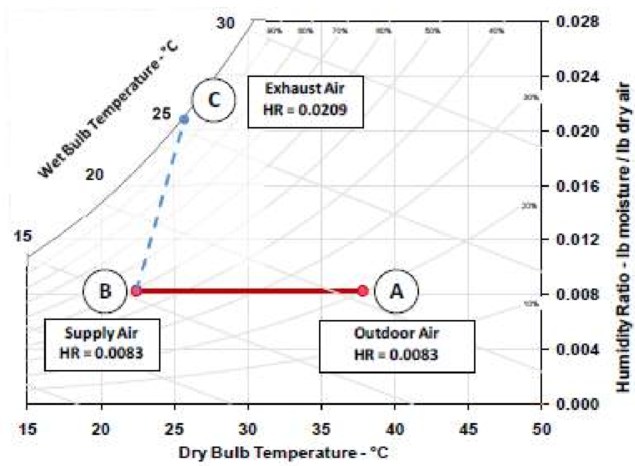

Figure 2: Psychrometric process for IDEC systems (Pistochini et al., 2011)

The energy consumption of evaporative coolers is usually 30-50% less as compared to that of MVC with the same capacity. As no compressors are involved, the co-efficient of performance (COP) values of evaporative cooling systems are 2-3 time higher than those of conventional MVC. (Maisotsenko & Reyzin, 2005). Also, we need to keep in mind that the equation of COP favors evaporative coolers (which deals only with sensible heat loads) over MVC (which deals with sensible as well as latent heat loads).

The IDEC technology uses a fraction of power for air and water circulation and can save up to 90% energy over MVC (Lechner, 2014). But, it is often reported that the energy and water consumption of such systems is very high (Porumb, Ungureşan, Tutunaru, Şerban, & BĂlan, 2016). To overcome this, more field experiments need to be conducted for understanding variation in the effectiveness of the IDECs along with water and energy consumption (Goetzler et al., 2014).

Laboratory evaluation of the 2005 model Coolerado® cooler showed that the unit can provide 9-12 kW cooling capacity and the WBE ranged from 81% to 91% with average COP over 8.8 for all the test conditions (Elberling, 2006). Laboratory evaluation results for Coolerado® hybrid system reported the cooling capacity as 13.4 kW, COP of 12.1 and water consumption as 1.9 liters/kWh (Kozubal & Slayzak, 2015).

When testing a IDEC at Beijing, China (average summer wet bulb depression is 4.1 °C), WBE of 85%, WC of 2.6 to 3 litres/kWh and cooling capacity of 2.5 kW was reported. (X. Zhao, Yang, Duan, & Riffat, 2009). Another study theoretically and experimentally evaluated the performance of IECs at Athens, Greece (average summer wet bulb depression is 14 °C). WBE of 97% to 115%, WC of 2.5 to 3.0 litres/kWh and cooling capacity of 0.4 kW was reported (Tertipis, 2013). This means that evaporative coolers are capable of having WBE more than 100% provided the wet bulb depression is high.

Further, research shows that IDECs can provide thermal comfort conditions in those places where DECs could not provide thermal comfort conditions due to high wet bulb temperature (Heidarinejad, Bozorgmehr, Delfani, & Esmaeelian, 2009). A post-occupancy evaluation study of passive downdraught evaporative cooling tower shows that the thermal comfort votes are close to neutral in monsoon and on the colder and warmer sides of neutral in winter and summer respectively (Thomas & Baird, 2005).

Based on the literature above, it was known that water-retaining capacity (porosity) of materials, pad thickness, working climate, heat and mass transfer rate, pressure drop, supply air flow rate, the shape of evaporative cooling pad and durability are important factors in system effectiveness (Koca, Hughes, & Christianson, 1991), (X. Ã. Zhao, Liu, & Riffat, 2008), (Xuan, Xiao, Niu, Huang, & Wang, 2012).

3. Research methodology

The research study comprises of a field testing of low energy cooling system (LECs) in the hot and dry climate of Ahmedabad.

Ahmedabad city is located in state of Gujarat in India. Ahmedabad lies in western India at 23.03°N latitude and 72.58°E longitude at 53 metres above mean sea level. The annual mean DBT of the Ahmedabad city is 28 °C. Annual average high DBT ranges from 28 to 35 °C whereas annual average low DBT ranges 22 to 28 °C. Recorded high and low DBT is 45 and 10 °C. Mean DBT during summer (March to June), monsoon (July-October) and winter time (Nov to Feb) time is 32 °C ,29 °C and 22 °C respectively. Mean RH during summer, monsoon and winter time is 45%, 71% and 52% respectively. The wet bulb depression ranges from 10 to 15 °C throughout the year except for the monsoon months. This means that location is hot and dry for most of the year. The average annual rainfall is about 782 millimetres.

The case study was chosen such that it has IDEC size above 10,000 CFM. Also, it should have scope of conducting thermal comfort “Right Now Right Here” (RNRH) surveys while the LECs is operating. RNRH surveys of at least 20 occupants should be possible every week for five to six months starting from July 2018. One relevant case study was identified after contacting various stakeholders.

The data gathering method involved collecting architectural drawings of the space being served by IDECs, single line drawings (SLD) of the power distribution system, measuring indoor and outdoor environmental parameters, measuring energy consumption of the IDECs and conducting RNRH surveys.

Architectural drawings of the space and SLDs were obtained from the concerned site office. Indoor environmental parameters including DBT, RH and T_G have been measured using the data loggers with instantaneous logging interval of 1 hour. Data loggers were installed at IDECs for measuring supply air DBT and RH. DBT, RH and T_G were measured for the indoor space. Outdoor DBT and RH was obtained from an automated weather station located in Ahmedabad city. Integrated hourly energy consumption of the IDECs, a water pump, blower and exhaust fan were measured using energy meters (EM). These EM were installed with required current transformer (CT) ratings. Equipment specifications are summarised in Table 2.

The data from data loggers and EM were extracted using USB and RS-485 cables respectively. This was done to avoid data loss. Spreadsheet software was used to keep a track of the collected data through all the site visits. These spreadsheets contain information about the equipment serial number, date of installation, location of equipment, timestep of reading and parameters being measured. Following equations were identified to assess the effectiveness the IDECs.

1. **Wet bulb effectiveness (WBE)**

$$\varepsilon_1 = \frac{T1-T2}{T1-T1'} \quad \text{(Duan, 2011)}$$

2. **Dewpoint effectiveness (DPE)**

$$\varepsilon_2 = \frac{T1-T2}{T1-T1''} \quad \text{(Duan, 2011)}$$

3. **Volume flow rate**

$$\dot{V} = area\ of\ duct\ x\ resultant\ velocity \quad \text{(Duan, 2011)}$$

4. **Mass flow rate**

$$\dot{m} = \rho_{air} \,.\, \dot{V} \quad \text{(Duan, 2011)}$$

5. **Cooling capacity**

$$Qc = \frac{Cp \,.\, \dot{m} \,.\, (T1-T2)}{3.6} \quad \text{(Duan, 2011)}$$

6. **Water consumption (WC)**

$$WC = \dot{m}.(X2 - X1) \quad \text{(Bishoyi \& Sudhakar, 2017)}$$

7. **Specific Water consumption**

$$SWC = \frac{WC}{Qc} \quad \text{(Tertipis, 2013)}$$

8. Co-efficient of performance (COP)

$$\text{COP} = \frac{Qc}{W} \text{ (Duan et al., 2012)}$$

ASHRAE standard 55 (ASHRAE-Standard 55, 2010), RP-884 (Dear et al., 1998) and the Indian model for adaptive comfort-IMAC (Manu, Shukla, Rawal, Thomas, & de Dear, 2016) were identified for developing a thermal comfort survey questionnaire. The semantic differential scale was used to form an integrated framework to record the occupants' answers.

The RNRH survey questionnaire included questions about the acceptance, preference, and sensation for the thermal environment, air quality, air movement, and overall thermal comfort.

Questionnaire also included items about height, weight, clothing type (Rawal, Manu, Shukla, Thomas, & de Dear, 2016). Chair type and activity level (ASHRAE-Standard 55, 2010) of the occupant at the time of survey was considered for the calculation. However, occupants' activity level for the preceding hour were also recorded. Time, date and season of the survey were also noted. The thermal comfort scale is sourced from ASHRAE-Standard 55, 2010, Dear et al., 1998 and Schiavon, Yang, Donner, Chang, & Nazaroff, 2017. The scale is summarised in Table 3.

The survey was scheduled every week on Sunday. The survey questionnaire was printed on the paper and the subjects were interviewed. Indoor conditions such as DBT, RH, T_G, and air velocity (vertical and horizontal) were measured along with each survey. Equipment were given stabilisation time of two minutes. Measurements were taken at a height of 0.9 m at a distance of 0.3 m on the face side of the occupant.

Table 2: List of equipment used for data collection

Name of the equipment	Specification of the equipment	Image of the equipment	Logging interval	Purpose
HOBO U12-012 data loggers	**Measurement range:** Temperature: -20° to 70°C RH: 5% to 95% RH **Accuracy:** Temperature: ± 0.35°C from 0° to 50°C RH: ± 2.5% from 10% to 90%, below 10% and above 90% ±5% **Resolution:** Temperature: 0.03°C at 25°C RH: 0.05% RH		1 hour	Monitoring indoor environment

Name of the equipment	Specification of the equipment	Image of the equipment	Logging interval	Purpose
HOBO U12-012 data loggers with external TMCx-HD type sensors (air temperature/globe temperature)	**Measurement range:** Temperature: -40° to 50°C **Accuracy with U12:** ±0.25°C from 0° to 50°C **Resolution with U12:** 0.03° at 20°C **Housing:** Copper-plated sensor tip	 Air temperature sensor  Globe temperature sensor	1 hour	Monitoring indoor environment
Secure Elite 440-442 energy meter	**Measurement voltage range:** 100V to 415 V, AC 3 phase 4 wire (3 phase 3 wire) **Voltage Tolerance:** 30% to +20% of V_n **Current range** Available 1-2A and 5-10 A in single variant (field configurable) **Main frequency** 50/60Hz with ±5% tolerance **Communication:** RS485 Modbus half duplex		1 hour	Monitoring energy consumption
CTs from Rishabh instrument	**CT type:** square type, XMER series **CT ratings used:** 20/5A, 50/5A and 75/5A		1 hour	Monitoring energy consumption
Extech Heat stress WBGT Meter Model HT30	**Wet Bulb Globe Temperature (WBGT)** Range**:** 0 to 50°C Accuracy: ±2°C **Black Globe Temperature (TG)** Range: 0 to 80°C Accuracy: ±2°C **Air Temperature (TA)** Range: 0 to 50°C Accuracy ±1.0°C **Humidity: Range:** 0 to 100%RH Accuracy**:** ±3%RH		Stabilisation time of 2 minutes	Thermal comfort, RNRH-surveys

Name of the equipment	Specification of the equipment	Image of the equipment	Logging interval	Purpose
TSI Velocicalc-9565	**<u>Velocity (TA Probe):</u>** Range: 0 to 50 m/s Resolution: 0.01 m/s Accuracy: ±3% of reading or ±0.015 m/s, whichever is greater **<u>Temperature (TA Probe):</u>** Range: -10 to 60°C Accuracy: ±0.3°C Resolution: 0.1°C **<u>Relative Humidity (TA Probe):</u>** Range: 5 to 95% RH Accuracy: ±3% RH Resolution: 0.1% RH **<u>Response Time:</u>** Velocity: 200 milli sec Temperature: 2 minutes (to 66% of final value) Humidity: <1 minute (to 66% of final value)		Stabilisation time of 2 minutes	Thermal comfort, RNRH-surveys

Table 3: Scales used for thermal comfort

Thermal sensation		Thermal acceptance		Thermal preference		Air movement sensation		Air movement preference		General comfort	
Hot	+3	Acceptable	+2	To be warmer	+3	Much too breezy	+3	More air movement	+3	Very comfortable	+6
Warm	+2	Unacceptable	+1	No change	+2	Too breezy	+2	No change	+2	Slightly comfortable	+5
Slightly warm	+1			To be cooler	+1	Slightly breezy	+1	Less air movement	+1	Just comfortable	+4
Neutral	0					Just right	0			Just uncomfortable	+3
Slightly cool	-1					Slightly still	-1			Slightly uncomfortable	+2
Cool	-2					Too still	-2			Very uncomfortable	+1
Cold	-3					Much too still	-3				

4. Case study description

The case study selected for this research is located in 50 kms from Ahmedabad city. The building complies well with the selection criteria mentioned under the methodology section. It has an IDECs of 30,000 CFM capacity which is serving 465 m^2 of area. The schematic working of the IDEC is shown in Figure 3. The system consists of two water supply pumps, a water tank, heat exchanger, blower and exhaust fan. This all components are housed in one structure and the conditioned air is supplied into the room using left side duct as shown in Figure 4.

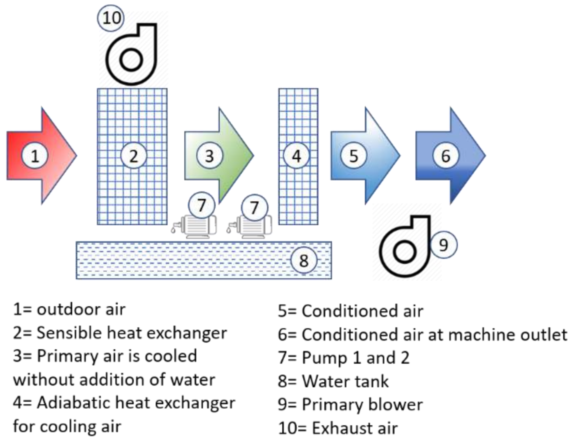

Figure 3: Schematic of IDEC

Figure 4: IDEC as installed on site

The facility is operated from 8:00 AM to 6:00 PM and around 40 occupants are present during working hours. Space is divided into two sections as shown in Figure 3. Section 1 has a gas furnace to cook Indian breads (Rotis & Nan Paratha), whereas section 2 has frying machines. Internal heat gains are very high due to this large cooking equipment. The IDECs isn't turned off during the lunchtime as the system takes stabilisation time. The occupants stand throughout performing their activities. Space is occupied for whole week including Sundays except for festival or maintenance time.

For indoor monitoring; data loggers were placed at 5 positions; 4 loggers were placed in the space (2 loggers in each section) as shown in Figure 5 . The other data logger was placed at the supply side of the IDEC measuring DBT and RH.

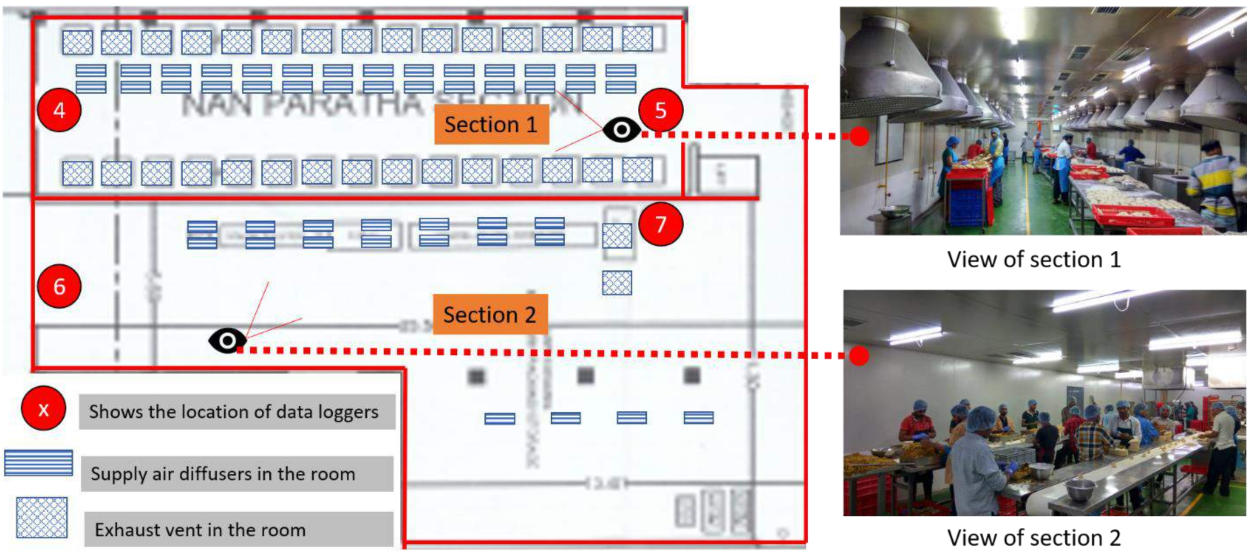

Figure 5 Plan showing data logger position, supply air and exhaust vents along with the view of both the sections

Four locations were identified for measuring the IDEC energy consumption as shown in Figure 6. One EM measures IDEC energy consumption; other three EM measures energy consumption at component level i.e., water pump, supply and exhaust fans.

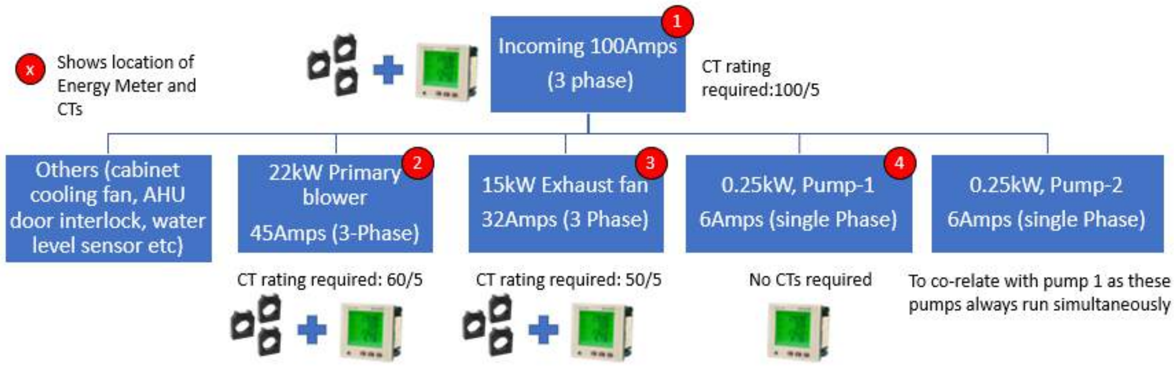

Figure 6: SLD of IDECs showing location of energy meter with its respective CTs. Source: Self

For the thermal comfort surveys, RNRH thermal comfort survey questionnaires were printed on paper. Occupants were interviewed to fill the response sheet based on their experience of thermal comfort. The measurements for the indoor environment was taken simultaneously with the surveys.

5. Results and analysis

The IDECs performance was recorded for a period of 6 months from July 2018 to December 2018. Various performance governing parameters were measured and then analysed. The system operation time considered to identify the system cooling performance is from 8:00 AM until 6:00 PM. A normal probability plot is one way you can tell if data fits a normal distribution as shown in Figure 7 and Figure 8. Z-value which is a numerical measurement of a value's relationship to the mean in a group of values are plotted against normalised measured data. A straight line indicates that data does fit a normal probability distribution. It was observed that the R^2 value for outdoor and supply air temperature is 94% and 89% respectively which is well within the acceptable ranges (Cohen, 1988). The illustration shown in Figure 7 and **Error! Reference source not found.** represents that the collected data can be considered for further analysis.

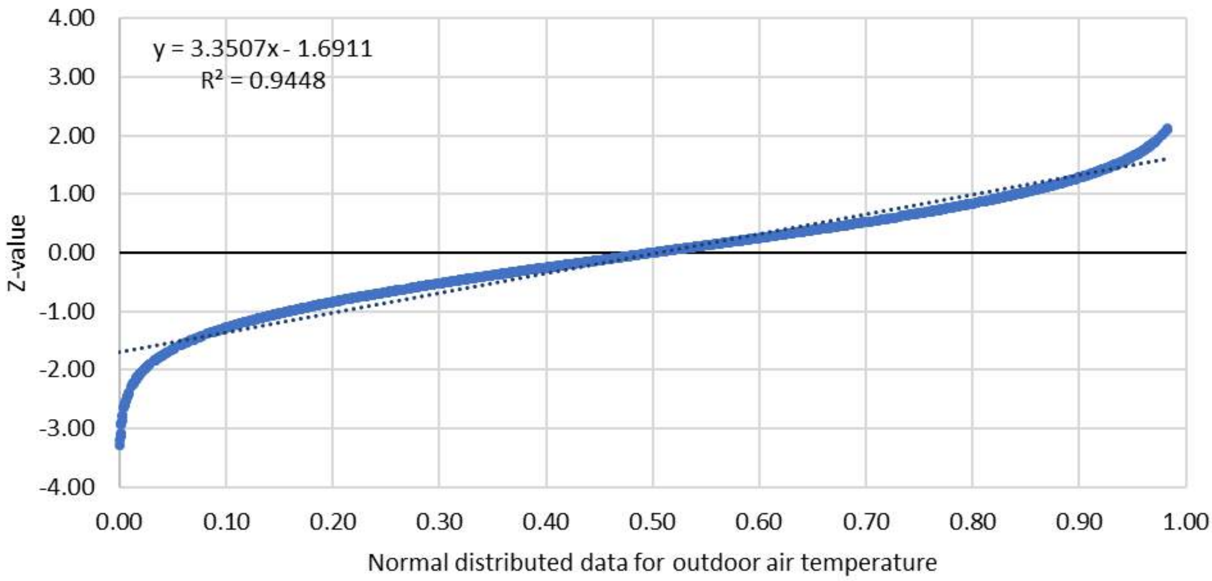

Figure 7: Graph showing normal distribution of outdoor air temperature

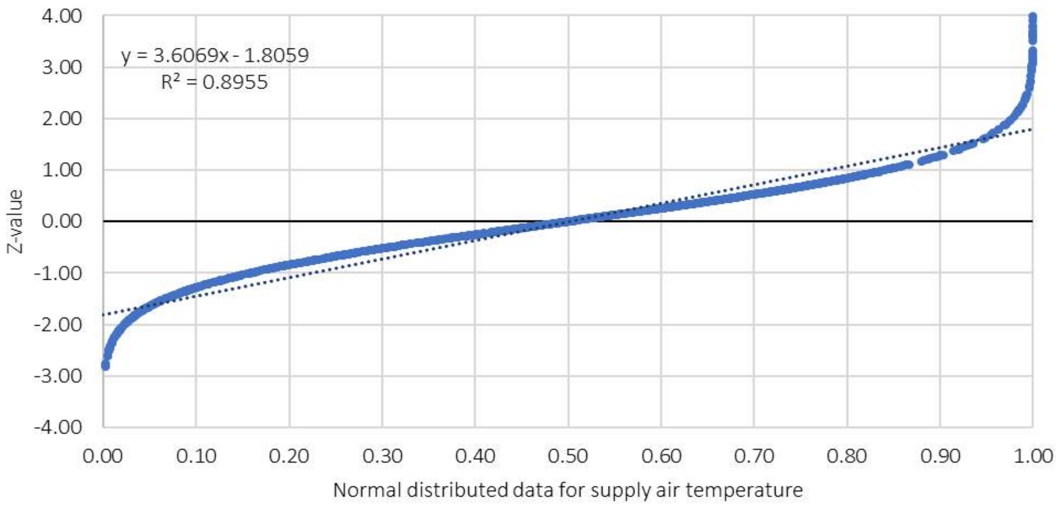

Figure 8: Graph showing normal distribution of supply air temperature

Figure 9 shows range of RH at outdoor and supply air. Figure 10 shows the range of DBT at outdoor and supply air. This has been measured from July to December 2018.

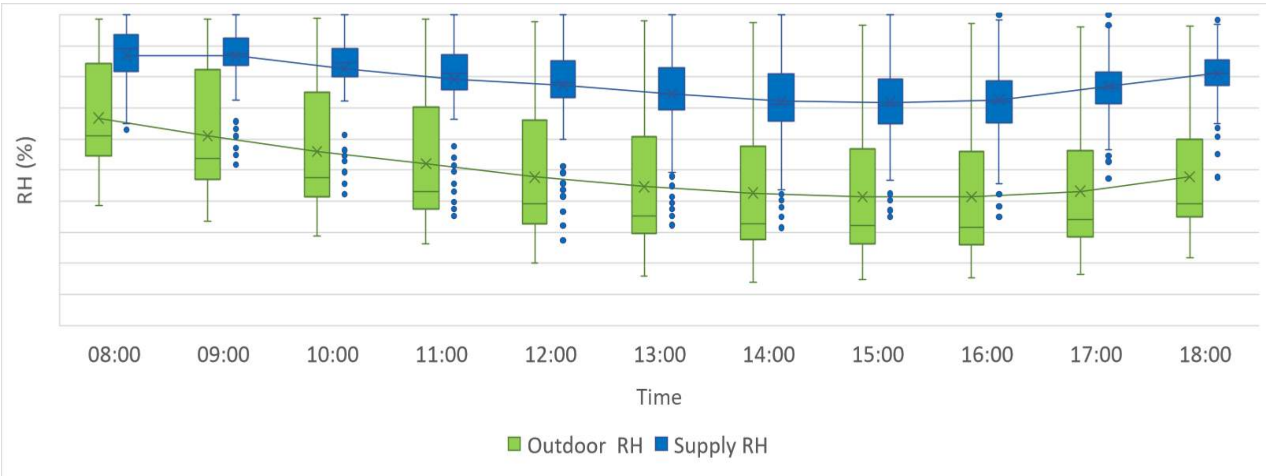

Figure 9: Box plot showing variation in outdoor and supply RH with respect to operating hours from July to Dec 2018.

Based on Figure 9 and Figure 10 it was known that the IDECs, when switched on, is able to add humidity and reduce the indoor air temperature. During 8:00 to 11:00 AM, a ΔT_a of 3-4 °C and saturation deficit of 20-25% is observed. A maximum ΔT_a of 6 °C and saturation deficit of 35% is observed from 12:00 to 6:00 PM.

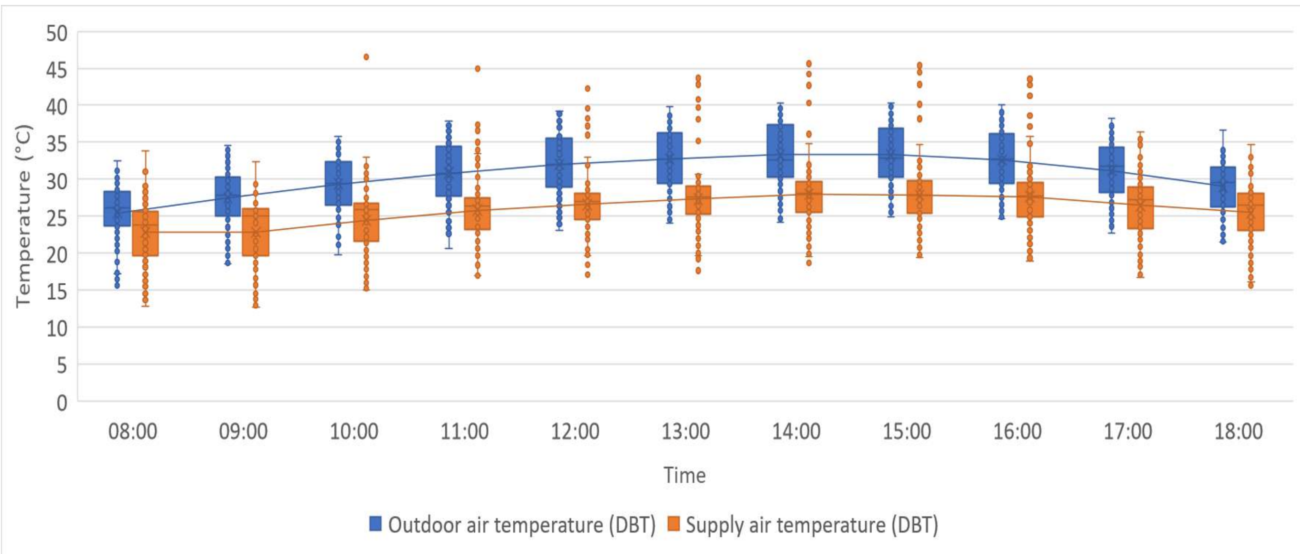

Figure 10: Box plot showing variation in outdoor and supply DBT with respect to operating hours from July to Dec 2018.

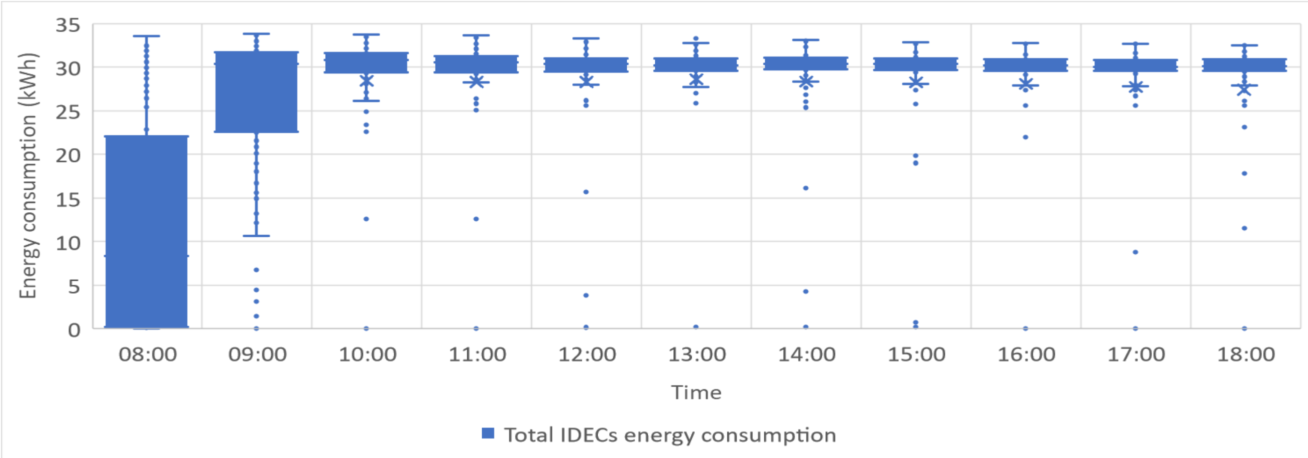

Figure 11: Box plot showing pattern of IDECs energy consumption with respect to operating hours from July to Dec 2018.

Figure 11 and Figure 12 shows the pattern of calculated WBE and measured energy consumption of the IDECs from July to December 2018. It is observed that during the morning hours when the system is turned on, the WBE and energy consumption varies a lot. This means that the system is taking approximately one hour for stabilization. Energy consumption varied from 0-33 kWh, whereas the WBE varies from 25-100%. As the day proceeds energy consumption stabilizes at 31-33 kWh. But, the WBE ranges from 75-85% during the 9:00 AM to 12:00 PM and 50-65% from 1:00 to 6:00 PM. We can also see that the IDEC yields WBE over 100% at few instances. This is because of the two-step cooling process and theoretically 100% DPE is possible.

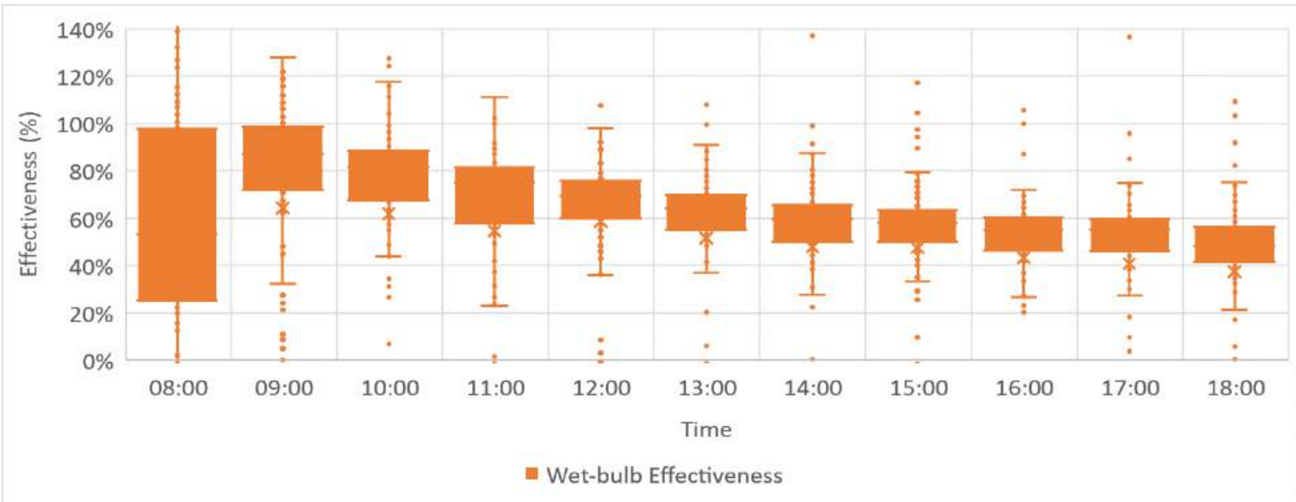

Figure 12: Box plot showing variation in WBE with respect to operating hours from July to Dec 2018

Figure 13 shows the daily energy consumption along with WBE and DPE from August to December 2018. It is observed that the during the months of Aug, Sep and Oct (monsoon months) WBE and DPE ranges from 55-83% and 42-61% respectively with energy consumption range of 29-30 kWh/day. Whereas, during the months of Nov and Dec (winter months) WBE and DPE ranges from 41-67% and 23-44% respectively with energy consumption of 23-28 kWh/day. WBE and DPE are greater when the difference in between indoor and outdoor humidity ratio is higher. This also means that the greater cooling effect is dependent not only the wet bulb depression, but also on the saturation deficit of the intake air.

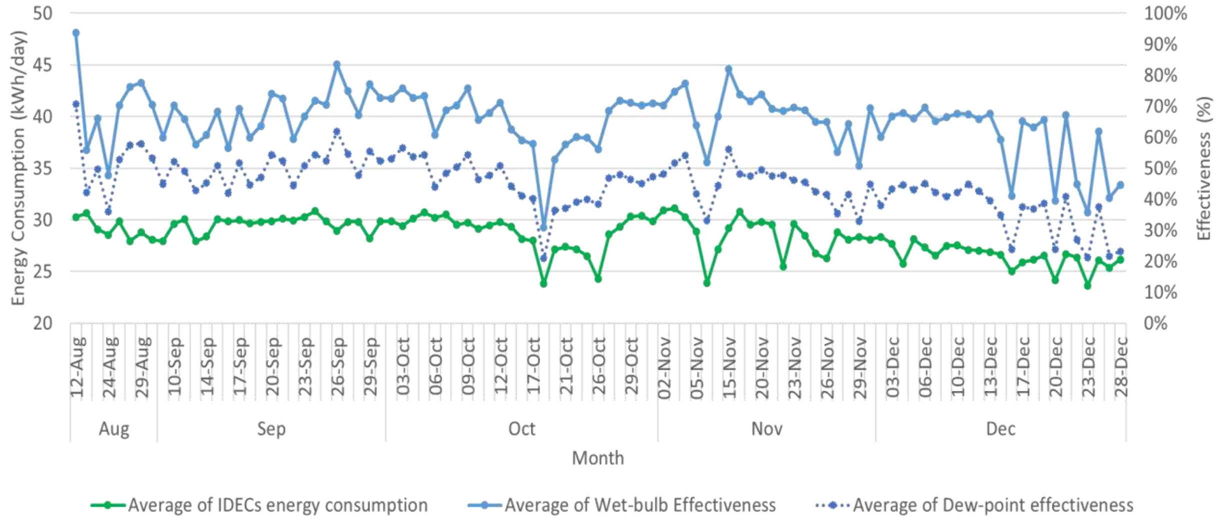

Figure 13 Graph showing pattern of energy consumption with respect to WBE and DPE from Aug to Dec 2018.

Figure 14 shows the water consumption of the IDEC with respect to the difference in humidity ratio from August to December 2018. The water consumption during monsoon months is observed to be in the range of 15-30 liters/day. Whereas, winter months shows the water consumption values as high as 122 liters/day. Higher water consumption could be observed when the difference in humidity ratio is more. This is predictable because during the monsoon months there is a very little scope of adding humidity to the outdoor air which is nearly saturated. At this point, it becomes challenging to further reduce the air temperature by evaporation of water. As operating conditions of the IDEC is not conducive for the IDEC operation.

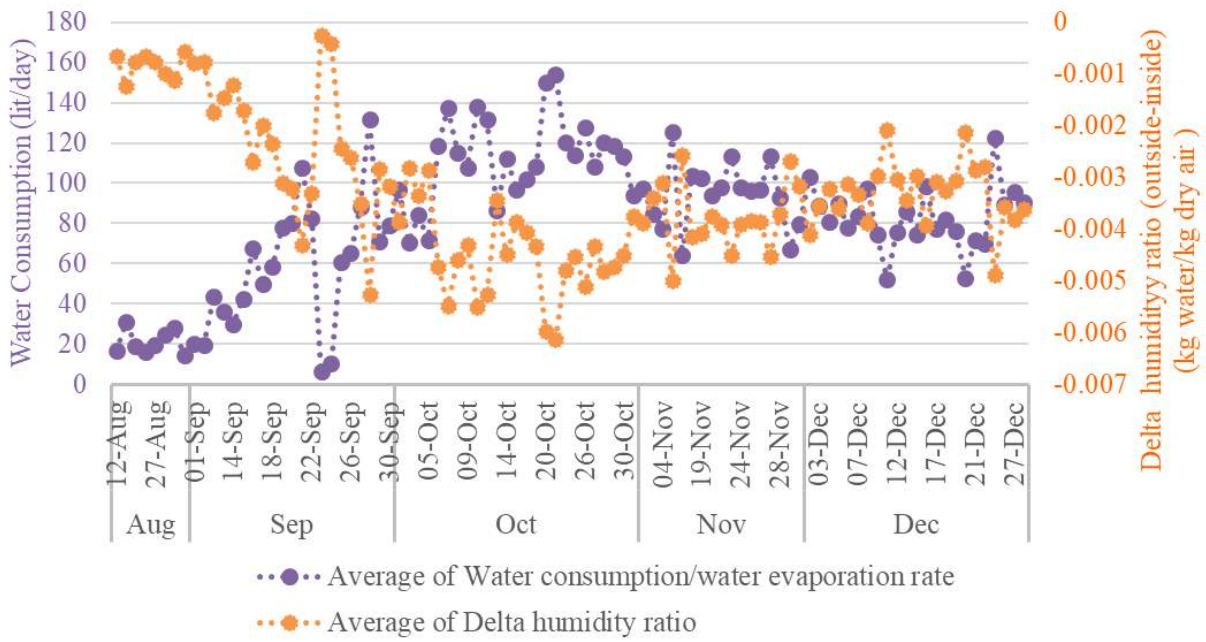

Figure 14: Graph showing range of water consumption with respect to delta humidity ratio from Aug to Dec

140 RNRH surveys were done from the period of July to December 2018. Figure 15 shows the linear relation between predicted mean vote (PMV) and actual mean vote (AMV). It was found that the PMV tends to deviate from AMV. Deviation of PMV is on the hot side side of thermal sensation.

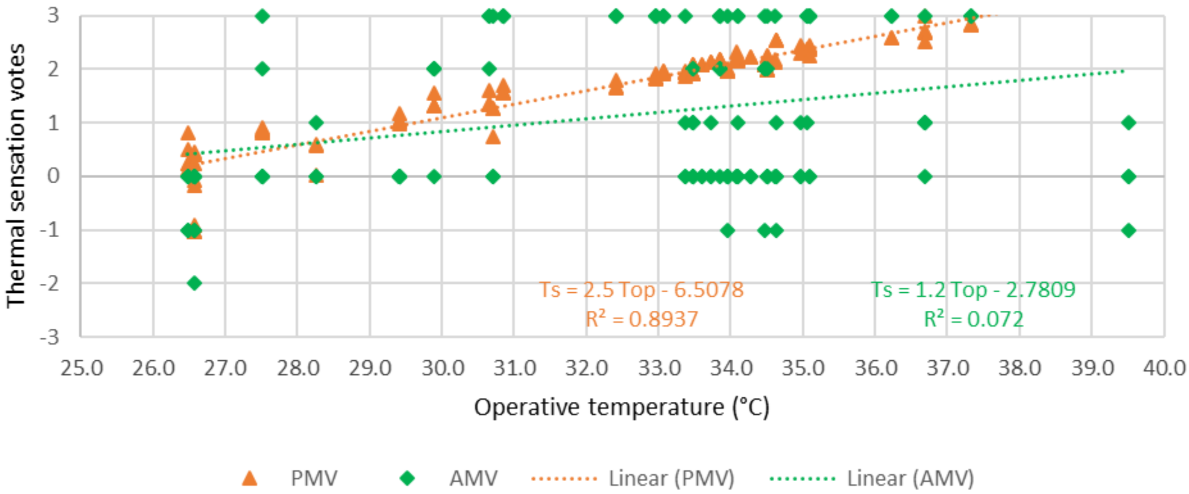

Figure 15: Graph showing the PMV and AMV with respect to operative temperature

Conducting RNRH surveys helps to understand the occupant's thermal sensation. Thermal sensation votes, thermal acceptability and thermal preference are shown in Figure 16, Figure 17 and Figure 18. This was done by creating a temperature bin of 1 °C.

It was observed that 79% of the total surveyed population feels hot, warm or slightly warm as the indoor air temperature rises beyond 30 °C. On further investigation it was found that these occupants were either working in front of gas furnace or frying machine where the T_g ranged from 38-41 °C and air velocity recorded was 0.1 m/s. Also, 55% of population showed non-acceptance to the prevailing thermal conditions and wanted to be cooler.

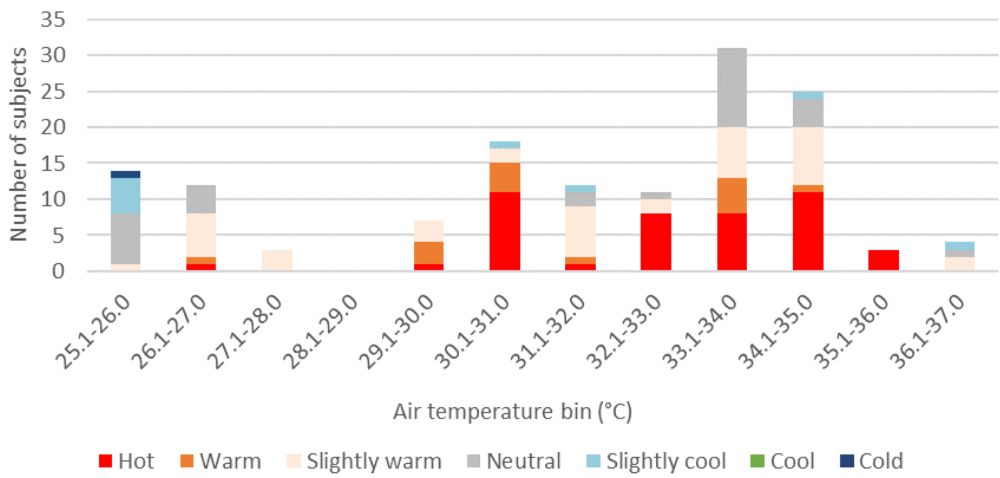

Figure 16: Thermal sensation votes with respect to air temperature

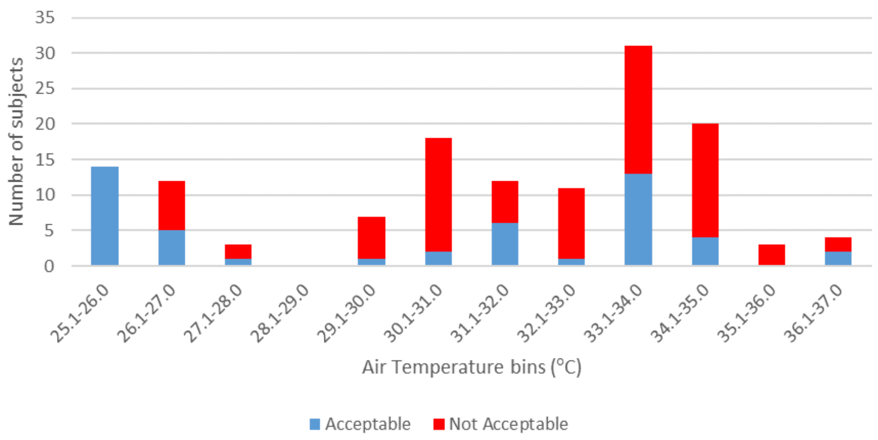

Figure 17: Thermal acceptability votes with respect to air temperature

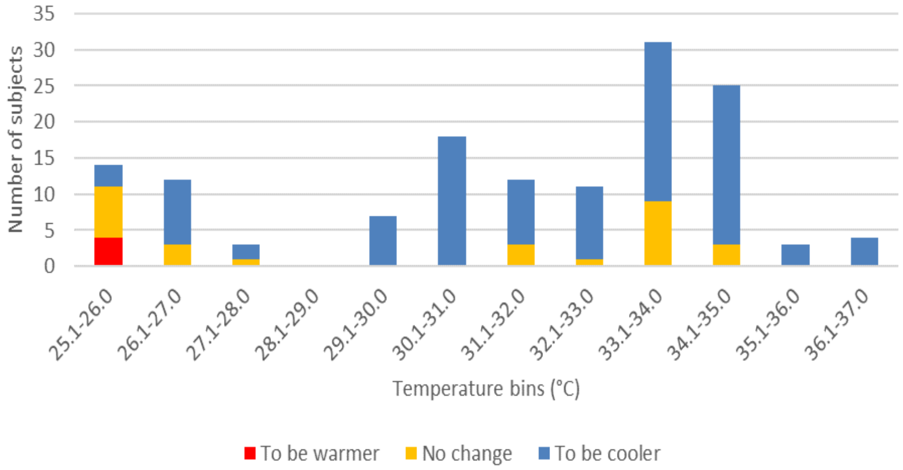

Figure 18: Thermal preference votes with respect to air temperature

Further to understand this 90% acceptability range for ASHRAE and IMAC along with the operative temperature. Operative temperature was calculated from measured TA and TG. It was observed that out of 140 RNRH surveys, only 3 fall into the 90% acceptability range of IMAC and ASHRAE during the month of December as shown in Figure 19.

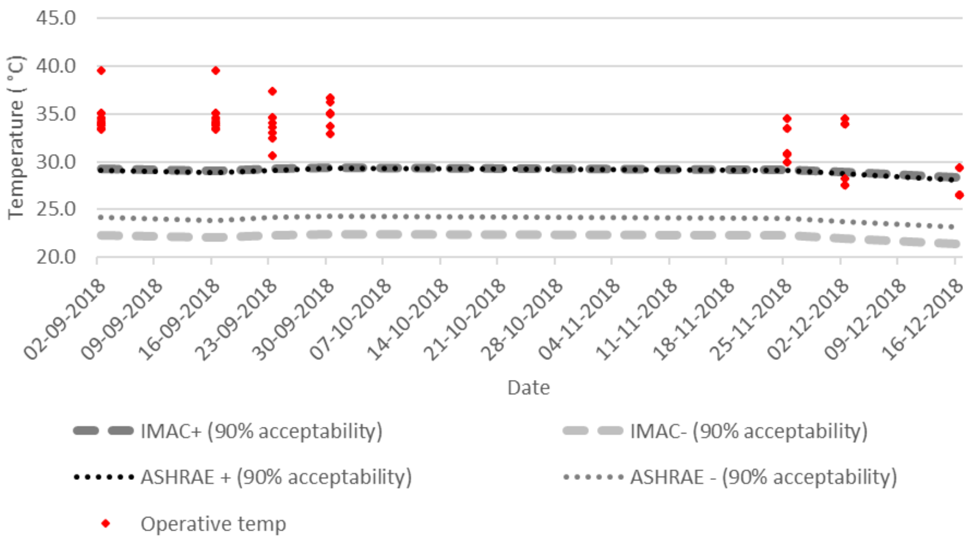

Figure 19: Operative temperature with respect to 90% acceptability limits of ASHRAE and IMAC.

6. Discussion:

Evaporative cooling technology is environmentally friendly and has the potential to minimize the use of MVC systems. WBE of the IDEC in this study is found to be 83% during the monsoon months which is comparable to experimental evaluation of WBE of 90-110% in similar climatic conditions (Mohammed A. 2013). This means that results of this study are in line with literature review. Despite of high effectiveness, occupants have constantly voted the indoor environments as hot and wanted to be cooler. On further investigation it was found that the design air flow of IDEC was 30,000 CFM but produced only 12,500 CFM. This could be because the system maintenance hasn't been done from a long time. Now, if the IDEC achieved designed airflow then the possibilities are that the WBE might not vary much, but additional 50% airflow might help counter the heat generated by the cooking process.

7. Acknowledgements:

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Reclaiming refugee agency and its implications for shelter design in refugee camps

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Abstract: Refugee agency refers to the notion of decision making exercised by forced migrants, and their efforts aimed at improving life in the context of displacement. As such, it has emerged as a useful concept to channel discussions about the challenges of current refugee encampment practices, which we argue encompasses consequences for the design and provision of shelter solutions. Building on the evidence collected in selected refugee camps of Jordan and Ethiopia, we suggest that acknowledging and incorporating the voices of refugees can not only enhance their well-being in climatically, socially and politically challenging environments, but it could also be beneficial to other actors such as humanitarian agencies and host governments. While we recognize the constrains arising in these contexts, we focus on the importance of adaptations and customization of shelters that we found to be the leitmotiv and, more critically, a fundamental humanizing factor of refugee experience in camps. The refugees' freedom to make choices about their own shelters can then be used to rethink how to deliver better environments in which camp inhabitants can live in dignity. Although engineering design can only facilitate agency, rather than give it, it could help build the consensus about the pre-requisites of what constitutes truly 'appropriate' shelters.

Keywords: refugee, camps, shelter, agency, design, Jordan, Ethiopia

1 Introduction

In the area of refugee studies, the term refugee agency has been juxtaposed against the cultural representation of displaced people as voiceless and passive victims portrayed as the objects of humanitarian interventions, rather than the subjects capable of making choices and taking control of their life trajectories, albeit in very difficult situations. The first narrative depicts refugees as oppressed by institutions, in this case, by camp management, whereas the one that emphasizes the strategies used by them to oppose this domination tends to romanticize the encampment. Both approaches, however, reveal a degree of interpretative bias by either underestimating the autonomy of refugees whilst demonising role of the humanitarian sector, or by exaggerating the refugee's capacity to resist institutional, legal and political structures embedded in the refugee administration (Fresia 2007).

Humanitarian sector is often seen as overtly preoccupied with technical solutions given the requirements of dealing with emergency situations, as well as the character of funding, namely that donors tend to be more generous at the beginning of a crisis, with funds dwindling with time passage. The often-ad hoc, rushed, and therefore not including consultations with refugees, response of the sector to a crisis can be interpreted as geared towards control and surveillance (Agier 2010). Furthermore, the lack of participatory approach has led to erroneous aid programmes (see Zetter (1991) and Crisp (2001) for an overview) and the call to embed refugees' views in implementation of aid is not new; multiple studies have shown that refugees are agents capable of articulating their own needs and seeking solutions to challenges that they face (Essed et al. 2004; Dona 2007; Harrell-Bond & Voutira 2007; Brun & Lund 2010). Wilson (1992, p.226) points out that refugees suffer the most not when less than average level of assistance is provided, but when their own survival and adaptation strategies have been particularly limited by authorities and/or relief agencies in the name of concerns for security and control, or merely for the purpose of administering aid more smoothly. On the other hand, it is evident from interviews that we carried out with humanitarian staff in Jordan that leaving refugees to their own devices might lead to technically inappropriate solutions, and consequently, possible risks of fire, flooding and other hazards. A third perspective, aiming to combine the aforementioned approaches, recommends that humanitarian interventions should explicitly include refugees in their programming, fully recognising their agency and potential to ameliorate their living standards in the situation of displacement (Harrell-Bond 1986; Harrell-Bond 1989; Allen 1996; Hyndman 2000; Chimni 2009).

In our interdisciplinary project 'Healthy Housing for the Displaced', we argue that detangling those complex relationships between refugees, humanitarian actors and host countries can lead to enhancing the sustainability of aid initiatives, as well as to fostering refugees' ownership of programmes implemented by the sector. Not only is the project multivocal due to its interdisciplinary character, but also because we work with all the actors engaged in camp governance, namely refugees, UNHCR and other UN agencies and International Non-Governmental Organizations (INGOs), as well as representatives of host governments. Up until now, the project identified shelter performance shortcomings and characterised the thermal needs of camp dwellers in Jordan (Albadra et al. 2017) and proposed consequent design solutions (Fosas et al. 2018). Furthermore, it has suggested negotiating a consensus which challenges the current dichotomy (McGrath et al. 2018), calling all actors to work together in order to improve shelters for displaced populations (Albadra et al. 2018). Building on these efforts, we advocate here for refugee agency to be the fundamental guiding principle of the shelter provision process. In this context, refugee agency is a factor that guarantees dignity of camp dwellers and, entails certain design practices as emanating from the field work conducted in this project.

2 Institutional framework

Refugee camps are regulated settings governed by bodies representing a host state; the United Nations High Commissioner for Refugees; and other UN agencies alongside INGOs, as well as small local organizations. Shelters in refugee camps are loosely regulated housing units. Their dimensions are defined by the Sphere Project (2011) and follow the requirement that each shelter should provide a minimum three-and-a-half square meters of covered living space to every resident. In many cases, this is not implemented in practice; for example, in the Hitsats camp (Ethiopia) an average of five to nine persons live in one concrete block house which is only 4m x 5m. Some regulations are vague, and therefore either not followed at all, or easy to negotiate, for example the requirement "where possible" to provide shelter that is acceptable "socially and culturally" to its intended occupants (The Sphere project 2011, p.258). To the best of our knowledge, there is no institutional actor responsible for making shelters culturally appropriate for a particular group of people, and it is either ignored or left to largely unstructured consultations with refugees such as those carried out by UNHCR in some Ethiopian camps (UNHCR & ARRA 2017).

Discussion on refugees' agency in refugee camps inevitably involves the aspect of time, namely the alleged dichotomy between temporariness and permanency. The often-quoted average time of 17 years that refugees spend in camps is actually inaccurate; it does not refer to camps – majority of refugees live in urban areas – and it is limited to the duration of displacement situations, not the time that people stay in exile (Devictor & Do 2016). The length of protracted refugee situations does however last decades, with oldest refugee camps dating back to 1947 (Cooper's Camp in India, following the partition) and 1948 (Palestinian camps in the Levant set up after the establishment of Israel). What we often saw in the course of our research was a narrative that permitting refugees to improve their shelters will influence their decision to stay in the camp for longer; therefore, those adaptations are undesirable from the perspective of host states and donors, and sometimes refugees themselves, as the homemaking process may be seen as undermining their claims for long term solutions to displacement. Under this discourse, ensuring that refugee camp remains a transient space would, for instance, facilitate an easier management of possible returns, the preferred UNHCR durable solution to refugee crisis. This argument is built on the assumption of a rigid dichotomy between temporariness and permanency, and consequently, the association of shelter enhancement with permanency. We argued elsewhere (Hart et al. 2018) that it is lack of alternatives, and/or ongoing conflict in the country of origin, rather than degree of satisfaction experienced in a camp, that impacts refugees' decision to relocate.

Depending on the political context, host states impose a different set of their own rules, for example in relation to buildings materials. The Jordanian authorities forbid usage of concrete in Syrian refugee camps as it symbolically signifies the permanence of camps and recalls the Palestinian presence in the country largely composed of different refugee groups that have previously blended into the Jordanian nation-state. On the other hand, in Hitsats, Eritrean refugee camp in North Ethiopia, all shelters are essentially permanent and built of bricks, and there are no restrictions in relation to adaptations made by refugees. Overall, camp administration policies and practices are not rigid, even though they often strive at appearing so; they may change their position over time, and this tends to fluctuate towards relaxing the rules (Hart et al. 2018). For example, residents of Zaatari camp in Jordan were initially provided with communal kitchens and bathrooms. People did not want to use them, and eventually were given private facilities instead. In a more regulated Azraq camp refugees repetitively plant trees outside their shelters in the night, even though they are then removed by the authorities in the daytime. The assumption is that one day the governmental authorities will turn a blind eye to this practice (and probably they will). In Hitsats refugees are not allowed to keep dogs as a precaution against rabies outbreak, but in one instance a puppy was hidden during the day and roamed freely in the night; by the time she grew up, no one seemed to remember about the regulation that was forbidding dogs in the camp. Therefore, it seems that the relationship between refugees and actors managing the camp often takes form of a cat-and-mouse game, an unspoken testimony of refugees' autonomy battling against the institutional odds.

3 Refugee's agency and shelter adaptations

Drawing on the anthropology of architecture, we argue that through the production of material forms, such as dwellings, people define and order socio-cultural relationships in the process that mutually constitutes one another, subjects and objects (Vellinga 2007, p.761). In other words, one could coin a dictum, "how the things that people make, make people" (Küchler & Miller 2005, p.38, as cited by Vellinga 2007) which very much resonates in the context of displacement camps, effectively in the state of constant re-making by refugees.

3.1 The case of Zaatari and Azraq camps in Jordan

A very good example of this mutually constitutive relationship is the construction of *al madafah*, space for receiving guests. None of the surveyed shelter solutions accounted for guestrooms in their design, and refugees have themselves built spaces needed to welcome visitors. The primary function of such spaces is to offer a comfortable setting for the very important cultural practice of visiting, serving food and drinks to one's guests, a prerequisite to harmonious communal life. Islamic Sharia law explicitly recommends that hospitality should be a principle guiding the design of dwellings in the Muslim context (Othman et al. 2015). The guestroom also allows to uphold one's social status and family honour, and therefore re-asserts social identity after experiencing the rupture caused by conflict and forced migration.

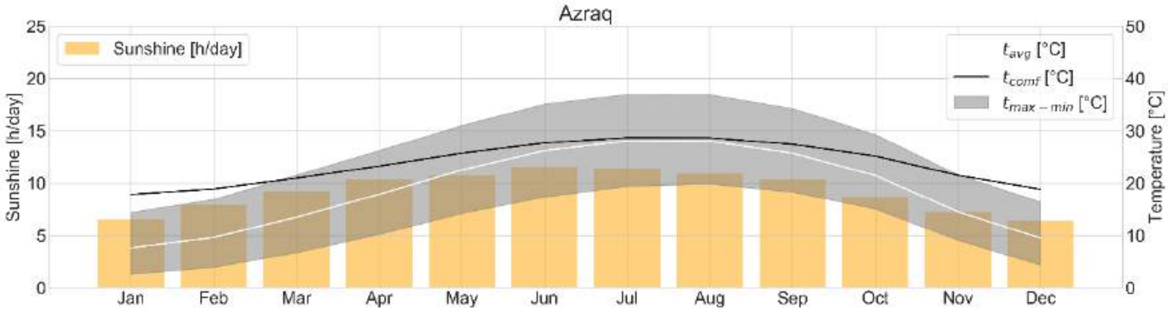
Taking Zaatari as an example, the conditions in the camp allowed for an unintended exercise of ownership by the refugees over their shelters. Given that these are highly portable caravans, refugees could relocate within the camp and freely arrange their shelters to create the spaces they needed (Albadra et al. 2018). Some people have over time developed, depending on their skills and financial situation, very elaborate guestrooms that included bird towers, water fountains and small gardens, providing refuge from the summer heat. According to our interviews with UNHCR staff in Jordan, at least 50% of the camp was effectively re-made by refugees themselves. From the institutional actors' perspective this led to health and safety hazards; for example, people were moving caravans in the way that was blocking the access to roads in case of emergency.

On the contrary, Azraq camp opened at a later stage, and was ready for inhabitation prior to the arrival of refugees. Azraq designers seem to have considered the shortcomings of Zaatari camp from a care-giver's perspective — rather than from the refugees' perspective — into a highly organised plan based on villages, districts, blocks and shelters[1]. Focusing on the shelter solution, the design did not take advantage of the of the climate at the location (Figure 1a), being mainly constrained by cost, speed of construction, structural and fire safety. These resulted in a single-room lightweight shelter made of steel where the only heavyweight element of the construction is the concrete slab, which uses the internal walls as the formwork (Figure 1-b). As such, the shelter cannot be reconfigured in the same ways the caravans were in Zaatari, and the main space is used as a bedroom during night time and a guestroom during daytime.

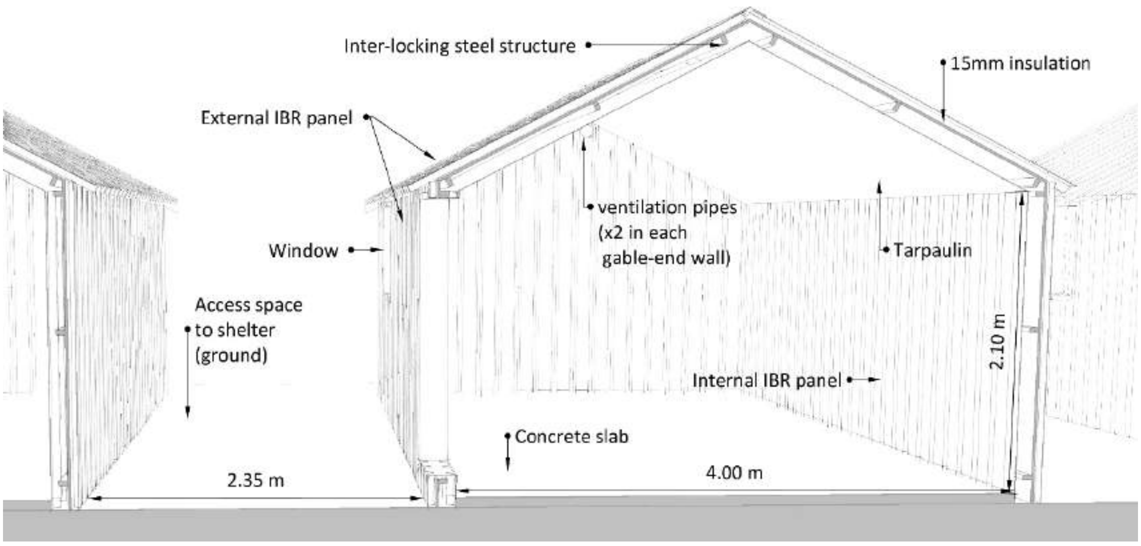
The current in-use state of the shelters clearly highlights the shortcomings of the original design and the ways in which the owners adapted the space (Figure 1-c). People inhabiting these shelters report high levels of thermal discomfort as assessed in field studies (Albadra et al. 2017), since the lightweight construction follows closely the wide range of daily external temperatures (Figure 1-a). This causes, for example, internal condensation in winter and surfaces becoming too hot to touch in the summer. At present, many shelters have been retrofitted with an extra layer of 15mm insulation in the internal walls besides people's own adaptations including hanging fabrics. In many instances, the inhabitants have even opened new windows to enhance natural ventilation. The reasons are that the ventilation pipes provided cannot be operated by the occupants and cause excessive sand ingress, and that privacy is not preserved with the window on the same side of the entrance to the shelter. The concrete floor is usually carpeted and sprayed with water in the summer to provide some evaporative cooling. Since the walls are drilled to the structure and anchored into the ground, the shelter can only expand in-between other units, an

[1] See Dalal et al. (2018) for a discussion on the planning of Zaatari and Azraq.

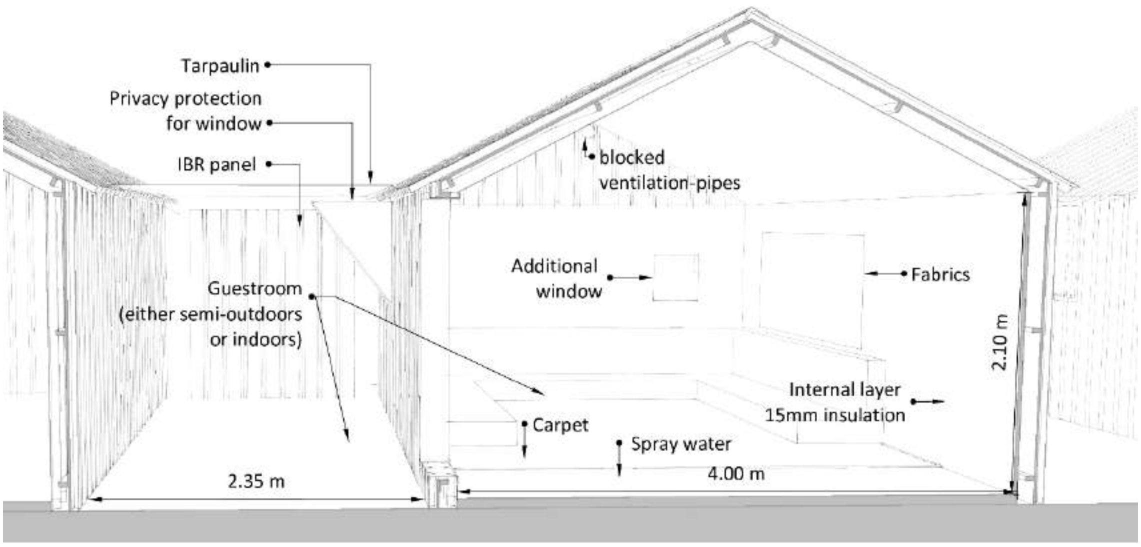
appropriation not foreseen in the design and not allowed by the camp management. This space allows to cook outdoors to minimize the heat gain inside the shelter or to grow a small garden which is a cherished aspect of Syrian culture. The modification attempted by the owners in this regard is to enclose this space with an additional wall on one side or tarpaulins as an improvised roof. Overall, even though Azraq camp benefitted from pre-planning the infrastructure and the shelter design, it did not build on the unintended success of Zaatari in terms of refugee agency and the refugees' ownership of their shelters.



a) Climate overview – Nicol graph (data: Gelaro et al. (2017) and Schroedter-Homscheidt et al. (2017))



b) Shelter as designed



c) Shelter as used

Figure 1: Azraq case study (Jordan, latitude 32°N)

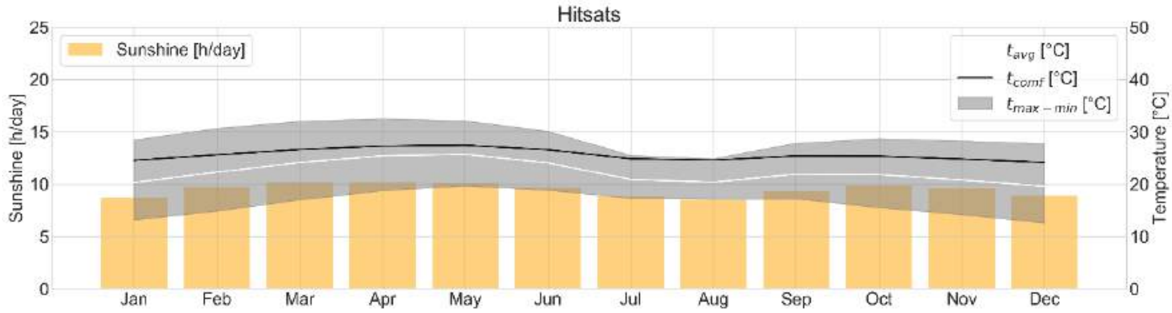
3.2 The case of Hitsats camp in Ethiopia

The case of the Hitsats refugee camp in Ethiopia depicts a different scenario both culturally and climatically. For instance, Eritreans socialize around coffee ceremony, *buna jebena*, which involves roasting raw coffee beans and takes on average 1–2 hours to prepare. It is traditionally performed 3 times a day, usually only by women, and a guest should drink three cups of freshly brewed coffee in order not to offend the host. Gender norms, and consequently, the understanding of privacy, are more relaxed in Hitsats than among Syrian refugees so in most cases we did not see any partitions inside the dwellings, even when these were inhabited by young single people of both sexes, who are the dominant demographic group in the camp. Young men and women living in one shelter tended to say that they are friends, and that they trust each other. They also shared household chores, with men bringing firewood and women preparing food. This is also due to the impact of indefinite compulsory military service in Eritrea: people aged 16–18 leave their family for military training, and friendship bonds acquire significant cultural meaning.

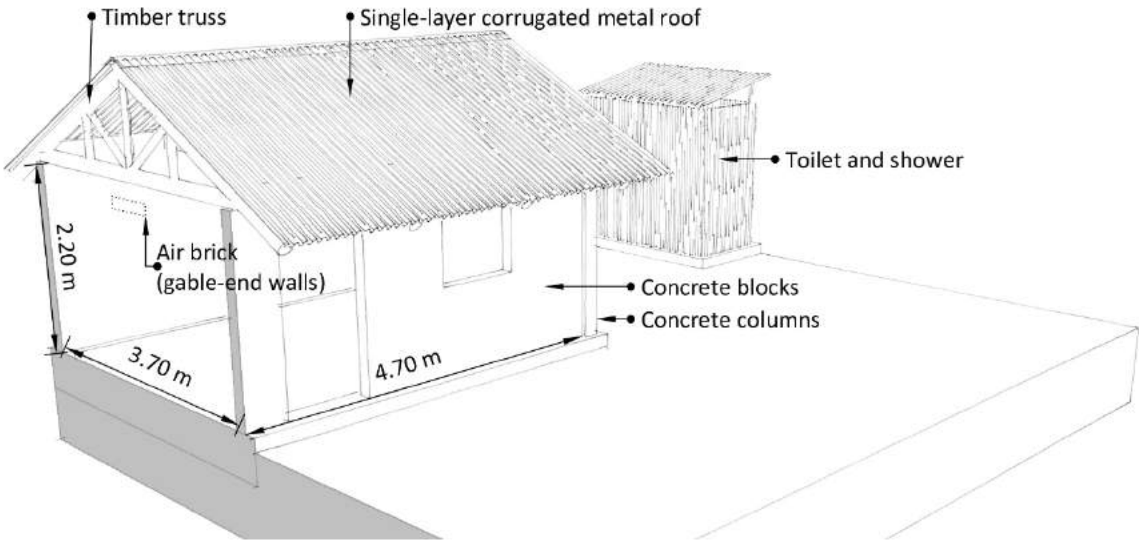
In terms of climate, Hitsats depicts relatively warm conditions, with temperatures in the range of 15–35 °C, and daily temperature swings of 15 °C approximately (Figure 2-a). As hinted by the temperature drop between June and September, there is a wet season that features not only high humidity but also strong rainfalls and wind gusts. The shelters here are made of concrete blocks for the walls and corrugated metal sheets of timber trusses for the roof (Figure 2-b). It is erected over flattened raised ground to minimize water ingress. The interior is an unfurnished single space of 17 m^2 with single-side ventilation through the door and the window, although gable-end walls include air bricks. The unit also features an external bathroom unit with a toilet and a shower detached from the shelter.

The adaptations performed by the camp dwellers are done on three levels (Figure 2-c). At interior-space level, it is the construction of mud furniture, mainly beds inside the shelters which recreates a sensory memory of home, given that people would not normally sleep on the floor in Eritrea. At shelter level, the main adaptations are to build a double roof because of water leaks and to paint the outer walls to repel insects. At plot-level, owners that can afford it build an outdoor sitting space to receive guests and perform the coffee ceremony because the single-sided ventilation system of the shelter does not provide enough ventilation to purge the smoke and the heat.

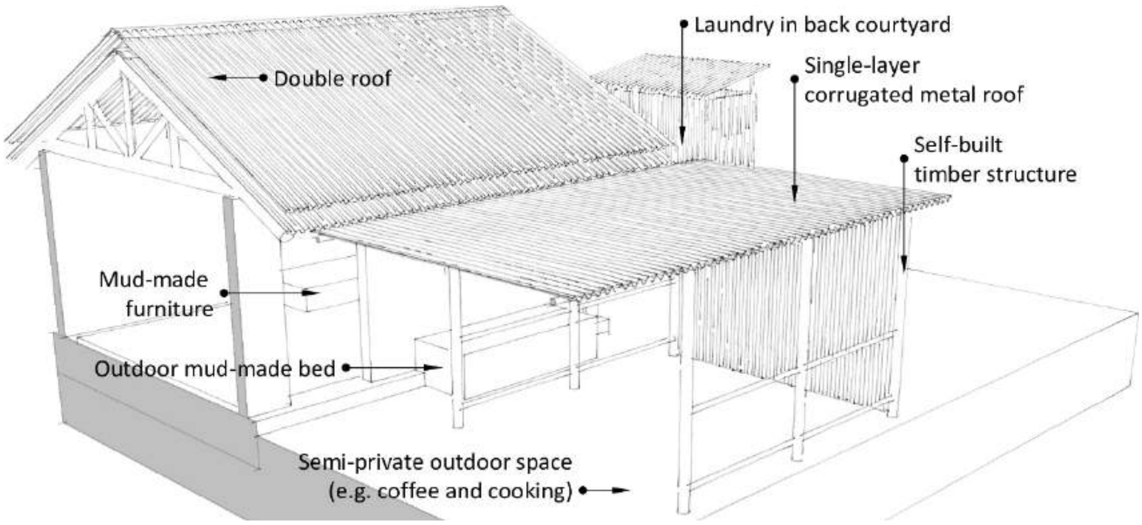
Prior to a formal thermal comfort study, a similar social survey to that performed in Azraq was conducted in Hitsats. Residents reported thermal comfort to be the highest concern when asked about their accommodation. Given that the comfort temperature is in general well within the mild external temperatures and that the shelter provides some thermal mass thanks to the bricks, this is speculated to be due to the single roof, lack of appropriate ventilation regimes due to single-sided ventilation, overcrowding of the shelter and heat gains due to cooking and related activities.



a) Climate overview – Nicol graph (data: Gelaro et al. (2017) and Schroedter-Homscheidt et al. (2017))



b) Shelter as designed



c) Shelter as used

Figure 2: Hitsats case study (Ethiopia, latitude 14°N)

4 Discussion

We have seen how cultural norms and practices play a fundamental role in how the affected populations adapt, modify and enhance their dwellings, not only in the case studies presented but also in the course of our fieldwork in other refugee camps and internally displaced people's settlements (Bangladesh, Nepal and Turkey). Whilst the importance of culture is nowadays generally acknowledged in the humanitarian sector's programming, it is an aspect that does not seem to inform current shelter solutions yet. Participatory approach tends to be applied to livelihoods and protection activities in refugee camps, rather than to shelter sector. We are calling for those efforts to be extended to shelter design, thereby reclaiming refugee agency as a fundamental aspect that should not be neglected in this process. The case studies presented here portray not only shortcomings that would have been overcome by an improved design methodology, but also how refugees do exercise decision-making to shape their environments, regardless of, and sometimes clearly at odds with the institutional constraints of encampment. This ability of humans to choose and to act autonomously is a prerequisite for dignity:

> *"To be an agent, in the fullest sense of which we are capable, one must (first) choose one's own path through life — that is, not be dominated or controlled by someone or something else (call it 'autonomy'). […] And having chosen, one must then be able to act; that is, one must have at least the minimum provisions of resources and capabilities that it takes (call all of this 'minimum provision') […] so others must not forcibly stop one from pursuing what one sees as a worthwhile life (call this 'liberty')." (Griffin 2008, p.33).*

Since refugees in camps are unable to enjoy full control over their lives, a combination of the top-down approach and bottom-up approach would be an initial step forward. This could combine the expertise of discipline-specific designers to establish the technical requirements and efficient use of resources of technical solutions with structured consultations carried out with refugees as soon as feasible. The preparation stage for transitional shelters should include a portfolio of culturally appropriate solutions in different contexts which could be developed with help of anthropologists. This would provide a basic framework to ignite conversations with refugees, not to impose those preconceived technocratic solutions on them.

Besides the discussions about the overall design of camps and the particular shelter solutions, we would like to draw the attention to how those two scales are articulated. As seen in these case studies, the immediate outdoor space to a shelter plays a fundamental role to support semi-private/public activities of special significance to camp dwellers. This suggests that shelter surroundings need to be explicitly accounted for in the planning of the camp as a space that can foster the agency of refugees. Although UNHCR does use the concept of 'plot' in their camp masterplans in some locations, what we recommend is to consider how the shelters can be expanded within such plots by refugees themselves.

It might be useful for all actors to think how the funds provided by donors at the onset of a crisis can be invested to establish camp infrastructure and agree with the refugees what the basic shelter provision needs to fulfil (e.g. private bedroom space, individual toilet facilities). Camp dwellers would then take over to maintain and extend their shelters into this space to further support the continuation of cultural practices of neighbourliness and forging a community the new location. Such a strategy would combine the technical requirements of institutional actors with the much-needed agency practice by camp dwellers.

5 Conclusions

This paper explores the idea of how agency not only humanizes the refugee experience but also how it can help tackling design challenges in complex situations of refugee crisis characterised by pressures faced by humanitarian agencies and demands articulated by host governments. We do not wish to neither normalize nor romanticize encampment in our attempt to reclaim refugees' agency towards improving current shelter practices. We acknowledge the precarity of life in a refugee camp, but we would like to draw attention to agency amidst the constraints that we observed in Zaatari and Azraq Syrian refugee camps in Jordan, as well as in Hitsats, Eritrean refugee camp in Ethiopia. We call for a dialogue between agencies and residents, in order to find a consensus between refugees' need for flexibility and the authorities' focus on manageability in the context of scarce resources and political constraints.

From the design perspective, it is crucial that designers support camp inhabitants in their efforts to improve the shelters through understanding of architectural settings in which social relations are conducted in a given culture with solutions that are not just technically and climatically relevant. An explicit acknowledgement of agency in the encampment situation would allow refugees to acquire a sense of control over their lives, while making an efficient use of limited resources available to those who govern refugee camps.

Acknowledgements

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The architecture of refugees

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Abstract: It is widely known that global warming could lead to a humanitarian crisis. In fact, the environmental and climatic conditions needed by people to survive are being increasingly disrupted. Europe is facing the worst displacement crisis since World War II, according to the United Nations High Commissioner for Refugees (UNHCR). There are more than 68 million refugees living in camps in harsh environments and extreme climates. Shelters provided are mostly inadequate due to several factors, such as space, privacy or culture. In addition, the thermal performance and the conditions inside shelters could cause health problems such as thermal stress or, in the worst case scenario, they could lead to death. This is an extremely important task, as we need a quick scalable housing solution that can create a space that meets comfort conditions in the face of a crisis of unknown duration. Thus, this research is focused on the assessment of thermal conditions in shelters from different climatic zones: Jordan, Afghanistan and South Sudan, and it also explores the possibility of achieving better results in a different country; following a previous study of the conditions in each country in order to fully understand their basic needs.

Keywords: Refugees, shelter, thermal stress, health risks, privacy and cultural safety

1. Introduction

Desertification and the consequent natural disasters threaten to change today's demographic map, according to a report by Christian Aid (Aid, 2018), which claims that one billion people will be displaced from their homes by 2050 as a result of climate change.

This problem began to get worse shortly after the end of World War II, and since 1970, it has resulted in millions of newly displaced people every year, according to UNHCR (UNHCR ACNUR, 2017). This annual report shows that multiple displacements characterized 2017, as the number of displaced people increased to 68.5 million, compared with 65.6 million in 2016, which means an average of 31 people being forced to flee their homes every minute, either across borders or within their own country.

These people, known as climate or environmental refugees, are facing a legal, political and social vacuum (Otto, 2017), as this term is not legally correct. International law does not recognize the climate or environmental refugee status and the definition of refugee does not include people displaced for environmental reasons.

According to the World Bank, unless action is taken, up to 86 million people could be displaced in Sub-Saharan Africa by 2050 due to climate change (EuropaPress, 2018).

More than half of those suffering this situation are children between 0 and 17, who account for 54% of people in refugee camps, according to available data from UNHCR (UNHRC ACNUR, 2017). It is important to bear in mind that 173 000 children fled unaccompanied by their parents or another family member who is of age.

The challenge posed by climate change, which causes those refugees to be displaced, makes it necessary to provide a proper response regarding shelters, at least as a temporary emergency solution.

The problem lies in the inappropriateness of shelters provided to those people. This is firstly due to factors such as space, habits or culture, since, as shown by Manfield's surveys (Manfield et al, 2004), the shelter is used, seen and valued differently depending on the ethnic and cultural background of its occupants. Secondly, this is due to the unsolved issue of the monitoring of thermal conditions, the lack of which usually poses health risks, such as thermal stress, exacerbation of diseases or, in the worst case scenario, death (UNHCR, 2017).

Thermal stress is the sensation of discomfort caused by staying in an environment in which body mechanisms must make an enormous effort to maintain its internal temperature. It is the lack of thermal comfort, according to IMF (IMF Business School, 2018).

Environmental (temperature, thermal radiation, relative humidity and ventilation), psychological and cultural, as well as individual conditions (metabolic consumption and clothing insulation) are essential for thermal comfort. If environmental conditions are extreme and individual conditions are not taken into account, we won't be able to counterbalance the heat or cold gained or lost and that's when a thermal stress situation arises.

These situations often occur in the shelters provided due to inadequate thermal conditions, as borne out by one of the baseline studies conducted by Fosas (Fosas et al, 2017), whose results show maximum indoor temperatures over 45°C. This research, located in the Azraq refugee camp (Jordan), managed to reduce internal overheating by 2.3% a year, thus easing thermal stress values.

In cold weather conditions, there have been up to 20 deaths in a single night, as UNHCR warned in 2017 (RTVE, Refugee crisis, 2017). This is due to poor shelters which are neither properly heated, nor prepared to be subject to extreme thermal changes. Rachel Battilana (Battilana, 2001) conducted a research on the design of a cold climate temporary shelter in Afghanistan. The test was performed under normal conditions (without the liner) and with the liner, and the logistical burden for the camp was reduced in the second case.

Taking all the aforementioned quantitative and qualitative factors into account, we are facing an urgent need to provide a temporary shelter solution that is able to offer safety, privacy and comfort. Therefore, this research is focused on evaluating thermal conditions in shelters from three climatic zones, as well as on developing an initial proposal for improvement based on the results obtained.

2. Methods

This research is focused on the assessment of thermal conditions in shelters in Jordan, Afghanistan and South Sudan, as well as on comparing the results obtained in their own countries with those that would be achieved if they were located in the weather conditions in the other two countries.

In order to conduct this research, we analyzed the following aspects:

2.1. Environmental conditions and basis for the analysis

The study was focused on three particular climatic zones: Jordan, Afghanistan and South Sudan (Figure 1). Therefore, a thorough analysis of the geographical and climate framework of each country, as well as their habits and culture and their refugee camps, was performed.

Figure 1. Location of climatic zones assessed.

Geographical and climate framework

Geographically, Jordan is characterized by its arid plateau on the east bank of the Jordan River and the Dead Sea. We focused on Amman, which is characterized by low rainfall, winds of up to 14.3 km/h, an extremely hot summer (with temperatures exceeding 32°C) and a mild winter (between 3°C and 11°C, although in extremely cold days, temperatures may drop below zero) (Weather Spark, 2018).

Afghanistan is a landlocked mountainous country with a relatively dry climate, which varies depending on the altitude and location (Worldmark Encyclopedia of Nations, 2017). In this case, we are in Sozma Qala, with very hot, dry summers (exceeding 34°C) and cold (sub-zero temperatures), dry and partly cloudy winters (Weather Spark, 2018). The most unpleasant features are dryness and dusty winds.

South Sudan is located in East Africa. This research was focused on Juba, where the wet season is very hot and oppressive. Over the course of the year, temperatures vary from 21°C to 39°C. Unlike the other two countries, South Sudan has a high rainfall, with an average precipitation of 142 mm (Weather Spark, 2018).

Habits and culture

Both Jordan and Afghanistan are countries where Islam, the official state religion, molds most customs and traditions, such as Ramadan or Eid al-Fitr. Muslims are divided in Sunni and Shia, and around 80% of Afghans are Sunni.

South Sudan is influenced by Christianity and, unlike the previous two countries, there is not a dress code. They wear lighter clothes in order to withstand high temperatures.

Refugee camps

We focused on the Azraq refugee camp (Jordan), the Gulan camp in Khost (Afghanistan) and the Ajuong Thok camp in Yida (South Sudan).

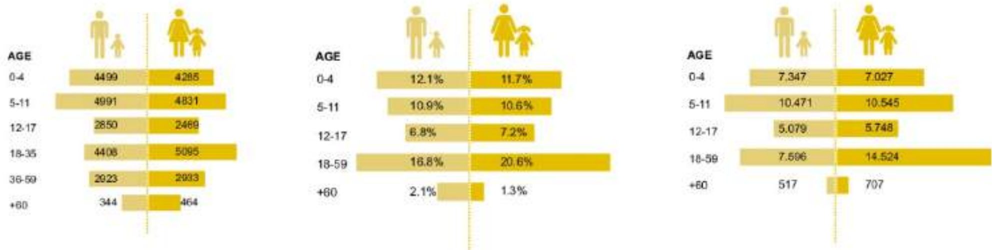
According to ACNUR FACT SHEET, the Azraq refugee camp is currently home to 36 699 refugees in four villages.

Meanwhile, 42391 of all refugees in Afghanistan are registered in Khost, according to the Operational Portal for refugees (Afghanistan, 2018). Most of these people come from the south, where the traditional strongholds of the Taliban insurgency are located.

Finally, the Ajuong Thok refugee camp currently hosts 40 502 people, according to the UNHCR South Sudan Fact Sheet (FACT SHEET SOUTH SUDAN, 2018). It is important to highlight that the majority of refugees in this camp are women, the majority of whom fled from human rights violations.

In most cases, these people leave their homes in search of a safer place, they come from urban settings and they are used to stable living conditions (according to verified statements).

Figure 2 shows the demography of the aforementioned camps.



Azraq (Jordan) **Gulan, Khost (Afghanistan)** **Ajuong Thok, Yida (South Sudan)**

Figure 2. Demography of refugee camps studied.

2.2. Case studies

First of all, it was necessary to know the type of shelters provided, by consulting the UNHCR Shelter Design Catalogue (UNHCR Shelter and Settlement Section, 2016).

This catalogue classifies shelters in four types: global shelters, emergency shelters, transitional shelters and durable shelters.

There are 4 types of global shelters, depending on their lifespan: from tents with a plastic sheeting to shelters having a self-supporting structure, wind resistance and snow loads.

Emergency shelters are classified in 5 types, according to their country. Local materials are often used.

Regarding transitional shelters, there are 3 different types, depending on their location as well. These structures have a longer lifespan and they try to maximize privacy and protect against severe weather conditions.

Finally, durable shelters in Pakistan and Iraq are brick constructions divided in up to two rooms and a living area.

The climatic zones on which this research is focused were selected because of their climate, as well as having the largest refugee camps. On this basis, the case studies are the Azraq T-Shelter, developed in Jordan and classified as a transitional shelter, as well as the Tent Shelter, developed in Afghanistan, and the Tukul Shelter, developed in South Sudan, both classified as emergency shelters.

Figure 3 and Table 1 and 2 show Location 01 that is developed in Jordan

Figure 3. Type 1 shelter

Table 1. Analysis conditions in type 1 shelter.

ANALYSIS CONDITIONS	
Number and gender of people	Family of 4 people (Man, Woman, 2 children)
Metabolic conditions Factor (Man=1.00, Woman=0.85, Children=0.75)	0.84
Clothing	Winter clothing (clo) 1.00 Summer clothing (clo) 1.00
Shelter size	24 m²
Density (people/m²)	0.166

Table 2. Features of type 1 shelter.

BUILDING ENVELOPE		Thickness
Wall	IBR sheeting Expanded Polyethylene IBR sheeting	0.35mm 1.5cm 0.35mm
Roof	IBR sheeting Expanded Polyethylene IBR sheeting	0.35mm 1.5cm 0.35mm
Door	Door cladded with flat corrugated iron sheeting and filled with Expanded Polyethylene insulation.	
Window	Steel window frame. 1m x 1m	
Infiltratio n	0.70 h^{-1}	

Figure 4 and Table 3 and 4 show Location 02 that is developed in Afghanistan

Figure 4. Type 2 shelter

Table 3. Analysis conditions in type 2 shelter.

ANALYSIS CONDITIONS	
Number and gender of people	Family of 4 people (Man, Woman, 2 children)
Metabolic conditions Factor (Man=1.00, Woman=0.85, Children=0.75)	0.84
Clothing	Winter clothing (clo) 1.50 Summer clothing (clo) 1.50
Shelter size	38.7 m²
Density (people/m²)	0.103

Table 4. Features of type 2 shelter.

BUILDING ENVELOPE		Thickness
Wall	UNHCR Tarpaulin	1cm
Roof	UNHCR Tarpaulin Bamboo structure	1cm Ø 5 cm
Rest zone	UNHCR tent covered by tarpaulin 1cm	
Floor	Tarpaulin 1cm	
Infiltration	0.70 h^{-1}	

Figure 5 and Table 5 and 6 show Location 03 that is developed in South Sudan.

Figure 5. Type 3 shelter

Table 5. Analysis conditions in type 3 shelter.

ANALYSIS CONDITIONS	
Number and gender of people	Family of 4 people (Man, Woman, 2 children)
Metabolic conditions Factor (Man=1.00, Woman=0.85, Children=0.75)	0.84
Clothing	Winter clothing (clo) 0.50 Summer clothing (clo) 0.50
Shelter size	21.6 m²
Density (people/m²)	0.214

Table 6. Features of type 3 shelter.

BUILDING ENVELOPE		Thickness
Wall	Adobe plastering technology Branches of local wooden poles Adobe plastering technology	2.5cm Ø 5 cm 2.cm
Roof	Covered by thatch Branches of local wooden poles	2.5cm Ø 5 cm
Door	Bamboo sticks	
Floor	Tarpaulin 1cm	
Infiltration	0.70 h-1	

3. Results and analysis

3.1. Quantitative results

Each case study was firstly assessed in its own climate and then it was tested in the climatic conditions of the other two countries, in order to determine if a better result could be achieved. Thus, nine analysis of the three case studies were conducted with the tool Design Builder.

In order to run the simulations, regardless of the climate data of each region, a series of specific characteristics and considerations were taken into account for each shelter, such as number of occupants, clothing, shelter size or building materials, as seen above.

Besides, all cases were focused on calculating three main parameters: internal and solar gain, comfort (relative humidity and operative temperature), and ventilation; bearing in mind that the results obtained correspond to the most extreme summer and winter weeks, respectively.

The average results obtained are shown below:

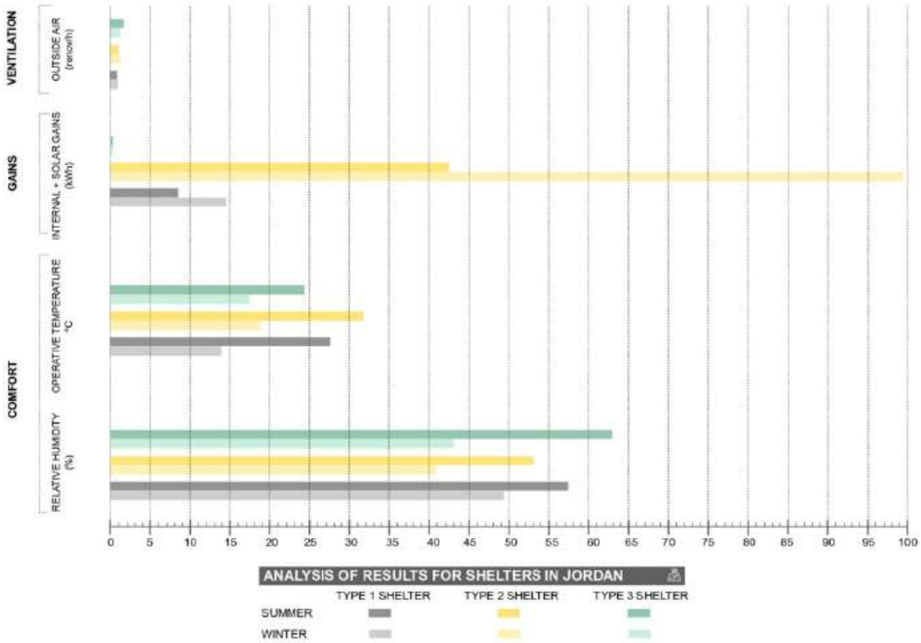


Figure 6. Results obtained from climate data of Jordan.

Figure 6 shows the results for the three shelters analyzed under the climatic parameters of Jordan.

As can be seen, the type 3 shelter achieved the best result regarding the operative temperature, with values ranging from nearly 20ºC in winter to 25ºC in summer, as opposed to type 1 and type 2 shelters, which reached higher values in summer.

However, the relative humidity in the type 3 shelter was high, reaching a value of 63% in summer. Besides, the solar gain was negligible, although it obtained an outside ventilation of up to 1.96 h^{-1}. As for the other two shelters, the type 2 shelter exhibited a solar gain of nearly 100kWh and the type 1 shelter ranged between lower, more constant values (10-15kWh).

Regarding the relative humidity, the type 2 shelter obtained an average value between 40% and 55%. Nevertheless, the ideal results were undoubtedly those achieved by the type 1 shelter: between 49% and 58%.

Ventilation was one of the most remarkable parameters. Even though it achieved very poor results in all cases, it remained more or less constant both in type 1 and type 2 shelters, with 0.70 and 0.72 h^{-1}, respectively.

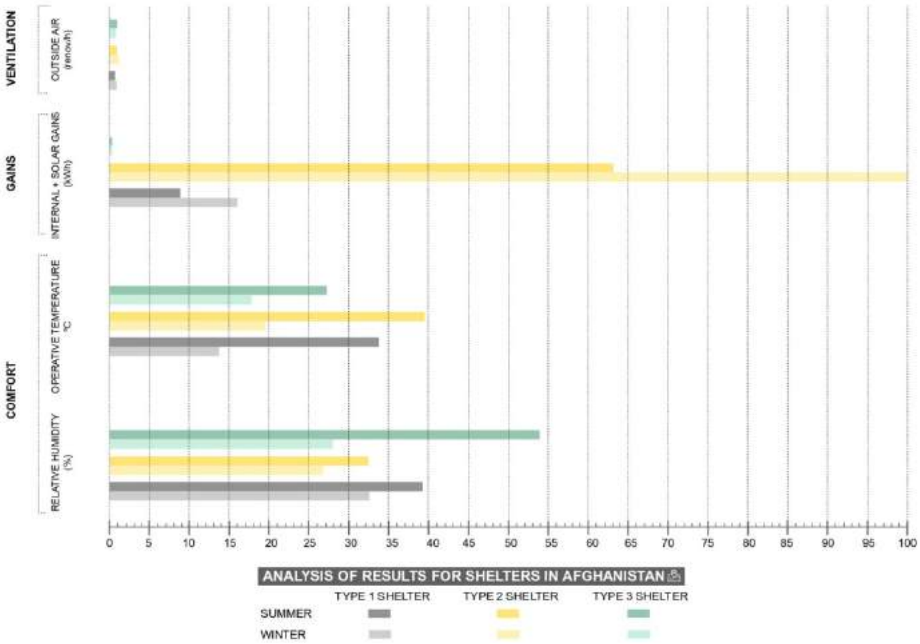


Figure 7. Results obtained from climate data of Afghanistan.

Figure 7 shows the results obtained for the shelters in Afghanistan, and it contains some points that are worth mentioning. The type 3 shelter continued to exhibit very interesting values regarding its operative temperature (18°C in winter and 27°C in summer), but its relative humidity decreased too much in winter, down to a 28%. Besides, its solar gain was insignificant.

There were a few similarities between type 1 and type 2 shelters regarding their relative humidity, as they showed values below 40%. Even though their operative temperatures in summer were very high, ranging from 30°C to 37°C, their results regarding ventilation and solar gain stood out once again, as they were similar to those obtained in the previous scenario.

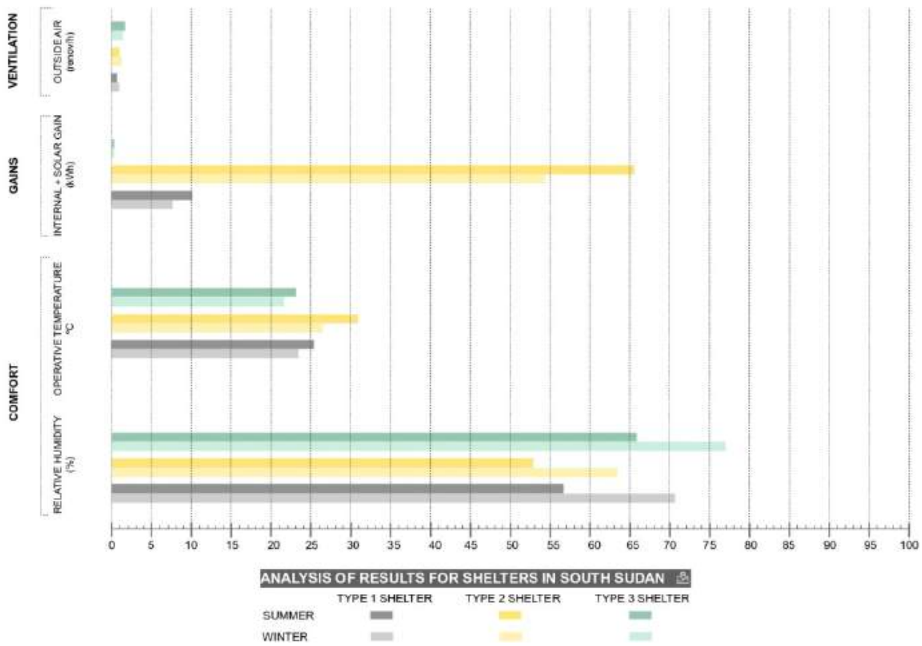


Figure 8. Results obtained from climate data of South Sudan.

Finally, figure 8 shows the results under the climate of South Sudan. It is noteworthy that in this case, the three shelters obtained higher values for relative humidity.

Operative temperatures were similar in the three cases, although the type 2 shelter obtained the higher values once again.

However, in this case, the type 3 shelter obtained outside ventilation values which were higher than those obtained by the other two shelters, ranging from 1-1.70 h^{-1}.

The situation regarding solar gain values remained the same: the type 2 shelter obtained high parameters, the type 1 shelter exhibited more constant values and the type 3 shelter showed negligible results.

In conclusion, the type 2 shelter obtained very high values regarding solar gain in every case, and its operative temperatures were the highest ones, especially in summer. Likewise, the type 3 shelter exhibited interesting values regarding comfort, but its solar gain was negligible. Meanwhile, the type 1 shelter showed the most constant and logical values in the three scenarios.

The results obtained were verified with Givoni's chart, which considers temperature, humidity and air in order to evaluate the thermal and comfort sensations. Regarding the climatic parameters of South Sudan in winter, the three shelters would fall within the comfort zone, according to this chart. The same is true for type 1 and type 3 shelters in summer, whereas the type 2 shelter would be outside that zone.

The results achieved with the climatic parameters of Jordan were similar to those mentioned above. In winter, the three shelters would be solved by internal gain heating. In summer, type 1 and type 2 shelters would be solved by natural and mechanical cooling, whereas the type 3 shelter would fall within the comfort zone.

Finally, the results obtained with the climatic parameters of Afghanistan showed the biggest differences. Type 2 and type 3 shelters would be solved in winter by internal gain heating, while the type 1 shelter would need passive solar heating. In summer, the type 1 shelter would be solved by natural and mechanical cooling, the type 2 shelter would need high thermal mass cooling with night ventilation and the type 3 shelter would fall within the comfort zone.

3.2. Qualitative results

A series of interviews conducted in parallel with this research were used in order to cross-check and merge the results obtained.

An overview of the most relevant aspects is shown in Figure 9:

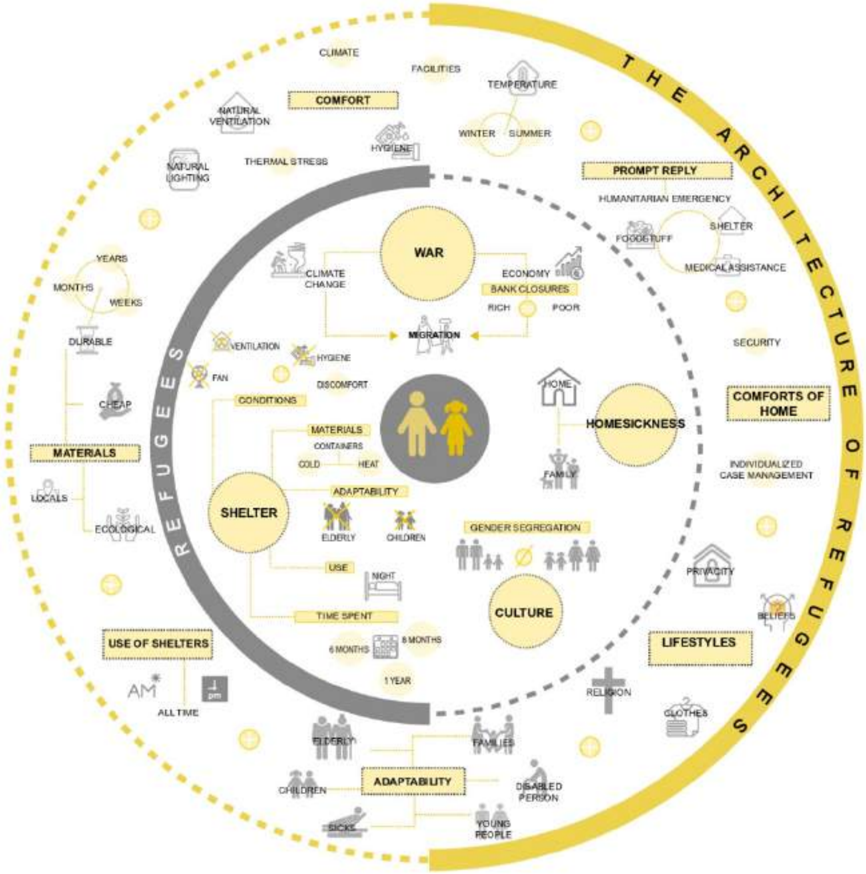


Figure 9. Overview of qualitative results.

Refugees stated that what they missed the most was their home, because they didn't feel as safe and comfortable as they did there, despite difficulties. Regarding their culture and the gender segregation inherent to their beliefs, they also noted that they needed a cultural privacy that they didn't have as refugees.

In relation to shelters provided, they claimed that the conditions regarding ventilation, hygiene or comfort were not appropriate. Likewise, shelters were not suitable for children or the elderly, and they could only stay indoors to sleep, due to the heat or cold (depending on the season) inside shelters.

Bearing all these aspects in mind, we drew a series of conclusions:

- Shelters must be prepared to be used at any time, which means that the materials used, in addition to meeting this factor, should be durable, cost-effective and locally available.
- They must meet comfort parameters, so they should be adapted to the climate, as well as being provided with natural ventilation and light, and a proper internal temperature in order to avoid any risk of thermal stress. All these factors have been corroborated by quantitative results.
- They must be suitable for all types of people, ages and families, taking their cultures, religions, habits and beliefs into account, thus providing an individualized case management.

4. Discussion and conclusions

Having analyzed all the results obtained, it was determined that the best-performing model in every climatic scenario was the type 1 shelter developed in Jordan.

It exhibited the most stable values, and all things considered, it provided the greatest comfort for its users, unlike the other two shelters.

Even though it is true that the type 3 shelter showed very constant values regarding its operative temperature (between 20ºC and 30ºC) in the three scenarios and its ventilation stood out above the other two shelters, its relative humidity exceeded 60% on several occasions.

Ventilation values for the type 2 shelter were very similar to those obtained by the type 1 shelter. In every summer scenario, it reached operative temperatures over 30ºC, which was the main reason to rule out this option, in addition to its pretty high values regarding solar gain.

Several initial improvement factors could be added in order to achieve the best scenario or the best shelter model. In this case, we would choose the type 1 shelter and change certain features:

Firstly, as discussed in the qualitative results and proven in the quantitative results, ventilation is a limited factor. In every simulation, the values exhibited were quite low, making it difficult to live inside the shelter. Regarding the type 1 shelter, it obtained 0.70 h^{-1}.

In order to improve this aspect, solar gain should be taken into account from the beginning, because if openings were increased to achieve an improved ventilation, the impact of solar radiation would rise, thus increasing solar gain and temperature.

Therefore, we should find a middle ground regarding the dimensioning of openings, in order to achieve a proper ventilation without an excessive solar gain.

Secondly, given that the shelter has an insulating layer, this could be changed and adapted to each climatic scenario, thus improving the thermal inertia and making it possible to improve the shelter in the Jordan and Afghanistan scenarios, reaching similar temperature values to those obtained by the type 3 shelter.

Thirdly, we should consider ventilation control systems which can be controlled and handled by the user, thus developing adaptive strategies.

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Siting considerations for a shelter in the extreme cold of Antarctica

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Abstract: Shelters in extremely cold regions are highly influenced by their site locations and significant improvements in their thermal performance can be achieved by simply orienting them to optimise the potential solar heat gains available and minimising the impacts of cold, strong winds around the structure. This paper presents of numerical simulations of insolation and wind exposure on a remote site in Collis Bay, King George Island in Antarctica where a 'polar Lodge' was erected and tested in February 2019. The results of the study clearly demonstrated the complexity of issues involved in optimally positioning a structure in extreme conditions and its entrance to take maximum advantage of the energetic landscapes and minimising its potential to fail for a range of weather related reasons. The paper shows that in this particular location, with predominant winds from the south east and high latitude, a windbreak could double as heat storage during the summer.

Keywords: Insulation, Antarctica, Wind, Extreme Climate, Tent.

1. Introduction

The production of a shelter in a remote location is a challenge in any climate due to difficulties in transportation and assemblage and nowhere more so than in extreme climates. In such circumstances advantage must be taken from every and all opportunities to ensure the best performance of the structure. Firstly, the function of shelter from the elements is of paramount importance, and the provision of protection from the wind, rain, snow and sun as well as the less visible effect of the thermodynamics of the impacts of these climatic features on the topography and vegetation of the location.

This paper describes work carried out in preparation to erect a second iteration of an earlier shelter used in a field experiment that raised an adapted Mongolian yurt at a site in Collins Bay, King George Island, Antarctica undertaken in January 2016 by an international team, working on the Polar Lodge project (Cantuária et al., 2016 and 2017). Due to extremely high winds, gusting up to 200km/h this first structure (Polar Lodge 1 – PL1) collapsed. The challenge for the 2019 team was to not only ensure that the new structure (PL2) can withstand such extreme events but also to optimise its performance through the use of innovative materials and assemblage and simulation to minimise the impact of the wind on the structure and optimise the potential solar gains available at its latitude of 62 degrees south.

The tent is an expansion of an existing small research outpost, a nautical mile away from the main Chilean Escudero research station and it will be used by researchers from that facility in future as a field work base for both sleeping and working. This factor influenced the need to design a tent in which one could walk and stand, not one in which researchers simply sleep (Guedes et al. a), 2019). Thus, a key requirement of the structure is that people can remain thermally safe both during the night and day during the November to March research season at the station, which roughly corresponds to the Antarctic Summer (Guedes et al. b), 2019). This paper outlines the choices that influenced the exact siting of the tent and its orientation to both the sun and the wind in that particular micro-location in an asymmetric rock canyon between a slightly raised headland and the steeper rock walls to the inland side of the site.

Figure 1. Birds eye view (drone photo) of the Polar Lodge on site at Collins bay at the bottom at the Bellingshausen Glacier. PL2 is the dome-like black tent behind the existing permanent orange shelter.

2. Choice of site location

The Polar Lodge project was instigated under the auspices of the Portuguese ProPolar programme that provides logistic support for scientific work carried out in the Arctic and Antarctica and has responded to a request from INACH, the Chilean Antarctic Institute to provide a temporary remote live / work facility in Collins Bay. The 2019 Polar Lodge team (PL2) had identified two possible sites in Collins Bay and on the 17th of February visited the site to weigh up the respective merits of each location.

At 9:05am the PL2 team were taken on a Zodiac to visit the Collin's Bay sites. The review of the potential sites was completed with a walk around and the taking of photos of the two alternative sites. The original location of PL1 was on a raised levelled site below an upper stretch of moss bog between a raised headland and the landside hill. It is situated next to the Orange Pod, an existing, orange, horseshoe section, permanent living pod used as temporary accommodation by researchers. It is a steel ribbed structure infilled with 10 cm extruded polyurethane insulation and a plastic tarpaulin exterior coating and internal plywood finishes.

Figure 2. View of the Red Pod showing the metal frame sunk on legs into concrete foundations more than a meter deep.

Figure 3. View of the Red Pod showing the metal frame sunk on legs into concrete foundations more than a meter deep.

The need for additional workspace / storage for the pod is evidenced by the small, open A Frame tent found to the east of the Orange Pod on the PL1 site. This is one of the two being reviewed for the 2019 siting. The second site considered was on a level section of the upper beach beneath the cliff to the south of the beach. This site beneath the bluff had been completely covered with snow in the summer 2016. It was free from snow this year.

Figure 4. View form the raised beach site.

A range of Considerations were taken into account when deciding on the best location for PL2 and these are outlined in Table 1.

Table 1. Comparison of the two possible Collin's Harbour Sites

ISSUE	S1 – ORIGINAL	S2 – UPPER BEACH TERRACE
Levelling	Site levelled already in 2016	Requires levelling – c.3 hours work
Solar Access	Good	Good
Wind	Exposed between headland bluff and inland hill in a small valley. Wind around it also complicated by the Red pod located next to it. Exposed to northerlies and southerlies – would need wind scaping. The 2016 tent collapsed during extreme winds that were claimed by the boat pilot to have been exceptional	Very sheltered from the southern winds – exposed to the north easterlies incoming from across the bay and beach
Snow	Free from snow in 2016 as exposed windy site does not encourage drifting. Moss bog	In 2016 all the beach was covered in snow almost down to the sea. 2018 / 9 has had much more rain than snow
Rain	Site slightly raised and dryish	Site slightly raised and dryish
Waves/ storms	At a safe height to escape most winter storms	The boat pilot said that even the upper beach terrace can be hit by extreme waves
Usefulness	The proximity of the Red Pod and the A Frame evidence that researchers there need more space means that PL2 is likely to be well used, and convenient to use	This may be useful but not as convenient as a tent on the site adjacent to the Red Pod. As this site is a snowbound one it will be available for less of the year for
Research Value	The higher wind at SI that felled PL1 in 2016 will mean that the extreme structure of PL2 will be tested to its limits – and thus	The tent pitched on this site may provide new research opportunities to see how the tent performs in snow drift conditions that may actually enhance the

	benefit its value in the architecture of extreme climates	thermal properties of the structure if the tent can be accessed. It also may not.
Security	The proximity of the Red pod means it will be regularly visited over a year that will enhance its security	Less secure than S1
Maintenance	Its proximity to the Red Pod mean it can be regularly visited and checked upon. The extent to which it is maintained will be a function of its usefulness to the Chilean Base	The more remote location means it will be less easy to check upon and also it being probably less useful than the originally sited tent means it will be less useful, less valued and hence less well maintained
Public Relations Value	Attractive 360^{0} site views good for PR shots. Proximity to the Red Pod makes it more attractive to the Chilean Base researchers, thus better maintained and more likely it is to survive well and be a research success, thus great for ProPolar	Less so that the original site as it can be photographed from one side only, facing the cliff

3.Optimising for solar gain

According to the modelling, the cumulative monthly insolation varies from a highest of 4,490kWh for the month of December to the minimum of 152kWh in June. The summer months from November to March are the months when the lodge gets the highest amount of sun from the north. Due to the high latitude, the period of daylight is long with the sun up at azimuth 150° and set at 210°. As a consequence, notice on Figure 5 (December) there is a considerable amount of heat gain on the windbreak even though this is located on the southern side of the tent.

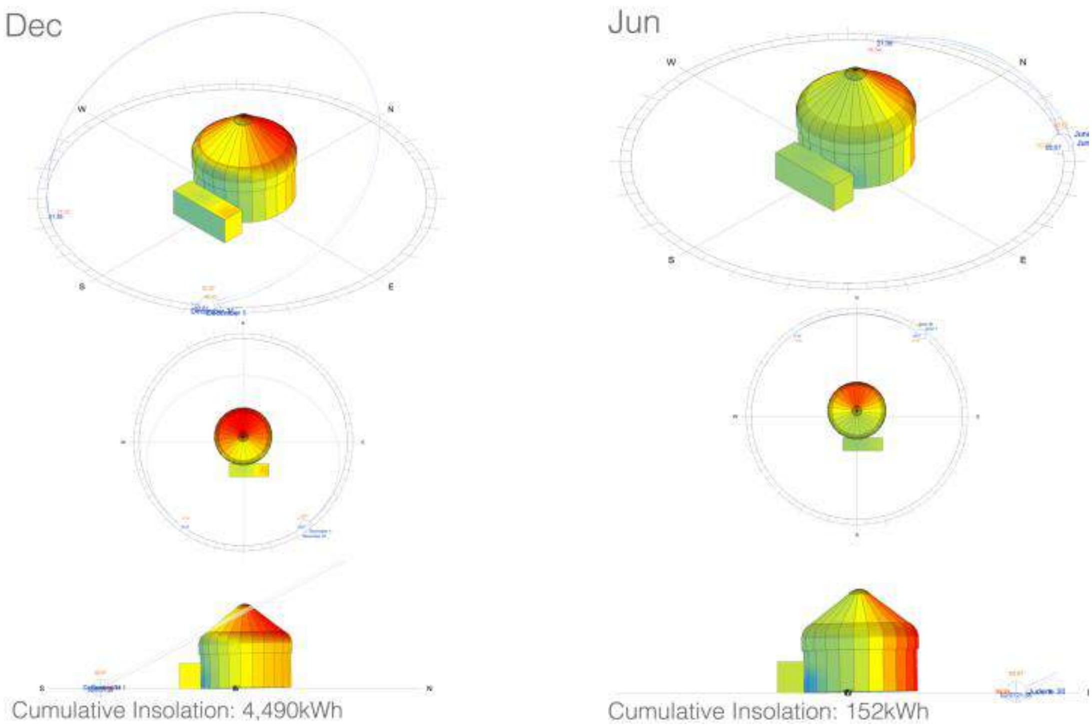


Figure 5. Cumulative monthly solar insolation for December and June.

4. Optimising for wind

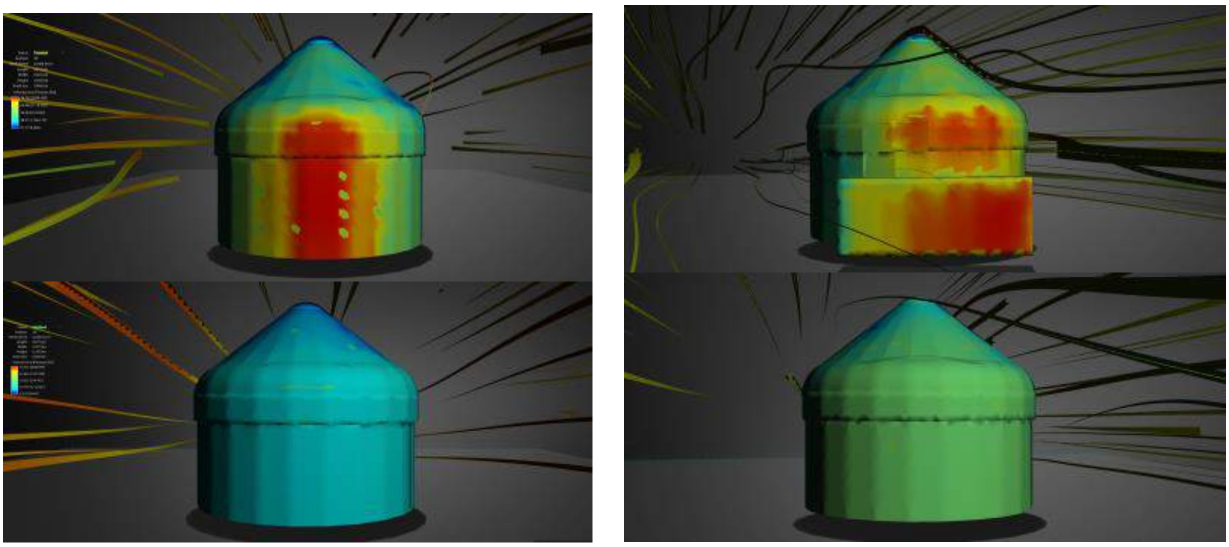
4.1 Reducing the structural impact of the wind

4.1.1 Wind characteristics of the area

The wind rose at adjacent airfield shows a maximum windspeed 138km/h SE wind which is also the most frequent direction (synoptic measurements every 3 hours since 1970). However, more recent non-synoptic data has measured wind gusts up to 220Km\h. During an extreme weather event two months after the erection of PL1, it was reported that informal measurements around the site reached wind speeds of up to 200km/h. This exceptional gust level has been assumed as a proxy to the wind channelling around the PL1 site.

4.1.2 Reducing the wind Impact on the tent

Modelled simulations of wind up to 62 meters per second (mps) (approx. 220 Km/h), causes lateral pressure forces, both positive (windward), and negative (leeward), on the tangents of the tent of up to +1814.134Pa and -2734.888Pa, respectively, as illustrated on Figure 6.



(a (b

Figure 4. Wind simulation of lateral pressure forces on the tent at wind speeds of 220 km/h, also note on (top) windbreak not only decreases positive pressure (windward) on the tent but also decreases (leeward) negative pressure on the tent (bottom). Modelled in Autodesk Flow Design Build: 103.2014.04.29.

5. Impact with a windbreak

The wind simulations revealed that a considerable amount of pressure on the structure would be transferred to the windbreak located on the SSE side (Windward). This windbreak is made of local stones piled up in large bags that are part of the tent set.

5.1 Minimising snow deposition around the entrance

According to experts in Antarctic tent setups, the local snowfall is high (commonly up to four meters), that the deposit of snow around the entrance must be avoided. Therefore, the traditional approach of orienting the tent entrance towards the leeward side, which is used around the world is not an option here, as the venturi effect allow for snow deposits on the leeward side of the tent. Such setup could render the entrance blocked during a blizzard and the occupants locked in. The solution often used, therefore, is to have the entrance face the windward side of the tent, as the high wind speeds make it harder for large snow deposits to accumulate there. However, this solution creates other problems, such as wind blowing inside the tent and, in critical situations, blowing it off.

Using modelling, and since we could not create a full shelter for the door (planned for version PL3), we created a partial windbreak for the tent on the windward side and located the entrance in an area of tangent high wind. This also influenced the positioning of the windbreak at SSE, rather than SE which is the predominant wind direction. The extra angle offers the vertical edge of the windbreak to the wind, further reducing its forces on the tent and windbreak, reducing air turbulence, and further sheltering the entrance at SSW. The SSE angle is responsible for the slight vertical asymmetry of pressure distribution as seen in Figure 6b) top.

5.2 Limitations of the wind modelling

Detailed topographic modelling of the landforms around the site have not been undertaken but are planned for the PL3 season. Due to the wind channelling between hills and buildings, the maximum wind speeds at the micro-scale are expected to exceed the windspeed at the macroscale as measured at the airfield of reference. A preliminary partial modelling effort considering solely the two shelters revealed a windspeed increase in the channel between them of 10mps from 62 to 72mps.

6. Discussion: Balancing benefits for sun and wind

Undoubtfully, wind resistance is the crucial challenge which dictates the position of the windbreak Windward at (SSE). The high latitude, which causes long days of sunlight during the season in which the lodge is mostly used, implies that the sun rises at azimuth 150° and sets at 210°, allowing for some direct sunlight to reach the windbreak. This affords the storage of heat during the day that shall be released during the colder nights, potentially contributing to the thermal comfort of the tent.

7. Conclusions

In extreme climates because each unit of extra beneficial energy that can be harvested, or damage avoided, simply by correctly siting a structure can be critical to the success or failure of the shelter and, in extremis, the risks and costs can be catastrophic (Roaf et al., 2019). The ultimate measure of the success of such a structure lies not necessarily in the comfort of the occupants, but in the degree of the physical and thermal protection that is provided to the occupants by the shelter.

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Thermal Performance of a Movable Modular Shelter for Extreme Cold Conditions: A Study in Collins Bay, Antarctica.

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Abstract: This paper summarizes the results of a pilot study on the performance of a movable modular shelter in extreme cold conditions. The shelter was designed by a mixed team of Architects and Engineers and will be used by researchers carrying out field work in the Antarctic Peninsula. Preliminary results confirm its viability, ease of use, and satisfactory thermal comfort performance. Considerations are made on contextual factors, such as comfort expectations, local climate characteristics, and design construction issues.

Keywords: Thermal Comfort, Extreme Cold Climates, Bioclimatic Design, Modular Shelter.

Introduction

The Design of the shelter was developed throughout 2018 by the Polar Lodge project team - a mixed team of Architects and Engineers from the Higher Technical Institute (University of Lisbon), Heriot-Watt University (UK) and the University of Bahrain (Kingdom of Bahrain).

Figure 1. The Polar Lodge shelter, February 2019, Collins Bay, Antarctica.

The objective of the Polar Lodge Project was to design and build a sustainable, low-impact, optimized, modular lodge, to facilitate scientific studies in the Antarctic. This lodge presents a new environmental and sustainable approach to creating resilient structures for the extreme cold, combining ancient tent design with leading edge modern technologies and materials. The major drivers for the design include that the structure should be: modular; easy to transport and fast to assemble by a small team; resistant to high winds; have minimum impact on the ecosystem; and be comfortable.

An innovative yurt-like tent was produced by July 2018, using an innovative bio-composite structure and experimental lightweight envelope and structure, designed to withstand extreme high winds, and extreme heat and cold.

This new Module follows on from a 2016 experimental prototype that collapsed in 200km/h winds in the Antarctic (Guedes, 2016): its structure, form, and building materials were overall upgraded, under the supervision of Prof. Sue Roaf (Heriot-Watt University), in order to respond to the severe conditions found in Antarctica.

1. Local Climate

Antarctica is the coldest continent on Earth, with minimal recorded temperatures ranging from −93.2 °C to −98 °C (Vizcarra, 2018). The continent has an EF Köppen classification of ice-cap climate, with very cold, and generally extremely dry weather (it is technically a desert, averaging 166 mm of precipitation per year). Temperatures in inland Antarctica rarely rise to 0°C even in summer.

With exception of a few seaside areas, snow rarely melts, and, after being compressed, forms the glaciers. The continent is rarely penetrated by weather fronts, due to the effect of of the katabatic winds. Cold air sweeps down from the central plateau toward the ocean, particularly in spring and autumn.

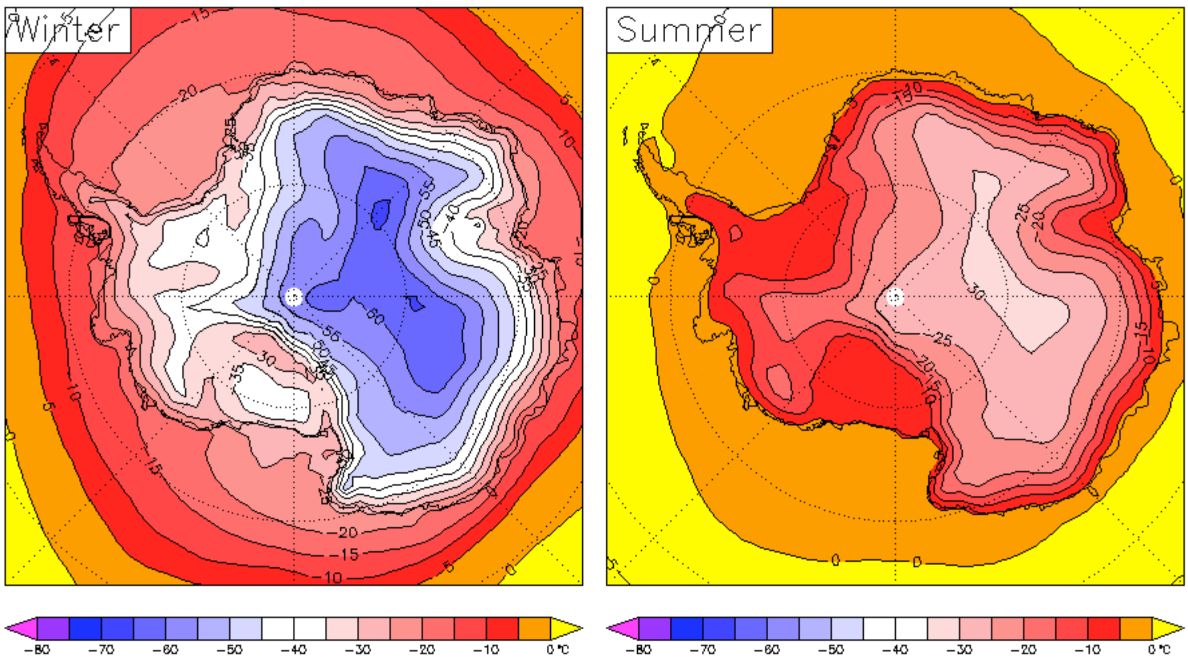

Figure 2. Surface Temperature charts for Winter and Summer (source: European Centre for Medium-Range Weather Forecasts, 2018)

Antarctica also holds the record of the strongest winds: winds can easily reach gale force, between 100 and 200 km/h, and in places where the wind flows through narrow valleys, it can attain a speed of 90 m/s (325 km/h). There are on average 11.6 days per month when the wind exceeds 100 km/h (Bromwich, 1989).

2. Thermal Comfort Expectations

Most of the research projects carried out in Antarctica involve a significant degree of fieldwork. Scientists are primarily lodged in existing station' buildings, or in research ships, and from there they proceed to take samples and measurements in the field – sometimes requiring several days of camping in remote locations outside the stations, in severe weather conditions.

A brief survey was carried out by Guedes et al. in January 2016 in the Antarctic peninsula, in both station buildings and camping sites, in order to assess the performance of station buildings and tents, and the users' expectations. Eight stations were monitored, and two camping sites, involving 43 respondents.

Overall, conditions in the base buildings or research ships are quite similar to what can be found in a standard home in Chile, i.e. inside temperature is controlled, varying between 18ºC and 26ºC. Common areas (laboratories, living rooms, study rooms) tend to be tightly controlled, whereas in sleeping rooms some differences were noted, resulting from individual preferences, i.e. some occupants opened the windows for a while to reduce perceived overheating[1].

Figure 3. Working room at the Chilean Escudero station (left), dining room at the Spanish' Gabriel de Castilla station (right)

Figure 4. Typical tents for field work' research in the Antarctic peninsula.

The feedback obtained from field campers was revealing: the large majority, even newcomers to Antarctica, perceived life in the camping site as being normal and acceptable for that predetermined period of time: the harshest hours were at night, when

[1] This "energy inefficient" behaviour was generally not frowned upon by the stations' managers – we guessed that the importance of individual adaptive control and wellbeing was a priority over energy efficiency…

temperatures get very cold – but one would be protected with sleeping bags (with an insulating capability withstanding -40ºC), and by the tent. However, the large majority stated that they would welcome an “upgrade” in terms of internal comfort (thermal and ergonomic), especially if the field work would take several days, and, most of all, their main fear and concern was the strong wind: every year campers have to be rescued as tents fly (sometimes several kilometres) when a sudden storm occurs (as experienced by the authors in 2016, when tens of campers had to be rescued from their sites by the Chilean Navy after a sudden storm with wind gusts over 200km/h).

In summary, the lesson taken from past experience is that besides the obvious need for resistance to gale-strong winds, the new Lodge design should improve internal comfort as much as possible (the sense of security and feeling of “homely”, and thermal insulation and stability) – in tune with the field researchers’ expectations.

3. Design Considerations

The focus of the new Lodge design was the structural optimization for resisting strong winds - which will be referred in other papers (Guedes et al. 2019; Pinelo Silva et al 2019; Roaf et al 2019) – and the improvement of comfort performance. For the latter purpose, a survey was carried out in the UK in early 2018 by Prof. Sue Roaf, in order to identify the best suitable envelope materials, in terms of durability, weather endurance, and thermal insulation capabilities.

The final decision felt upon two innovative materials for the skins: 1) a space blanket type multi-layer double skin from ORVEC of Hull, and 2) re-used Dyneema racing yacht sails for the outer coat from *Northsails* in Palma de Mallorca, Spain.

The optimised timber structure was made by *Yurtmaker* in Telford, and the tent cloths were manufactured by the master tent makers at *Sheerspeed* in Honiton. Insulated flooring was made of re-cycled plastic bottles by *Weaver Green* in Salcombe.

Figure 5. Transport of the (whole) Lodge in a Zodiac, heading from Escudero to Collins bay.

The portability and ease of assembly’ objectives were accomplished: The whole Lodge fitted in a single Zodiac boat, and was transported from Escudero to a remote location in Collins Bay, within Collins glacier. It was then mounted in approximately 2 hours.

Figure 6. Left: First two layers of ORVEC put over the structure. Right: the external (third) layer of DYNEEMA.

4. Results: Discussion and Further Work

Five HOBO data loggers were placed inside the Lodge during one week, to measure Air Temperature (ºC), Relative Humidity (RH%) and Lighting levels (Lux). Instantaneous measurements were also carried out, obtaining Globe Temperature, Air Temperature, and Relative Humidity.

FLIR and SEEK thermal cameras were also used to register the performance of the Lodge, particularly during night time – when temperature drops significantly. An Anemometer was also used for wind speed measurements.

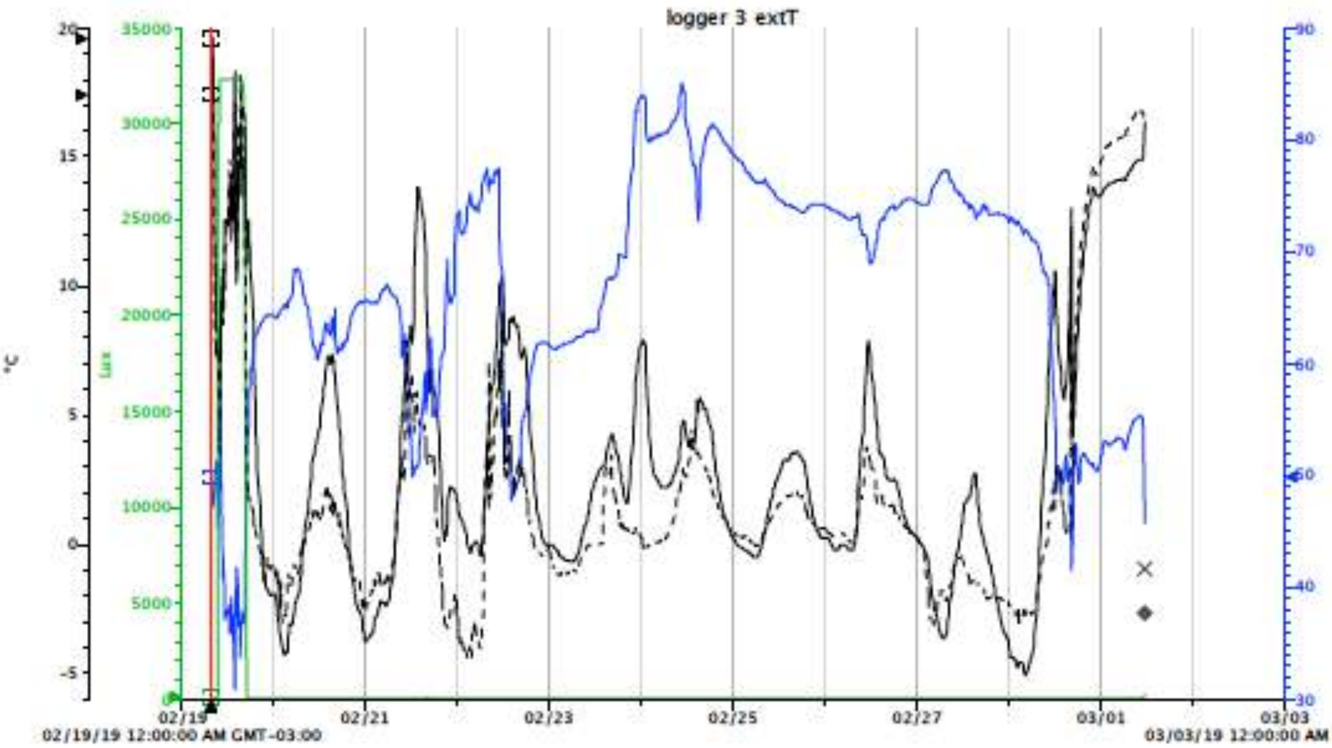

Figure 7. Monitoring of the lodge with a HOBO data logger: Internal Temperature (black line), External Temperature (black dashed line), and Relative Humidity (blue line).

The results showed that, when unoccupied, during the daytime the internal temperature was generally about 5ºC above external temperature: the black surface of the

Lodge starts absorbing solar radiation in the morning, and the heat remains trapped inside until night time.

The lodge was occupied by two people on the night of the 22nd and on the night of the 24th. On the night of the 22nd no heat sources were used: the body heat was enough to keep the internal temperature of the Lodge up to 5ºC higher that the external temperature. On the night of the 24th a small gas heater was used during three hours (9pm to 00am), and the temperature of the lodge remain well above external temperature throughout the night. The two occupants reported to have had a very comfortable night sleep in both the 22nd and the 24th.

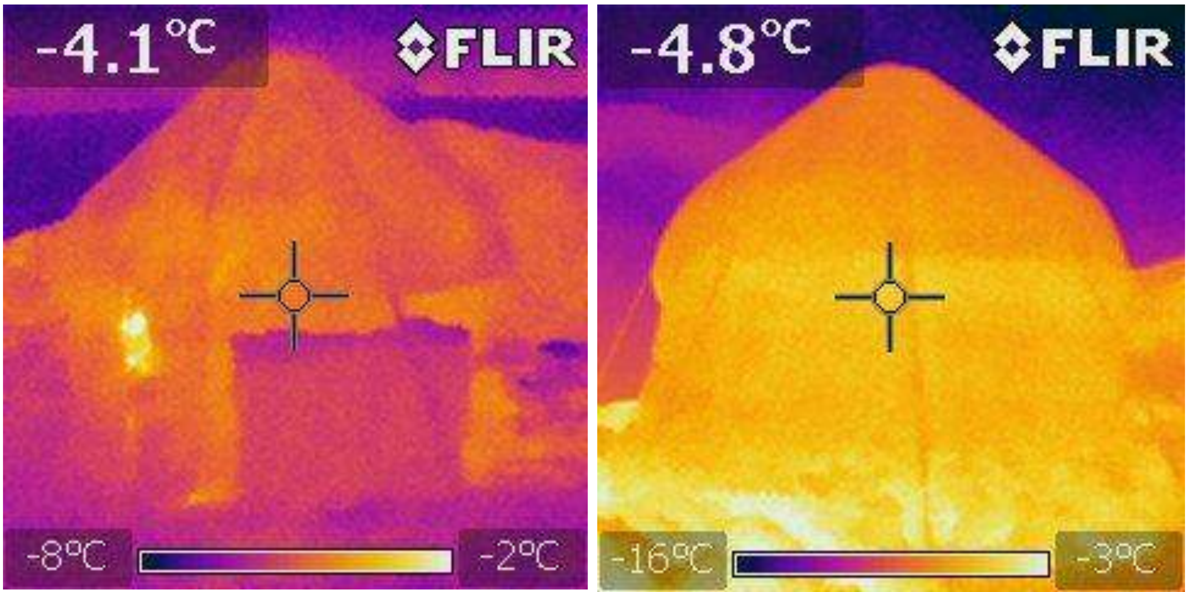

Figure 8. FLIR thermal photographs of the Lodge at night, viewed from outside on the 24th, showing no thermal bridges, and a very good insulating behaviour. Only a small spot revealed heat getting out: the door we had to open to come outside to get the shots (left picture).

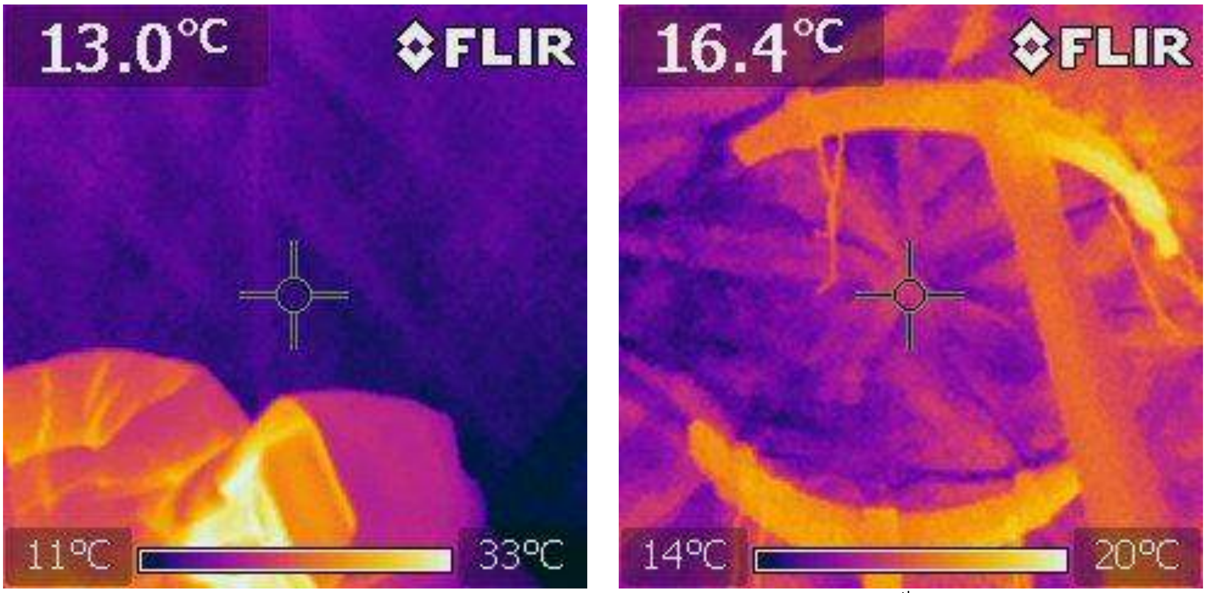

Figure 9. FLIR thermal photographs of the Lodge at night, on its interior, on the 24th. The internal temperature recorded by the FLIR cameras was 12ºC at body level on average – quite higher than the temperature recorded by the HOBO data logger, as the latter was placed at ground level.

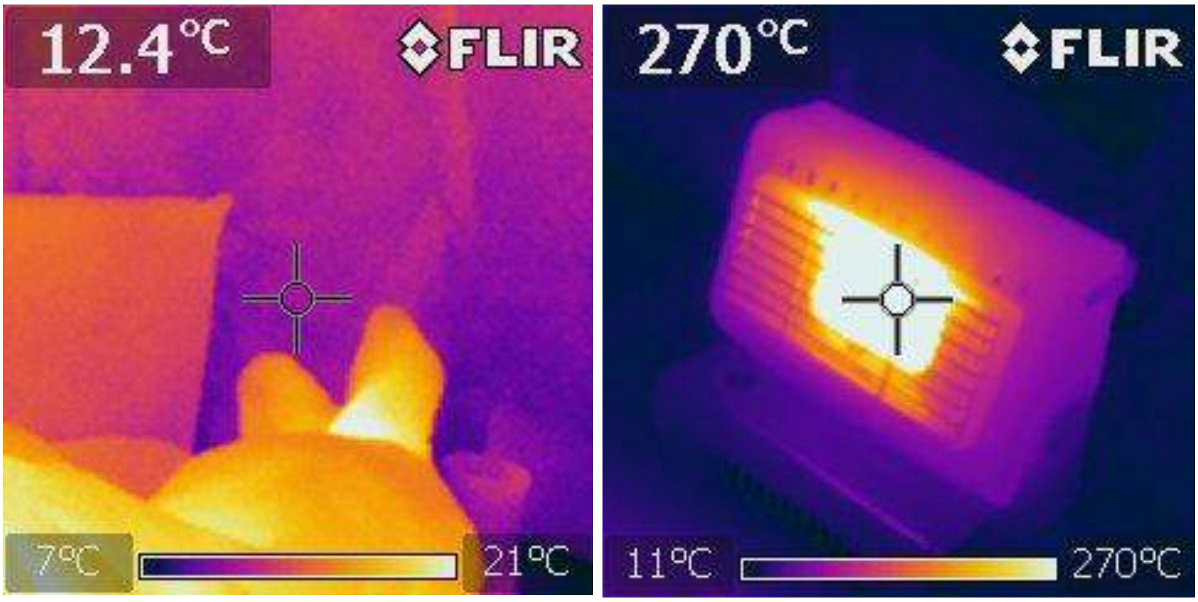

Figure 10. FLIR thermal photographs of the Lodge at night, on its interior, on the 24th. On the right the small gas heater used on the 24th, on the left a shot at body level, showing a very acceptable temperature of 12.4ºC, which remained stable throughout the night, even after the gas heater was shut at midnight.

In terms of RH%, it increased to values reaching 90% during the sleepover nights – but neither of the occupants felt any excessive humidity, which could perhaps be explained by the nature of the internal envelope materials.

A CO_2 monitor from Gas Sensing in Cumbernauld and a Carbon Monoxide monitor from Honeywell UK were also used, and limit values were surpassed on the night of the 24th due to the gas heater. A Flue will be implemented next year to avoid these situations.

Due to cost considerations and the short time available to manufacture the Lodge, it was decided that the present prototype would not have the zenital window, typical of the Yurt – as its implementation would considerably increase costs and manufacture time, and reduce the resilience of the envelope at its most stressed location. Its insertion on the Lodge is foreseen for the coming Antarctic campaign of 2019/2020. Solar lighting graciously was provided by Velux, and truly compensated this shortcoming.

The lodge will be used until the end of Summer (late March) and again from November 2019 till March 2020. Feedback from users, including questionnaires, will be collected during these periods, and posted online (at extremelodge.com). This will allow a more thorough assessment of the Lodge, leading to its optimisation.

Further issues concerning the performance of the materials, structure and overall comfort will also be assessed in the next campaign.

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Adaptive behaviours of elderly for cooling in Tropics: Field studies in naturally-ventilated aged care homes

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Abstract: Ageing population is a key global challenge in next several decades and majority of this demographic shift is confined in Asia. Thus a burgeoning demand on care homes for elders is evident and continues to grow. Elderly are more susceptible to the impacts of the extreme temperatures due to decreasing trend in the ability to regulate body temperatures. Thus the elders perceive overheated environments as thermally comfortable when it poses threats to their health. This study experimentally investigated the adaptive behaviours of elders for cooling in naturally ventilated aged care homes in Tropical city of Colombo, Sri-Lanka. Onsite field studies are consist of simultaneous personal monitoring and questionnaire surveys. Results explicitly prove overheated indoor environments. Mean thermal sensation of 0.99 with a mean thermal preference of -0.63 informs the need of cooler interiors. Mean neutrality temperature of elders is 30.2°C. Discrepancy between simple regression analyses in estimating the neutral temperature establishes the presence of behavioural adaptations. The most prominent adaptive behaviours of elders to satisfy cooler sensations are changing the place by going outside and modification of indoor thermal environment by switching on fans. Moving towards open areas such as courtyards and verandas plays an important role in thermal adaptation. Clothing adjustments and bathing are less preferred thermal adaptation strategies of elders in summer. Thus these findings highlight the importance of integrating semi outdoor spaces in the designs of aged care homes to promote heat resilience of elders in tropical climates.

Keywords: elders home, tropics, adaptive behaviours, cooling, overheated interiors

1. Introduction

Population ageing is a key global challenge for future development of the world. At present 8.5% of the world's population is over 65 years and two third (67%) of world's older persons are in developing countries. People living in low and middle income countries are ageing much faster rate than richer countries over the next 30 years and 65% of this demographic shift is confined in Asia (UN, DESA, 2017).

Ageing is a natural process that generally includes the change in physical and cognitive abilities (Van Hoof et. al., 2006:2010; Blatties, 2012). Elders are particularly susceptible to the impacts of temperature extremes as ageing tends to decline their ability to regulate body temperatures. Hence, overloading on cardiovascular and respiratory systems instigate heat related morbidity and mortality (USEPA, 2016; Kovats and Hajat, 2008; Havenith, 2001).

Tropical and subtropical countries are evident for adverse warming effects due to an increase in the highest temperatures from 1-3°C by 2020 and by 2080 from 3-5°C (IPCC, 2007). This increasing amplitude of temperature variability is mostly confined to developing countries and the vulnerabilities to weather and climate shocks of people living in economically deprived countries will increase in future (Bathiany et al, 2018).

Thus Climate change and population ageing are synchronized global issues increasing dramatically over next several decades which will enforce a future societal challenge on human health and well-being of developing countries in tropical Asia (UNFCC, 2017).

1.1. Indoor thermal environment and health impacts

Older people spend above 90% of their time inside homes mostly moving between bedrooms and living rooms (Almeida et al, 2014; Brooks et al, 1991; EPA, 2019). Thus the indoor thermal environments are likely to better represent heat exposure of elders and challenging their comfort, health and overall sense of well-being.

As the thermal perception and the physiological responses change with age it is evident that an older person may perceive an environment to be thermally comfortable when in fact it may pose threats to their health (Bills et al, 2015). Moreover their capacity to take personal actions to protect themselves against temperature extremes is reducing with ageing. Thus the mild temperature drifts can cause significant physiological responses (Schellen et al, 2010) and it is paramount important to protect elders from even mild thermal changes.

Behavioural thermoregulation is the most influential means of reducing heat exposure and customary control for heat illnesses. Risk of heat illnesses are synergistically increases by combination of several personal risk factors such as low physical fitness, lack of acclimation, morphological factors of body, age, disease status, fatigue and medication (Goldman, 2001). Extreme heat has led to increases in hospital admissions and mortality of the elderly and cause renal and cardiovascular problems (Nitschke et al, 2011; Hansen et al, 2008).

1.2. An overview of ageing population in Sri Lanka and aged care homes

Sri Lanka's ageing population is expected to increase dramatically over the next 30 years. Those 60 years of age or over currently account for 9.8% of the population. This figure is expected to rise to 24.8% by 2040 which represents the 3rd highest percentage of elderly citizens in an Asian Country. At present nearly 2.6 million people (approx. 12.5% of the population) are above 60 years of age and by 2041, one in every four Sri Lankan is expected to be elderly.

Although there are national policies and programs in place for older persons, Sri Lanka needs to better prepare for the need and challenges of an increasing ageing population by ensuring, enabling and supportive environments.

Ageing is associated with physical inability and caring of elderly parents has been the cultural attributes of the Sri Lankan tradition. However, due to present shifts in socioeconomic development due to urbanization, transformations from extended to nuclear families, falling family size, women in workforce and migration limit the capacity of families for elderly care and the former models are unlikely to be sustainable. Thus there is a burgeoning demand on care homes for elders at present and this trend will continue to grow.

Research on thermal perceptions of elders and accurate thermal comfort ranges in tropics are yet to be established. Limited interest is evident for research focuses on indoor thermal environments of elderly care homes in developing countries experiencing extreme hot climates (Yen et.al, 2009). Studies conducted in climate chambers inform the behavioural and individual differences change the preferred indoor thermal environments for elders (Tsuzuki et al, 2002; Enomoto-Koshimizu et al, 1997).

Available few studies of Portugese, Chinese, Korean, Taiwanese and Thai elders living in care centers informs a diversity in indoor thermal environments and thermal comfort ranges. Korean elders prefer cooling season which is warm and slightly hot, without air-conditioning (Yang et al, 2016). Elders in Portugal prefer adaptive measures such as decreasing clothes and natural ventilating of rooms (Guo et al, 2016).

Thus emphasize the significance of onsite field investigations in which the older adults are given personal control options over their thermal environment (Van Hoof et al, 2006).

Moreover prioritize the necessity of more research on thermal preferences of older adults with physiological and social cultural differences in varying climates.

Field studies on thermal comfort in tropics are less represented and no studies are available for thermal comfort research on varying age groups of Srilankans. Within the context of demographic shift in present and future, research focusing on local elderly population are paramount important. Thus the study explores aged care homes of Sri Lanka with a focus on appraisal of tropical living environments of elders to understand their thermal comfort needs and behavioural reactions in adjusting to harsh indoor environments.

2. Method of Study

The onsite field investigation of this study is consists of simultaneous measurements of indoor environmental parameters and a questionnaire survey to appraise thermal sensation and adaptive behaviours of elders permanently residing in 7 randomly selected aged care homes. A pilot walk through survey was performed to familiarise with the location and daily routine activities of elders and subsequently the experimental schedule was confirmed.

Field study was conducted over 20 days in the hot summer month of August 2018 and the subjective survey was performed during two time slots from 11am to 12pm and 2 to 3.30pm. These time periods represent relaxing and communal activities of the elders before and after the lunch time from noon to 1:00 pm. Each participant was personally handled by two data collectors for recording of objective measurements and administering of the questionnaire.

Figure 1. Indoor environments of investigated elders' homes

2.1. Study location and sample of naturally ventilated aged care homes

The field survey was performed in Colombo district (6°55'N and 79°50'E), the capital city of Sri Lanka, which has the highest percentage of elderly population of the country (DSC, 2012). Köppen Geiger climate classification signifies Colombo as type 'Af' an equatorial fully humid climate with hot and rainy seasons. Annual monthly mean and maximum air temperature and relative humidity varies within the range of 26.2-28.8°C and 29.2-31.4°C and 78.3-83.6% and 90.2-97.9% respectively. Climate of Colombo is predominately uncomfortable and consistent throughout the year with the hottest period ranging from August to March (Rajapaksha, 2017). There are 64 authorised aged care homes (ACHs) in Colombo district and the selected building sample of this study is consists of state owned aged care homes. These buildings are predominantly naturally ventilated and the indoor environments are shown in Figure 1.

2.2. Participants

A total of 155 healthy individuals were randomly selected to participate in the survey. People aged 65 and above was considered as elders in previous research (Yang et al, 2016; Jiao et al, 2017; Wang et al, 2018; Tartarini et al, 2017; Bae et al, 2017). The national policy on protection and promotion of rights of older persons define the age 60 and above as Senior citizens of Sri Lanka (NPCS, 2006).

Thus the participating elders of this study are aged 60 and above (up to 80 years). Fitness of the participants were evaluated according to the 4-points frailty scale (Rockwood et al, 2005) shown in Table 1. The qualified participants of this study represent points 1-3 of this scale which categorize as a sample of elders with a good status of physiology and psychology.

Table 1. The frailty scales of elders

No.	Frailty Scale	Measures
1	Very fit	Robust, active, energetic, well-motivated and fit
2	Well	Without active disease, but less fit than people in category 1
3	Well with treated disease	Disease symptoms are well controlled with those in category 4
4	Apparently vulnerable	Although not frankly dependent, have disease symptoms

Table 2. Specifications of Instruments, accuracy and comparison with standards

Parameter	Instrumentation	Accuracy	ISO7726 & ASHRAE 55,
Ta	HOBO UX-100 Temp/RH sensors & data logger	± 0.3°C	Minimum ±0.5°C; ideal ±0.2°C
RH		±3.5%	± 5%
Tg	Blackglobe L, thermometer, CR 1000x data logger	±0.21°C	Minimum ±2°C; Ideal ±0.2°C
v	VelociCalc 9545A, Hot-wire Anemometer	±0.015m/s	± 0.05m/s

2.3 Field measurements and questionnaire

The measured physical parameters of this study include indoor air temperature (T_a), relative humidity (RH), black-globe temperature (T_g) and air velocity (v). Specifications and accuracy of instruments are given in Table 2. With reference to the ANSI/ASHRAE 55-2013 and ISO-7730 standards for seated subjects, thermal parameters were measured and recorded at a height of 0.6m from the ground within a range of 1m in the vicinity of the subject. These criteria ensure a realistic representation of the thermal environment directly encountered by the subject. Measurement intervals of all physical parameters are 10 seconds.

Standardized equation given in ISO 7726 was used in calculation of the mean radiant temperature and operative temperature (ISO, 2001).The measured indoor air temperature (T_a), calculated mean radiant temperature ($\overline{T}_r$) and air speed (v) were used in calculation of the operative temperature (T_{op}) based on the standardized equation as follows;

$$T_{op} = \frac{Ta\sqrt{10\text{v} + \overline{T}_r}}{1 + \sqrt{10}\text{v}} \quad (1)$$

A significant strong relationship of air temperature and operative temperature with $p<0.001$ and a correlation coefficient (R^2) of 0.904 proves the precision of equation 1.

The questionnaire of the survey is composed of three sections. Section 1, 2 and 3 is consists of questions related to anthropometric details and basic information, thermal subjective sensation votes and adaptive behaviours on thermal comfort respectively. Summary of the data collected in each section is listed in Table 3. Participating elders were seated inside for 15mins prior to the commencement of the interview survey and the interviewers completed the paper based questionnaire composed of native language.

Table 3. Summarized questionnaire of the survey

Section 1	Section 2			Section 3
Basic information	Thermal sensation	Preference	Acceptability	Behavioural adaptations
Gender, Age	Cold (-3)	Cooler (-1)	Acceptable (1)	Mechanical cooling (use of fans)
Weight , Height	Cool (-2)	No change (0)	Unacceptable (0)	Going outside
Residing years	Slightly cool (-1)	Warmer (1)		Changing clothes
Clothing	Neutral (0)			Closing or opening windows
Activity	Slightly warm (1)			Bathing, drinking water
Furniture used	Warm (2)			Washing hands and face
Preferred place	Hot (3)			Going to indoor open spaces

3. Results and Discussion

The results are presented in four main parts such as personal information, indoor thermal environments, subjective thermal responses and adaptive behaviours. Data were analysed based on the statistical analysis of SPSS version 21 (version 21; IBM SPSS). The statistical analysis methods used to analyse the significance and correlation are one way analysis of variance (ANOVA) and Spearman's rank coefficient at a significant level of 0.05.

3.1. Anthropometric Profile of participants

Table 4 shows the anthropometric profile of the participating elders in the age group of 60 to 80 years (mean = 71). The study sample of 155 elders is consists of 98 females and 57 males permanently residing in the respective aged care home for 2 years or more.

Average time these people had lived in Colombo was 52 years and signifies that the participants are acclimatized to the climatic conditions. The number of female respondents was greater than males because of the lower number of males in aged-care homes.

This trend is consistent with the previous studies conducted in elderly care centers of Asian countries such as China, Korea and Thailand (Bae et al, 2017; Jiao et al, 2017; Wang et al, 2018; Sumavalee et al, 2016). Average age of an elderly Srilankan male and female is 71.5 and 70 years old with a height of 160 and 149cm and weight of 55.8 and 52.3kg respectively. The surface area of human body was estimated by equation (2) (Yu et al, 2003).

$$SA = 0.015925\ (H_t\ W_t\ )^{0.5} \quad (2)$$

Where SA is body surface area in (m^2), H_t is height in (cm) and W_t is weight in (kg). Mean SA values are 1.51 & 1.4 for males and females respectively. Mean physiological data of Srilankan elders are lower than the Chinese, Korean and Thai elders.

Table 4. Summary of the anthropometric profile of elders participating in this study

Gender	Age (Years)	Height (m)	Weight (Kg)	Body Surface (m2)
Male	60-80 (71.5±6)*	1.42-1.75(1.6±0.07)	38-82 (55.8±9.7)	1.2-1.9 (1.51±0.16)
Female	60-80 (70±6)	1.04-1.65(1.49±0.12)	27-85 (52.3±10.5)	0.9-1.9 (1.4±0.18)

* Number in the parentheses indicates the mean value ± s.d.

3.1.1. Metabolic rate and clothing insulation

During the field investigation interviewers recorded the commonly worn tropical clothing ensembles of the elders. Casual indoor clothing ensembles of elderly females are long frocks, blouse and a long skirt or Lungi. Male clothing is primarily a sarong with a short sleeve cotton shirt or t-shirt. Majority of the elders were in barefoot and few were wearing rubber slippers. Figure 2 shows the tropical clothing ensembles of elders and their everyday typical behaviours during a hot summer daytime.

(a) Female: Blouse and Lungi (b) Male: Sarong and T-shirt (c) Female: Long frock and Barefoot

Figure 2. Everyday tropical clothing ensembles of elders

Accepted clo estimation methods of ISO 9920-2004, ASHRAE standards 55-2004 and 2013 was used in formulating the value of clothing insulation (I_{clo}) for typical clothing ensembles (McCullough, et al, 1983; McCullough, et al, 1985; Olesen, 1985; Olesen et al, 1988). In addition the effect of foot wear and the material of furniture were added to the clothing insulation. During the survey all respondents were seated on a chair or on the bed. The minimum, maximum and average thermal insulation of tropical attires of elders are 0.18clo, 0.58clo, 0.39clo with a standard deviation of 0.08.

Mean clo-value of male and female elders are 0.41clo and 0.38clo respectively. These clo-values are higher than summer clo values of Thai elders but lower than Chinese and Taiwan elders (Sumavalee et al, 2016; Jiao et al, 2017; Hwang et al, 2010). ASHRAE standard 55-2013 specifies the mean clothing insulation of 0.5clo as the summer standard and the average of 0.39clo of the Srilankan elders' indicates a lower value of clothing insulation.

Metabolic rate is the energy produced by human body which varies with activity level and declines with the age. The resting metabolic rate (RMR) lessens with the age due to decrease in lean body mass and increase in body fat (Piers et al, 1998). Interview survey of the questionnaire was administered while the elders were seated on a chair or bed. More than 90% of elders were reclining and doing activities while seated. Thus the most metabolisms were 1.0, which indicates 'seated, quiet' or 'seated, reading or writing'. In comparison with the previous studies on elders 1.0 met was considered as the metabolic rate (Yang et al, 2016. Jiao et al, 2017). This metabolic rate and the individual I_{clo} value computed for each participating elder were used in the calculation of PMV. Difference between characteristics of male and female were not analyzed in this study.

3.2. Indoor Thermal environments

Figure 3 represents the distribution of indoor air temperature and relative humidity in seven investigated aged care homes. A box plot in these graphs indicates the range of indoor air temperature and relative humidity experienced by the participants in respective aged care home. As shown in figure 2a and b, air temperature and relative humidity vary in the range of 29.1°C to 35.9°C and 57 to 78% demonstrating a mean temperature and relative humidity variation of 31.7 to 33°C and 62 to 74% among all indoor spaces of ACHs respectively.

The polynomial trend lines of the mean Ta and RH with R^2 of 0.8 confirms a consistency between thermal environments and proves all participants are exposed to comparable indoor thermal environments in the investigated free-running ACHs.

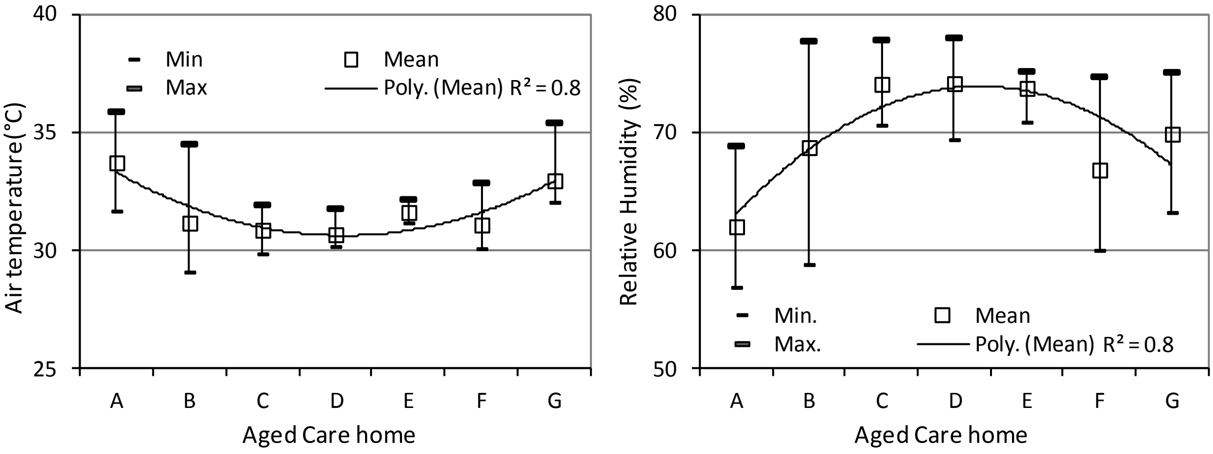


Figure 3. Personally exposed indoor thermal environments (a) Indoor Air Temperature (b) Relative Humidity

Distribution of indoor operative temperature and wind velocities among all investigated aged care homes are shown in Figure 4. The operative temperature ranges from 29 to 37°C (mean 32.2°C). Although 97% of operative temperatures are between 30 to 35°C, majority are concentrated in the range of 31 to 33°C. Interior spaces of these naturally ventilated aged care homes are evident for low wind velocities as 50% of frequency is in the range of 0.05 to 0.2m/s. The mean wind velocity was 0.29m/s. With low wind velocities, operative temperature became further increased and all these factors proved that the indoor environments were not exposed for adequate natural ventilation.

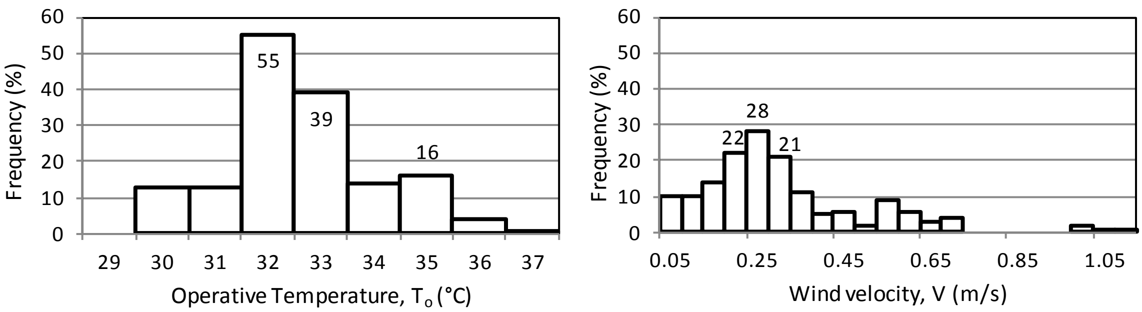


Figure 4. Distribution of indoor operative temperature (To) and Wind velocities (V) in all aged care homes

ASHRAE 55-2013 standard on thermal comfort recommends an indoor air temperature range of 19 -28°C and 80% of upper humidity level. People living in higher ambient temperature tend to feel more comfortable in higher temperatures. Thus the comfort temperatures of any given location correlate with mean outdoor temperature (Nicol, 2004). Mean ambient air temperature for the month of August is 28.1, and as given in equation 3 the comfort temperature is 27.9°C.

$$\mathrm{Tc} = 0.534\mathrm{Ta} + 12.9 \qquad (3)$$

Numerous thermal comfort studies conducted in tropical climates showed that the comfort temperatures of subjects in naturally ventilated buildings are higher than the air-conditioned buildings (Karyono et al, 2015). Thus the established thermal comfort ranges of the studies performed in free-running buildings in tropical climates of Singapore (de Dear et al, 1991), Malaysia (Djamila et al, 2013), Thailand (Busch et al, 1992) and Indonesia (Feriadi et al, 2004) are 28.2-28.8°C, 27-32.6°C, 25.6-31.5°C and 29.2-29.9°C respectively. Due to the limitations in accurate thermal comfort ranges of the elderly in tropics this study consider the morbidity and mortality threshold temperature identified for elderly in subtropical climates of Thai and Taiwan which is 30°C and 31°C respectively. Thus threshold temperature of discomfort adopted in this study is 31°C. Moreover this value is in agreement with the thermoneutral zone for elderly which is approximately 30-32°C (Kingma et al, 2012). Mean indoor temperatures at ACHs in Sri Lanka are overheated and 2.8°C higher than a similar study performed in elderly care centers of China (Wang et al, 2018).

3.3. Subjective thermal responses

Mean thermal sensation of the elders was 0.99 which represents a sensation of slightly warmer than neutral and their mean thermal preference was -0.63, which represents the need of cooler indoor environment than no change. Differences between genders were not considered in the analysis as the number of males is less compared to females.

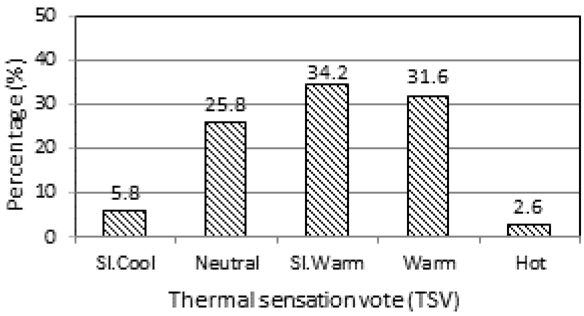


Figure 5: Percentage of elderly thermal sensation vote

Table 5: Cross tabulation of TSV, TA and TP

TSV	T_{op} (°C)	TA		TP		
		0	1	-1	0	1
-1	31.8	4	9	0	9	71
0	31.9	2	69	1	85	0
1	32.1	42	20	49	4	14
2	32.5	48	2	47	2	0
3	32.4	4	0	3	0	14
Total		100	100	100	100	100

TSV: Thermal Sensation Vote; TA: Thermal acceptance
TP: Thermal preference; T_{op}: Operative temperature

3.3.1. Thermal Sensation Votes (TSV)

Figure 5 shows the distribution of thermal sensation in a scale of five votes from slightly cool (-1) to hot (3) sensations. Slightly warm was the most common response with 34.2% followed by neutral and warm responses with 25.8% and 31.6% respectively. Among all votes neutral, slightly warm and warm accounts for 91.8% responses from elderly during the interviews performed in their commonly used indoor spaces. Generally people voting three categories of thermal sensation (-1, 0, 1) are considered as comfortable and only 66% of the votes were within the comfort range of TSV (-1, 0, 1). With 34% of warm and hot thermal sensation votes confirms the elders are living in thermally unacceptable indoor environments.

3.3.2. Thermal preference (TP) and Thermal acceptance (TA)

Relationship between Thermal Sensation vote, acceptance and preference is shown in Figure 6. The majority (64.5%) of the elderly reported unacceptable indoor thermal environments and prefer cooler (65.8%) conditions. Spearman rank correlation of $p<0.001$ signifies a strong significant relationship of TSV with TA and TP. TSV showed the highest correlation with thermal preference with a correlation coefficient of 0.769 ($p=0.000$).

Nearly equal number of elders voted for neutral sensation (TSV=0) have accepted thermal environment and preferred no change. Percentage distribution of thermal preferences of prefer warmer (-1), no change (0) and prefer cooler (-1) are 4.5%, 29.7% and 65.8% respectively. Substantially negligible percentage (3.2%) of elders with slightly cool thermal sensation preferred a warmer environment.

Cross tabulation of TSV with TA and TP is illustrated in Table 5. The value T_{op} represents the corresponding average operative temperatures of thermal sensation votes of -1, 0, 1, 2 and 3. According to Table 5, an increase in T_{op} from 31.95 to 32.65 is evident for slightly cool (-1) to warm (2) thermal sensations. Similar proportion of (96%) elders are evident for the vote 0 (unacceptable) for TA within the thermal comfort range of 0≤TSV≤3 and vote of -1 (prefer cooler) for comfort range of 1≤TSV≤2. Many field studies have suggested people in hot climates might prefer a sensation slightly cooler than neutral (Humphrey et al, 2007; Damiati et al, 2016; Rijal et al, 2010).

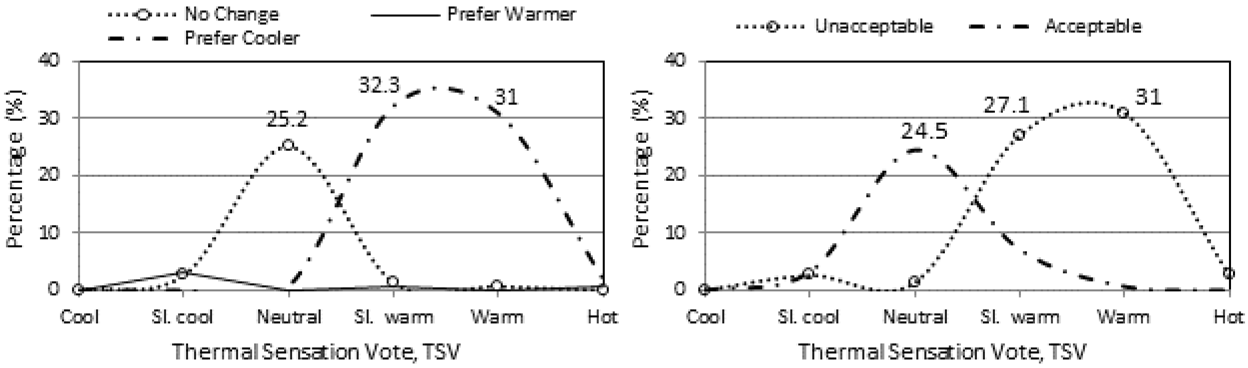


Figure 6. Relationship between TSV, TP and TA

The results are in agreement with the previous studies and explicitly proves majority of the elders prefer slightly cooler indoor environments. Present living environments of ACHs are characterized as “overheated”.

3.4. Thermal sensation votes compared to PMV and operative temperature (T_{op})

The predicted mean vote (PMV) of each participating elder was calculated using the web based tool developed according to ASHRAE standard 55-2017 (CBE,2017). PMV was calculated using measured indoor thermal environments and personal parameters such as air temperature, RH, MRT, air velocity, clothing insulation and metabolism (EN15251, 2007).

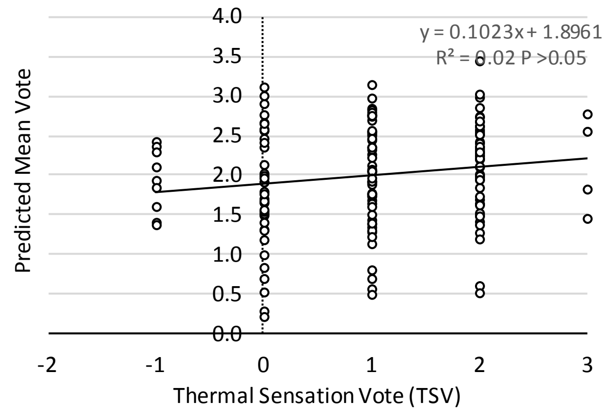


Figure 7. Relationship between TSV, TP and TA

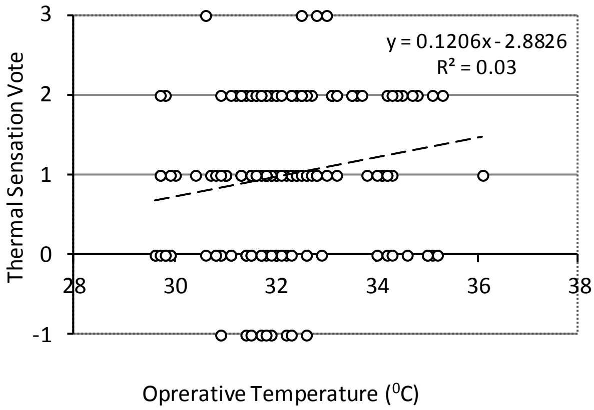


Figure 8. Relationship between TSV and T_{op}

Figure 7 shows a comparison of TSV and PMV. The PMV was 1.99±0.64, which is higher than the mean TSV of 0.99. Relationship between TSV and PMV is not significant ($p>0.05$; $p=0.065$). A lower slope is evident due to higher PMV with slightly warm to hot thermal sensations and shows that PMV overestimated TSV and agrees with the studies for naturally ventilated buildings in hot climates (Dhaka et al, 2015; de Dear et al, 2001; Yao et al, 2009). Inaccurate assumption on PMV sensitivity to air velocity, metabolism and clothing insulation will lead to greater misunderstandings. Results further confirm the limitations of PMV validity range for application in tropical climates (Humphrey & Nicol, 1998) and also influences in differences of metabolism and physiological responses between younger adults and elderly (Schellen et al, 2010).

3.5. Neutral temperature

3.5.1. Linear regression method

Scatter diagram of T_{op} and TSV with the established linear regression equations are shown in Figure 8. Linear regression represents a significant relationship between TSV and T_{op} ($p<0.001$). The slope of equation (4) is 0.12°C^{-1} indicates that for every 8.3°C change in operative temperature would have a unit change in TSV. Thus the neutral temperature (TSV, 0) is 23.9°C and the comfort band is from 15.6 to 32.2°C (TSV of -1 to 1).

$$\mathrm{TSV} = 0.1206\mathrm{x} - 2.8826 \quad (4)$$

Similar studies conducted for Thai, Pakistani, Indians and Chinese subjects are evident for a lower slope of 0.32° C^{-1}, 0.19° C^{-1}, 0.15° C^{-1} and 0.25° C^{-1} respectively (Karyono, 2000; Nicol & Roaf, 1996; Kumar et al, 2016; Zhang et al, 2010). The lower slope of equation (3) informs higher adaptation of elders to indoor thermal environments. As shown in Figure 8, the measured operative temperature ranges from 29.7 to 35.9°C and the estimated neutral temperature of linear regression method is artificially low. Thus informs the unreliability of simple regression analysis in field surveys as the presence of behavioural adaptations artificially lower the regression coefficient and estimates a low neutral temperature (Humphrey & Nicol, 2007; Rijal et al, 2010). Hence, the results prove the elders are adjusting their cooling needs in overheated interiors through various behaviours and the Griffith method was used to determine the neutral temperature (Indraganti, 2010).

3.5.2. Griffiths' method

Griffiths' method calculates the neutral temperature (T_n) for each participant elder from the operative temperature (T_{op}) and regression coefficient (α) as shown in equation (5).

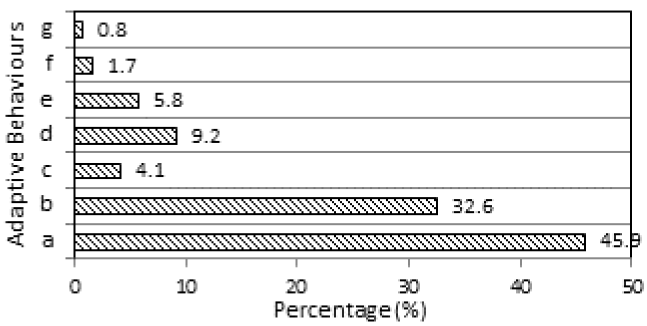
$$\mathrm{T_n} = \mathrm{T_{op}} + (0 - \mathrm{TSV})/\alpha \quad (5)$$

The constants 0.25, 0.33 and 0.5 are used as regression coefficients for 7-point thermal sensation scale (Humphrey et al., 2013). These regression coefficients were used in estimation of mean neutral temperature as shown in Table 6.

Table 6: Neutral temperatures of Griffith method

RC (°C^{-1})	T_n (°C)		
	N	Mean	S.D.
0.25	155	28.16	3.84
0.33	155	29.14	2.99
0.5	155	30.17	2.15

RC: Regression coefficient (α) ; T_n: Neutral temperature
S.D.: Standard Deviation



a. Going outside; b. Mechanical cooling (switch of fan) c. Going to an indoor open space; d. Bathing; e. Changing clothes; f. Drinking water or cold soft drink; g. Washing face and hands

Figure 9: Thermal adaptive behaviours of elders

Variation of mean neutral temperatures between coefficients is 1°C^{-1} and evident for a less difference. In comparison with the measured operative temperature for neutral votes on the sensation scale a close agreement is evident for the mean neutral temperature of regression coefficient of 0.5°C^{-1}. Thus the mean neutral temperature predicted using the

Griffiths' method is 30.2°C, which is 6.3°C higher than the neutral temperature estimated using the TSV regression method. Neutral operative temperature of this study is approximately 2°C higher than the field investigations of naturally ventilated buildings in Singapore and India.

As the thermal perception decreases progressively with the age and less active lives with lower metabolisms, the older adults prefer warmer indoor environments (Scehllen et al, 2010). Similar study of Thai elders in peak summer season informs 36°C as the mean comfort temperature (Sumavalee et al, 2016). Since the subjective thermal responses greatly affect the thermal sensation vote, it's important to understand the adaptive behavioural patterns of elders in accepting higher indoor temperatures.

3.6. Thermal adaptive behaviours of elders

The adaptive comfort theory is based on the concept of natural reactions of people arising from their expectations on comfort in relation to their environment (Brager et al, 1998). Adaptation helps the occupants to satisfy their personal needs to improve the 'fit' of indoor thermal environment and incorporate all physiological mechanisms of acclimatisation, behavioural and psychological processes of occupants.

Thus the clearly differentiated adaptation categories are behavioural adjustments, physiological acclimatization and psychological habituation or expectations. (Folk, 1974; Goldsmith, 1974). Behavioural adjustments tend to make a person comfortable in three adjustment categories such as personal, technological or environmental and cultural. Personal behavioural adjustments are active interaction of occupants in adapting to the existing thermal environment by changing personal variables such as adjusting clothing, activity, posture, consuming food, drinking and moving to a different location. Technological behavioural adjustments are controls to thermal environments by opening or closing windows, blinds or adjusting mechanical conditioning systems (Nicol et al, 2004).

Adaptive behaviours of elders were identified through observations and discussions during the pilot walk through survey and included as multiple choices in the questionnaire. Primary objective was to understand the adaptive strategies that the elders would customarily use when they felt an uncomfortable indoor thermal environment. Results are evident for both passive and active receivers of their indoor thermal environment which signifies 22.6% and 77.4% of the sample respectively. Figure 9 summarizes habitual behaviours of active receivers in adapting to the indoor thermal environment. According to Figure 9, going outside (45.9%) and use of fans (32.6%) are the most common thermal adaptive behaviours in daily life of elders. Comparatively, much a lesser extent the elders perform behaviours such as bathing (9.2%), changing clothes (5.8%), Going to an indoor open space (4.1%), drinking water (1.7%) and washing face and hands (0.8%).

These adaptive behaviours of elders inform two processes of adaptations to thermal environment by adjusting themselves or by adjusting the environment. Findings from similar studies of Chinese and Taiwanese elderly inform changing clothes or closing or opening windows were the most popular behavioural adaptations in summer climates (Hwang et al, 2010; Jiao et al, 2017). These elders prefer conventional methods to adapt to uncomfortable indoor thermal environments with no involvement of energy consumption.

Although reducing of clothing is the most popular behavioural adjustment in an uncomfortably hot environment but the conservative habituation and expectations of Srilankan elders has limited its necessity. Moreover, inhabitants of passive buildings control their indoor thermal environments by opening and closing windows and characterize as a widely practised behavioural adjustment for hot climates in Tropics.

However, opening of windows in early morning is a cultural habit of Srilankans and it is an essential action in their daily lives. Thermal preference is influenced by psychological factors such as culture and perception (Spagnolo et al, 2003; Kitayama et al, 2004; Thorosson et al, 2004). Thus, a quite different behavioural pattern is evident for Srilankan elders as thermal expectations result from a confluence of current and past thermal experiences, cultural and technical practices.

Results explicitly demonstrate that the elders prefer cooler indoor environments and have reacted through a personal or technological behavioural adjustment. The most prominent personal and technological behavioural adjustments of Srilankan elders are changing the place by going outside and modification of indoor thermal environment by switching on fans respectively.

Figure 10. Colonnaded open verandas integrated with outdoor gardens and semi-outdoor courtyards

Figure 10 shows the mostly preferred locations of naturally ventilated aged care homes such as colonnaded verandas integrated with outdoor gardens and semi-outdoor courtyards. However inclusion of these spaces in the internal planning of the aged-care homes is limited. Lack of integration between open spaces and mostly used interior spaces such as bedrooms and living rooms increases the tendency in the use of mechanical cooling by switching on fans. Thus the findings inform a synergy between psychological and behavioural adjustments to accomplish thermal preference of cooler indoor environments by promoting air movement and exposure to more breezes.

4. Conclusion

This paper investigated the indoor thermal environments to understand the thermal comfort needs of elders and their behavioural reactions in adjusting to harsh indoor environments. A thermal comfort field study was conducted in 7 naturally ventilated aged-care homes in tropical fully humid climate of Colombo, Sri Lanka. Perceived thermal environments of 155 elders in the age group of 60 to 80 years were collected in a questionnaire survey along with simultaneous objective measurements of physical environments. The conclusions derived from the detailed analyses and discussions are as follows;

- Indoor temperature of all aged-care homes were in the range of 29.1°C to 35.9°C.
- Relative humidity was in the range of 57% to 78% with predominantly low velocities.
- Interiors of all aged care homes were overheated and represent a heat-strain thermal status for its users.
- Actual mean thermal sensation of elders was 0.99 informing a TSV of slightly warm.
- Mean thermal preference was -0.63 and elders need a cooler indoor environment.
- Strong significant correlation was established among Thermal sensation (TSV), acceptability (TA) and preference (TP).
- Mean neutral temperature predicted in Griffiths' method was 30.2°C, which was 6.3°C higher than the neutral temperature predicted the TSV regression method.

- Elders have performed varying adaptive behaviours to achieve cooling thermal sensation in these naturally ventilated interiors.
- Commonly practised adaptive behaviours of Srilankan elderly were going outside and switching on fans.
- The thermal preference of more cooler indoors and the psychological need for air movement and exposure to more breezes has influenced the adaptive behaviours of elders in overheated interiors.
- Design limitations on less integrated open spaces with indoors have promoted the use of mechanical cooling by switching on fans.

Elders prefer more natural indoor environments integrated with colonnaded verandas outdoor gardens and semi-outdoor courtyards. Inclusion of these transitional indoor spaces promotes adaptive thermal behaviours of elderly for cooling in tropical hot climates. The far reaching design implications with inclusive passive designs justify more comfortable, healthy and low-energy living of elders in tropics in the context of warming climates.

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Experimental assessment of thermal comfort conditions in educational buildings in Cyprus using different ventilation strategies and window opening patterns

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Abstract: This paper presents findings from extensive field surveys of educational architecture in Cyprus during the winter and summer periods, and simultaneously explores the impact of natural ventilation on the indoor thermal environment. The study included seasonal indoor and outdoor monitoring of physical parameters. During the summer, the objective of the ventilation experiments was to achieve the most effective cooling strategy; thus, both single-sided and cross-ventilation strategies were employed for different times of the day in four classrooms. During the winter, the objective was to achieve optimum air quality with the least adverse impact on thermal comfort; thus, window operation patterns of single-sided ventilation strategies were examined. During the winter period, the operative temperature is below the acceptable comfort zone, while during the summer period, the findings show the vulnerability of the occupants to summertime temperatures. During the winter, a closed classroom shows the best results in terms of operative temperature; however, this conflicts with the air quality. During the summer, the case of cross-ventilation, both during the day and night, is the most efficient and operative way to passively cool educational architecture. The results of the experiments carried out in this study can be applied to inform strategies aimed at improving thermal comfort and reducing energy use in both new and existing educational buildings.
Keywords: thermal comfort, physical measurements, natural ventilation, educational buildings, East-Mediterranean region

1. Introduction

In recent years, educational buildings have played an important role in creating environmental awareness by generating a productive social environment and conditions which encourage students to develop. In order to achieve this, work is needed to further enhance the circumstances and environments for students, also taking into account the quality the condition of the classroom's indoor environment. Several studies highlight that undesirable conditions negatively affect the learning abilities and performance of the students (James and Cristian 2012, Barrett et al. 2015, Zomorodian et al. 2016). Moreover, considering that students spend one third of their time inside school buildings, health and wellbeing issues should be of high interest (Annesi-Maesano et al 2013). In Cyprus, as in other East-Mediterranean countries, schools are often free-running buildings and as such, the temperature of the buildings is not controlled, thus, in one day, there may be significant variations in temperature (Almeida et al. 2016). For the provision of thermal comfort, a considerable amount of energy is consumed for the heating and cooling of the space.

The integration of passive design strategies regulates indoor climate conditions. Especially during the summer period, passive measures are the only means of improving the thermal conditions in educational buildings in Cyprus; therefore, they are of great importance for the comfort and performance of the occupants. Many studies highlight that natural ventilation is an important cooling strategy, not only for the Mediterranean region, but also for other climates (Michael et al. 2017, Liping and Hien 2007, Santamouris and Allard 1998). Furthermore, it was found that naturally ventilated buildings consume less energy by 30-40%

compared to mechanically ventilated buildings (Kolokotroni and Aronis 1999, Gratia and Herde 2004). Several diverse design elements influence the performance of natural ventilation. These include the way the space is ventilated (for example by single sided ventilation or cross-ventilation), as well as the ratio between the walls and windows, the type of opening and the floor area. Of all these various considerations, the one with the biggest effect on the ventilation rate of the building, is the ventilation mode (Fung and Lee, 2014).

Within this framework, the current research aims to investigate the thermal comfort conditions during the winter and summer periods in a typical secondary school in Cyprus, and simultaneously examines how natural ventilation effects the indoor thermal environment. The objective of the ventilation experiments during the winter was to achieve optimum air quality with the least adverse impact on thermal comfort; thus, window operation patterns of single-sided ventilation strategies were examined in four classrooms. During the summer, the objective was to achieve the most effective cooling strategy; thus, both single-sided and cross-ventilation strategies were employed for different times of the day. The data was recorded both during the week and on weekends. The thermal environment was evaluated using the adaptive comfort model (EN 15251). The results of this study can be used to inform plans to improve and reduce energy use in educational buildings, as well as to inform both the design of new educational buildings and the refurbishment of existing premises.

2. Research Methodology

2.1. Case study description

The study was conducted in a secondary school in the urban area of Nicosia (latitude 35°10′ N and longitude 33°21′ E), Cyprus, and forms a section of a more extensive research paper regarding various assessments on indoor environmental quality in schools of Cyprus. The island has a typical Mediterranean climate, featuring hot-dry summers and cold-wet winters.

The building under study was designed and erected by the Technical Services of the Cyprus Ministry of Education and Culture, who are responsible for the design and structure of all schools in Cyprus. This renders the uniformity of schools in terms of their construction, morphology and typology; therefore, the case study can be considered as representative of educational buildings in Cyprus (Fig. 1) (Michael and Heracleous 2017). Classrooms are slightly rectangular, and their dimensions are around 7.00×8.00×3.20m (W×L×H) (Fig. 2). Classrooms have a linear disposition which enables the placement of openings along the two longer sides of the room. The case study refers to the Archbishop Makarios III Secondary School in Nicosia.

Figure 1. Secondary schools in Cyprus are almost always characterised by a uniformity of typology, morphology and construction, (a) Linear disposition of classrooms (b) internal view.

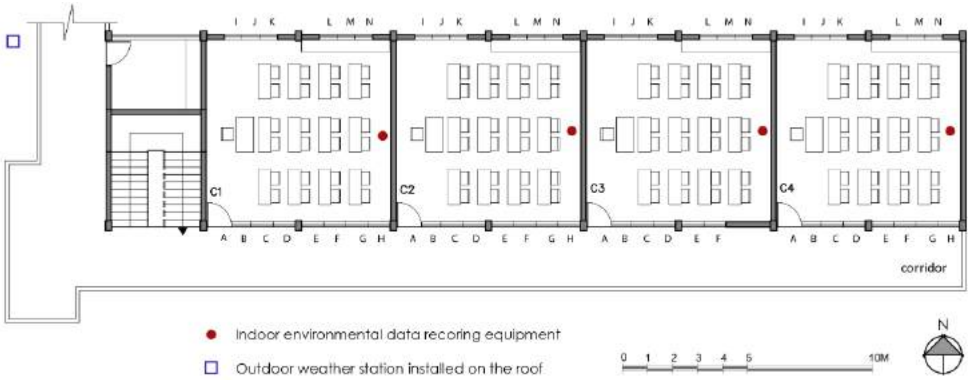

Figure 2. Layout plans of a characteristic secondary school classroom in Cyprus. Openings are marked from A to N, and the recording equipment used to monitor the indoor and outdoor environmental conditions are indicated in red.

The analysis of indoor comfort conditions and the experimental procedure of different ventilation strategies was carried out on four typical classrooms of general education, on the first floor, with south orientation. Extensive windows on one side, and clerestories on the other, allow the natural lighting and heat gains to get into the classrooms. The openings-to-floor ratio is 35%. It is worth noting that no building or plant elements shade the openings. More specifically, in each classroom, there are six glazed windows on the south side, i.e. C-H; a fixed glazed window on the south side, i.e. B; a semi-glazed door on the south side, i.e. A; four fixed clerestories on the north side, i.e. I, K, L, N, and two openable clerestories, i.e. J and M (Fig.2). The access to the classrooms is through a two-meter semi-open corridor that simultaneously offers sun protection to the southern openings (Fig.1). Clerestories on the other long side of the classroom have no solar protection. In order to eliminate solar radiation, students use internal black-out curtains; however, at the time of the experiment, they were kept open. The classroom has an occupancy profile of 23-25 students on weekdays from 07:30h to 13:35h with three small breaks; however, in some cases, students are moved during the day to other laboratories, fitness rooms or classes to engage in other activities. The thermal properties of the building components are summarised in Table 1. In addition, the airtightness was defined at 9.4 air change rate per hour (ach), at a pressure difference of 50 Pa, after an experimental procedure took place using the fan pressurisation method described by ISO 9972:2015.

Table 1. Construction characteristics and material of a typical school premises in Cyprus

Building Elements	Construction Detail	U-Value (W/m²K)	G-value	Effective Thermal Capacity (KJ/m²K)
External Wall	200mm single layer of brick and three layers of plaster (20-25mm)	1.389	-	120
Internal Wall	100mm single layer of brick and three layers of plaster (20-25mm)	1.235	-	120
Roof	Concrete slab and asphalt layer of 5mm	3.239	-	240
Ground Floor	Concrete slab and tiles	1.6	-	232
Window	6mm single glazed and aluminium frame	6	0.82	-
Airtightness	9.4 ach @50 Pa			

2.2. Field study methodology

A field study was carried out to assess comfort conditions, and the effect of different ventilation strategies on thermal comfort in educational buildings during the cold winter period, specifically from 10th February to 16th February 2018, and the warm summer period from 19th May to 25th May 2018. Data was collected during both occupied and unoccupied periods. The pattern of occupancy for each classroom varies throughout the week. It is noted that some classrooms were also used in the afternoon (14:45-18:00h), with a smaller number of occupants, i.e. 6-8 in each classroom. It is also worth noting that technical heating is available during the winter through a central heating system in operation between 07:00-10:00h every weekday and between 14:45-17:45h on Monday, Tuesday, Thursday and Friday.

Thermal environmental variables, such as air temperature, mean radiant temperature, globe temperature, air velocity and relative humidity, were measured. As per the European standard EN ISO7726 (2001), all parameters were logged at 1.1m height from the floor. The equipment was placed in selected locations, as shown in Fig. 2. The devices could not be placed in the middle of the room as they would obstruct the normal class schedule. Recordings of the environmental parameters inside the classrooms were set at periodical five-minute intervals. Four LSI-Lastem Heat Shield base modules (ELR610M) were employed to measure the operative temperature indoors. An outdoor weather station was installed at the same time on the building's roof, at a height of 10m above street level, which means around four metres above the regular height of buildings found in the immediate vicinity. The specifications of the measurement instruments are summarised in Table 2.

Table 2. Instruments' specifications

Name	Parameter	Range	Accuracy
LSI-Lastem Heat Shield base modules (ELR610M)	Natural Wet Bulb Temperature	-20 – 60 °C	±0.3 °C
	Globe Temperature	-20 – 60 °C	±0.3 °C
	Dry Bulb Temperature	-20 – 60 °C	±0.8 °C ±0.4 °C (10-40 °C)
	Relative Humidity	0 – 100 %	1.8% RH (10-90%)
Hot wire LSI Anemometer ESV125	Air speed	0.01 – 20 m/s	± 10 cm/s (0.5-1.5 m/s) 4% (>1.5 m/s)
Vantage Pro 2 Plus weather station	Air Temperature	-40 – 65 °C	±0.3 °C
	Relative Humidity	1 – 100 %	±3 %

The objective was to evaluate the thermal comfort conditions of educational buildings under a range of diverse ventilation methods and window opening configurations. During the summer, the ventilation experiments aim to achieve the most effective cooling strategy; thus, both single-sided and cross-ventilation strategies were employed for different times of the day in the four south facing classrooms. Specifically, the different experimental ventilation strategies were examined during the weekend, and on Monday and Tuesday (four consecutive days). Specifically, single-sided ventilation and cross-ventilation were proposed during the daytime, and cross-ventilation were proposed during the daytime and night time, and night time alone. In Case 1, single-sided daytime ventilation occurs, and windows were opened during opening hours in the morning, i.e. 07:00-13:30. The openings that remained fully open were A, C, and F. For comparison, in Case 4, cross-ventilation occurs, and windows were opened during opening hours in the morning, i.e. 07:00-13:30. The openings that remained fully open were A, C, F, J and M. In Case 2, cross-ventilation was proposed for both daytime and nigh time, i.e. 07:00-13:30 and 21:00-07:00. The openings that remained fully open were A, C, F, J and M. In Case 3, the classroom remained closed during the teaching period to reduce heat gains; however, the door (opening A) remained fully open throughout the day to maintain indoor air quality. Cross-ventilation is proposed during the night, i.e. 21:00-07:00, to reduce the extensive heat stored on the building envelope. It is noted that in all cases under study that employed night ventilation, the door of the classroom remained closed for safety reasons. It is worth mentioning that the specific windows were selected alternatingly in order to achieve a uniform distribution of air inside the space. Table 3 presents the various ventilation strategies and window opening configurations which were studied during the warmer summer months.

Table 3. Ventilation strategies and window opening patterns examined during the field study summer period. Dots indicate open windows during specific time-periods of the day.

Case / Classroom		**Ventilation strategies**	**Window opening patterns**		
			Openings remained open	Day (07:00-13:35)	Night (21:00-07:00)
Case 1	R1	Single-sided	A, C, F	■	-
Case 2	R2	Cross	A,C, F, J, M	■	■
Case 3	R3	Cross	A,C, F, J, M	-	■
Case 4	R4	Cross	A,C, F, J, M	■	-

***During nighttime ventilation, opening A (door) remained closed for security reasons**

The second experimental procedure was carried out during winter period. The objective was to assess the thermal comfort conditions of educational buildings, using different window opening patterns that maintain air quality with the least adverse impact on thermal comfort. Thus, window opening patterns of single-sided ventilation strategies were examined in four south facing classrooms. The data was monitored for both occupied and unoccupied hours. Specifically, the different experimental ventilation strategies were examined during the weekend, on Monday and Tuesday (four consecutive days). The openings that remained fully opened were C and F (half of the openable windows in the single sided classroom). In Case 4, windows were opened during all break times (08:50-09:10h, 10:30-10:50h and 12:10-12:1l5h), in Case 3, windows were opened in the last two breaks, while in Case 2, windows were opened during the last break only at midday. In Case 1, all the openings remained closed, i.e. no ventilation was monitored, to be used as a reference scenario. Table 4 summarises the different ventilation strategies examined during the field study winter period.

Table 4. Ventilation strategies and window opening patterns examined during the field study winter period. Dots indicate open windows during specific time-periods of the day.

Case / Classroom		**Ventilation strategies**	**Window opening patterns**			
			Openings remained open	Break time		
				1st break 20 mins	**2nd break** 20 mins	**3rd break** 5 mins
Case 1	R1	No ventilation	-	-	-	-
Case 2	R2	Single Sided 1	C, F	-	-	■
Case 3	R3	Single Sided 1	C, F	-	■	■
Case 4	R4	Single Sided 1	C, F	■	■	■

2.3. Data Analysis Methodology

The influence of each of the various ventilation alternatives on the indoor conditions was assessed by looking at the recorded temperatures from both the indoor and the outdoor environments, side by side.

Thermal comfort is assessed using the Adaptive Comfort Standards (ASC) which is incorporated in the EN 15251. The Adaptive Comfort Standard (ASC) is used only in naturally ventilated buildings where occupants have different expectations, compared to those who stay in technically supported buildings, due to their adaptation to the external environment (Nicol and Humphreys, 2010). The occupants are considered to do sedentary activities with a metabolic rate ranging from 1.0 to 1.3 met and clothing insulation is anticipated to 1 clo for winter and 0.5 clo for summer. When looking at the information from only the free-running buildings, the relationship between the indoor thermal comfort temperature and the outdoor running mean temperature can be calculated by:

Tc (°C) = 0.33Trm +18.8 (1)

where, Tc is the predicted comfort temperature when the running mean of the outdoor temperature is Trm. The prevailing mean outdoor air temperature (Trm) is the arithmetic average of the mean daily outdoor temperatures over a period of seven sequential days prior to the day in question.

CIBSE recommends that new buildings, major refurbishments and adaptation strategies should conform to Category II in BS EN 15251. Category II represents 80% of the acceptability limits of indoor operative temperatures and are estimated using Equations 2 and 3. While, the corresponding 90% of acceptability limits are obtained by subtracting 1°C to the upper 80% acceptability limit and adding 1°C to the lower 80% acceptability limit (EN 15251,2007).

Lower 80% acceptability limit (°C): 0.33 Trm +15.8 (2)

Upper 80% acceptability limit (°C): 0.33 Trm +21.8 (3)

For the purpose of this study, the calculation of the operative temperature (to) is based on an average air temperature (ta) and mean-radiant temperature (tr), as shown in Equation 4. Value A is a function of the relative air speed (Vr) as shown in Table 5.

$$t_o = A\, t_a + (1 - A)t_r \quad (4)$$

Table 5: Value A as a function of the relative air speed

	<0.2 m/s	0.2 to 0.6 m/s	0.6 to 1.0 m/s
A	0.5	0.6	0.7

Moreover, air temperature (ta) is recorded directly, while mean radiant temperature (tr) is calculated using Equation 5. The parameters included in Equation 5 are globe temperature (tg), air velocity (Va), air temperature (ta), globe diameter (D) and emissivity (ε).

$$t_r = \left[\left(t_g + 273\right)^4 + \frac{1.10\ x10^8 V_a^{0.6}}{\varepsilon\, D^{0.4}}\left(t_g - t_a\right)\right]^{\frac{1}{4}} - 273 \quad (5)$$

3. Field study results

The recordings of the external wind environment show that the prevailing daytime wind flow (07:30-13:30) during the winter period is mostly north-oriented. The average wind speed is 1.56 m/s and the maximum wind speed is 4.5 m/s (Fig.3). During the summer period, the prevailing daytime wind flow (07:30-13:30) is north-east oriented (NNE 23°); while the prevailing night time window flow (21:00-07:00) is west oriented. The average wind speed is

1.45m/s and 1.70m/s for the daytime and night time respectively, and the maximum wind speed is 4m/s and 3.1m/s respectively.

During the winter period, the indoor-recorded field data indicates very low levels of air speed i.e. <0.1m/s in all classrooms as a result of the widely applied ventilation strategy; i.e. single-sided ventilation, and the fact that openings face south, i.e. contrary to the prevailing wind. During the summer period, the indoor air velocity measurements ranged from 0.0m/s to 0.6m/s during the daytime, and from 0.0m/s to 0.1m/s during the night ventilation period. The low levels of air speed during the night are attributed to the fact that the openings face south/north.

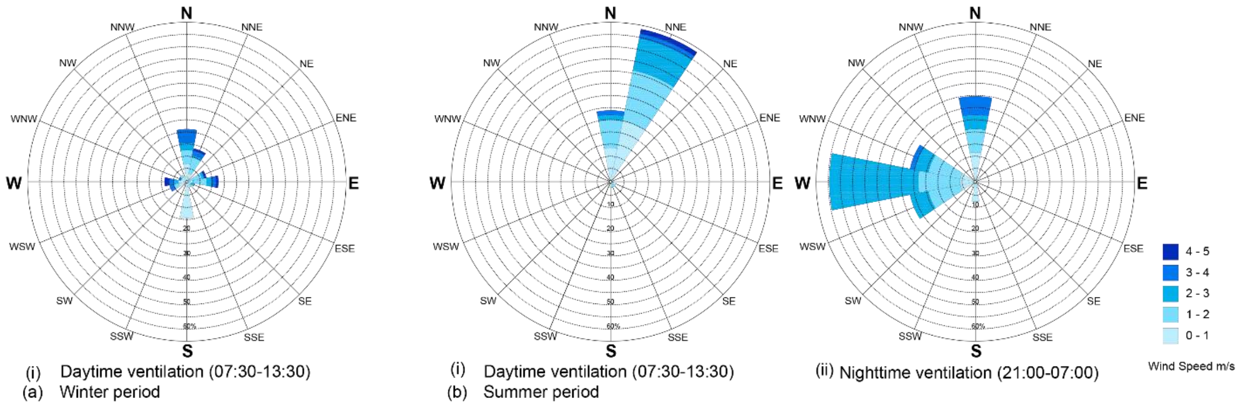

Figure 3. Examination of outdoor wind environments for the (a) winter (b) summer period, i.e. 09th February - 16th February 2018, and 19th May - 23th May 2018 respectively, during daytime, i.e. 07:30-13:30h, and night-time, i.e. 21:00-07:00.

Table 6 shows a review of the indoor and outdoor environmental parameters in classrooms which have been naturally ventilated in the occupied summer period, i.e. 19th – 23th May 2018. The external temperature during that period varies from 23.6°C to a peak of 38.1°C, with a mean diurnal fluctuation of 12.7°C. During the occupied time i.e. 07:30-13:30, the external temperature varies from 24.8°C to 37.3°C, with a mean diurnal fluctuation of 10.7°C. The average running mean temperature during the summer period was 27.7°C. The comfort zone was set for 80% and 90% acceptability within classrooms as shown in Fig. 4. Depending on the external conditions, the thermal comfort zone rages from 24.3°C-25.3°C to 30.3°C-31.3 °C for 80% acceptability and from 25.3°C-26.3°C to 29.3°C-30.3°C for 90% acceptability. Figure 4 shows the assessment of thermal comfort conditions in the four selected south facing classrooms with different ventilation strategies, i.e. single-sided ventilation during day (Case 1), cross-ventilation during day (Case 4), cross-ventilation during day and night (Case 2) and cross-ventilation only during night (Case 3). The shaded area denotes the periods that the classrooms were occupied.

Table 6. Outdoor and indoor-recorded values and percentage of occupied time within acceptable comfort limits during the summer period i.e. 19th-23th May 2018 between 07:30-13:35.

Ventilation Strategy/ Classroom	Day	Outside air temperature (°C)			Inside air temperature (°C)			Operative temperature (°C)			Percentage of occupied time within acceptable limits (%)	
		Tmax	Tmin	Tmean	Tmax	Tmin	Tmean	Top_max	Top_min	Top_mean	80%	90%
Case 1/R1	weekend_D1	37.3	25.5	32.8	33.6	30.3	31.7	33.9	30.6	32.0	13	7
	weekend_D2	36.6	25.9	32.5	34.1	30.6	32.2	34.3	30.8	32.4		
	weekday_D1	36.2	24.8	31.4	33.4	30.6	33.0	33.9	30.9	32.5		
	weekday_D2	32.7	25.2	28.6	32.9	31.2	31.8	33.1	31.6	32.1		
	weekday_D3	34.7	22.8	29.5	32.5	29.0	30.7	32.6	29.7	31.1		
Case 2/R2	weekend_D1	37.3	25.5	32.8	33.5	29.2	31.3	33.7	29.4	31.4	39	12
	weekend_D2	36.6	25.9	32.5	33.7	29.4	31.6	34.0	29.5	31.8		
	weekday_D1	36.2	24.8	31.4	33.4	29.2	31.3	33.9	29.4	31.8		
	weekday_D2	32.7	25.2	28.6	32.5	29.5	30.9	32.6	30.1	31.4		
	weekday_D3	34.7	22.8	29.5	32.2	27.8	30.2	32.5	28.3	30.7		
Case 3/R3	weekend_D1	37.3	25.5	32.8	32.2	29.0	30.7	32.4	29.2	30.9	33	11
	weekend_D2	36.6	25.9	32.5	32.5	29.4	31.3	32.8	29.7	31.5		
	weekday_D1	36.2	24.8	31.4	32.6	29.3	31.2	33.3	29.5	31.7		
	weekday_D2	32.7	25.2	28.6	32.2	30.1	31.1	32.4	30.4	31.5		
	weekday_D3	34.7	22.8	29.5	31.7	27.9	30.3	31.8	28.3	30.6		
Case 4/R4	weekend_D1	37.3	25.5	32.8	34.1	29.8	31.8	34.1	30.0	31.8	19	7
	weekend_D2	36.6	25.9	32.5	34.3	30.7	32.4	34.3	30.8	32.5		
	weekday_D1	36.2	24.8	31.4	34.1	30.7	32.2	35.5	31.5	32.6		
	weekday_D2	32.7	25.2	28.6	32.8	30.4	31.3	34.3	31.1	32.5		
	weekday_D3	34.7	22.8	29.5	32.8	29.2	31.0	32.5	30.8	31.6		

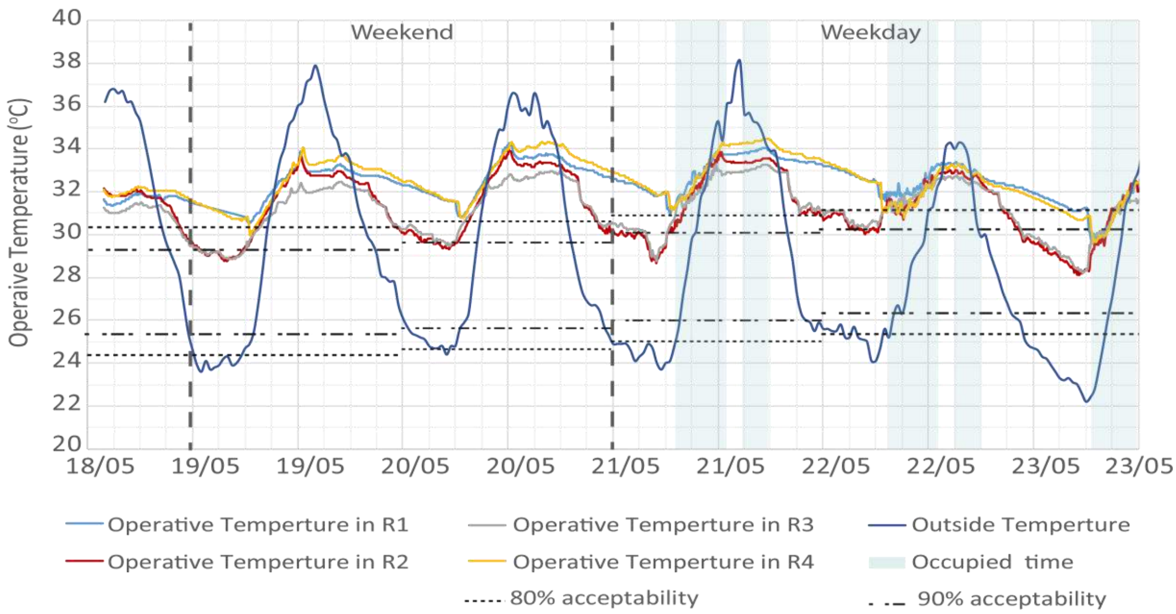

Figure 4. Operative temperatures for thermal comfort assessment of natural ventilation strategies under study during summer period i.e. 19th May- 23th May.

During the application of a single-sided ventilation strategy during the daytime (Case 1), the air temperatures indoors each day correspond to the air temperatures of the external environment, while the indoor air temperatures during the night shows higher levels compared to the external ones. More specifically, the mean daytime indoor air temperature is 0.9 °C higher than the outdoor, while the mean nocturnal temperature indoor air temperature is 7°C above the respective mean nocturnal outdoor temperature. The mean indoor diurnal fluctuation is 4°C. As shown in figure 4, a rapid reduction of operative temperatures of the order of 1°C occurred over an hour, as the heat was released outside with the opening of windows at 07:00. In terms of the adaptive comfort model, the mean diurnal operative temperatures exceed the acceptability limits. The mean operative temperatures vary from 31.1°C to 32.5°C during the occupied times, i.e. 07:30-13:35, showing a minimum operative temperature of 29.7°C between 07:00-08:00 in the morning, due to the opening of the windows, while between 13:00-14:00 the maximum temperature is 34.3°C.

More specifically, operative temperatures fall within the 80% acceptability limit for 13% of the occupied time and only 7% within the 90% acceptability limit. Operative temperatures exceed the upper acceptability limits for all occupied hours during the afternoon (i.e. 14:45-18:00) as well as during the night.

During the application of the cross-ventilation strategy during the daytime (Case 4), similarly to Case 1, the daily indoor air temperatures follow the pattern of outdoor temperatures, while the indoor air temperatures during the night remain higher than the external ones. More specifically, the mean daytime indoor air temperature is 0.8°C higher than the outdoor, while the mean nocturnal indoor air temperature is 7.1°C above the respective mean nocturnal outdoor temperature. The mean indoor diurnal fluctuation is 3.7°C, i.e. lower than the single ventilation strategy. As observed in figure 4, a steep decrease of operative temperatures of about 1°C occurred over half an hour, with the opening of windows at 07:00. Moreover, it was noticed that the classroom with cross-ventilation is more effective until midday, as it shows slightly lower air temperatures of the order of average 0.2°C compared with the classroom with single-sided ventilation. However, after midday classroom R4 showed higher temperatures compared to classroom R1 and this may attribute to the fact that classroom R4 is more exposed to the external environment (three surfaces exposed to the outdoors). In terms of the thermal comfort assessment, the cross-ventilation strategy results in indoor temperatures that exceed the thermal comfort zone for a smaller period, compared to single-sided ventilation. The mean operative temperatures vary from 31.6 °C to 32.6°C during the occupied time, showing a minimum operative temperature of 30°C between 07:00-08:00 in the morning, due to the opening of windows, while between 13:00-14:00, the maximum temperature is 35.5°C. It is worth mentioning that although a small decrease was observed in the operative temperatures when the windows were closed at 13:35 letting the solar gains out, an increase in temperature occurred from 15:00 to 18:00, as the heat energy absorbed by the building envelope was released into the internal environment. Operative temperatures fall within the 80% acceptability limit for 19% of occupied time and only 7% within the 90% acceptability limit. Operative temperatures exceed the upper acceptability limits for all the occupied hours of the afternoon (i.e. 15:00-18:00), as well as during the night.

During the application of the cross-ventilation strategy during the day and night (Case 2), nocturnal air temperatures follow the patterns of external temperatures closer when compared to the other two strategies (Case 1 and 4). The day following the application of night ventilation, classroom R2 remains at lower temperatures compared to classrooms R1 and R4. More specifically, the mean daytime indoor air temperature is only 0.1°C higher than the outdoor temperature. It is worth mentioning that in three of the five days under study, classroom R2 shows lower mean daytime indoor air temperature than outdoors. Concerning the mean nocturnal temperature, the indoor air temperature is only 3.1°C above the respective mean nocturnal outdoor temperature. The mean indoor diurnal fluctuation is 5°C, i.e. higher than the other two-abovementioned strategies, due to night ventilation. In terms of the adaptive comfort model, Case 2 shows the best performance during the occupied time. Specifically, the mean diurnal operative temperatures fall within the 80% acceptability limit for 39% of occupied time, while they fall within the 90% acceptability limit for 12% of the time. Operative temperatures exceed the upper acceptability limits for all the occupied hours during the afternoon (i.e. 15:00-18:00), while during the night they exceed the 80% and 90% acceptability for 21% and 44% of the occupied time respectively. The mean operative temperatures vary from 30.7°C to 31.8°C during the occupied time. Classroom R2 shows a minimum operative temperature of 28.1°C between 05:00-06:00 in the morning due to night ventilation, while a maximum temperature of 34°C happens between 13:00-14:00. During night ventilation, heat that remained in the indoor environment as well as heat absorbed in the building envelope is removed, ensuring better thermal conditions and reducing the peak operative temperatures the next day. The application of cross-ventilation during the daytime allows the indoor daily temperatures to correspond to outdoor air temperatures.

During the application of cross-ventilation only during night (Case C3), nocturnal air temperatures follow the patterns of external temperatures similar to Case 2, i.e. cross-ventilation during the day and night. The mean nocturnal temperature is only 4.8°C above the respective mean nocturnal external temperature and the mean indoor diurnal fluctuation is 4.4°C, i.e. lower than Case 2 due to lower peaks. During the following day of the application of night ventilation, classroom R3 remains at lower temperatures compared to classroom R1 and R4, similarly to Case 2. However, as the windows close at 07:00 in the morning, the indoor temperatures slightly increase compared to Case 2 where cross-ventilation was applied during the day. This increase lasts until 08:00-08:30 in the morning; after that, the indoor air temperatures remain at lower levels compared to Case 2, as classroom R3 remains closed blocking the solar gains; however, they are still above the acceptable limits. It is worth mentioning that during the weekend, the difference between the indoor daytime temperatures of R3 and R2 is stronger compared to the indoor daytime temperatures on weekdays (Fig.4). This is attributed to the fact that during the week, the classroom that is closed and occupied (i.e. Case 3) show elevated indoor temperatures due to the heat produced by the occupants. In terms of the adaptive comfort model, Case 3 shows similar performances as Case 2 during the occupied time. Specifically, the mean diurnal operative temperatures fall within the 80% acceptability limit for 33% of occupied time, while they fall within the 90% acceptability limit for 11% of the time. The slightly worse performance compared to Case 2 during occupied time can be attributed to the closed windows during the effective cooling, which lasts until 8:00-8:30 in the morning. Operative temperatures exceed the upper acceptability limits for all the occupied hours during the afternoon (i.e. 15:00-18:00), while during the night they exceed the 80% and 90% acceptability for 22% and 53% of occupied time respectively. The mean operative temperatures vary from 30.6 °C to 31.7°C during the occupied time (similarly to Case 2). Classroom R3 shows a minimum operative temperature of 28.2°C between 05:00-06:00 in the morning due to night ventilation, while a maximum temperature of 33.3°C happens between 13:00-14:00. This is the lowest peak temperature observed in all of the classrooms under study.

The analysis also showed correlation between the hourly operative temperature of the classrooms and the external temperature ($p<0.05$). As observed, the classrooms that applied night ventilation, i.e. Case 2 and Case 3, show the strongest correlation ($r= 0.87$ and $r= 0.78$ respectively) compared to classrooms that applied daytime ventilation, i.e. Case 1 and Case 4 ($r=0.5$) (Table 6).

Table 7 presents a statistical round-up of the indoor and outdoor environmental parameters in classrooms which are naturally ventilated during the occupied winter period, i.e. 09th – 16th February 2018. The external temperatures during that period varies from 8.5°C to a peak of 18.7°C, with a mean diurnal fluctuation of 7.4°C. During the occupied time, i.e. 07:30-13:35, the external temperature varies from 10.7°C to 18.7°C, with a mean diurnal fluctuation of 5.7°C. The average running mean temperature during the winter period was 14.8°C. The comfort zone was set for 80% and 90% acceptability within classrooms as shown in Fig. 5. Depending on the external conditions, the thermal comfort zone rages from 20.5°C-

20.8°C to 26.5°C -26.8 °C for 80% acceptability and from 21.5°C-21.8 °C to 25.5°C-25.8 °C for 90% acceptability. Figure 5 shows the assessment of thermal comfort conditions in the four selected south facing classrooms with different window patterns, i.e. no ventilation (Case 1); ventilation during the last five minute break (Case 2); ventilation during the last two breaks (Case 3) and ventilation every break-time (Case 4). The shaded area denotes the occupied period of classrooms.

Table 7. Outdoor and indoor-recorded values and percentage of occupied time within acceptable comfort limits during the winter period i.e. 09th-16th February 2018 between 07:30-13:35.

Ventilation Strategy/ Classroom	Day	Outside air temperature (°C)			Inside air temperature (°C)			Operative temperature (°C)			Percentage of occupied time within acceptable limits (%)	
		Tmax	Tmin	Tmean	Tmax	Tmin	Tmean	Top_max	Top_min	Top_mean	80%	90%
Case 1/R1	weekend_D1	18.5	12.3	15.9	21.0	19.3	20.3	21.1	19.6	20.4	34	18
	weekend_D2	18.7	14.9	16.7	19.4	18.4	18.9	19.4	18.5	19.0		
	weekday_D1	16.6	10.9	14.0	22.2	17.1	20.2	21.8	17.5	20.3		
	weekday_D2	17.9	10.9	14.3	22.7	18.9	21.6	22.5	20.4	21.7		
Case 2/R2	weekend_D1	18.5	12.3	15.9	20.7	19.2	20.1	20.8	19.4	20.2	25	4
	weekend_D2	18.7	14.9	16.7	19.4	18.7	19.1	19.4	18.7	19.1		
	weekday_D1	16.6	10.9	14.0	21.9	17.4	19.9	21.8	17.7	20.0		
	weekday_D2	17.9	10.9	14.3	21.6	17.2	20.4	21.4	17.9	20.6		
Case 3/R3	weekend_D1	18.5	12.3	15.9	20.2	19.2	19.8	20.2	19.3	19.9	12	3
	weekend_D2	18.7	14.9	16.7	19.1	18.4	18.7	19.1	18.4	18.8		
	weekday_D1	16.6	10.9	14.0	21.8	17.2	19.8	21.3	17.5	19.8		
	weekday_D2	17.9	10.9	14.3	21.7	17.2	19.6	21.2	19.4	20.1		
Case 4/R4	weekend_D1	18.5	12.3	15.9	19.7	18.5	19.2	19.8	18.6	19.3	0	0
	weekend_D2	18.7	14.9	16.7	18.5	17.6	18.0	18.5	17.7	18.1		
	weekday_D1	16.6	10.9	14.0	19.9	16.5	18.2	19.4	16.8	18.3		
	weekday_D2	17.9	10.9	14.3	19.8	15.7	18.2	19.5	15.9	18.3		

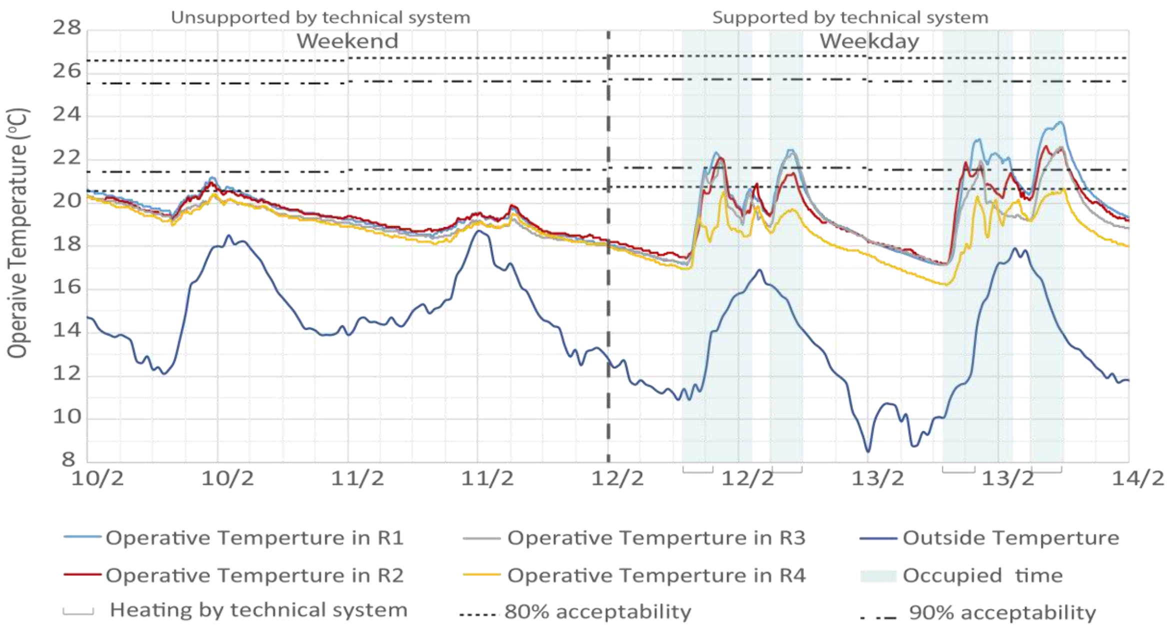

Figure 5. Operative temperatures for thermal comfort assessment of window opening patterns under study during winter period i.e. 10th February- 14th February.

As observed in Fig. 5, the indoor operative temperatures during the winter period, at times when the classrooms are unoccupied, is generally stable as it is unsupported by technical systems. During occupied periods where a heating system is provided, the indoor temperature shows higher fluctuations. The correlation between indoor temperatures and external temperatures shows that classroom R4 has the strongest correlation (r=0.742) compared to other classrooms, possibly due to the higher number of surfaces exposed to the external environment (Table 7). This correlation is more visible during occupied times where technical heating is provided. It is worth mentioning that during the weekend, when no technical heating is provided, all classrooms are below the acceptable thermal comfort limits.

One of four classrooms (Case 1) remained without any natural ventilation during the winter period, for reference purposes. The mean diurnal indoor air fluctuation in classroom R1 is 2.9°C, while the external mean fluctuation for the same period is 5.7°C. Classroom R1 (Case 1) shows the highest indoor temperatures compared to other cases due to lesser heat losses through ventilation. Specifically, mean daytime indoor air temperature is 5°C higher than the outdoor temperature. The mean operative temperatures vary from 19°C to 21.7°C during the occupied time, i.e. 07:30-13:35, showing a minimum operative temperature of 17.5°C between 07:00-8:00 in the morning, while the maximum temperature between 12:00-13:00 during unoccupied time (unsupported period by technical heating) was 21.1°C. More specifically, operative temperatures fall within the 80% acceptability limit for 34% of occupied time and only 18% within the 90% acceptability limit, even with the provision of technical heating. During afternoon sessions (i.e. 15:00-18:00), operative temperatures are below the lower 80% and 90% acceptability limits for 56.1% and 67.6% of occupied hours. It is worth mentioning that a mean gradual temperature reduction of 1.4°C is observed by switching off the heating system over an hour.

With regards to the experimental procedure of different window opening patterns, classrooms R2 and R3 show similar behaviour. Specifically, the mean diurnal indoor air fluctuation for classroom R2 and R3 is 2.8°C and 2.7°C respectively, while the mean daytime indoor air temperature is 4.6°C and 4.3°C respectively, higher than the outdoor. The 20-minute ventilation during the second break (10:30-10:50h) in R3, reduced the operative temperature by 1°C when the outdoor temperature is below 15°C. The five-minute ventilation which occurred in the last break (12:10-12:15) does not affect the internal conditions in both classrooms. The mean operative temperatures of R2 and R3 vary from 19.1°C to 20.6°C and from 18.8°C to 20.1°C respectively during occupied times, i.e. 07:30-13:35. The minimum operative temperature occurred in both classrooms between 07:00-8:00 in the morning, with values of 17.7°C and 17.5°C for classrooms R2 and R3 respectively. For classrooms R2 and R3, operative temperatures fall within the 80% acceptability limit for 25% and 12% of occupied time respectively, and only 4% and 3% respectively within the 90% acceptability limit. During the afternoon sessions (i.e. 15:00-18:00), operative temperatures in R2 and R3 are below the lower 80% acceptability limit for 65% and 60% of occupied hours and below the lower 90% acceptability time for 80% and 74% of the occupied time respectively.

Classroom R4 exhibits the lowest performance concerning thermal comfort conditions, however, according to a study performed by the authors, it showed the best performance concerning indoor air quality. The study showed that ventilation is required during every break time to reduce the concentration of CO_2 (Heracleous and Michael, 2018). The mean indoor diurnal fluctuation in classroom R4 is 2.2°C, while the mean daytime indoor air temperature is only 3.7°C higher than outdoors. It is worth mentioning that during the weekend, R4 shows similar behaviour to other classrooms. During the week, with the provision of technical heating and a steeper drop of external temperatures, classroom R4 shows lower temperatures of 2.2°C compared to Case 1_R1, and of 1.2°C and 1.5°C compared to Case 2_R2 and Case 3_R3 respectively. It is noteworthy to state that the ventilation which occurred during the first break (08:50-09:10h) in R4 does not affect the indoor conditions. The mean operative temperatures vary from 18.6°C to 19.8°C during the occupied time, i.e. 07:30-13:35, showing a minimum operative temperature of 16.4°C between 07:00-8:00 in the morning, while a maximum temperature of 20.3°C was noted between 12:00-13:00 during unoccupied times (periods unsupported by technical heating). As noticed, operative temperatures are below the acceptability limits for all the occupied and unoccupied times, even with the provision of technical heating.

Table 8. Correlation between the measures internal temperature and the external temperature

	Pearson correlation	
Space	Winter	Summer
Case 1_R1	0.526*	0.500*
Case 2_R2	0.593*	0.871*
Case 3_R3	0.515*	0.785*
Case 4_R4	0.742*	0.500*
***Correlation is significant at the 0.05 level (2-tailed)**		

4. Conclusion

This paper aims to investigate the indoor thermal comfort conditions in a typical classroom of a secondary school in Cyprus and explore the impact of natural ventilation on thermal comfort both in the heating and cooling period. In this framework, various ventilation strategies and window opening patterns were examined in order to identify the most effective strategy for the improvement of thermal comfort.

A comparative analysis for the present study has enabled a scientific quantitative experimental in-situ assessment that provides valuable data in the area of passive measures and thermal comfort. The key findings of the current study are as presented below:

- During the summer period, the findings showed that occupants suffer from summertime temperatures. The most usual ventilation strategy of single-sided ventilation and more rarely cross-ventilation during daytime, fail to maintain thermal comfort conditions most of the time.
- During the summer period, the environmental climatic conditions of the Mediterranean region, featuring a high diurnal fluctuation, allow the exploitation of night ventilation strategy.
- The research established that night ventilation alone or even with combination with daytime ventilation has the highest cooling performance efficiency. Night ventilation alone shows lower peak temperatures. However, it shows a lower percentage of time within the acceptability limits compared to the case of cross-ventilation during the day and night. This is because cross-ventilation during the day allows the removal of heat produced by the occupants and absorbed heat gains through windows. Moreover, ventilation during the day maintains indoor air quality and increased wind speed, which in turn makes occupants feel more comfortable.
- The study confirms that cross-ventilation strategies using the clerestories (the smaller window located on the upper portion of the external wall) also serve to aid the removal of hot air, therefore playing a significant role in improving the indoor thermal comfort conditions, especially in comparison to single-sided ventilation.
- During the winter period, the findings show that classrooms remain within the comfort zone only during the time that is supported by technical heating. During the weekends, i.e. periods which are unoccupied and non-technically supported,

classrooms exhibited temperatures below the lower acceptability limit of the thermal comfort zone.

- The application of natural ventilation strategies during every break-time does not compromise thermal comfort and has a beneficial impact on the reduction of CO_2 concentration.
- Statistical analysis demonstrates correlations between the mean temperature of classrooms and the external temperature ($p<0.05$).

The results of the experimental assessment presented herein demonstrate the impact of environmental variables and quantify the positive contribution of different ventilation strategies and window opening patterns on the indoor thermal conditions in educational buildings in hot and dry climatic conditions. The study reveals the necessity for an appropriate manual airing routine for thermal comfort and air quality in the indoor built environment, with positive consequences on the well-being and the productivity of educational building occupants. The results derived from these experiments can be used to advise plans which intend to enhance thermal comfort and decrease energy usage in educational buildings, as well as in the design of new buildings and the refurbishment of existing educational edifices.

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Impact of urban geometry on indoor air temperature and cooling energy consumption in traditional and formal urban environments

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Abstract: This study explores the effect of outdoor microclimatic environment on indoor conditions in a tropical warm-humid climate. An indoor air temperature and building energy performance analysis is carried out for the real case-study areas to examine the impact of urban geometry on building indoor conditions. The study incorporates microclimatic data from CFD, micro-climatic tool ENVI-met into building energy performance analysis using IES-VE. Findings reveal that diversity in urban geometry in deep urban canyons is helpful in reducing the indoor air temperature and cooling load. On average, cooling load in model rooms in the formal area is 21% higher for 1st floors (40% for top floors) compared to the corresponding rooms in the traditional area. In terms of solar gains, the difference was 30% for the 1st floors and 91% for the top floors, with rooms in the formal area having the higher ranges. Furthermore, the room air temperature in the traditional area was found to be 0.6-1.6^{0}C lower than those in the formal area.

Keywords: ENVI-met(V4); IES-VE; building energy performance; tropical climate; urban geometry

1. Introduction

The geometry of urban forms can affect the heating, cooling, lighting and ventilation of the individual buildings as well as the microclimate of the streets, squares, courtyards or gardens that contain them (Strømann-Andersen & Sattrup 2011). Their study had found that the geometry of urban canyons can create a variation on total energy consumption in the range of up to +30% for offices and +19% for housing for North-European cities. Traditional, compact urban form in other European city centres were also found to minimise undesirable building heat losses or gains (Vartholomaios 2017; Rode et al. 2014). Strong correlation between the urban geometry parameters (Aspect ratio, Sky View Factor (SVF), etc.) and microclimatic conditions is found in studies in high-density tropical regions (Sharmin et al. 2015). Kikegawa et al. (2006) have conducted a geometrical analysis for 23-wards in urban Tokyo and identified the Sky View Factor (SVF), an urban geometry parameter, to be the most crucial geometrical index of urban canopies that directly affects the cooling energy demand. Furthermore, one of the main microclimatic factors to affect energy consumption in an urban area is the variation in air temperature, i.e., lower air temperature resulting in lower cooling load. According to Santamouris et al. (2001), air temperature distribution in urban areas is highly affected by the urban radiation balance, which is basically a repercussion of urban geometry.

Findings from microclimatic monitoring in Dhaka as discussed in Sharmin et al. (2015) suggest that urban forms that are more variable with irregular plot sizes and building heights, mostly in traditional areas, have positive responses with respect to the synoptic climate, while planned areas with uniform plot sizes and building heights show a tendency to develop daytime urban heat island effect. An east-west orientated street in a formal residential area was found to be up to 6.2^{0}C warmer than a street in a Traditional Residential Area (TRA) in the same orientation. It is apparent that the differences are directly linked to the specific geometric pattern of the areas and can be defined by parameters like uniformity versus diversity and compactness versus openness. Uniform heights, equal building separation and plot sizes can lead to a harsher urban microclimate, while variety in these may foster positive changes. Lack of such variety can affect even the compact urban areas and deep urban canyons. A statistical analysis of climatic variables in the above study showed moderately strong and significant correlations. This reveals that urban geometry and the resultant climatic variables may be one of the most important factors for affecting the microclimatic conditions in a tropical climate.

From the finding of the above study, it can be speculated that the diversity in urban geometry in the traditional areas will affect the internal conditions of the adjacent buildings as well. The deep canyons with variable building heights will modify the radiation balance through mutual shading and, consequently, the solar gain in the indoor surfaces in the urban canyon. Thus, it will create an altered and perhaps cooler indoor ambience in the adjacent buildings. At the same time, the top floors of the tallest buildings in the traditional areas will presumably suffer worse conditions due to higher solar exposure. In formal areas, on the other hand, almost all top floors will have a similar high solar exposure due to their equal heights. It is assumed that the modified radiation budget due to the morphological diversity will play a greater role in altering the indoor conditions compared to air temperature differences recorded in the actual sites.

The methodology and findings from the study will aid in devising strategies to lower energy consumption and room air temperature in buildings by considering the impact of the neighbouring urban textures in a tropical, warm-humid climate. However, it should be emphasised that energy models are simplified for easy comparison and the internal gains, ventilation and cooling profiles are kept the same across all models. Therefore, despite using real case study sites, the energy calculation in the simulation models will differ from the real buildings, not least because buildings are rarely air conditioned. Nevertheless, the analysis will reveal important comparative outcomes and lessons related to urban form.

2. Methodology

This study compares the results of an indoor air temperature and cooling load analysis between two residential sites in Dhaka city with different urban geometry characteristics: one is a Traditional Residential Area (TRA), which has mainly grown out of spontaneous development under loose planning controls. A traditional area is predominantly residential with small-scale commercial activities and variable building forms, heights and plot sizes. The street layouts in these areas often create varying patterns with narrow and twisting streetscapes. Green spaces, especially community areas like parks or gardens, are not common. The other residential type in this study is planned area or Formal Residential Areas named as FRA, with buildings of equal height and width, and roads laid out in a grid-iron pattern.

The study mainly discusses residential sites as residential energy consumption in the LDCs (least developed countries, as the case-study area) comprises of 30-95% of the total energy use compared to 25-30% in the developed countries (DCs) (Foysal et al. 2012). This means that reducing the residential energy consumption can significantly aid in lowering the total energy requirements in the case-study area.

The study has been carried out in two steps. Firstly, an indoor air temperature analysis is carried out for the buildings located in both formal and the traditional areas. In this scenario, buildings are running in a natural ventilation mode. Secondly, a cooling load analysis is carried out with the application of a cooling (air-conditioning) system in the buildings. The study has adopted the dynamic simulation software IES-VE for running the indoor analysis. The application of IES-VE was confirmed for other similar micro-scale studies, such as, Skelhorn et al. (2016); Lee and Steemers (2017) and Lau et al. (2016).

2.1. Case study areas

The case-study areas TRA1 (Traditional Residential Area 1) and FRA2 (Formal Residential Area 2) were chosen for their apparent variation of urban textures. In each area, an East-West (EW) and a North-South (NS) oriented urban canyon were chosen for the comparison. The urban canyons for this study are named as: TRA1EW, TRA1NS, FRA2EW and FRA2NS. Measurements were carried out in the urban canyons in autumn and in summer.

2.2. Use of microclimatic data for indoor simulations

In this study, microclimatic information was incorporated into building energy performance analysis. This uses the microclimatic data simulated using ENVI-met V4 with the field measurement data as a boundary condition for existing urban areas. Statistically significant and strong correlations were found between the measured and simulated air temperature (Ta) and relative humidity (RH) for the case-study sites (Sharmin & Steemers 2016). As the microclimatic data used in this study are generated using the actual boundary conditions for individual case-study sites, they closely predicted the actual air temperature variations that had occurred during the microclimatic monitoring (Table 1).

Table 1. Correlations between climatic variables in measured and ENVI-met (V4)-simulated scenarios

Site Name	Ta	Tmrt	*v*	RH
	Pearson's r (p value)	Pearson's r (p value)	Pearson's r (p value)	Pearson's r (p value)
TRA1EW	0.79 (0.000)	0.60 (0.01)	-0.75 (0.000)	0.72 (0.000)
TRA1NS	0.80 (0.000)	0.32 (0.7)	-0.56 (0.01)	0.71 (0.000)
FRA2EW	0.90 (0.000)	0.76 (0.000)	0.42 (0.07)	0.92 (0.000)
FRA2NS	0.87(0.000)	0.68 (0.001)	0.69 (0.002)	0.75 (0.000)

2.3. Selection of model rooms

Both east-west (EW) and north-south (NS) oriented urban canyons are examined in the traditional and formal sites. In each east-west urban canyon, two opposite buildings located at the middle-length of the canyon are chosen, one of which is north-facing and the other one south-facing. Likewise, an east-facing and a west-facing building are chosen in the north-south oriented canyons. In the case of TRA1EW, two buildings on each side of the canyon are selected to see the impact of horizontal location.

The first and the top floor of each building are considered assuming that the first floor will be affected by the mutual shading conditions inside the canyon, whereas the top floor will be subjected to the highest solar exposure. Each floor is divided into 5m x 5m rooms. For easy comparison, similar floor-plans are assumed throughout the buildings rather than the actual layout. Energy calculations were carried out for the middle rooms at the front facade. Figure 1 shows the location of the case study buildings and studied rooms in each urban canyon.

2.4. IES-VE model set-up

Indoor conditions are compared in terms of room air temperature, solar gain and natural ventilation conditions. Table 2 lists the thermal conditions, systems, internal gain, air exchanges and construction details for the model set-up in IES-VE. In IES-VE, solar gain is considered as the solar radiation absorbed on the internal surfaces of the room, plus solar radiation absorbed in glazing and transferred to the room by conduction.

Natural ventilation is compared in IES-Ve with *MacroFlo ext vent* defined as the sum of *MacroFlo* calculated air flows entering the room from the external environment. *MacroFlo* is the airflow simulation program in IES-VE for analysing infiltration and natural ventilation in buildings. Opening types and pressure differences are the main parameters considered during the airflow calculations in *MacroFlo*. Airflow rate q_n (m^3/s) is calculated using the following equation (Cheng et al. 2016):

$$q_n = C_d A_{op} \sqrt{2\Delta P/\rho} \quad (1)$$

Here, C_d is the discharge coefficient specified to be 0.62 in IES-VE, applied when openings have a small ratio to the adjacent space; ΔP *(Pa)* is the pressure difference across the opening; ρ (kg/m3) is the density of the incoming air; and A_{op} (m^2) is the net open area of the orifice (opening).

Energy performance is examined by comparing the cooling plant sensible load defined as: "the sensible cooling (non-negative) supplied to the room by its *Apache System room conditioning plant* or *ApacheHVAC* room units (radiators, direct acting heaters and chilled beams)". The dynamic thermal simulation in IES-VE is carried out by the *ApacheSim programme*. *ApacheSim* is established on the fundamental mathematical modelling of the heat transfer process occurring within and around the building (IES Virtual Environment, 2016).

Internal gain and construction details for the model set-up in the cooling load scenario is the same as the indoor air temperature scenario. Table 3 lists the thermal conditions, systems and air exchanges for the models in the cooling load scenario.

2.4.1. Internal gain

Internal gain has been adopted from the IES-VE ASHRAE database for a single-family housing. Internal gains from lighting, people and miscellaneous household equipment are considered. A customised occupancy profile for a family of six in Dhaka, as mentioned below, is used in the study.

2.4.2. Occupancy profile

The occupancy profile is assumed for a typical family structure considering the socio-cultural situations in Dhaka city. The family is made up of two working parents with two school-going children, one grandparent and a maid. In a working day, 30% occupancy is assumed between 08:00-14:00 with the grandparent and maid at home. 60% occupancy is assumed from 14:00 after the children return from the school. Full occupancy is assumed at 18:00 after both parents return from work. During weekends, 60% occupancy is assumed between 10:00-12:00 and 30% between 16:00-21:00. Full occupancy is assumed for the rest of the day.

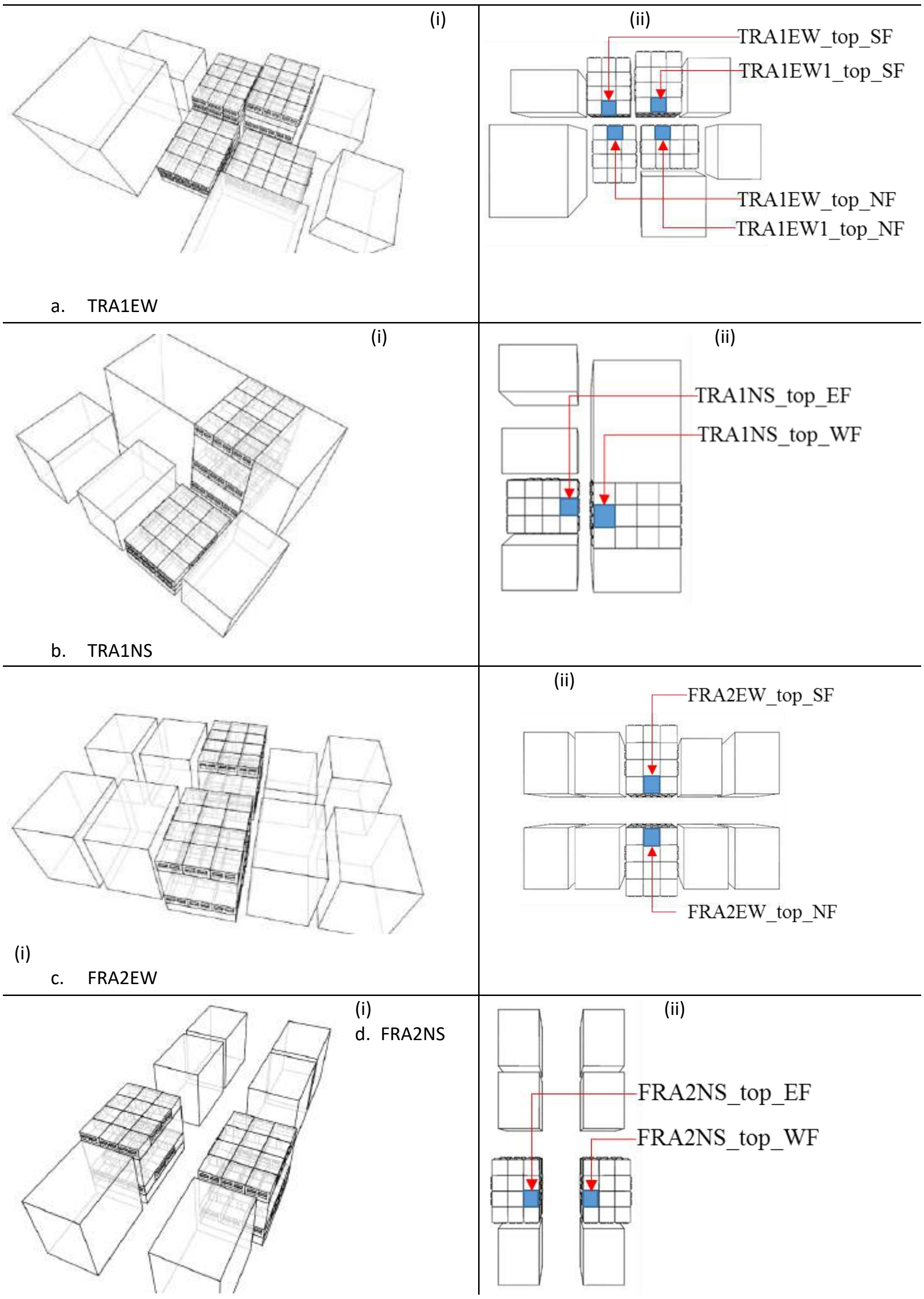

Figure 1. Perspective and top views of the case-study models for energy simulations TRA1EW, b. TRA1NS, c. FRA2EW and d. FRA2NS.

2.4.3. Opening type

For indoor air temperature analysis, sliding windows with a 50% openable area are selected as these are the most common window types in Dhaka. Considering the typical indoor comfort range between 24.0^{0}C and 33.0^{0}C (Mallick, 1996), windows are set to open when the indoor air temperature exceeds 24.0^{0}C and below 35.0^{0}C. Beyond these limits, windows are set to remain closed. It is assumed that above 35.0^{0}C air temperature, natural ventilation will increase thermal discomfort.

Table 2. Model Set-up in IES-VE for evaluating indoor air temperature

<table>
<tr><td>Building Template Manager: Thermal Conditions</td><td rowspan="8"></td><td>Construction</td></tr>
<tr><td>○ Building regulations: Heated or occupied room
○ Room conditions:
○ Heating: Heating Profile> Off continuously
○ DHW: Consumption> 0.0000 l/(h.pers)
○ Cooling: Off continuously
○ Plant: (auxiliary energy)> Off continuously</td><td rowspan="7">○ Roof:
Customised Roof for Dhaka
U – value: 2.9797 W/m^2K,
Total R value: 0.1956 m^2K/W,
Thickness: 228.3 mm
Composition: Felt/Bitumen Layers 12.7mm, Plaster (Dense) 6.3 mm,
Cast Concrete (Dense) 203mm, Plaster (Dense) 6.3 mm
○ Ground /exposed floor:
IES-VE Construction database
Name: Solid ground floor
U – value: 1.3479 W/m^2K,
Total R value: 0.000 m^2K/W,
Thickness: 750 mm
Composition: London Clay 750mm
○ External Wall:
Customised Brick Wall for Dhaka
U – value: 2.0097 W/m^2K,
Total R-value: 0.3276 m^2K/W,
Thickness: 266mm
Composition: Plaster (Dense) 6.3 mm, Brickwork 254mm, Plaster (Dense) 6.3 mm
○ External glazing:
Customised External glazing for Dhaka
U-value: 5.1742 W/m^2K
Thickness: 6mm
Composition: Outer Pane 6mm
○ Wooden Door:
U-value: 2.194 W/m^2K
Thickness: 40mm
○ Internal Partition:
Customised Internal Partition for Dhaka
U – value: 2.0411 W/m^2K,
Total R value: 0.2299 m2K/W,
Thickness: 139.6mm
Composition: Plaster (Lightweight) 6.3 mm, Brickwork 127mm, Plaster (Lightweight) 6.3 mm
○ Internal glazing:
Customised Internal glazing for Dhaka
U-value: 5.1742 W/m^2K</td></tr>
<tr><td>System</td></tr>
<tr><td>○ HVAC system: None
○ Auxiliary vent: None
○ DHW system: None
○ System outside air-supply: Off continuously</td></tr>
<tr><td>Air Exchanges</td></tr>
<tr><td>○ Natural Ventilation: Max Flow: 4.000, Unit: ach, Variation- when indoor air temperature exceeds 24^0C and remains below 35^0C, Adjacent condition: external air
○ Infiltration: Max Flow: 0.250[1], Unit: ach, on continuously, Adjacent condition: external air</td></tr>
<tr><td>Internal gain</td></tr>
<tr><td>○ Fluorescent Lighting: Reference: 1 - Single Family Lighting, Max sensible-10.764 W/m^2, Max power- 10.764 W/m^2, Rad Frac- 0.45, Fuel-Electricity, Variation- Occupancy Dhaka 6 member family_Weekly Profile, Dimming- off continuously
○ People: Reference: 225 - Single Family - 400, Max sensible- 65.941 W/person, Max Latent Gain-30.772 W/person, Occupancy- 37.161 m^2/person, Variation- Occupancy Dhaka 6 member family_Weekly Profile, Dimming- off continuously

○ Miscellaneous: 0.4 - Single Fam Equip, Max sensible- 4.306 W/m2, Max Latent Gain– 0 W/ m^2, Max power- 4.306 W/m^2, Rad Frac- 0.22, Fuel-Electricity, Variation- Occupancy Dhaka 6-member family_Weekly Profile</td></tr>
</table>

[1] The value represents a theoretical condition. Actual infiltration rate in a tropical country context would be much higher. This has been discussed in the limitations.

Table 3. Model Set-up for IES-VE model for the cooling load scenario

Building Template Manager: Thermal Conditions		**System**
○ **Building regulations:** Heated or occupied room ○ **Room conditions:** ○ **Heating**: Heating Profile> Off continuously ○ **DHW**: Consumption> 0.0000 l/(h.pers) ○ **Cooling**: Cooling system_Dhaka weekly (when outdoor air temperature exceeds 28^{0}C) **Set point**: Constant at 26.0^{0}C ○ **Plant:** (auxiliary energy)> Set to cooling profile		○ **HVAC system**: Dhaka System **Cooling mechanism:** Air conditioning **Fuel:** Electricity ○ **Auxiliary vent**: same as HVAC ○ **DHW system**: None ○ **System outside air-supply**: Set to cooling profile
Air Exchanges		
○ **Natural Ventilation:** Max Flow: 4.000, Unit: ach, Variation- when outdoor air temperature is below or equal to 28.0^{0}C, Adjacent condition: external air ○ **Infiltration:** Max Flow: 0.250[2], Unit: ach, on continuously, Adjacent condition: external air		

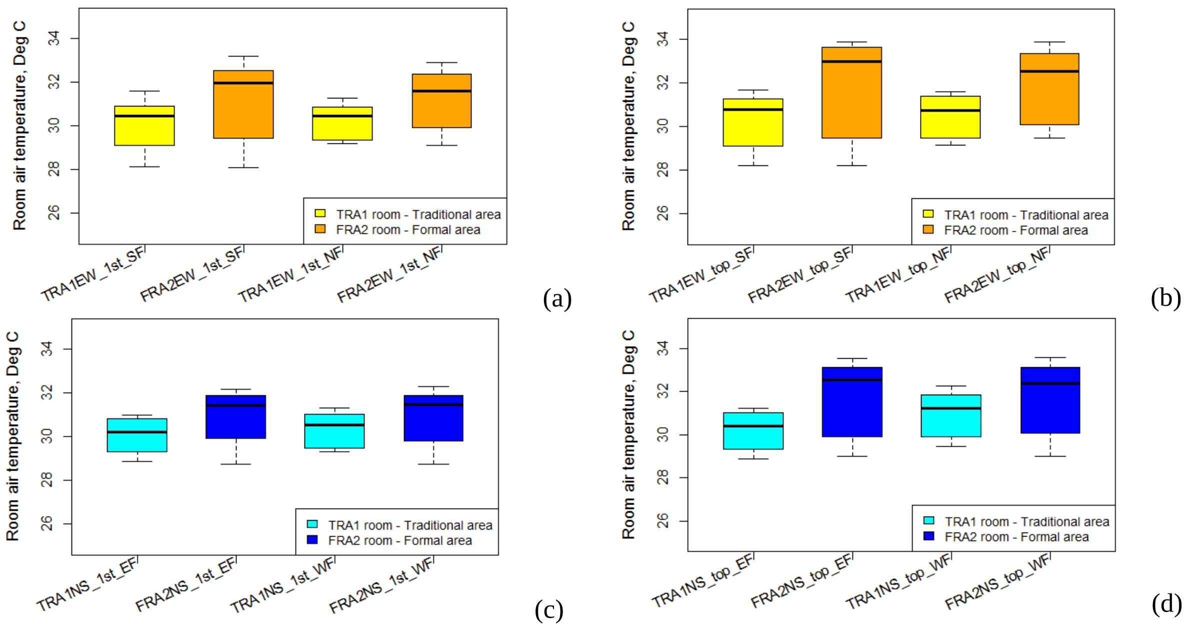

Figure 2 Room air temperature per hour over 24 hours: a. 1st floors in EW canyons, b. top floors in EW canyons, c. 1st floors in NS canyons and d. top floors in NS canyons

For cooling load analysis, windows are set to open when outdoor air temperature is less than or equal to 28.0^{0}C. The cooling system is activated when the temperature exceeds 28.0^{0}C. 28.0^{0}C is chosen as it is between the halfway in the comfort limit. Cooling set point temperature is set to 26.0^{0}C as this is typical to the case study area.

[2] The value represents a theoretical condition. Actual infiltration rate in a tropical country context would be much higher. This has been discussed in the limitations.

2.4.4. Air exchanges

For indoor air temperature analysis, air exchanges occur through natural ventilations with 4 air changes an hour (ach) and infiltration that is turned on continuously with 0.250 ach.

3. Results

3.1. Indoor air temperature analysis

3.1.1. Room air temperature

Comparing the mean indoor air temperature, rooms in traditional areas are found to be 0.6 - 1.6^{0}C cooler than the corresponding rooms in the formal areas in both EW and NS canyons. Figure 2 shows the boxplots of individual room air temperatures on an hourly basis for both 1st and top floors in EW and NS canyons. Each room air temperature is presented in terms of median, upper quartile, lower quartile, maximum and minimum values. Three-dimensional graphical images of air temperature ranges in the subject rooms are presented in Figure 3 and Figure 4.

The maximum temperature (33.9^{0}C) is found on the top floors in the EW canyon in the formal area in rooms FRA2EW_top_SF and FRA2EW_top_NF. The reason for top floor rooms in the EW canyons being warmer than rooms in the NS canyon is that EW canyons are subjected to higher and longer solar exposure. Top floors in the formal area are on average 2.2^{0}C warmer than the top floors in the traditional area. Due to the diversity of building heights, the top floors of lower buildings in traditional areas are subjected to mutual shading from the surrounding buildings, whereas top floors in the formal area are mostly exposed to direct solar radiation due to their equal heights. Again, top floors of tall buildings in the traditional area have a slightly lower temperature than the top floors in the formal area due to cooler outdoor microclimatic conditions in the former. Lowest room air temperature (28.1^{0}C) is found in EW canyon in rooms TRA1EW_1st_SF and FRA2EW_1st_SF. As they are located on the 1st floors, the rooms are cooler due to mutual shading from the opposite building.

The indoor comfort air temperature ranges in Dhaka for people engaged in sedentary activities, wearing ordinary clothing (0.5 clo), is between 24.0^{0}C and 33.0^{0}C in typical indoor conditions (Mallick, 1996). Following that, the average (median) air temperatures in the top floor rooms in the formal area are above the comfort limit.

3.1.2. Solar gain

Comparison of total solar gain in EW and NS canyon in Figure 5 shows that model rooms in the traditional areas for both 1st and top floors have lower solar gains than the corresponding rooms in the formal area. For the 1st floor, the difference is 30% and for the top floor, the difference is 91% on average. 1st floors in both EW and NS canyons have lower solar gains ranged between 0.77 – 1.43 kWh per room due to mutual shading, whereas all top floors in the NS canyon, except TRA1NS_top_EF, have higher (2.32 kWh per room and above) solar gains. The reason for TRA1NS_top_EF having one of the lowest solar gain (0.77 kWh per room) is that it remains under shade from the tall building located on the opposite side of the street. Here, all comparing is done on the basis of a single model room (with an area of 25m^2). The solar gain patterns in the rooms can be observed in Figure 6. It shows that rooms in the traditional area are better protected from high solar gain due to greater mutual shading. Since the excessive solar gain can increase the indoor air temperature, rooms in the traditional area have fewer chances of becoming overheated than those in the formal area.

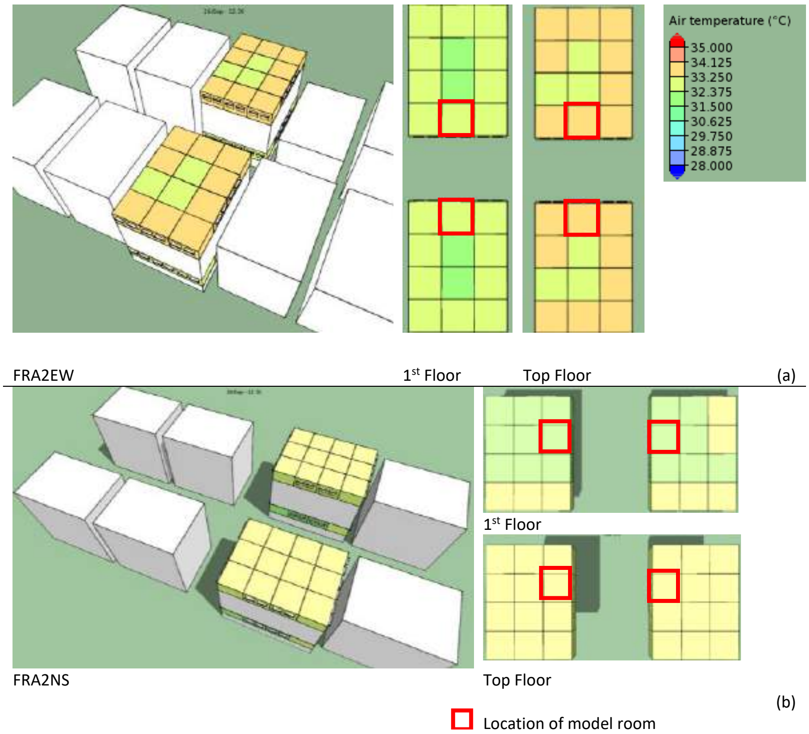

Figure 3. Room air temperature ranges in the formal area for 1st floors and top floors: a. FRA2EW, b. FRA2NS

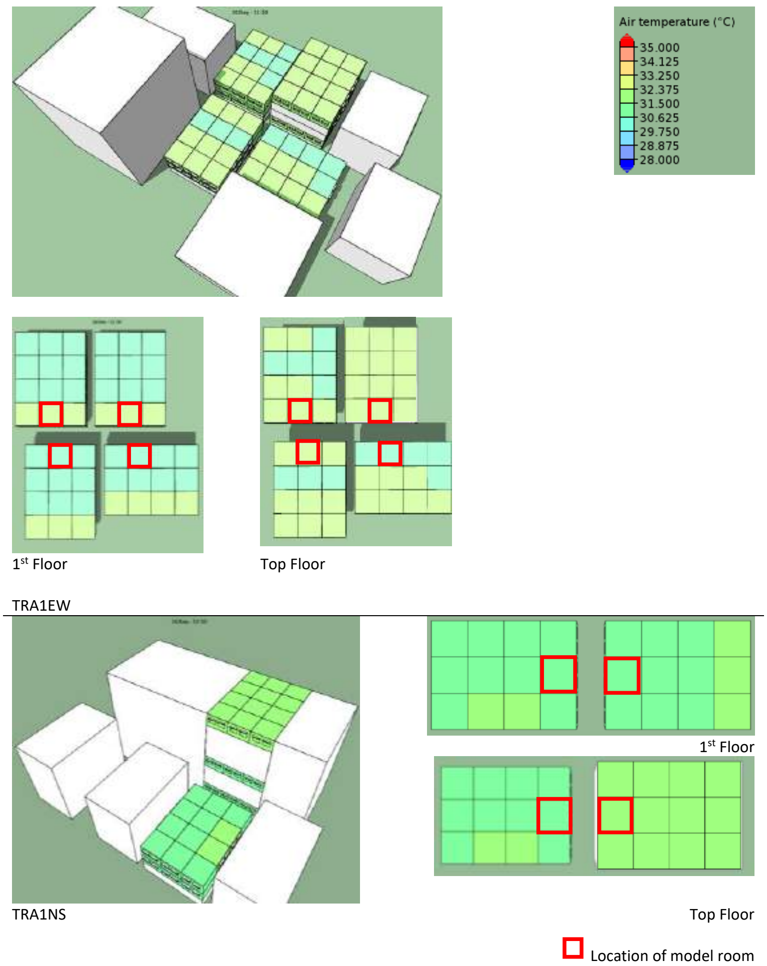

Figure 4. Room air temperature ranges in the traditional area for 1st floors and top floors: a. TRA1EW, b. TRA12NS

3.1.3. MacroFlo ext vent

The incoming air flow inside the room from the external environment calculated by the *MacroFlo programme* in IES-VE is defined as *MacroFlo ext vent*. Apparently, the differences in indoor air flow conditions between the 1st and top floor in both EW and NS canyons are insignificant. The boundary condition for wind speed at 10m height is used for IES-VE simulations, however this does not seem to have an impact on indoor ventilation conditions for rooms at different heights. The reason is that all case-study buildings for the IES-VE simulations are 6-storied or lower, except a 9-storied one in the traditional area. Therefore, the model rooms in this building, TRA1NS_1st_WF and TRA1NS_top_WF, show the highest variation in indoor airflow.

From the ventilation pattern in Figure 7, higher MacroFlo ext vent is observed in south-facing and west-facing rooms in the traditional area. This is because wind direction was predominantly from the south and south-west directions during the simulation periods. Rooms in the formal area have lower ventilation due to lower wind speed boundary conditions.

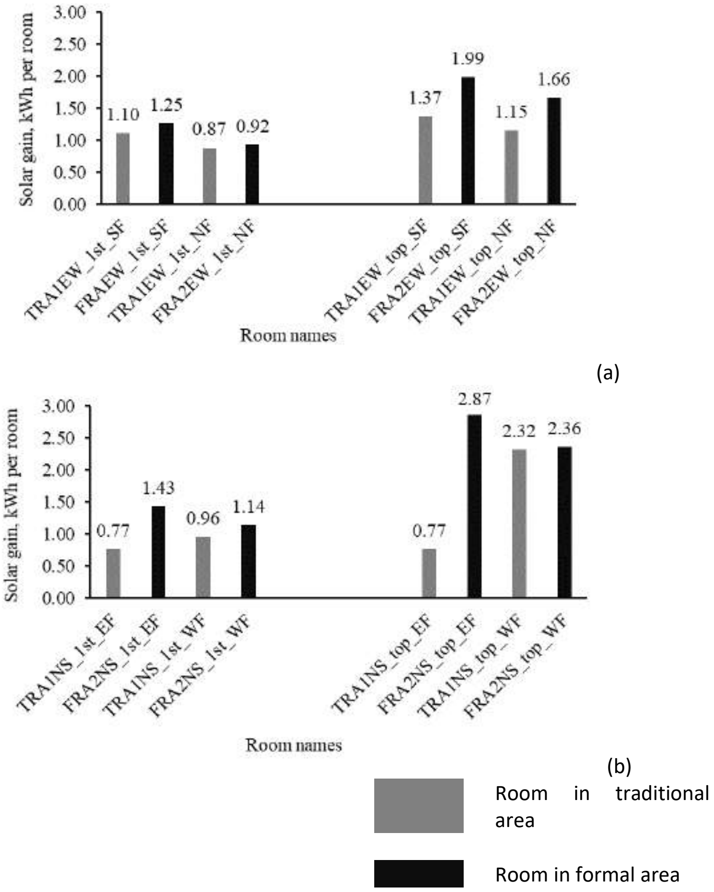

Figure 5. Total solar gain (kWh) in both 1st and top floors over 24 hours in a. EW canyon, b. NS canyon

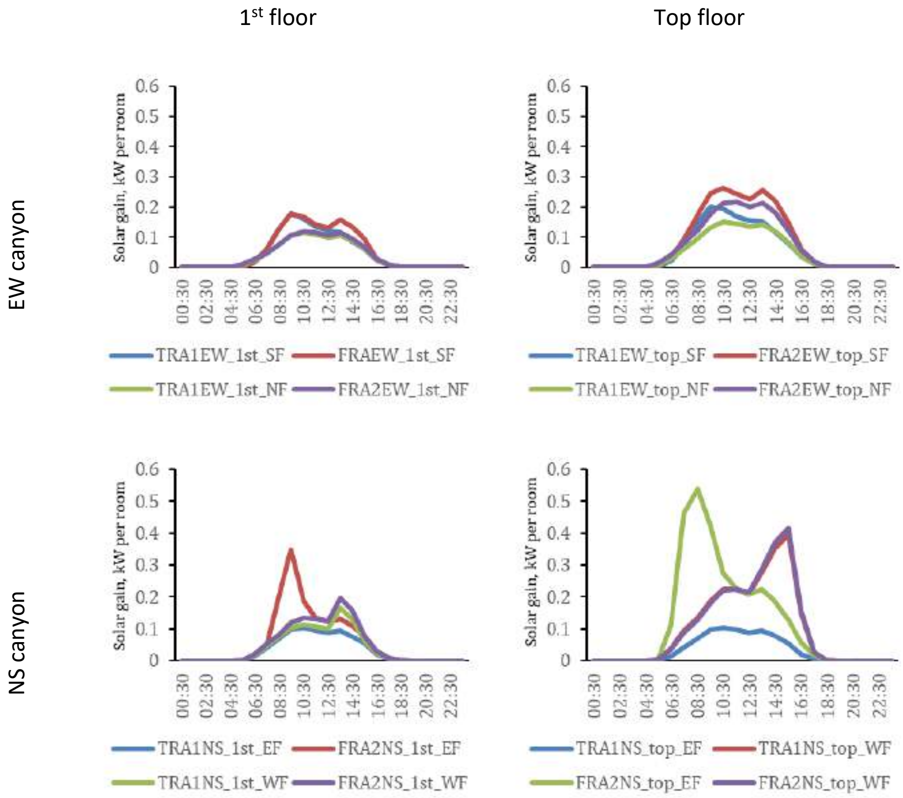

Figure 6. Solar gain (kW per hour) pattern in the model rooms

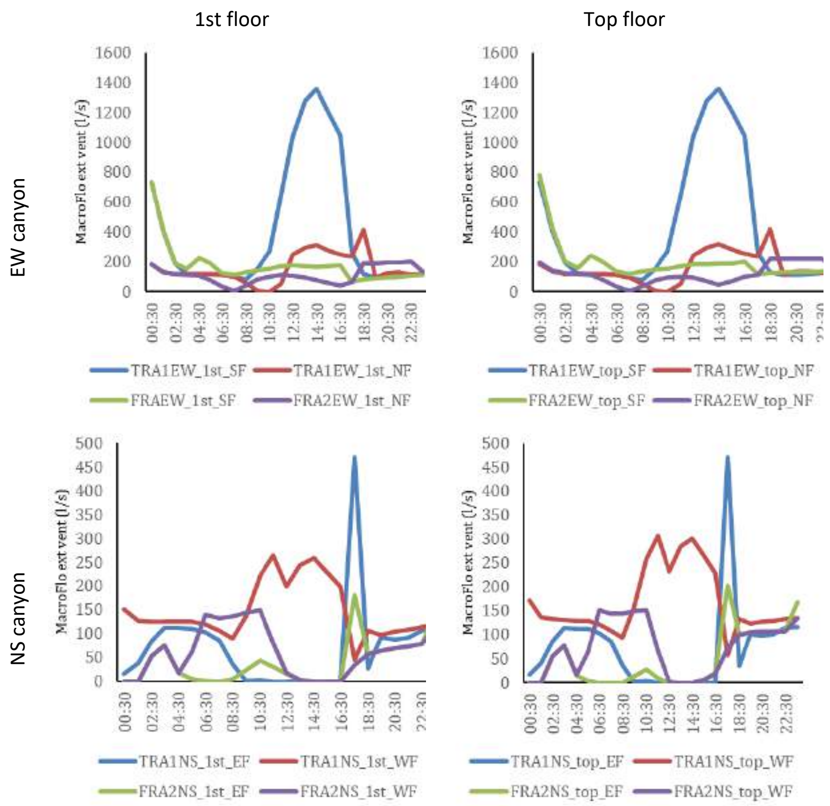

Figure 7. MacroFlo ext vent (l/s) per hour for 1st and top floors in EW and NS canyons

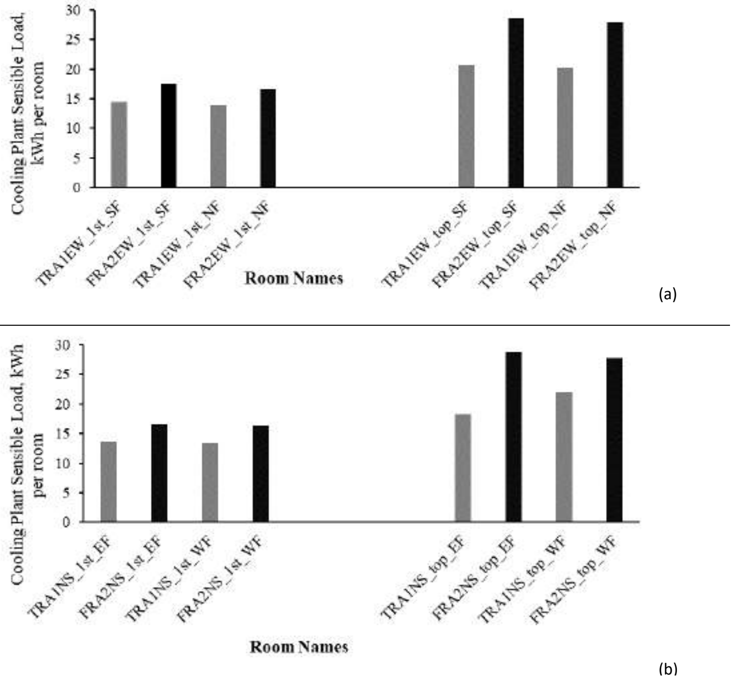

Figure 8. Comparison of total cooling load in 24 hours in a. EW canyon and b. NS canyon

3.1. Cooling load analysis

Comparison of the total cooling load over 24 hours in the east-west (EW) and the north-south (NS) canyons reveals that top floors consume 55% more energy (60% for NS canyons) than the 1st floors. Figure 8 (a, b) shows the cooling loads in EW and NS canyons respectively for both 1st and top floors. South-facing (SF) and north-facing (NF) rooms are represented in EW canyons and east-facing (EF) and west-facing (WF) rooms in NS canyons. Apparently, the south-facing and east-facing top floor rooms in the formal areas, namely FRA2EW_top_SF and FRA2NS_top_EF, consume the highest amount of energy for cooling. The other top floors in the formal area also consume a similar amount of cooling energy. This is due to the lack of mutual shading on the top floors of the formal area as all buildings have mostly similar heights.

In order to enable equal comparison in terms of cooling energy consumption, this study has used the model room as the unit of area ($25m^2$). Thus, the energy indicator is kWh, denoted for every $25m^2$.

For both 1st and top floors and EW and NS oriented canyons, rooms in the traditional area consume less energy than the rooms in the formal area. In the case of 1st-floor rooms, the south-facing (SF) and north-facing (NF) rooms in the formal areas (FRA2EW_1st_SF, FRA2EW_1st_NF) use 21% and 20% more energy than the corresponding rooms in the traditional area to maintain indoor comfort. For east-facing and west-facing rooms the differences are 23% and 21% respectively. The differences are far more evident on the top floors. For example, the south-facing, north-facing, east-facing and west-facing top floor rooms in the formal areas use 38%, 38%, 57% and 26% more energy respectively than the corresponding rooms in the traditional area. This can be explained by the air temperature differences between the areas as well as greater mutual shading in the traditional area due to the diversity of building heights.

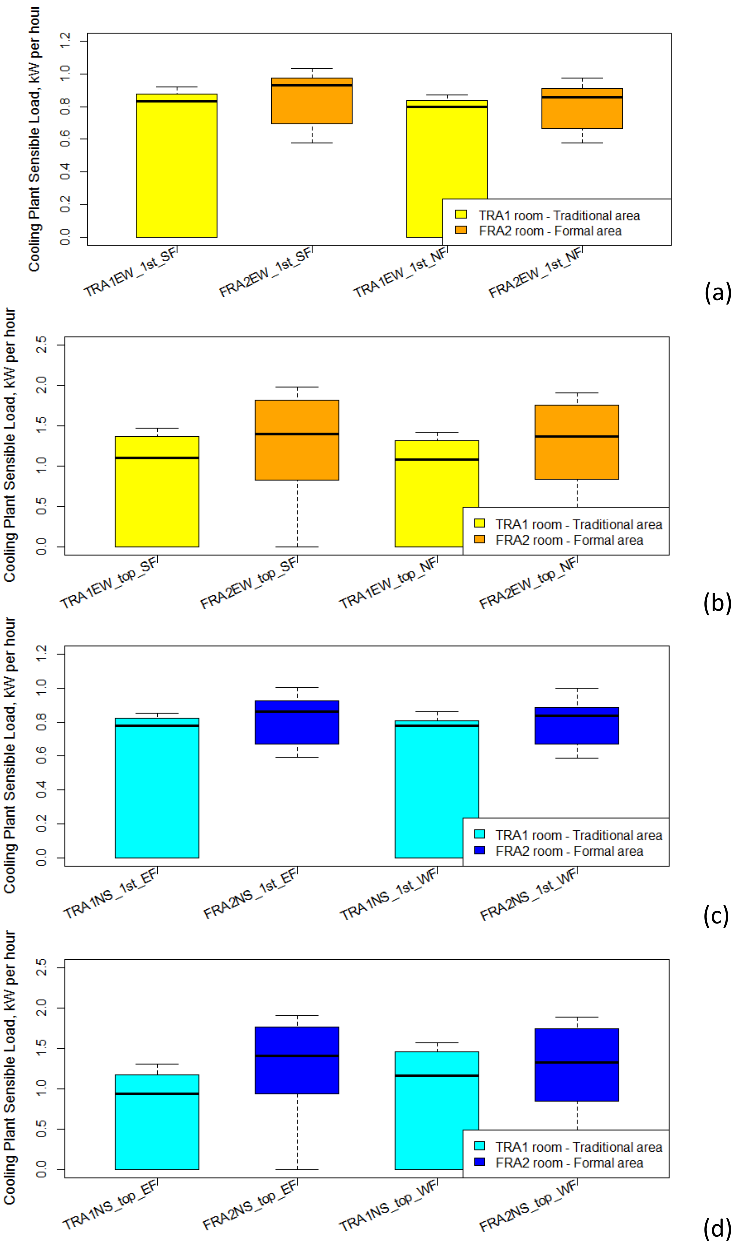

Figure 9. Average cooling load per hour over 24 hours: a. 1st floors in EW canyons, b. top floors in EW canyons, c. 1st floors in NS canyons and d. top floors in NS canyons

Figure 9 represents the average cooling load per hour over 24 hours for 1st floors and top floors in EW and NS canyons. Information for each individual room is presented in separate box plots showing the median, upper quartile, lower quartile, maximum and minimum values. It is evident that the 1st-floor rooms in the formal area are always in a cooling mode. On the other hand, all rooms in the traditional area take on a natural ventilation mode at some point of the day when the outside air temperature reduces to 28.0^{0}C or below. The cooling system is deactivated when this situation is reached. The IQRs (Inter-quartile range[3]) in the boxplot show that cooling load amounts in the traditional areas are clustered in the lower ranges (0.0-1.4 kW per room) of the scale, whereas the same for the formal areas are bunched along the higher ranges (0.7-1.8 kW per room).

[3] Represents 50% data in a boxplot

4. Limitations

The study has some limitations. Firstly, the energy simulation in this study, does not take into account the daylighting potentials. Even though the need for artificial lighting during daytime can be quite high considering the high-density urban context, it can be assumed that daylighting will save some amount of energy consumption. However, cooling energy is considered to be more important than lighting energy (during daytime) in this particular type of climate. Since the main purpose of the study is to look into the impact of urban geometry on building energy consumption, such shortcomings do not generate any critical problems.

Secondly, this study has used the default infiltration rates in IES-VE for the analysis of indoor conditions. Since the purpose here is to understand the relative differences among the models, the infiltration rate does not affect the outcome as it remains constant across the models. Nevertheless, to avoid confusion and to recreate actual situation in a tropical climate more accurately, future research should apply a more context-specific value for infiltration rates. For similar climates in Singapore, a typical infiltration rate for building energy simulation is 0.600ach with VAV (Variable Air Volume) system for centrifugal chiller plants (Shah et al. 2002).

5. Conclusion

This study has analysed indoor air temperature conditions and energy performance of a traditional and a formal residential area in a tropical, warm-humid context. The purpose of the study is to examine the effect of urban geometry on the indoor conditions of individual buildings in terms of room air temperature, solar gain and ventilation through external windows and energy demand for cooling to maintain indoor comfort conditions. The study has found that diversity in urban geometry in deep urban canyons, as observed in the Traditional Residential Areas, is helpful in reducing indoor air temperature and cooling load requirements. On average, the cooling load in model rooms in the formal area is 21% higher for 1st floors (40% for top floors) compared to the corresponding rooms in the traditional area. In terms of solar gains, the difference was 30% for the 1st floors and 91% for the top floors, with rooms in the formal area having the higher ranges. Consequently, the room air temperature in the traditional area was found to be 0.6-1.6^{0}C lower than those in the formal area. This has important implications for reducing indoor air temperature in a tropical warm-humid context. Concerning the climate, natural ventilation is another essential strategy to aid in the cooling of interior spaces through passive means. Due to apparent higher air-flow in the urban canyons in the traditional area, the interior airflow in the adjacent buildings was also higher.

There are two main reasons that contribute to better indoor conditions in the traditional area compared to the formal area. Firstly, the diversity in urban geometry in deep urban canyons ameliorates the outdoor microclimatic conditions by lowering air temperature and enhancing the airflow. Secondly, the variations in building heights provide necessary mutual-shading for the exposed roofs or top floors of the lower buildings as well as the flanking vertical facades. In the formal area, on the other hand, roofs or top floors are always exposed to high solar gain due to the equal height of the buildings. Additionally, because of wider urban canyons, vertical walls in the formal area receive greater solar radiation. Finally, the reduced airflow resulting from uniform urban morphology worsens the indoor ventilation. Overall, the findings of this study suggest that the choice of urban form has a significant impact on the indoor conditions of the adjacent buildings. This finding can be applied in practice to combat challenges of tropical climate in terms of urban planning and design guidelines by modifying urban geometry and incorporating diversity to achieve favourable indoor and outdoor conditions.

6. Acknowledgements

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Temperature studies of the effect of glazed facades and vegetation on urban heat islands in Brasilia

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Abstract: Brasilia is the designed capital city of Brazil inaugurated in 1960. Its plane like form has in its wings the residential sectors, and in the centre of the main body are sectors which compose the gregarious scale like the hotel and commercial sectors. Although Brasilia is not even 60 years old, it already has more than two million people and urban problems similar to secular metropolisis. As the city grows in an incessant pace, greenery is left aside in favour of buildings, which are now more robust and completely glazed, like those commonly found in countries north of the equator. This insanity of building relentlessly glass boxes in the tropics, is a trend that needs to be reversed and calls for an urgent sustainable agenda. This research aimed to analyze the consequences of this new architectural language, its influence on urban heat islands, microclimates, healthiness, and environmental comfort. Urban fragments formed by edifices with glazed envelopes were compared to buildings with sun protection elements. Urban spaces with and without vegetation were also compared. Thermographic photos illustrate the thermal intensity of distinct surfaces. Large temperature differences of more than 10ºC were registered on different surfaces and reflected on the adjacent microclimates, causing discomfort to the pedestrians, and an indication of diurnal urban heat islands.

Keywords: Urban heat island, glazed facades, vegetation, Brasilia

1. Introduction

Urban centres are usually places with the highest temperature indexes due to the heat islands, and it is possible to notice a great difference of temperature in relation to areas farthest from the centre. Each city has its characteristics and therefore the intensity and timing of the occurrence of heat islands may vary. The phenomenon can be aggravated by several reasons. In this research, the focus is on the use of glass on façades, where, especially the more reflective, can be one of the contributors to the occurrence of diurnal urban heat islands. Increase in energy consumption, mainly by the use of air conditioning, is another interference, in order to compensate the excessive heat and create climates more pleasant to the internal environments, generating a greater waste of money. Furthermore, thermal discomfort is imposed on the population that has to live or pass through the place with buildings that have glazed facades, due to excessive heat and glare.

2. Climatic Context of Brasilia

In arid and semi-arid regions, like Brasilia, the annual climatic cycle presents wide variations between the seasons, with particular significance in the case of ambient temperature and humidity, not only yearly but also on a daily basis. Due to the usually high percentage of clear days, the quantity and intensity of solar radiation is also relevant. The heat island effect due to urban construction coupled with these climatic features, are during the warm and dry season strongly negative pressures, enlarging the strain on urban microclimates.

A climate is usually considered after a period of 35 years of observations which is the climatic variation cycle, and the minimum necessary to configure the climatic conditions of a certain location. Since Brasilia itself is only 58 years old, and during the first years there was not much data registered, the characterisation of its climate is made a bit more difficult and complicated. It is also necessary to mention that the more the city grows, more its local climate tends to be affected, especially by the heat island effect. Studies from the Meteorological Centre of Brasilia (Inmet, 1996) indicate that the city has already heated up around 2ºC due to fast growth and development over the years (Figure 1). The study of the next climatic cycle, which should come out around 2025, will most certainly present an even more serious situation.

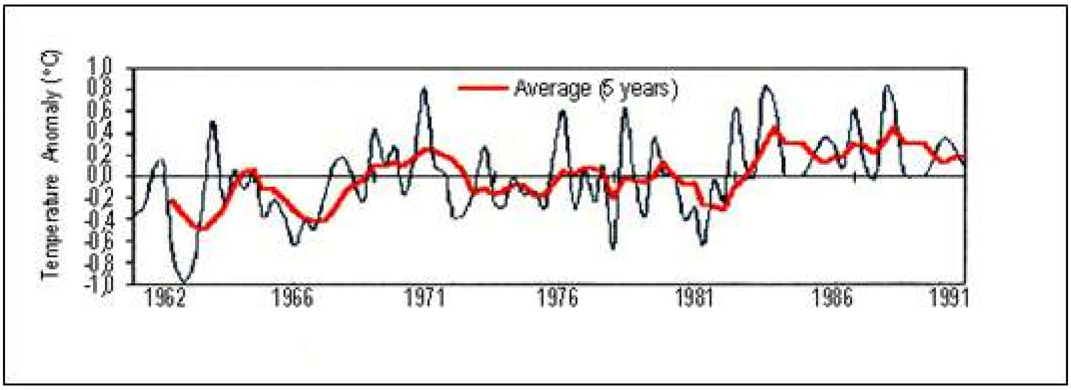


Figure 1. Temperature anomaly for Brasilia 1963-1995. (Inmet, 1996)

Brasilia is situated at more than 1000 metres above sea level. In accordance with the Koppen classification, internationally adopted, the climate types found in the DF are tropical aw and tropical of altitude cwa and cwb. In Nimer's classification, an adaptation for Brazil of Koppen's classification, the climate of the DF presents two subcategories: hot climate and sub-hot climate. In this type of climate there are two distinguished periods, one being the hot and rainy summer, the other the hot and dry winter. Rain is abundant in November, December, and January, contrary to what happens in June, July, and August. Between January and March the temperature increases and during the winter months starting in June it falls a bit. But day and night temperature differences also increases. Many times these temperature gaps are more than 10°C. Therefore, although the medium yearly temperature is around 22°C it is a false impression to think the climate is comfortable all year round.

The average humidity is 60%, which is not overall low because it is connected with the great temperature oscillations that occur during this time of year. Nonetheless, during the months of August and September, the relative humidity values are around 12%, dryness typical of a desert. These occur from 12:00 to 15:00, period of greatest insolation and evaporation of the day.

The low humidity can be very uncomfortable, especially to those who are not acclimatised to the region. It has been observed in the DF that during the dry season there is a difference of around 5% in relative humidity between Brasilia and its outskirts (Gouvea, 1995).

During this time of the year, rain is very scarce and with less than 5% of the annual precipitation, can be for many months non-existent. It has been registered 120 days without rain as can be seen in Figure 2.

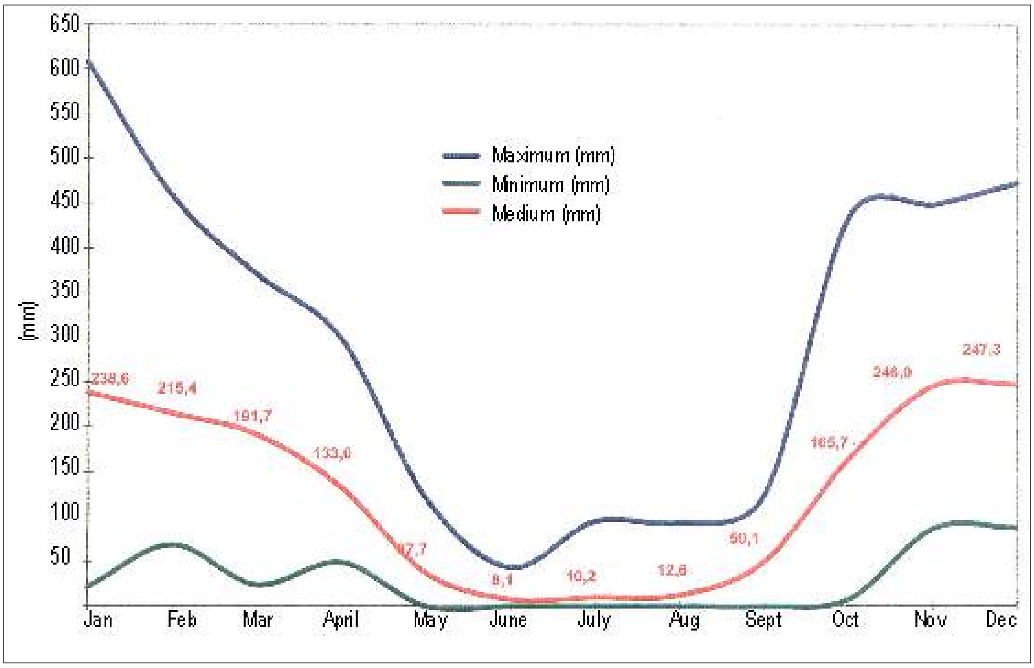


Figure 2. Distribution of the precipitation values through the years 1963-1995. (Inmet, 1996)

During this period, the grass dries up completely as does most of the local vegetation. Figures 3 and 4 show how the landscape changes from the rainy to the dry season. Since the landscape becomes arid and without moisture, it is very common for fires to occur.

Figure 3. Monumental axis in Brasilia during the hot-dry season. (Cantuaria, 2001)

Figure 4. Monumental axis in Brasilia during the hot-humid season. (Cantuaria, 2001)

3. Health Issues

During the dry period from May to October, situations of great impact occur. The high microclimatic temperatures and the lack of moisture in the air can be very unpleasant and unbearable. Due to the dryness, all the grass in public spaces dies, and airborne dust increases significantly. Health problems such as asthma, allergies, and other respiratory problems are frequent during this time of year. Skin dehydration and nose bleedings are also customary during this period. Hospitals become full of people with cases involving breathing and respiratory problems. In accordance with the Fundação Hospitalar do DF, cases of respiratory problems and allergies increase by approximately 30%. The irritated nasal mucous becomes more vulnerable to flu virus. If not treated in time, these flues can become sinusitis and pneumonia. The dry period becomes a problem of public health in the capital and educational campaigns, backed by all media, are announced.

The World Health Organisation (WHO) recommends a ‘state of alert’ in cases of relative humidity below 20%, and that all activities involving physical effort be cancelled. Furthermore, and also in accordance with WHO, District law 492/92 was created, considering relative humidity rates below 15% a case of ‘public calamity’. The law states that people working in public institutions, banks, and schools, as well as all students, should stay home due to stress, strain, and physical effort which may be hazardous to the health. Every year, since 1994, the Meteorological Institute of the Federal District has registered days in which the humidity level was below 12%. The lowest value recorded by the Centre was 9%, which is compatible to the Sahara Desert. In external places, due to the excessive dryness of the atmosphere, dead grass and bushes catch fire very easily, putting the public at risk. It should be mentioned that temperature and humidity measurements by the Meteorological Centre are taken in Brasilia itself, where more densely vegetated areas can be found. The problem is aggravated in the satellite cities and even more in the social housing settlements in the outskirts, where the urbanisation process of “land clearing” in addition to the asphalt areas, creates an environment which reduces relative humidity to extremely low levels, and also aggravates the dryness in microclimates with temperatures well above those of the Meteorological Centre.

The dry season also punishes mainly the inhabitants of the satellites and settlements, which have to live with the dust. The lack of trees, grass, and vegetation in these places, increases the wind velocity and consequently lifts dust particles. The urban surface has a larger number of obstacles, which makes it more difficult for the wind to get through. Landsberg (1981) says that in general, a city has 20 to 30% less wind than a rural area. The excessive dust and dryness will eventually lead to asthma, eye irritation, skin dryness and nose bleeding. (Cantuaria, 2001)

Specific models for the tropical and subtropical regions have to be developed because the analysis of the climate without reference to the sensations it causes to the local man are of not much application. In the case of the Federal District, the main problem as already stated is the lack of humidity. The comfort chart shown in Figure 5 is based on data of WMO where the limit of temperature for the tropics is from 20° to 29°C and humidity from 30% to 78%. Olgyay (1960) proposes 30% to 65%. It is said to be tolerable temperatures varying from 22ºC up to 30°C, considering the relative humidity does not exceed 50%. Furthermore, Gomes (1980) classifies climates as very dry those below 55%.

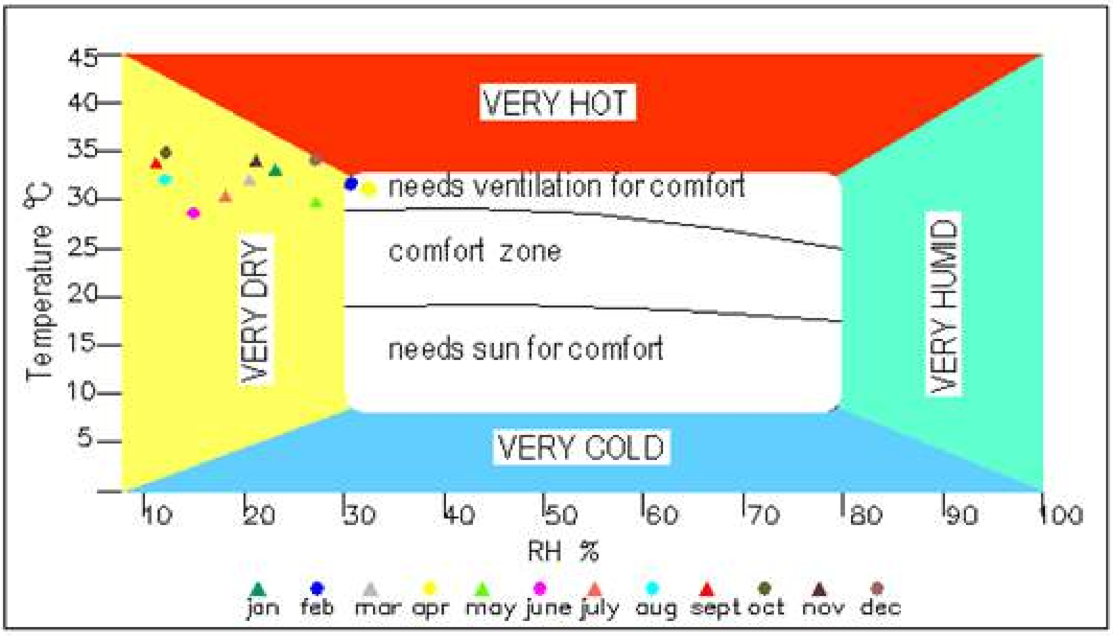


Figure 5. Monthly Mean Maximum Temperatures and Monthly Mean Minimum RH plotted on comfort graph (After WMO).

Monthly mean maximum temperatures and monthly mean minimum humidity are plotted on the chart to give a better idea of the diurnal sensation during the year. Although all months are outside the ideal comfort zone, from November to May they are within the limits accepted universally of 20% humidity. On the other hand, the dry months of the winter season, June to October, are below these limits. The chart illustrates the sensation during the dry period and makes it more evident the problem that the city has with humidity.

4. Methodology

This research focuses on urban heat islands. The method used in this study was remote sensing, where measurements of surface temperatures are made. The measurements are of the amount of energy reflected and emitted by different surfaces, by different facades, in the same urban area. Urban fragments were photographed in the South Wing and the North Wing of Brasilia.

The areas chosen to measure the heat islands were the commercial and hotel sectors, located on the north and south wings, as they have a large number of buildings with varying facades, some with almost 100% of the facade covered by glass and others with a lower percentage. Differences are due to the year of construction and renovation of the buildings. The more recent the greater the portion of the facade covered by glass as it represents a status of "wealth and trendiness".

During the fieldwork, photographs were taken using the FLIR C2 photo camera, which provides both thermal photos with the measurement of the temperatures emitted by the surfaces at the chosen points, as well as the original photos of the site. Photos were taken of the west facing facades and of the ground below the chosen buildings, at two distinct times. First in the beginning of the afternoon, from 12-15:00, when the sun is more intense and second at the beginning of the night, from 19-20:00, when it is possible to note the existence or non-existence of the islands of heat. Comparisons were made between the two photos taken at the selected locations and at their respective times. In addition to the photos, the THDL-400 Thermo-hygrometer was used to measure temperature and humidity of the general sectors at the same time.

Brasília being a planned city ensures certain prerequisites for its constructions, such as maximum height of the buildings, however, these requirements do not influence the materials that will be used on its façades. The earlier, modernist architecture of the South commercial and hotel sectors, is different from the later contemporary architecture of the North commercial and hotel sectors. It presents façades with lower percentage of glass, use of solar protections and balconies, which does not exclude the existence of buildings with a large part of its facade covered by glass, but shaded. The amount of vegetation and permeability of the soil in the North or South sectors is very small. However, the South commercial sector contains more shaded locations, compared to other sectors, in both wings. These shadows are provided by vegetation, by buildings themselves and space configurations, having a much larger number and proximity to the buildings. The relative air humidity of the city centre, which is already low, is aggravated by all these factors, especially in the dry season, which was the time chosen to illustrate this research.

5. Study Cases and Results

The areas selected for research were SCS (South Commercial Sector) and SCN (North Commercial Sector), as well as SHS (South Hotel Sector), and SHN (North Hotel Sector). These sites were chosen because they are part of the gregarious scale of Brasilia, places of meeting, socializing, and tours. The gregarious scale is shown below in red in Figure 6.

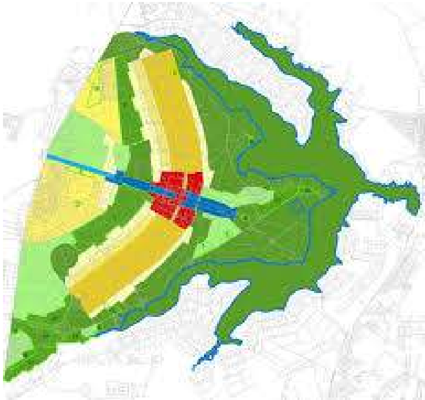
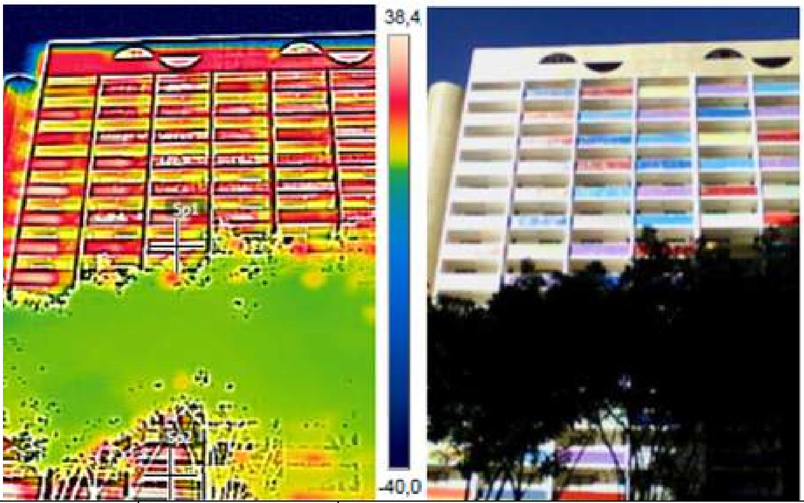


Figure 6. Map of Brasilia and its four urban scales: red is the gregarious scale, yellow the residential, blue the monumental, and green the bucolic scale. (Codeplan, 2018)

Figures 10-22 present temperature recordings and termal images of urban fragments.



Sp1	35.4ºC	Obs: Point 2, situated below the vegetation presented lower temperature due to green shading.
Sp2	24.2ºC	
Temperature: 31.9ºC		Relative Humidity: 33,2%

Figure 10. St. Plaza Hotel, daytime.

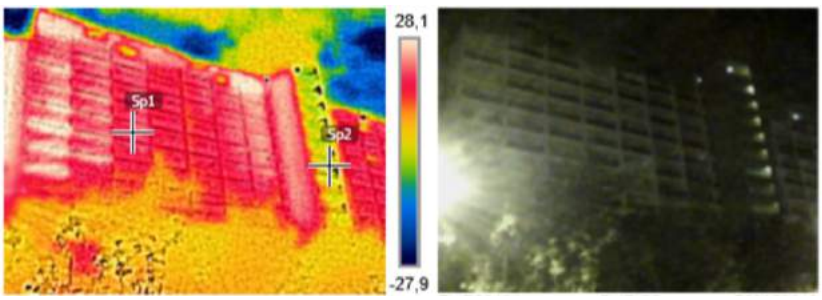


Figure 9. St. Paul, night time.

Sp1	23.9ºC	Obs: Point 2 shows the temperature difference of materials, where glass presented a lower temperature.
Sp2	17.9ºC	
Temperature: 28.4ºC		Relative Humidity: 39.3%

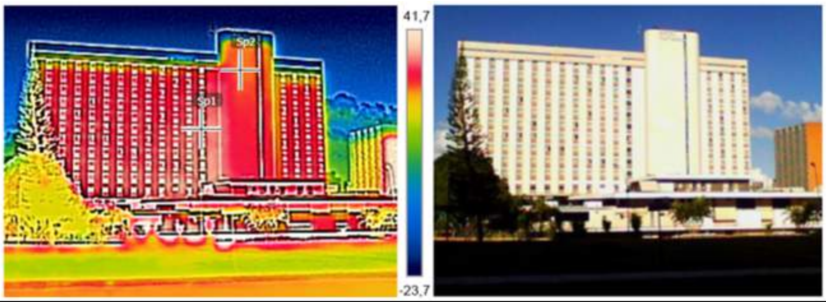


Figure 10. National Hotel, daytime.

Sp1	36,8ºC	Obs: point 1, located in one of the glass windows, had a higher temperature than point 2, as it absorbed a larger amount of radiation.
Sp2	29,5ºC	
Temperature: 31.8ºC		Relative Humidity: 33.4%

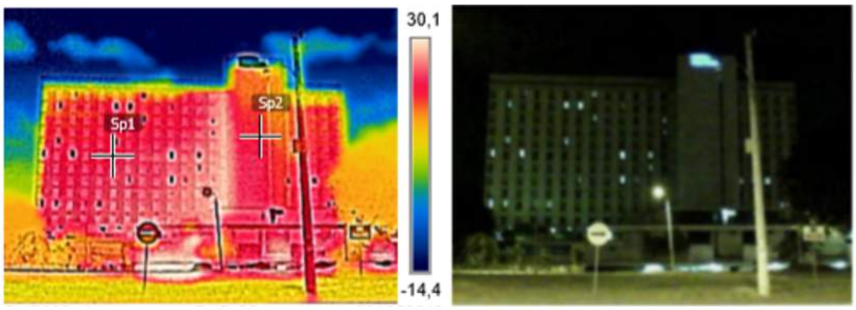


Figure 11. National Hotel, night time.

Sp1	23.6ºC	Obs: Point 1, located in the window, lost a greater amount of radiation, decreasing the temperature considerably, but point 2, located in an area where the material is concrete, lost less radiation.
Sp2	22.9ºC	
Temperature: 29.1ºC		Relative Humidity: 38.8%

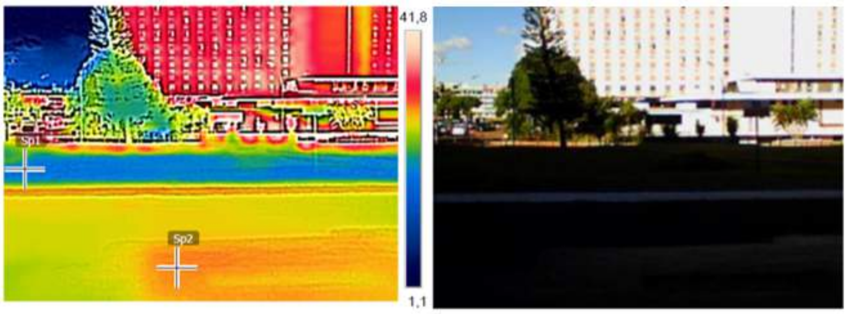


Figure 12. Ground microclimate close to the National Hotel, daytime.

Sp1	21.0ºC	Obs: Point 1, located in the vegetation, presented more than 10°C difference from point 2, located on the asphalt. Both points were shaded.
Sp2	31.2ºC	

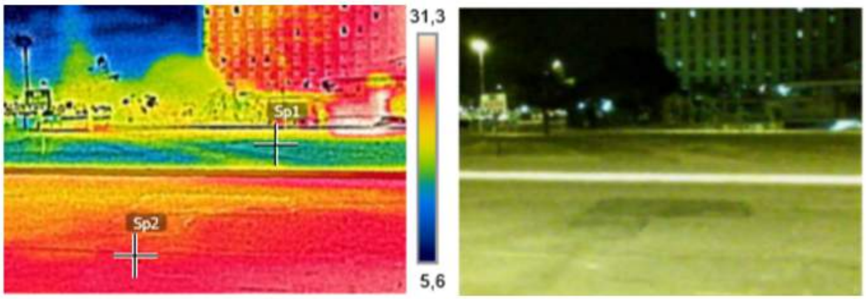


Figure 13. Ground microclimate close to the National Hotel, night time.

Sp1	18.4ºC	Obs: Point 2, situated on the asphalt, lost a greater amount of radiation compared to point 1, located in the vegetation.
Sp2	25.0ºC	

In the South Commercial Sector, data of 4 buildings were registered. Newton Rossi and Montreal buildings: On the façade, being considered the first outer skin, the Newton Rossi building has no glass, as does the Montreal building.

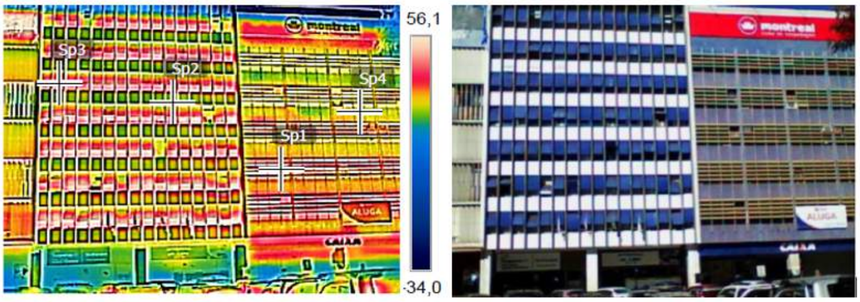


Figure 14. Newton Rossi and Montreal buildings, respectively, daytime.

Sp1	42.0ºC	Obs: Points 1 and 2 show the temperature of the windows protected by brises soleil. Points 3 and 4 show the temperature of different materials used in the façades of the buildings. It is possible to see significant temperature differences from one building to another, even though both are side by side.	
Sp2	33.9ºC		
Sp3	52.2ºC		
Sp4	35.6ºC		
Ambient Temperature: 31.5ºC		Relative Humidity: 31.8%	

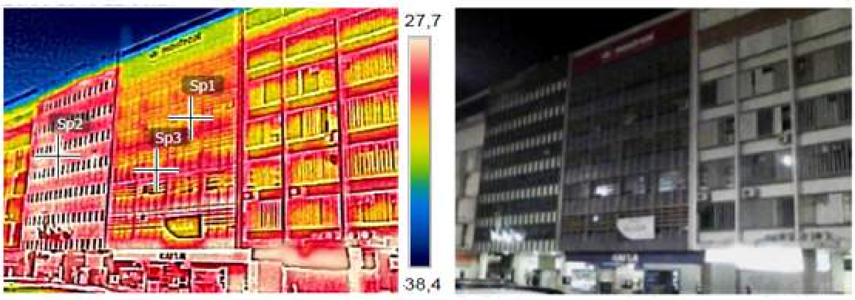


Figure 15. Newton Rossi e Montreal buildings, respectively, night time.

Sp1	22.4ºC	Obs: In the early evening the Montreal building, points 1 and 3, had a higher temperature difference between the materials, showing a great loss of radiation.	
Sp2	26.4ºC		
Sp3	24.0ºC		
Ambient Temperature 28.8ºC		Relative Humidity: 38.3%	

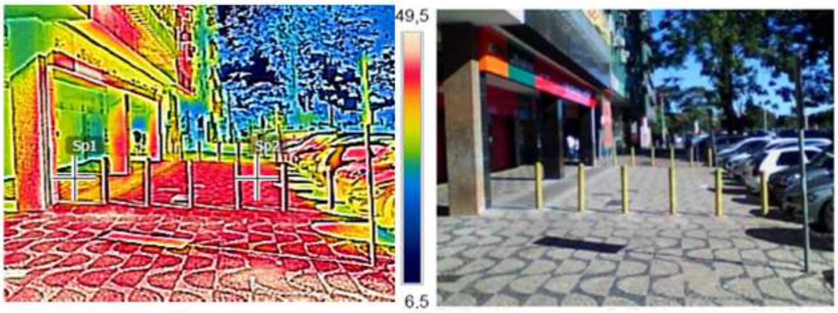


Figure 16. Ground near Newton Rossi and Montreal building, respectively, afternoon.

Sp1	34.4ºC	Obs: The temperature of the ground just ahead of the buildings is greater in point 2, because it has no protection, being exposed to the sun all day. Unlike point 1 that at certain times is shaded by buildings.
Sp2	44.4ºC	

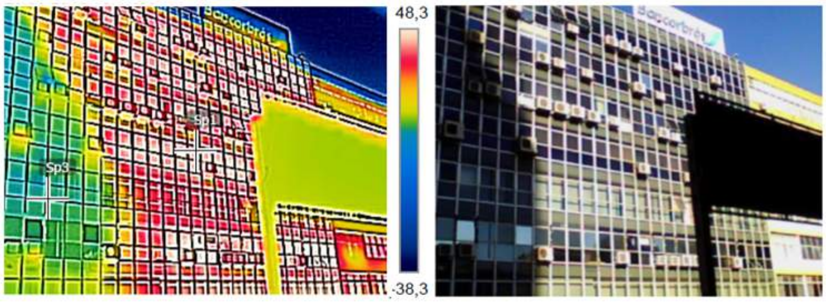


Figure 17. Bancorbrás building, daytime.

Sp1	44.5ºC	Obs: Considering the first skin of the envelope, the building has a greater percentage of glazing in relation to the others of SCS, approximately 70%. A considerable difference can be seen between exposed point 1, and point 2, shaded by vegetation.
Sp2	21.3ºC	
Ambient Temperature: 32.6ºC		Relative Humidity: 31.9%

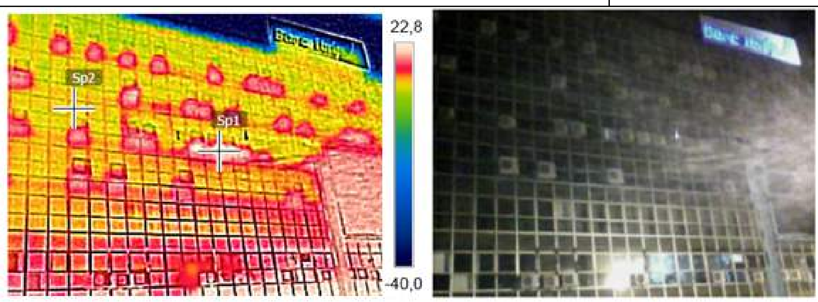


Figure 18. Bancorbrás building, night time.

Sp1	23.1ºC	Obs: During the evening it was possible to observe that the temperature of point 1, which was exposed to the sun for the longest time, fell by almost half. The continuous heat emitted by air conditioning can be clearly noted.
Sp2	18.8ºC	
Ambient Temperature: 28.7ºC		Relative Humidity: 39.0%

Brasilia Shopping: The facade is approximately 90% glazed.

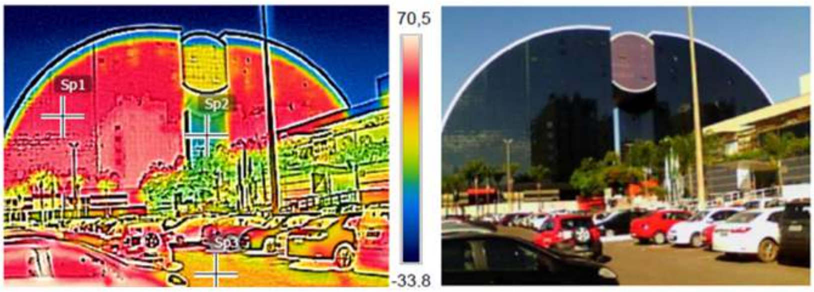


Figure 19. Brasilia Shopping, daytime.

<table>
<tr><td>Sp1</td><td>55.3ºC</td><td rowspan="3">Obs: Points 1 and 3, which were exposed to the sun, registered a higher temperature than point 2, shaded by the building.</td></tr>
<tr><td>Sp2</td><td>22.1ºC</td></tr>
<tr><td>Sp3</td><td>46.2ºC</td></tr>
<tr><td colspan="2">Ambient Temperatura: 32ºC</td><td>Relative Humidity: 31.3%</td></tr>
</table>

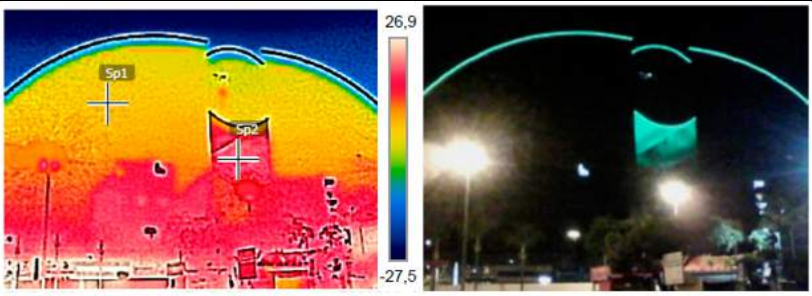


Figure 20. Brasília Shopping, night time.

<table>
<tr><td>Sp1</td><td>16.3ºC</td><td rowspan="2">Obs: The glazed façade presented a great reduction in temperature. The hottest point absorbed energy from the lighting.</td></tr>
<tr><td>Sp2</td><td>21.7ºC</td></tr>
<tr><td colspan="2">Ambient Temperature: 28.4ºC</td><td>Relative Humidity: 38.4%</td></tr>
</table>

The South Commercial Sector, with facades built with sun protection elements and containing a low amount of glass, had an average surface temperature of about 37°C during the day. It is also possible to notice that the type of solar protection influences the temperature of the façades. The South Hotel Sector (SHS) had an average temperature of 34ºC. In this sector there is also little use of glass in the facades, and mostly the buildings have balconies. Glazed facades averaged 50ºC.

During the night the surface temperature of the buildings falls, reaching an average of 23ºC in the Southern Commercial Sector, with a difference of 13.8ºC from the afternoon to the beginning of the night. The South Hotel Sector also presents an average of 23ºC, having a difference of 11.4ºC, showing a smaller loss of the radiation in comparison to the SCS, this means that the buildings of the SCS are emitting to the environment a greater amount of the radiation absorbed during the day.

Just below the buildings, where there is no vegetation or solar protection, the ground temperature is higher as the surface absorbs a greater amount of radiation. During the day the average temperature of these surfaces in the SCS is 34.1°C, but in vegetated or shaded areas, temperatures of 27.5°C was registered. During the night the temperature drops, and areas without vegetation had a temperature of 25,3°C and the difference between the while the ground temperature of vegetated areas was 8,1°C lower. The SHS sector registered milder temperatures compared to SCS, averaging 29.3 ° C during the day and a difference of 7.5 ° C between vegetated or shaded and paved areas. In the early evening period the average temperature drops to 22.9 ° C and the difference between vegetated or shaded and paved areas decreases to 1.3 ° C.

Based on the field studies in the South Hotel Sector held around 14:00 p.m., where the temperature, CO² and humidity were measured, with professional equipment to obtain more accurate results, it was concluded that the sites that have the most vegetation, has greater shading and consequently lower temperatures and more humidity. In the images of the measurements the strong solar incidence is evident in the facades of the hotels, causing high temperatures, reflecting on the sidewalks and the existing vegetation becomes insufficient to soften the high index of reflection.

Measurements around St Peter Hotel from the south hotel sector, also focused on the urban vegetation, despite not displaying a dense concentration of greenery. From 14 to 18:00, it only receives only its own shading and in places where it receives direct solar radiation, the temperature reaches around 55°C, therefore unbearable to remain in the place. Compared to other places where there is vegetation in their surroundings, such as the Bonaparte Hotel and the Post Office (next to the St Peter), significant temperature differences were recorded. Local temperatures were registered at 27°C, while the shading locations ranged from 22°C to 25°C. (Figure 21)

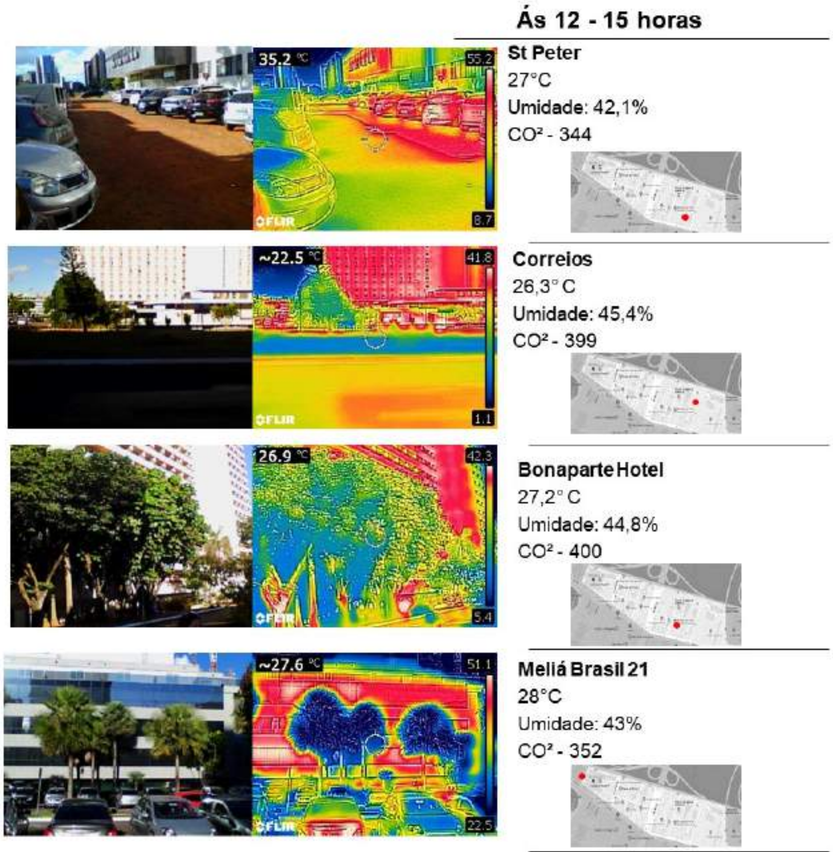


Figure 21. South Hotel Sector, daytime

At the end of the South Hotel Sector, Melia Brasil building is situated, and is the area with the least vegetation of this sector. This urban fragment registered the warmest microclimate at 28ºC. (Figure21)

The same measurements made in the South Hotel Sector were executed in the South Commercial Sector at the same day time of 12 to 15 hours and in the night period from 19 to 20 hours. The facades of commercial buildings, sidewalks, squares and parking lots were measured. It is also observed that where there is a greater mass of vegetation, there is a drop in temperature and CO^2 index, creating a more pleasant microclimate for the pedestrians and users of the buildings.

In the parkings, there are some clusters of vegetation, but since it also receives direct solar radiation, the temperature are higher, making it an unpleasant place.

In the square of the Police Station there is a significant drop in ambient temperature, from 28°C to the measured value of 26.9°C ambient, in the hottest time of the day (12 to 15 hours). A difference in CO^2 level can also be noted, due to the higher concentration of vegetation. In the night time, the microclimate reaches 19°C. (Figure 22)

Due to the very low density and sparce vegetation surrounding the Camargo Correa building, there is not much shading. Although the vegetation is measuring around 24°C, the building external microclimate continues with the elevated temperature.(Figure 22)

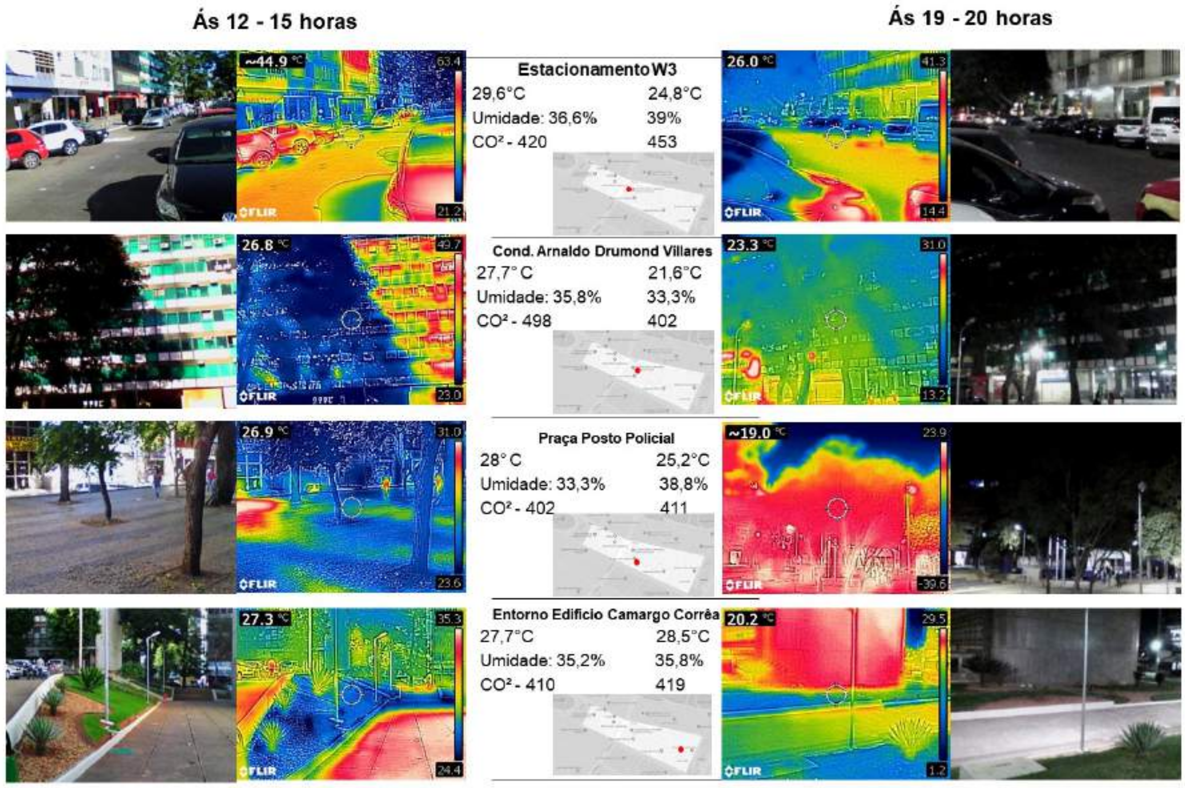


Figure 22: South Commercial Sector

6. Conclusions

This study suggests that during the day the extensive use of glass in facades affects the microclimate thermally, by increasing surrounding surface temperatures. They also cause visual discomfort for pedestrians due to excessive glare from reflection of direct solar radiation. On the other hand, facades that are designed with solar protection elements like balconies and brise soleils, or use concrete for their envelope, minimize glare effects.

Energy efficient glazings are more expensive and therefore seldom used. Glazing with low energy efficiency stimulates the use of air conditioning, which also adds to heating the air externally. On hot days, the reflection of solar radiation is increased by the use of glass. The heat comes from increased absorption of solar radiation by surfaces that retain it like pavements and asphalt. These urban surfaces are also dry, aggravated by the lack of green areas and water bodies, generating energy accumulation, further heating the air.

The increase in temperature of the local microclimate during the day, suggests the occurrence of diurnal heat islands. At night, the microclimate is not affected directly by the glazed facades, as the radiation is quickly dissipated. The “traditional” heat island, at night, exists in both the North and South Sectors. This is due to the space configuration, with excess built surfaces, of pavements, asphalts, and buildings, aggravated by the amount of cars on site, and the sparse vegetation, which does not provide great sun protection or increased humidity during the day.

The South Wing is older than the North Wing, containing more trees, fewer glazed facades, and greater use of architectural elements to block the sun, therefore avoiding visual discomfort due to glare, and providing more shading, ameliorating the thermal sensation. Furthermore, the use of shading elements and radiation control, intercepts the energy in the correct place before it reaches the building, causing the heat to be obstructed, reflected and dissipated into the external air. In addition to acting efficiently, the control elements bring expression to the building, as can be observed in the examples of modernist architecture, as opposed to contemporary “glass boxes”. It is possible to minimize the losses or gains of heat by the energy balance of glazing on facades.

Research results in the North wing suggest the occurrence of what can be called diurnal urban heat islands, caused by the high reflectance of the solar rays by the glazed and mirrored facades that are absorbed by the ground, generating an increase in surface temperatures, humidity reduction, and causing greater microclimatic thermal discomfort during the day.

Considering the stage of this study and the extent to which it was conducted, there is a clear indication that vegetation makes a difference in the creation of more comfortable microclimates and in the mitigation of urban heat islands. However, larger green masses are required to supply the needs of the researched areas and to reduce the impact of solar incidence. In order to improve the microclimate and to reduce the heat islands, it is important the use of urban vegetation, which shades the ground and blocks it from direct solar radiation, lowering the absorption and emissivity of the radiation, while increasing the humidity of the microclimate. As shown in the research, the sites studied have a high temperature where there is no vegetation shading density. Therefore, results from the researched urban fragments, strongly indicate the presence of heat islands due to dense constructed areas with sparse vegetation and significant amount of paved areas.

This research opens up opportunities for new studies in places with greater green masses coming from the gregarious scale, such as the City Park located in Brasilia, to obtain increasingly concrete results based on the existence of heat islands, and the importance of vegetation to soften these. It is also reinforced that, in Brasília, a hot and dry climate, species choices should be taken into account when planning public spaces, since the attenuation of solar radiation is an influential parameter. In this sense, there is also indication of studies in the choice of species of tall size and with good density of shading.

Further research is recommended to confirm the observations mentioned above, and also to verify the greater energy consumption of air conditioning caused by the choice of the external facade cladding, and therefore also rising costs of bills and maintenance of the building. It is also important to take into account the ventilation of the environment. Ventilation helps to reduce the heat accumulated during the day, reducing the emission of radiation at night, and is an important factor for cooling the open space and the surrounding building skin. Further research in this area would also be beneficial.

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Innovation in Construction: the case of BIPV customization in extreme climates

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Abstract: Building Integrated Photovoltaics (BIPV) represents one of the many areas of construction innovation, which have evolved to address global environmental concerns caused by the negative impact of fossil fuel consumption. Existing literature however asserts that despite significant benefits, knowledge and communication are barriers to innovation. In addition, the limited degree of BIPV innovation adaptability to contextual/regional customer specifics further suppress its the uptake. The aim of this research is thus, to investigate custom BIPV products –as an example of technological innovation in hot climate conditions. Secondly, the study presents the development of a novel BIPV communication approach towards improved adoption/uptake. The dual aim is to design custom BIPV products for hot climates, which meet customer preference to increase adoption. Case study reviews following the Design Research Methodology (DRM) was used to understudy both objectives. The reviews report cooling load reduction up to 1.9% and energy efficiency increase up to 10% in referred BIPV custom strategies. Towards BIPV communication, 82% of respondents (n=69) are specifically guided by communicated environmental and economic benefits. Also, 60.2% (n=103) focus on the performance of the system and 30.3% on the cost. The BIPV and architecture communities will potentially benefit from this on-going investigation based on its significance towards a more human-centred green future.

Keywords: Building Integrated Photovoltaics, Innovation, Customisation, Communication

1.0 INTRODUCTION

The multi-faceted nature of the concept of innovation resonates with its associated multi-disciplinary definition relating to product development, marketing and technological perspectives (Garcia and Calantone, 2002), and organisational transformations (Baregheh et al., 2009). In the architecture discipline, both building design and construction ultimately create unique “products” based on input from “source”, being the user/client, manufacturers, architects and several other professionals. This philosophical idea frames the ‘product’ with ‘source’ link that represents a dimension of innovation and creativity in architecture. This process effectively defines the suggested classification of innovativeness in literature (Baregheh et al., 2009); as the creation of something new (new building projects), or improvement of an existing aspect (retrofitted buildings). Buscemi et al (2015) boldly state that innovative components lead to highly efficient buildings and integration of novel renewable energy products, which can produce clean energy along with functions that are typical of the building envelope. This position assertively defends the idea of “creation” while adding the contemporary architectural emphasis on renewable energy building integration.

Building Integrated Photovoltaics (BIPV) is an innovation in photovoltaic (PV) technology, which converts the building from an energy consumer to an energy producer (Hagemann, 2004). It has become a meeting point within the construction and PV industries; advancing its multi-functionality as a building component while providing energy capable of advancing net-zero targets (Baetens et al., 2012). BIPV represents construction industry innovation by further ingenuity as a green product as it harnesses renewable energy from the sun. However, studies show that innovative technologies require a substantial commitment to information spreading to facilitate market development, and adoption by strategies such as customer education (Van De Ven et al., 1999). It has been discovered that this is also the case with BIPV (Prieto et al. 2017; Tabakovic et al. 2017).

The energy capacity added by Solar PV to the world energy mix in 2016 was about 303 GW, of which 3.4GW was from BIPV (van Sark et al., 2017; Sawin, 2017; IEA PVPS, 2017). Apparently, providing only 1% of this share, despite three decades in the market and its multiple benefits suggests that BIPV technology, as a type of innovation is plagued by significant limitations. In a previous work (Attoye et al, 2017), an overview of BIPV adoption was carried out; from which, six major BIPV adoption barrier categories were identified. These include education/information, cost, product issues, project database availability, and industrial issues.

1.1. Research Aim

Expanding the reach of existing literature, this study has two main aims. Firstly, to investigate custom BIPV products –as an example of technological innovation, in hot climate conditions. This seeks to address concerns with BIPV design and product types to resolve related concerns. Secondly, the study reflects on the development of a novel BIPV communication approach towards improved adoption/uptake and its capacity to resolve the identified knowledge barrier relating to BIPV. This dual aim addresses nexus between product design and its communication/awareness to encourage customer acceptance.

1.2. Research Design

The first objective was carried out in two stages; firstly, a descriptive qualitative overview of multiple case studies which clearly describe the architectural integration of BIPV. This case study approach was selected to identify opportunities in hot climates for BIPV customisation. A review of related studies on BIPV custom designs was carried out and three (3) hot climate studies were identified. To address the second research objective, the systematic process for the development of a BIPV communication approach was compared with two internet surveys to access the effectiveness of the said approach. This comparative evaluation was qualitatively carried out and areas of further research identified.

2.0 BACKGROUND

BIPV maintains the clean renewable energy status of the PV technology but also goes beyond this to address some of the challenges faced by the alternative utility-scale systems. Unlike these, BIPV provides energy at the point of use, removing the need for the long distance transmission of electricity with its associated transmission and distribution (T&D) costs and as well as conversion/line losses (Bakos et al., 2003; Sharples & Radhi 2013; Timilsina et al., 2012). Savings in capital expenditure for land are also removed as the building envelope provides the needed supporting structure for the solar panels (Bakos et al., 2003; Sharples & Radhi 2013; Yang, & Zou, 2016; Byrnes et al., 2013). From a social perspective, users are provided with a degree of energy autonomy as BIPV potentially encourages household load-shifting and reduced levels of energy consumption (Sauter and Watson, 2007; Dunn & Peterson, 2000).

Several modes of classifying BIPV exist; some are standardized while others are emerging. These include classifications based on type of Photovoltaic technology e.g.

monocrystalline, polycrystalline, amorphous, organic, dye sensitized (Singh, 2013; Parida 2011), or type of BIPV product e.g. tiles, modules, glazing or foil (Jelle et al., 2012, Jelle, 2015). Others are location in the building e.g. roof or façade (Heinstein et al., 2013, Farkas, 2011) and customisation mode e.g. Systematic Parametric Variation (SPV), Modification of Conventional Features (MCF), Enhanced Design Modularization (EDM) or Compositional Modification and Hybridization (CMH) (Attoye et al., 2017). A compilation of BIPV benefits relating to design, cost and environmental aspects was deduced to represent the vast opportunities, which are congruent with BIPV adoption. Table 1 shows the extracted list from a previous work on BIPV potentials.

Table 1: Benefits of BIPV
Source: Adapted from Attoye et al (2017)

ASPECT	REFERENCE
1. Design-related benefits	
– View and daylighting—semi-transparent options allow for light transmission and contact with exterior	Montoro et al., 2011; Pagliaro et al., 2010
– Aesthetic quality—integration in buildings as a design element	Jelle, 2016; Montoro et al., 2011
– Sun protection/shadowing/shading modulation—used as fixed or tracking shading devices	Jelle, 2016; Heinstein et al, 2013
– Replacement of conventional materials such as brickwork	Heinstein et al, 2013
– Public demonstration of owner’s green ecological and future-oriented image	Montoro et al., 2011;
– Safety—applied as safety glass	Montoro et al., 2011;
– Noise protection—reaching up to 25 dB sound dumping	Jelle, 2016; Heinstein et al, 2013
– Heat protection/Thermal insulation (heating as well as cooling)—improving the efficiency of cells by cooling through rear ventilation	Jelle, 2016; Heinstein et al, 2013
– Visual cover/refraction—one-way mirroring visual cover	Farkas et al, 2013; Montoro et al., 2011;
2. Economic Benefits	
– Removal of the need for the transmittance of electricity over long distances from power generation stations	Sharples & Radhi 2013; Bakos et al., 2003;
– Reduction in capital expenditure for infrastructure and maintenance	Sharples & Radhi 2013; Bakos et al., 2003;
– Reduction in land use for the generation of electricity	Yang & Zou, 2016; Byrnes et al., 2013
– Material and labour savings as well as electrical cost reductions	Jelle, 2016
– Reduction in additional assembly and mounting costs; lowering of total building material costs and significant savings	Jelle & Breivik, 2012;
– Ongoing costs of a building are reduced via operational cost savings and reduced embodied energy	Morris, 2013
– Combined with grid connection, FITs; cost savings equivalent to the rate the electricity is close to zero	Yang & Zou, 2016; Hammond et al., 2012
3. Environmental Benefits	
– Reduction of carbon emissions	Yang & Zou, 2016;
– The pollution-free benefit of solar energy	Jelle & Breivik, 2012;
– Reduces the Social Cost of Carbon (SCC) relating to the health of the public and the environment	Yang & Zou, 2016;

In hot climates, several studies have been conducted on various aspects of BIPV such as energy generation (Elnosh et al, 2018, Hassan et al, 2014), thermal management (Hassan et al., 2014) and building integration (Bahr, 2014; Elarga et al, 2016). John et al (2018) investigated the performance degradation of PV modules installed in Dubai for more than 2 years. Results show that mono-Si PV modules have the lowest degradation rate of 0.07%/yr, compared to CIGS (3.9%/yr) and Poly-Si (2.9%/yr). Aoul et al (2018) reported that building integration of PV systems on a school building could provide up to 10% of the total energy consumption in the representative investigation under the Abu Dhabi climate. Emziane and Ali (2015) studied field performance of four different roof mounted PV systems for a year in Abu Dhabi. They report that the poly-Si types have a higher annual yield than the mono-Si types. Dehwah and Asif (2019) specifically investigated the overall impact of rooftop photovoltaic (PV) systems on the energy performance of residential buildings in Egypt. Their findings suggest when 25% of the building roof can provide 19% the electricity demand and a 2% cooling load reduction due to the shading effect of panels. Elnosh et al (2018) carried out an experimental study on six (6) different types of photovoltaic (PV) modules in the Dubai climate. The study reports that over a two-year period, the highest yield and loss due to temperature are linked with bifacial monocrystalline modules. In addition, poly-Si modules generally showed higher yield due to a combination of temperature effect and soiling effect on the samples. The lowest loss due to temperature was reported on the CdTe module, which also had highest loss due to soiling. In addition, while lower tilt angles have higher vulnerability to soiling losses, the temperature loss effect was relatively low.

2.1. BIPV Customization

The consensus among related researchers, based on professional surveys, is the overwhelming interest in solar technologies and active solar design solutions. One report found that 80% of respondents ranked these as issues as important but less than 10% actually apply (Wall et al, 2012). According to the international interdisciplinary IEA Task 41 survey in 2012, the needs of architects with regards BIPV include increase in knowledge of available information on solar systems. It was also found out that the low satisfaction level of current market offer of products can be addressed by increasing the visual appeal and appropriate integration designs. BIPV potentials have been expressed in previous studies by focusing on customisation potentials (Attoye et al, 2017a), innovation (Attoye et al., 2017b) and sustainability potentials (Attoye et al., 2018). Customization of BIPV products or integration systems is another step in the development of innovative products for the construction industry to encourage acceptance. Potentially, BIPV customisation can achieve 2-80% improvement in energy generation based on the kind of design (Attoye et al, 2017a). Some studies focus on specific aspects, which advance the architectural design objectives such as aesthetics and daylighting alongside basic energy generation.

Van Berkel et al (2014) in relation with UNStudio presented a report to illustrate the range of design aspects relevant to the aesthetic integration of PV in façade design. They address the need to use the façade to establish a "…distinguishing brand image to propel the qualities of the PV module into the domain of design products and high-end building". Lien (2016) developed an artistic c-Si type BIPV module in an experimentation driven by the goal to increase product aesthetics. Buscemi et al (2015) and Kang et al (2016) designed a DSSC glass-block product and investigated bifacial solar cells respectively. Both studies aid development of highly efficient buildings, integration of renewable energy products, and development of glass-to-glass products for ease in retrofitting. Nagy et al (2015) developed a thin-film adaptive solar façade (ASF) integrated as a shading component to address issues of bulkiness of existing BIPV roof modules. Luo et al (2017) designed and developed a thin-film photovoltaic blind double skin façade (PVB-DSF) to achieve "modern aesthetics as well as superior system performance to conventional glazing facade." They also sought in part, to address issues of thermal comfort, energy savings, and the initial, high cleaning, operating, inspection and maintenance costs in comparison to the conventional façades.

3.0 METHOD

This section focuses on a case study of specific investigations towards BIPV customisation in hot climates. Due to the constantly evolving nature of PV technology, studies selected for this section were limited to the last five years to advance currency of the results. BIPV and PV façade manufacturers provide certain custom services, such as the varying power ratings, shape, glass, printing and colours. Others include changes in cell arrangement and the glass surface (clear glass, prism, enamelled) with different properties (i.e., glare reduction) and finishing (Bonomo et al., 2015). This review evaluates four (4) aspects of customisation categorised, deduced and referred in a previous study (Attoye et al, 2017a). These are, firstly, Innovation & Custom category defining the physical characteristics; Customisation strategy, which explains the technological development and the Architectural function. The customisation strategy is defined by four types, being;

- Systematic Parametric Variation (SPV): iterative parametric changes to reach an optimum goal
- Modification of Conventional Features (MCF): modification of conventional BIPV parts
- Enhanced Design Modularization (EDM): upgrade of BIPV façade types into unique modules
- Compositional Modification and Hybridization (CMH): combination of special materials with BIPV

This a novel presentation of BIPV customization, as well as other aspects above are used as guides to the discussion section of the selected cases. Figure 1 shows the relationships, definition of the various aspects used for the case evaluations.

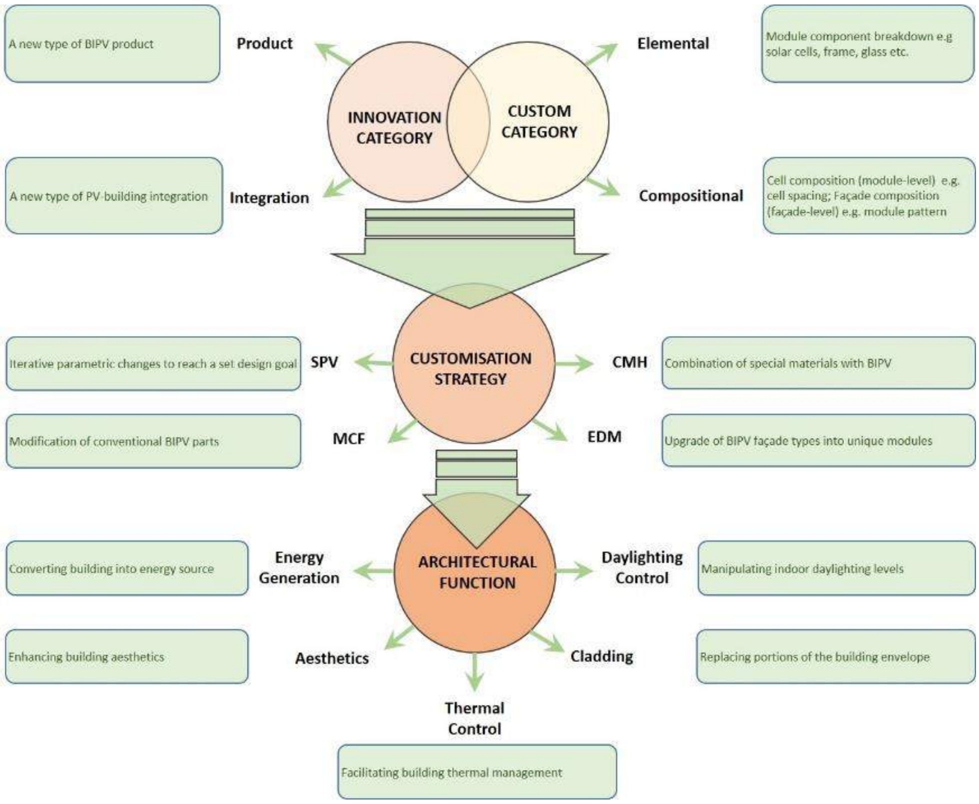

Figure 1: Case Study Evaluation metrics

It is important to state that the selected cases ought to represent a very specific category of BIPV investigations; being full-scale BIPV customisation experiments in hot climates. The results of these studies are extracted to highlight the power output/Cell efficiency/Heating or Cooling loads where the information is provided. Focus was also given to comparisons with a base case (standard BIPV) and the highest output (where optimization based on parametric variation was investigated) of the studies. Selected cases, which met all aforementioned criteria, are:

- **Case 1:** Design of a BIPV-Phase Change Material (PCM) façade component (Hassan et al., 2014)
- **Case 2:** Improvements of a semi-transparent BIPV double skin façade (DSF) (Elarga et al., 2016)
- **Case 3:** Design of a BIPV blind system (Bahr, 2014)

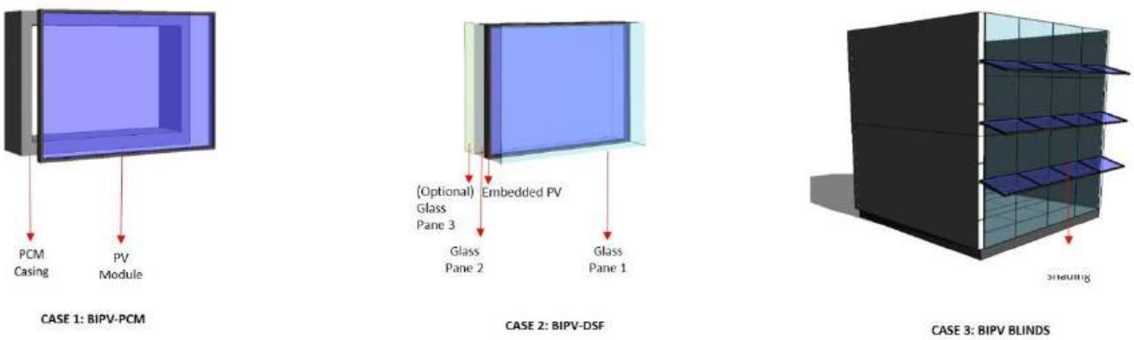

Figure 2: Cases of BIPV custom studies in hot climates

4.0 DISCUSSION: Architectural aspects of the Cases

The three cases reflect the creation of a new BIPV custom product and generating a new design based in part on conventional PV modules. In two of the cases, varying degrees of integration into the façade are also initiated by the new designs. As per the customisation level, elemental changes were made in two of the cases and compositional changes in all three. In Case 1, a PCM chamber was fabricated and added to the back of the PV module; the hybrid BIPV-PCM module designed represents a BIPV façade element as per the researchers' intent. The PCM element was added to absorb the heat generated by the PV cells due to extreme temperatures. It's thermos-physical properties allows for a change of state from solid to liquid over each diurnal cycle to ensure continuous reduction of the panel temperature. This strategy provided a 32.5% temperature drop and 10% increase in energy efficiency of the custom product.

In Case 2, a double skin BIPV façade was developed. The two innovative angles include, the use of forced and natural ventilation towards "integrative customisation", as well as embedded PV cells between two glass panes. The second provides a new custom product while the first allows for a flexible integration approach. By using varying ventilation modes and glass layers, the product optimises the customisation approach to achieve cooling load reduction up to 1.9% and increase in energy production up to 6%. While the focus was on the quantitative energy output, a preliminary qualitative assessment of this product may suggest its easy adaptability as a cladding element. The use of glass-to-glass layers as well as double glass layers may also be beneficial based on climatic needs. In Case 3, the customisation approach was used to design a new system of integration implicit to the design of a new product. BIPV shading modules may be upgraded by this approach into a blind system. Varying the cell technology, module spacing and the conventional module position relative to the façade provides both product and integrative customisation. Adapting BIPV into the shading position provided a cooling load energy saving of 7.11kWh/m^2 with c-Si modules and 6.89 kWh/m^2 with a-Si.

These representative cases of BIPV customisation for hot climate integration presents several ideas further investigation. These three cases present general customisation strategies of hybridisation, modification and modularisation for hot climate design adaptation. Novel investigations into the combination of all to design a prototype design may well be ingenious. Focusing on the strengths of each approach and the reported results, Table 2 is an overview of the investigated cases based on the research investigation framework presented in Figure 1 above.

Table 2: Research investigations on BIPV façade customization.

CASE	Country of Study (Location)	Deductions from Experimental Investigations					Research Results
		Objective	Custom Category	Customization Level Investigated	Customization Strategy (Description)	Architectural Potential	
1	Pakistan (Wall)	Energy and Cost Saving of a PV-Phase Change Material (PV-PCM) System	Product	Elemental (Phase-change materials); Compositional @Module-level (Module design)	SPV;CHM; EDM (Passive cooling of BIPV with solid-liquid PCMs)	Energy generation; Thermal control	Temperature drop: 16% (PV PCM-1); 32.5% (PV PCM-2) Ave energy efficiency increase: 7% (PV PCM-1); 10% (PV PCM-2)
2	UAE (Double Skin Façade)	Performance and energy improvements of semi-transparent PV cells	Product & Integration	Compositional @Module-level & Façade-level (Number of glass layers, Ventilation mode)	MCF; SPV; (Application of alternate ventilation modes and number of glass layers)	Energy generation; Cladding	Cooling load reduction: 1.5% (DSF forced vs. natural), 1.9% (Single Layer forced vs. natural) Annual energy production increased by 2.5% (DSF) 6% (Single Layer)
3	UAE (Window Blinds)	Energy, Cooling and Cost analysis of BIPV blind system	Product & Integration	Elemental (cell technology); Compositional (Module position)	EDM; SPV (Prototyping based on conventional façade design component)	Energy generation; Thermal control;	Ave. power output: 41.55 kWh/m² (c-Si); 43.22 kWh/m² (a-Si) Cooling load Energy Saved: 7.11kWh/m² (c-Si); 6.89 kWh/m² (a-Si)

5.0 BIPV COMMUNICATION

Beyond developing building design typologies, this on-going research is also investigating a novel BIPV communication approach towards improved adoption/uptake. The goal is to understudy its capacity to resolve the identified knowledge barrier relating to BIPV. The published and patent-ready approach was presented in a previous study (Attoye et al, 2018) and is diagrammatically shown in Figure 3. In summary, the ideology put forward is based on the “diffusion of innovation” theory by Everett Rogers (Sahin, 2006) which asserts that relative advantage (i.e., benefits) is the strongest predictor of the rate of adoption of an innovation. The BIPV communication approach thus focuses on presenting BIPV adoption benefits from an environmental, economic, social, and design point of view. The accompanying survey found out that 90% of respondents (n=69) were inclined towards BIPV adoption if proper communication of innovation is presented. In addition, environmental and economic benefits were consideration most impacting by 82% of sample.

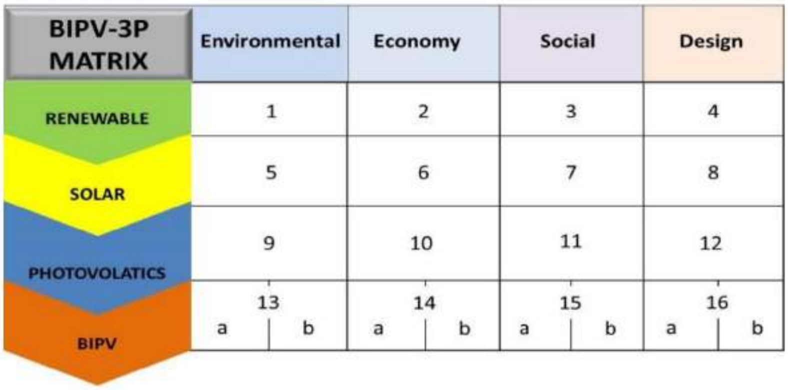

Figure 3: BIPV-3P Matrix: Novel BIPV communication approach
Source: Attoye et al (2018)

The core objective is now to assess other decision determinants to develop a more robust communication approach. The approach taken involves two stages; engage stakeholders with BIPV options as a guide to understanding preferences and designing a building prototype for the context. This work is on-going as part of a PhD dissertation and will be published soon. The first part of this has been integrated into a pilot survey (n=103) where 60.2% of respondents are primarily driven the performance of the system, 30.3% by cost and the rest by its aesthetics (Figure 4).

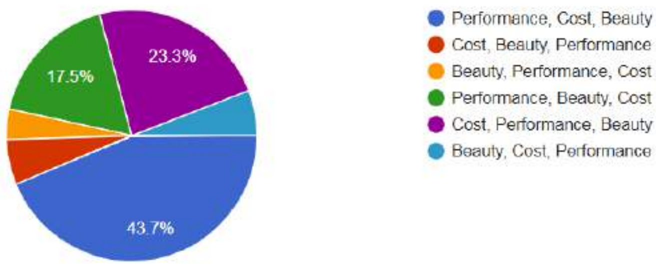

Figure 4: Respondent response to decision determinant

This design-communication approach is thus potentially able to intuitively make recommendations to both designers, developers and manufacturers while engaging potential customers. Addressing adoption barriers from this dual dimension is a novel approach with significant benefit to the BIPV design and architecture community. Further research is required to justify aspects of decision determinant, category of client and overall design objective.

6.0 FURTHER RESEARCH

This study brings to light the fundamental issues of interest in customisation of BIPV for hot climate. Design integration, Energy generation, Cooling load impact and Stakeholders' preference have been identified. In each aspect, significant work is on-going, and more is required. With design integration, there is a need to explore vernacular architecture styles in the geographical context and create BIPV custom designs, which identify with the local architecture. Prototypes aligned with the "*mashrabiya*" (sunscreen) or "*barjeel*" (wind-catcher) may prove to be significantly innovative. Further work on energy generation potentials of various PV technologies in various locations on the façade is crucial to develop a quantitative comparative assessment to guide architects in practice. Associated with this is the impact on the cooling load as an added benefit of particular interest in the region, comparing seasonal generation with related energy saving potential. In the UAE, these ideas have already begun to filter into the policy direction of several emirates, such as Abu Dhabi's *Estidama* rating system since 2009, Dubai's solar initiatives since 2015 and Ras Al Khaimah's 2019 Green Building Code, *Barjeel.* It anticipated that a research and development projects in the region will fast track a region-wide multi-disciplinary investigation into these aspects of the BIPV technology.

7.0 CONCLUSION

This multi-objective study is part of a wider research to investigate BIPV opportunities and potentials in the UAE as an example of a hot climate. This paper presented a review of BIPV customisation case studies, which show possible cooling load reduction up to 1.9% and energy efficiency increase up to 10% in referred BIPV custom strategies. In addition, architectural potentials of BIPV customisation were identified relating to thermal control, aesthetics, and cladding, alongside energy generation. BIPV communication beyond BIPV design was also identified as a secondary objective of the study. Previous investigations show that 90% of sampled respondents are inclined towards BIPV based on communication of its benefits, and 82% are specifically guided by environmental and economic benefits. In addition, a second pilot survey shows that the performance of the system is a major decision determinant for 60.2% of potential BIPV customers while 30.3% consider cost as a primary consideration.

Although experimental and quantitative investigations on BIPV, PV-facades, PV characterisation and other related aspects will continue, significant attention must also be given to predicators of customer acceptance. This subtle qualitative aspect represents a growing area of interest in BIPV investigations over the last 5 years. Understanding BIPV adoption determinants, adapting this to BIPV design products and research may potentially increase its acceptability and global impact.

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Non-Invasive Assessments of Thermal Discomfort in Real Time

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Abstract: People make distinctive gestures or movements when they are thermally uncomfortable, for example self-hugging when uncomfortably cold or brow-wiping when hot. Extreme thermal conditions reinforce this tendency. These gestures may be affected by various competing motivations such as emotional or physiological responses and cultural traditions. Several software applications can now identify and track movements of a person's skeletal joints or keypoints in real time; these include hands, arms, elbows, head, etc.. A procedure was created to identify gestures related to thermal discomfort and then to decide if a person is uncomfortably warm or cold. When a discomfort-related gesture is detected, it is scored based on the type of gesture and recognition confidence. This score is fed into a "Thermal Comfort Index" (TCI). A zero TCI corresponds to thermal neutrality and higher positive or negative values correspond to feelings of warmth or cold, respectively. The TCI diverges further from zero when the detected gestures are frequent or intense. A key feature is a "library of gestures"; the procedure consults this library to determine if a particular gesture might be associated with thermal discomfort. This method was applied to a single person but could also be applied to large groups. This method of tracking thermal discomfort is well suited for locations where occupants are not easily able to communicate thermal preferences.

Keywords: thermal discomfort, non-invasive measurement, gesture, Kinect, HVAC

1. Introduction

The maintenance of thermal comfort using a building's HVAC system represents a major use of energy and a cause of greenhouse gas emissions. Additional indirect costs and environmental burdens are caused by building materials, clothing (clo value), and even food to assure thermal comfort. One element of a climate policy must therefore focus on avoiding overheating or overcooling buildings. Energy waste will occur when people are thermally uncomfortable as a result of the energy supply used for overheating or overcooling and this waste has the potential to be especially large in extreme climates. Thus, identifying situations where people are thermally uncomfortable is a high priority for saving energy, reducing emissions, and improving thermal comfort.

The traditional method of determining a person's thermal comfort utilizes a subjective assessment. The subjects—sometimes occupants—are asked if they feel thermally uncomfortable. The subjects then respond with an opinion ranging from "very cold" to "very hot". This procedure has been developed and refined by many researchers, notably

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by Fanger (1973). Relationships have been established between key environmental determinants of thermal comfort (air temperature, activity level, clo value, etc.) and the proportion of the population likely to be comfortable or the conditions leading to the fewest complaints about thermal discomfort. This approach is useful for establishing the general conditions to maintain thermal comfort but is not applicable for management of buildings with changing conditions and occupants. Other limitations include:

- assessments are typically performed in carefully controlled conditions (that is, not in the "wild");
- assessments are static and not in "real time";
- responses to thermal conditions can change depending other circumstances, notably adaptation (de Dear et al., 2013); and
- in actual buildings, it is difficult to link occupants' current feelings of thermal comfort to the building's HVAC system and create an effective feedback control system.

Some methods have been developed to circumvent those drawbacks. Social media and digital data collection can be used to quickly and frequently collect thermal discomfort information. In one example, students could "vote" through an app if a lecture room was uncomfortable (Sanguinetti et al., 2017). The university then used this information to check the HVAC system. At least one commercial app enables office workers to solve thermal comfort issues by reporting their satisfaction (Sanguinetti et al., 2017). HVAC savings of up to 20% are claimed (Comfy, 2016). These procedures are driven more by complaints than based on statistically representative assessments of thermal comfort. Occupants are more likely to complain when they are experiencing extreme discomfort rather than mild discomfort (although there is little research on this aspect).

Nevertheless, the underlying technique of assessing thermal comfort continues to rely on subjective, rather than objective, metrics. Maintaining thermal comfort in real-world situations also relies on communication (or participation) between the occupants and the building operator. Complaints about thermal discomfort may not get relayed to the building operator in many situations, such as in classrooms, cinemas, and public spaces. Alternative techniques for tracking thermal discomfort are therefore attractive. An effective technique is therefore proposed to have the following characteristics:

- be non-invasive;
- provide an objective measurement of thermal comfort;
- require no active participation by subjects;
- operate in real-time; and
- not conflict with privacy norms.

With these features in place, HVAC systems can incorporate thermal comfort in their real-time operating decisions.

This paper presents a method of assessing thermal comfort that meets the five characteristics listed above. The method is based on recognition of human gestures or movements that are associated with thermal discomfort. The paper begins with a short review of non-invasive techniques of tracking thermal discomfort. The concept of specific gestures related to thermal discomfort is introduced and a method of tracking them is described. Finally, a procedure for calculating a thermal comfort metric is presented, along with a way to link this measurement to an HVAC system. By focusing on discomfort, this method appears to be particularly well suited for addressing thermal comfort in extreme conditions.

2. Non-invasive Measurement of Thermal Discomfort: Related Work

A non-invasive method of sensing thermal discomfort means that the occupants do not need to participate actively or passively in the sensing procedure. Put another way, they do not need to communicate with the sensing/control system in order for their levels of thermal comfort to be registered.

Numerous studies have been undertaken to correlate a person's physiological stress in response to excessively warm or cold conditions (Nicol and Humphreys, 1973). Evidence of perspiration or high surface skin temperature are two indicators of stress. For example, Chad and Brown (1995) compared responses of athletes (weight lifters) and typists in a hot environment. They found higher mean skin temperatures among the lifters. They also found that heat stress from strenuous tasks induced physiological disturbances in the form of more frequent fatigue-induced muscle contractions. Adaptations to thermal discomfort can also be visible, such as sweating and *cutis anserina* (goose bumps). Some of these methods require sensors attached to hands and other locations on the subjects; however, recent improvements in remote sensing make non-contact measurements possible. For example, Cheng et al. (2017) used a simple digital camera and image magnification to remotely assess minute variations of temperature on the backs of the subjects' hands under strong thermal stimulus. The technique still requires personalized skin temperature models and smooth skin, so it not yet suitable for commercialization.

The procedures to measure physiological response are awkward and may be site-specific; for these reasons they can be applied only to constrained environments and limited populations (Epstein and Moran, 2006). These limitations may become less important as new technologies become available. For example, wearable devices offer opportunities for less intrusive measurement (Jin et al., 2014). Recent developments in infrared photography and image-recognition also make it possible to identify specific locations on a person (or groups of people) and evaluate the thermal characteristics. Similar techniques are already widely employed in crowd surveillance in order to identify stress or other behaviours. These approaches have not yet been applied to thermal comfort and warrant further investigation. For the moment, however, significant obstacles remain before a system can perform continuous, physiological measurements of many subjects in real-life settings and then translate them into thermal discomfort assessments.

It is also important to note that most physiological methods sense changes related to discomfort rather than comfort. Indeed, most studies employed extreme thermal conditions so as to enhance sweating, muscle contractions, etc., which will facilitate recognition of the effect. These methods may be less useful in office-type conditions but potentially more valuable in extreme thermal environments, such as presence of localized high temperatures or direct sunlight.

A second non-invasive method identifies gestures associated with thermal discomfort. Examples include hugging oneself (when cold) or wiping one's brow (when hot). These gestures—which can also be called movements, poses, positions, or behaviors—may be static or dynamic. Parents almost instantly recognize when their children are warm or cold. They see gestures and body positions that, collectively, translate into a conclusion regarding a child's thermal comfort. Similarly, most people can detect discomfort in fellow humans based on casual observation. They know (consciously or not) that a person feeling cold will often huddle, shiver, or hug himself; while a person feeling warm may wipe his brow or sit splayed in order to intercept ventilation and maximize heat transfer.

Non-verbal communication of this type has been studied within the field of Kinesics starting with Birdwhistell (1952), in which gestures ("kinemes") are found to convey meaning and have ordered rules sufficient to be called a grammar. One aspect of this communication noted in Ekman (1976) is that the meanings of non-verbal gestures may vary from culture to culture, an aspect that must be taken into account for a system recognizing thermally-related gestures.

Nicol and Humphreys (1973) noted that "posture" played a role in thermal regulation. However, researchers have not systematically compiled or even examined those postures related to human thermal discomfort. Most reporting has been anecdotal or tangential to intended research goals. In one case, Havenith et al. (2002) noted that subjects being tested in cold conditions needed frequent reminders not to clench fists or assume hunched positions with reduced body surface areas. Similarly, Raja and Nicol (1997) observed that subjects that were exposed to cold sought to reduce their surface area by clenching their fists and bringing their arms close to their body. Clarke et al. (2006) observed that people adjust their posture or clothing to maintain thermal comfort in a changing environment. De Carli et al. (2007) also noted the dynamic process of clothing adjustment over time by building occupants. Raja and Nicol suggested that adjusting posture in order to minimize thermal discomfort was a general habit of humans and that postural response constituted a form of "thermal body language." They noted that no technique existed (at the time of their paper in 1996) to evaluate different postures. This is not surprising because no technology existed to observe and track gestures.

Major technical advances in gesture recognition have taken place in the last two decades. The first was a "marker based system" (MBS). Small markers were attached to the major joints of a subject, which an external device could precisely locate and track. In principle, this allowed a scanning system to track changes in the skeletal geometry as the subject performed various movements. This technology had two drawbacks. First, these measurements could be performed only in a laboratory or under controlled conditions. Second, the system lacked sufficient precision to detect fine movements such as those associated with thermal discomfort.

The Microsoft Kinect, introduced in 2010, was a major advance in gesture recognition. The Kinect was designed to give players of video games control through movements of their entire bodies in three-dimensional space (Zhang, 2012). The Kinect relies on a bank of optical and IR sensors, combined with considerable computing power, to construct a, continuously updated, three-dimensional digital description of the player's skeletal geometry. The Kinect takes the observed skeletal geometry and inserts the information into the game. For example, a player could pretend to swing a bat at a ball seen on a screen and the Kinect would insert the player's body geometry into the figure on the screen; as the player swings the bat, so too would the figure on the screen. The Kinect added a new level of realism and participation into video games. Given the innovative sensor system and associated gesture processing software, the Kinect sensor array was incredibly cheap—less than USD100. Since 2010, however, other companies have begun offering similar gesture recognition sensor hardware and associated software, including ArcSoft, Crunchfish, Sony Depthsensing Solutions, and Intel RealSense. Open-source recognition programs have also emerged, such as OpenPose.

The Kinect and its successors enable researchers to reliably and economically recognize specific gestures. For example, Galna et al. (2014) employed the Kinect to assess movements associated with Parkinson's disease. Eleven movements, such as "sit to stand"

and "hand clasping" were compared with absolute measurements taken by a Vicon MBS system. They found that the Kinect measured gross spatial movements to a clinically acceptable level of accuracy but the system was not yet accurate enough for smaller movements (such as hand-clapping). Ibañez et al. (2014) used the Kinect to recognize simple athletic gestures, such as "smash", "punch", "swipe right", and "swipe left". Importantly, they created confusion matrices to measure the success at recognition and distinction between gestures. In a similar fashion, Saha et al. (2014) used a Kinect to observe gestures related to human emotions, such as happiness, sadness, and relaxation. A classification accuracy above 90% in a group of ten subjects was observed. These studies were first steps towards objective identification of gestures.

3. Research Method and Results

3.1. A Library of Thermal Discomfort Gestures

Most people can recognize thermal discomfort in another person based on a quick view of body language, but these gestures have not been codified in any systematic way. Therefore, a library of gestures associated with thermal discomfort was compiled. The library was constructed through searches of open-source image libraries and simple public observation of common gestures related to thermal discomfort. Students were also asked to demonstrate gestures that they typically made when feeling warm or cold. Not surprisingly, gestures varied with context, culture, and gender (and presumably with other factors we have not yet considered). Despite these variations, the significance of most of these gestures was intuitively obvious to human observers. Table 1 lists some of the gestures compiled from the sources described above. Each gesture was assigned a name, a brief description, and a condition (e.g., feeling hot or cold). Some of these gestures are easily identified in a static image but others only make sense when they are viewed dynamically. In real life there are many more thermally related gestures than are listed in Table 1. A mature system of thermal discomfort detection will need a more comprehensive "library" but the concept can be demonstrated with this limited set.

Many of these gestures are also associated with emotions. For example, self-hugging may indicate defensiveness or disagreement and hand-rubbing may indicate positive anticipation. Indeed, posture and position represent an important method of non-verbal communication (Mehrabian, 2017). For this reason, the identification of a combination of thermally-related gestures is more compelling than a single thermally-related gesture.

Table 1. A library of thermal discomfort gestures

Condition	Gesture	Description
Feeling too warm	Self-fanning	Back and forth motion of the hand near the head to cause movement of the air in the direction of the face
	Brow-wiping	Movement of the hand across the forehead, as to remove sweat
	Collar-tugging	Repeatedly pulling the collar away from the neck, to increase airflow in the area between shirt and body
	Splayed posture	Spreading some or all of the limbs away from the body in an attempt to maximize skin area available for cooling

	Hair movement	People with long hair will lift their hair to increase ventilation to their neck
Feeling too cold	Hands in pocket	Placing the hands in the pockets to raise their temperature
	Self-hugging	Placing both arms inward across the chest
	Hand-rubbing	Rubbing the hands rapidly against one-another to generate heat through friction
	Blowing on cupped hands	Blowing warm air onto the hands to raise the skin temperature
	Buttoning-up	Fastening buttons near the top of a shirt to decrease air movement between shirt and chest
	Shivering	An involuntary response of the body which raises overall temperature through high frequency, low amplitude muscle oscillation
	Contracted posture	Moving some or all of the limbs inward towards the body, to decrease the amount of surface area

3.2. The Geometry of Thermal Discomfort Gestures

The Kinect was then programmed to recognize simple gestures of thermal discomfort. The Kinect detects and stores body positions as sets of lines and vertices, representing limbs and joints. Subjects were asked to perform the gestures in a laboratory. The laboratory was simple: a standard office with constant illumination and without distractions by other persons. Subjects stood up during test periods, at least one meter from walls and other surfaces. The Kinect was mounted 2 – 3 m from the subject at a height of about 1.5m above the floor.

Four gestures were selected from Table 1: two for feeling cold ('self-hug' and 'button up'), and two for feeling warm ('brow wipe', and 'collar tug'). A subject performed each of the four gestures, while being tracked by the Kinect. Two "ideal types", or reference gestures, are represented in Figure 1.

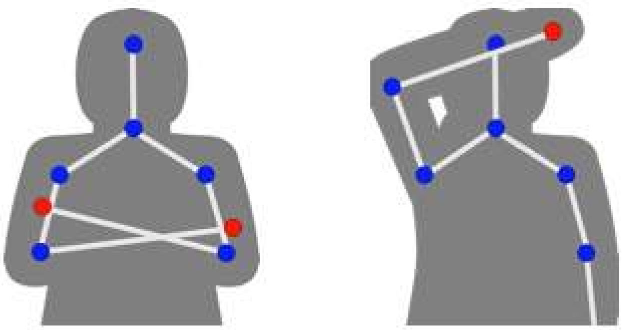

Figure 1. Skeletal geometries associated with self-hugging (left) and brow-wiping (right)

Each reference gesture was described as a set of rules for joint relationships. These relationships are described for the four gestures in Table 2. For example, in the reference position for “self-hug”, each hand must be close to the opposite elbow, and each elbow must be below the same-side shoulder. Every gesture in the library must be described by a set of such rules. To date the library consists only of static gestures; however, the procedure could be adapted to accommodate dynamic gestures, such as self-fanning.

Table 2. Rule-based relationships for gestures associated with thermal discomfort

Gesture Name	Rule-Based Relationship
Self-hugging	Each hand must be close to the opposite elbow and each elbow must be below its respective shoulder
Buttoning-up	The two hands must be close to the neck and elbows below the shoulders
Collar-tugging	Either hand must be close to the neck (but only one hand)
Brow-wiping	Either hand must be close to forehead

3.3. Translating Gestures into Information about Thermal Comfort

A program was developed to store the library of gestures, control the Kinect, oversee the tracking, compile the incoming data, and interpret the results. The key features of the program are described below and in Figure 2.

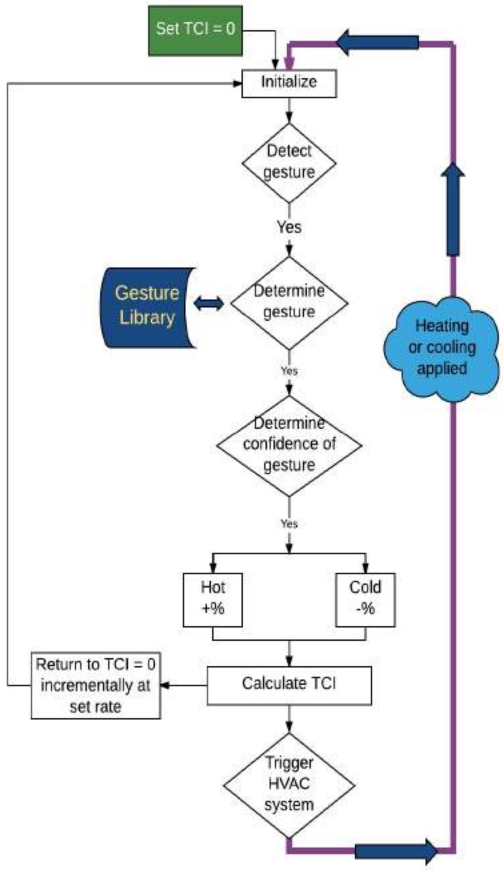

Figure 2. Logical flow chart to detect thermal discomfort gestures and calculate Thermal Comfort Index (TCI)

As the subject moves through various positions, the Kinect continuously monitors the person's body geometry. These movements are expressed as a set of geometrical relationships among joints. If a position is maintained for a specified time, the program notes the detection of a potentially significant gesture. If the subject's body geometry shifts before the minimum time elapses, the Kinect re-commences the search for a significant gesture. A "significance threshold" was set at 2 seconds, but this threshold could easily be adjusted for future trials.

When the program detects a gesture, it consults the gesture library to determine if the gesture expresses thermal discomfort. If the observed gesture does not resemble any of the stored gestures, it is discarded. If the program finds a match in the gesture library, it assigns a value of +1 to gestures associated with feeling hot and a value of -1 for gestures associated with feeling cold. Equal weight was assigned to each thermal gesture but field testing may demonstrate that some gestures correspond to more intense discomfort than others. In these cases, some gestures may have higher values. In addition, the program calculates the confidence level of its classification, based on the magnitude of discrepancy (if any) between observed and reference geometry. The size of the increment is reduced for gestures with lower confidence.

The program stores a running sum of these values. We call this sum the Thermal Comfort Index (TCI). When the TCI = 0 the subject is thermally neutral. If the subject is cold, then the observed TCI gradually decreases through successive gestures like self-hugging. If the gestures related to being cold persist, then the TCI will decrease. If the subject is warm, the TCI increases. If the subject continues to present gestures related to being warm, then the TCI will become increasingly positive and one can conclude that the subject is hot.

A dashboard was constructed to display the program's operation (see Figure 3). It captures the key elements entering into the TCI calculation, including the gesture detected (superimposing the Kinect-generated skeletal geometry over the actual image), the confidence in the gesture match, and a log of gestures. Finally, it shows graphically the course of the TCI over time in response to detected gestures.

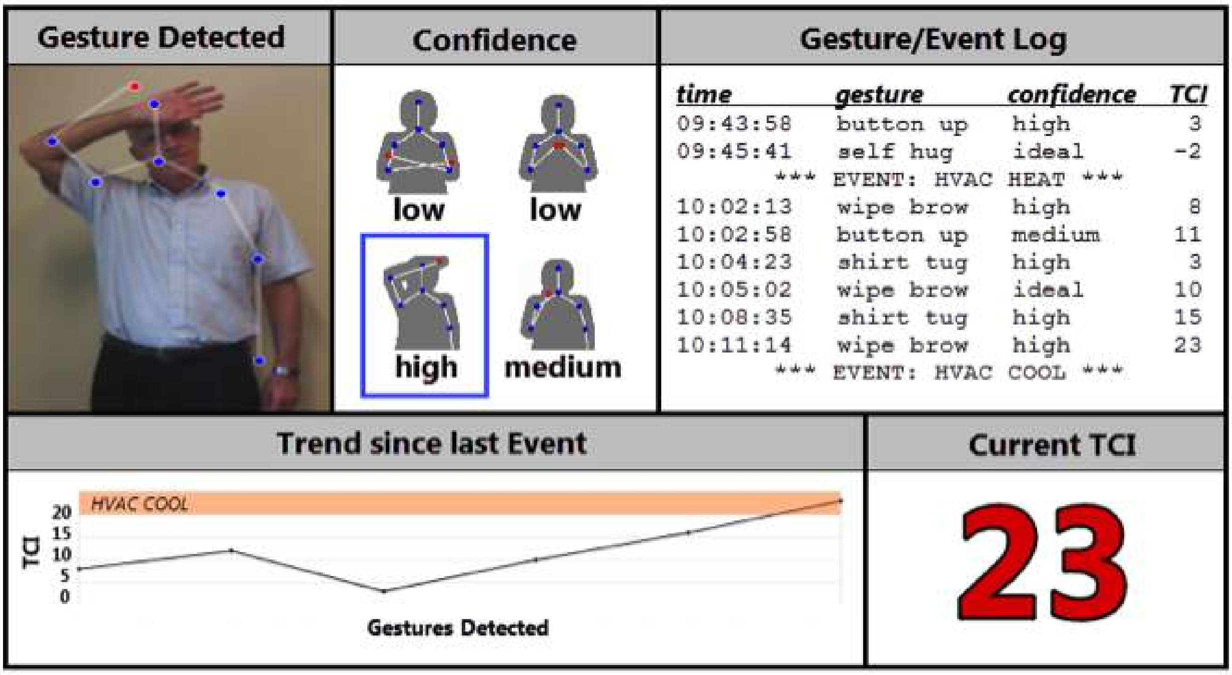

Figure 3. Dashboard displaying key features of gesture detection, TCI calculation, and HVAC control

3.4. Linking Thermal Discomfort Gestures to the Control of Heating and Cooling Systems

The procedure described above offers a means of objectively quantifying thermal discomfort based on observed gestures. It tracks discomfort dynamically and detects a person's changing requirements, such as changes in activity level, clothing level, and radiant temperature. These capabilities would appear to be useful in more effectively controlling heating and cooling systems, leading to energy savings or improved comfort. Further modifications of the program were made to link the procedure to HVAC systems.

First, it was assumed that the gesture-based system would work in tandem with the conventional thermostat. The thermostat would maintain the room's temperature within a wide range, say 15°C – 30°C, that is, a 15°C deadband. Inside this range, however, the TCI calculation would "fine-tune" HVAC operation to achieve the fewest thermal-discomfort gestures.

When the TCI rises above a specified value, the program signals the HVAC system to cool the room. This is illustrated in the TCI trend plot in Figure 3 (lower left corner), where the trend rises into the orange band. Similarly, when the TCI falls below a threshold value, the program concludes that the occupant feels cold, and signals for heating. Meanwhile, the program monitors the elapsed time since the last thermal gesture. If no further discomfort gestures occur for a specified length of time, the program reduces the absolute value of the

TCI by one increment. These incremental reductions continue until the TCI = 0. In other words, the return of the TCI to zero reflects the program's deduction that the subject is at thermal neutrality (and is comfortable).

4. Discussion

A novel procedure to assess thermal discomfort and then control an HVAC system has been described. It meets the five criteria listed earlier. However, many aspects deserve further exploration. Additional research fits into three broad categories: the measurement of thermal comfort; practical issues related to using a Kinect-like system in buildings; and linking the TCI system to HVAC systems. Some of these issues are explored below.

4.1. Thermal Comfort Research: Can Comfort be Implied from Observations of Discomfort?

As a research tool, the TCI assessment procedure has both advantages and drawbacks compared to conventional thermal comfort measurements based on subjective assessments. First, it is an objective procedure that does not require interactions with the subjects. This avoids many potential pitfalls in experimental design. Second, the TCI approach is physiology-based, that is, it measures a body's physical adjustment of its heat balance with the environment. These responses may (or may not) represent what a person thinks. Third, the TCI approach can accommodate non-constant thermal environments and varying behaviour of the subjects. Researchers can, for example, easily assess the impact of modifying the thermal environment.

On the other hand, the nature of the relationship between TCI and thermal comfort is still unknown. Is it linear? Furthermore, voluntary thermal comfort gestures may be constrained by physical or cultural aspects. Many gestures will be difficult to detect when the subject is sitting at a desk, partially obscured by furniture, or in an unusual position. Some thermal comfort gestures are distinctly cultural. Together these features make the interpretation of thermal comfort gestures more complicated and problematic than the results of a questionnaire.

All of the gestures captured by the Kinect are associated with thermal discomfort. Does the absence of discomfort gestures imply that a person is comfortable? A threshold of discomfort may need to be reached before a person makes gestures, voluntary or involuntary. Also, do people employ subtle gestures when they are thermally comfortable? Unfortunately, no research has been undertaken in this area (partly because the tools were not available until recently). In any event, this approach appears well suited for extreme climates, where temperatures (and other factors) will deviate far from the standard comfort conditions.

Sensors can be expected to be to detect ever more subtle movements. For example, shivering is known to occur at specific frequencies (Nakamura and Morrison, 2011)(Nakamura and Morrison, 2011); these may soon be easily detectable and certain frequencies associated with precursors to discomfort. The accepted definition of thermal comfort is **"**The condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation" (ANSI/ASHRAE Standard 55). It implies that thermal comfort is inherently subjective and cannot be assessed in objective, physiological terms. This work shows that another definition and metric is possible, which may expand the definition of thermal comfort. The physiological and subjective approaches are not exclusive; instead, they provide complementary information. Further research will be needed to understand how they relate to each other.

4.2. Can Kinect-like Devices Function in Real-World Situations?

This work has demonstrated that recognition of thermally-related gestures is technically possible. However, there remain many practical problems to overcome before the technique can be incorporated in an HVAC control system. Some of these limitations are described below.

The weighting to each gesture still needs to be determined. In the present method of calculating the TCI, each gesture is treated as equally significant; however, some gestures are clearly more meaningful than others. Gestures (and the TCI) will need to be calibrated against other measurements of thermal discomfort (including subjective assessments).

How should thermal discomfort be measured in rooms with many people? This is important, because many of the most attractive applications for gesture tracking would be in public spaces (like cinemas) where occupants have no ability to change the temperature (and managers are seriously concerned about customer comfort). In this work, gestures of only one person were tracked. The Kinect works best for two or less players; with more people present it gets confused. A related limitation of the Kinect sensor arrays is range: they lose accuracy beyond a few meters. Fortunately, sensors, algorithms and computational ability have improved greatly since the Kinect. More recent solutions, such as OpenPose, can easily track many people over a large area. One strategy for large groups of people would be to constantly scan the occupants for discomfort gestures, not bothering to associate the gestures with specific people. The resulting measurement corresponds to a kind of group-averaged TCI.

Can the gesture-based approach function when occupants are in many different positions? The Kinect skeletal recognition software is optimized for people standing up playing video games. It is less successful creating the skeletal geometry for persons sitting behind desks, lying down, or crawling. Future editions of skeletal recognition software might be able to include more positions associated with unique groups. For example, Microsoft made special efforts to enable Kinect to recognize movements by people in wheelchairs. Infants are another group where thermal discomfort gestures will be both unique and important.

Privacy is also a real problem. The Kinect easily recognizes individuals based on their skeletal geometry, facial features, and other information collected by the sensors. Occupants have a legitimate concern that their actions will be tracked and recorded, so a commercial version of this method must reflect the most recent regulations protecting personally identifiable information (Boeckl, Katie et al., 2018; European Parliament and of the Council, 2016). One partial solution would be to make a system that uses only the skeletal recognition aspects. Keeping the recognition computation close to the sensor, communicating only the TCI to the HVAC controls, would also decrease the amount of personally identifiable information being transmitted (Jia et al., 2016).

It is worthwhile to summarize the utility of this method in context with other participatory methods. There are circumstances where surveys, votes, or active participation by the occupants may not be feasible. These situations include: 1) there is no feasible way to regularly administer a survey; 2) the thermal environment is constantly changing; 3) a survey will interfere with organized activity (such as a wedding); 4) occupants are unable to respond (e.g. elderly or temporary occupants); and 5) the building operator lacks resources to perform and evaluate surveys.

4.3. Can Tracking Gestures Save Energy?

The principal advantage of tracking thermal gestures is that it avoids over-heating and over-cooling spaces when energy-saving temperatures, delivering greater thermal comfort, are possible. In situations where occupants are chronically thermally uncomfortable, tracking gestures may increase energy use. Still, it is important to understand the kinds of modifications needed in HVAC systems to incorporate gesture tracking.

A conventional thermostat responds to a change in temperature and the HVAC system supplies conditioning, using an anticipation algorithm to limit overshooting the desired temperature. The anticipation algorithm takes into account the capacity of the HVAC system and other thermal characteristics of the building. A similar gesture-based anticipation algorithm needs to be developed. The algorithm must capture the rate of change in TCI arising from HVAC operation.

Heating and cooling systems might need further modifications to incorporate gesture control. If, for example, gestures provide a more sensitive measure of thermal discomfort, then smaller, more precise HVAC output could be exploited. Greater precision might be accomplished by a dedicated, low-capacity feature, rather than full-load cycling. The impacts on energy consumption depend on the technology.

In practice tracking thermal gestures will include simultaneous detection of several subjects. These subjects will reveal the provided thermal climate based on their own individual thermal comfort sensations. The thermal comfort index Predicted Percentage Dissatisfied (PPD) defines a minimum 20% level of dissatisfaction. A multiple-subject gesture-based tracking method will need to interpret the distribution of gestures signaling dissatisfaction.

The first step in answering these questions is to perform a series of pilot tests. These tests should take place in both controlled and typical environments. The tests in a controlled environment could help verify the link between gestures and thermal discomfort. The tests in actual buildings would demonstrate the feasibility of integrating the gesture data into HVAC controls.

4.4. Future Work

This paper describes the key aspects of a method to automatically detect human gestures related to thermal discomfort; however considerable work must be undertaken to translate this concept into a reliable means of controlling an HVAC system. Several areas of future investigations that appear especially fruitful are listed below.

4.4.1. Expansion of the Gesture Library

Defining more poses will be useful for improving the robustness of the method proposed in this paper. Five gestures were defined in this paper (see Table 3) that are not yet recognizable by the Kinect. Table 3 lists five more gestures that deserve further research.

Table 3. New gestures for future work

No.	Gesture name	Level
1	Scratch head	Feeling warm
2	Roll up sleeves	Feeling warm
3	Cross legs	Feeling cool
4	Hands around neck	Feeling cool

5	Stamping feet	Feeling cool

Note that the gestures of crossing legs and placing hands around the neck are not unambiguously associated with feeling cool, so additional research may be needed to decide what—if anything—these gestures imply.

4.4.2. Thermal Comfort Measurement Based on Normal Cameras

The Kinect is an excellent machine but has several limitations that will prevent widespread applications. Most important, Microsoft has discontinued sales of the Kinect. While machines and software are still available, the price is relatively high. Second, the associated software is not open source. This limits improvements and updates. Fortunately, digital cameras in computers and smartphones now have nearly the same capabilities and are widely available at low prices. At the same time, several open source platforms are now available that can construct skeletal images (which is the key input to identification of thermal discomfort gestures). These "human pose estimation" platforms include OpenPose (Wei et al., 2016), DensePose (Güler et al., 2018), AlphaPose (Fang et al., 2018) and Human Body Pose Estimation (Insafutdinov et al., 2017). Another platform, DeepPose (Toshev and Szegedy, 2014) can perform pose estimation but is not open source. One (or more) of these platforms will be needed for the methods presented in this paper to be further developed.

4.4.3. Calibration with Subjective Determinations of Thermal Comfort

Comfort estimations derived from gestures must be compared to those derived from traditional comfort surveys. This information will help in relating the measurements of comfort and discomfort. These comparisons will never be totally satisfactory because one method is dynamic and the other static. Still, a comparison will help inform the general accuracy of the technique.

4.4.4. Incorporation of Machine Learning Techniques

One area of future study would be to advance the architecture from a static set of rule-based mappings between detected gesture and HVAC responses by incorporating machine learning. The logic described in Figure 2 would be changed to use image recognition to detect and determine a gesture (with a concurrent probability). This would be combined with an initial (or baseline) guess for how that gesture interacts with TCI, and finally another sequence model algorithm would gauge how effective the initial guess was and learn to make better guesses for how to trigger the HVAC system going forward.

Using machine learning could address some of the concerns about cultural or even more local differences regarding gestures, since each implementation of the system can learn those differences without *a priori* knowledge beyond some baseline. Further, it allows a 'voting algorithm' to emerge that makes the most sense for a given target population, rather than something that must be decided beforehand. Finally, this sort of system could detect gestures with a normal camera as opposed to needing the 3D capability of the Kinect.

4.4.5. Thermal Discomfort of Animals

The thermal discomfort of animals also deserves investigation. Animal thermal comfort affects not just animal health and welfare, but the economic health of the farming industry: the thermal comfort of livestock and poultry affects their growth and productivity (St-Pierre et al., 2003). Cows suffering from thermal stress produce less milk and fewer offspring

(Legrand et al., 2011). Although livestock discomfort is apparent to a trained observer, constant observation is not feasible for large herds. Animals cannot communicate their feelings of hot and cold in a natural language. Therefore, analyzing animal's behavior is an effective way to perceive the animal's thermal discomfort. Unlike for humans, there exists considerable research on poses and movements related to livestock thermal discomfort (Laer et al., 2015). The pose estimation platforms mentioned above are designed for humans. They can recognize humans (bipeds) but not quadrupeds like cows, goats, or dogs. The platforms must first be trained to recognize and disambiguate these animals' skeletons before thermal comfort can be studied.

5. Conclusions

A new method was introduced to assess a person's thermal discomfort based on close observation of human gestures. It relies on the voluntary and involuntary actions that a person takes to ensure that a heat balance with the environment is maintained. The method is potentially more objective than survey methods because it is based on a person's actual adjustments to maintain a heat balance with the environment and involuntary signaling of thermal discomfort. The method has only recently become feasible because of the declining costs of tracking skeletal geometry and the software available to use this information to recognize relevant gestures.

A key feature of the method is a library of gestures or poses related to thermal discomfort. Each gesture has a description of the skeletal geometry associated with it. Skeletal definitions for some of those gestures were created to demonstrate proof of concept; ultimately, this library can be standardized and made available to other researchers.

Prolonged tracking of these gestures can be converted into a metric, the Thermal Comfort Index (TCI) that reflects a person's current thermal comfort. The TCI could then drive an HVAC system and provide a highly-personalized thermal environment.

Each step in the development of this method raises new questions regarding the nature of thermal comfort and the technologies used to satisfy a person's need for thermal comfort. Nevertheless, the rapidly-improving capabilities in sensing, tracking, and computing mean that tracking and interpreting gestures will soon be even more effective. It will be a fruitful area for further research and, potentially, saving energy.

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The thermal and energy demand of Solar Decathlon Middle East prototypes and its classification by climatic seasons

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Abstract: For an architect today, the method to design a passive house in cold weather and the choice of the Architectural Actions (AA), are clearly established. When the question comes to how to build a passive house in hot, and extreme hot climates, the strategies are poor and often results of a combination of western strategies with a local relook. From several visits in Middle East countries, Saudi Arabia, UAE, Oman, Palestine, Qatar, we concluded that the strategy for low consumption houses is not established yet and poorly grasped.
Several reasons, as energy prices, invite designers and owners to rely on over usage of air-conditioning systems as measures to catch up on poor bioclimatic design. The method of the “Climatic Seasons” proposes an approach on bioclimatic design for extreme hot climates from an architect point of view. It is based on a Cooling Degrees Days (CDD) and Heating Degrees Days (HDD) approach. Local climates are classified according to the energy-hunger of six situations of the exterior temperature during night/day : cold/cold, cold/cool, cool/warm, cold/hot, cool/hot, and hot/hot as CDD and HDD of the twelve month of the year. This will create two main “house situations”: the house is closed or open to the exterior. We will associate passive strategies, “architectural actions”, to these two different ways to live in the house .

Several prototypes have been constructed and tested for the Solar Decathlon Middle East 2018, in November 2018 in Dubai (https://www.solardecathlonme.com/). This competition gathered 15 teams composed of students and scientists from all over the world. Each team proposed different architectural actions to reach low energy consumption, this paper analyses them and proposed a classification related to every climatic season, and discuss about their efficiency related to the results of the competition.

Keywords: bioclimatic architecture, solar decathlon middle east, low energy architecture, architectural actions, bioclimatic seasons

Introduction

The low energy consumption tendency and know-how in hot climate countries has been through an interesting development the last 10 years even if the main base of knowledge has not still easy access to methodologies, tools, labels, training... etc. Today more than 80% of people in the world live under a warm-hot climate, and millions of them under very hot climate. Cities like Dubai represent the struggle in between man and nature to make such as regions attractive for people despite the very harsh conditions during the long summer season. So far in recent and modern construction, buildings follow a model of architecture called "international" with little efforts on architectural principles for low energy consumption. Finally the comfort is achieved relying on technical equipment, including air conditioning that represents the highest energy consumption equipment.

Today, the international comfort standards cannot avoid the massif use of air conditioning systems, and its omnipresence and over-use has become a fact in the everyday life of the middle class in developed or emerging countries in hot climates, just like cool climate countries do with the heating. However in hot climate, like in cold climate, we find extreme contexts, countries that have shortages of access to electricity as some cities in Palestine or many countries in Africa and those who have an important energy access situation, as in Saudi Arabia or the United Arab Emirates. Paradoxically in both cases reach the low energy consumption is now a priority in national strategies for different reasons: one is designed to minimize the energy shortage, while rich countries aim to reduce exorbitant spending on subsidies in energy sold at prices below the cost of production for reasons of social solidarity.

From October 2016 to the end of 2018 the contest Solar Decathlon Middle Est took place nearby Dubai. This has been the first global scientific competition on low energy consumption houses in extreme hot weather region. Fifteen prototypes coming from all over the world: Malaysia, Australia, USA, France, Italy, Netherlands, Romania, Saudi Arabia, UAE, Palestine and Taiwan, tried their skills and strategies to face 15 days period competition to demonstrate how little they could consume but also how easily they could be a positive energy building.

In this paper we aim to present and analyze the different architectural actions proposed by the teams and to classified them by the method of the climatic seasons (Yusta-Bruneau-Bonneaud 2018) to propose architects to produce well founded architectural solutions which could help to improve the comfort and the future quality of life of low-income families in hot climates combining a passive thinking but high flexibility on design without neglecting the use of newest construction technologies.

“Very hot climate” definition for designers.

The term "hot climate" is often too general in western and European cultures. Wladimir Köppen defined "hot desert climate" as Bwh, where “B” meant a climate defined by little precipitation, “W” indicating an extreme arid one with annual precipitation under a certain threshold, and “h” meaning low latitude climate with temperatures average annual temperature above 18ºC, which basically means hot arid weather. This term covers all Saharan Africa, Arabia, south of the United States and the center zone of Australia. However In this classification not all countries undergo the same need to use air conditioning, specially the countries of the Arabian Peninsula and around the Red Sea and the Persian Gulf, where record-breaking temperatures are often measured. In 2004 the ASHRAE and IECC (International Energy Conservation Code) agreed to create a common classification more accurate, standard 90.1.: Zone 1: very hot and wet (1A)/very hot and dry (1B). A climate is rated 1B "very hot and dry climate" if it has more than 5000 Cooling Degree Days (CDD) at a temperature of 10ºC.

By this method, the city of Riyadh with 6026 CCD at 10ºC would be largely in this category. However with the same criteria, a city like Karachi in Pakistan with 6119CDD to 10ºC would be in the same category of hot climate even if it does not represent a climate as severe as the climate of the cities of the Arabian Peninsula. A higher temperature threshold would be more judicious to establish criteria to classify cities in extreme desert climates.

Table 1. Classification of cities based on their COOLING DEGREE DAYS at 26ºC

Celsius-based 2-year-average (2014 to 2015) cooling degree days for a base temperature of 26,0C in airports															Source www.degreedays.net
CDD 26ºC			Year	Month											
			TOTAL	J	F	M	A	M	J	Jl	A	S	O	N	D
EUROPE	FRANCE	NICE	40	0	0	0	0	0	3	23	13	1	0	0	0
		PARIS	29	0	0	0	0	0	5	16	8	0	0	0	0
	SPAIN	SEVILLA	305	0	0	1	4	35	54	99	84	21	6	0	1
		MADRID	253	0	0	0	0	12	44	108	71	17	1	0	0
	GREECE	ATHENES	293	0	0	0	0	8	40	97	108	38	2	0	0
MIDDLE EAST	SAUDI ARABIA	RIYADH	1630	1	6	22	102	218	272	327	326	223	123	10	0
		DJEDDAH	1509	21	28	61	99	159	177	240	261	198	154	76	35
		MEDINAH	2061	6	16	64	136	249	314	333	392	322	189	34	6
		MAKKAH	2324	44	59	115	182	271	308	340	338	290	221	104	52
	UAE	DUBAI	1769	1	12	26	100	221	259	334	339	249	179	45	4
	IRAN	ANWAZH	1840	0	1	8	85	232	340	402	388	266	115	3	0
	OMAN	MASCATE	1541	0	14	18	144	272	283	248	197	180	143	40	2
		SALALAH	586	3	6	25	70	118	117	26	15	48	80	57	21
	PALESTINE	NABLUS	156	0	0	0	5	17	19	28	50	29	8	0	0
		JERICHO	1102	0	2	16	55	123	158	228	259	174	76	10	1
	ISRAEL	JERUSALEM	315	0	1	3	11	29	31	59	93	66	19	3	0
AFRICA	SUDAN	KHARTOUM	2056	45	76	167	215	294	292	231	173	204	220	100	39
	CHAD	N'DJAMENA	1543	53	100	191	219	254	206	108	53	73	133	113	40
	NIGER	AGADEZ	2008	28	64	139	212	298	322	240	170	214	214	92	15
		NIAMEY	1776	58	104	190	249	270	224	128	81	111	188	130	43
AMERICA	USA	PHOENIX	1222	0	3	20	41	99	263	287	263	178	64	4	0
ASIA	INDIA	NAGPUR	1154	8	35	93	187	284	192	88	65	64	75	44	19
	PAKISTAN	KARACHI	1035	2	8	43	108	152	193	143	107	109	110	50	10
OCEANIA	AUSTRALIA	ALICE SPRINGS	658	108	99	90	23	3	0	0	3	18	88	112	114

If we consider that heat discomfort starts at 26º, under relative humidity conditions around 50%, and most of the air conditioning equipment starts also at 26º, then CDD26º is a good reference to classify the "hunger" for energy on active cooling of a climate. The choice of 26ºC is an arbitrary one and it depends on cultures and lifestyles. Cultural and social factors can have strong influence on the accepted "hot temperature" that we will not study in this paper.

Based on this method, Table 1 shows a classification on cooling energy needs based on a start of the cooling needs at 26º (considering that most of the existing air conditioning systems do not consider relative humidity parameters). It is clear that the GCC countries (Saudi Arabia, UAE…) are way far ahead on cooling needs that any other zone in the world.

Introducing Relative Humidity parameter on the hot weather classification method

Using only the CCD to classify a region climate might lack the integration of comfort, or disconfort, that relative humidity creates on people. Very often this two parameters and shown separately, while the comfort sensation due to humidity and temperature together can be given by one value, as show several methodes as Heat Index or Humidex. By using two cities from the region, Dubai (UAE) and Medine (KSA), we want to explore the differences on ranking of two cities with a similar temperature range but with a significance differences on relative humidy : Dubai as a wet climate and Medine as a dry one. We have compared the difference that could occur in the classification if the temperature used to obtain the thermal stress of a site (Yusta 2018) was not done by using the CDD and HDD of the dry air temperature but the sum of the Cooling Degres Hours (CDH) divided by 24. Further comparison is done by using the resented temperature proposed by Humidex´s table of equivalences and how this could modify the ranking of hot climate cities as a way to better understand the potential on air conditioning usage. A forth comparison is shown by using the formula of Heat Index. It is shown (Table 2) that:

1- The calcul by CDDays and the equivalent with CDHours gives significatif differences of between 10 to 20% (figures 1 and 2 "temperature de l'air")

2-The use of resented temperature given by Humidex creates real big differences in between two sites: Dubai goes from 1873 CDD26ºC to 3709 CDD26ºC equivalent Humidex and whereas Medine goes from 1872 CDD26ºC to 1947 CDD26ºC equivalent Humidex, showing clearly that a given level comfort in Dubai will be harder to obtain than in Medine, with higher electricity expenses due to air conditioning and air desiccant procedures.

3- The values of the Heat Index formula cannot be used out of a certain range of temperatures, the authors consider that out of the range 23ºC-38ºC the polynomial of HI formula gives values that do not represent resented temperature. Medina shows a lower CDD26ºC by using the HI (1546) that it has by using just the dry air temperature (1872), whereas Humidex proposes a significant increase of this parameter (1947).

Table 2. Comparison of two cities based on their COOLING DEGREE DAYS at 26ºC

DUBAI

TEMPERATURE DE L'AIR

PAR MOIS	CDD 26ºC	HDD 26ºC	CDD 19ºC	HDD 19ºC
	1873	912	3826	167
Janvier	1,39	250	44,4	74
Fevrier	11,8	160	89	34
Mars	39,1	105	169	11,7
Avril	125	24,7	310	0,06
Mai	232	2,45	440	0
Juin	318	0	534	0
Juillet	352	0	569	0
Août	360	0	577	0
Septembre	221	1,9	429	0
Octobre	66,6	59,8	228	4,39
Novembre	10,4	145	99,3	20,5
Décembre	2,66	163	83,9	22,3

HEAT INDEX

PAR MOIS	CDD 26ºC	HDD 26ºC	CDD 19ºC	HDD 19ºC
	2988	912	5086	167
Janvier	48,3	250	80,1	74
Fevrier	44,8	160	136	34
Mars	57,2	105	211	11,7
Avril	156	24,7	356	0,06
Mai	351	2,45	566	0
Juin	561	0	777	0
Juillet	545	0	762	0
Août	483	0	700	0
Septembre	393	1,9	602	0
Octobre	112	59,6	296	4,39
Novembre	20	145	143	20,5
Décembre	15,4	163	142	22,3

HUMIDEX

PAR MOIS	CDD 26ºC	HDD 26ºC	CDD 19ºC	HDD 19ºC
	3709	708	5844	144
Janvier	19,1	217	87,4	66
Fevrier	70,4	133	170	29,2
Mars	135	68,8	299	9,21
Avril	254	12,2	452	0
Mai	436	2,21	651	0
Juin	629	0	845	0
Juillet	606	0	823	0
Août	560	0	777	0
Septembre	480	0,08	699	0
Octobre	206	36,4	390	3,21
Novembre	53,9	116	168	16,3
Décembre	20,2	122	140	20

MEDINE

TEMPERATURE DE L'AIR

PAR MOIS	CDD 26ºC	HDD 26ºC	CDD 19ºC	HDD 19ºC
	1872	826	3795	164
Janvier	1,39	250	44,4	74
Fevrier	11,3	160	89	34
Mars	39,1	105	169	11,7
Avril	125	24,7	310	0,06
Mai	232	2,45	440	0
Juin	318	0	534	0
Juillet	352	0	569	0
Août	360	0	577	0
Septembre	221	1,9	429	0
Octobre	66,6	59,6	228	4,39
Novembre	10,4	145	99,3	20,5
Décembre	1,49	76,2	23,1	19,3

HEAT INDEX

PAR MOIS	CDD 26ºC	HDD 26ºC	CDD 19ºC	HDD 19ºC
	1546	826	3530	164
Janvier	57,9	250	77,1	74
Fevrier	20,5	160	113	34
Mars	24,3	105	185	11,7
Avril	83,4	24,7	281	0,06
Mai	172	2,45	387	0
Juin	257	0	473	0
Juillet	285	0	502	0
Août	301	0	518	0
Septembre	165	1,9	373	0
Octobre	42,7	59,6	228	4,39
Novembre	15,6	145	137	20,5
Décembre	14,5	76,2	38,6	19,3

HUMIDEX

PAR MOIS	CDD 26ºC	HDD 26ºC	CDD 19ºC	HDD 19ºC
	1947	807	3836	141
Janvier	0,92	242	43,8	66
Fevrier	9,54	160	82,5	29,2
Mars	27,5	109	151	9,21
Avril	107	27,8	289	0
Mai	229	4	442	0
Juin	347	0	563	0
Juillet	373	0	590	0
Août	395	0	612	0
Septembre	225	2,38	439	0
Octobre	64,2	53,5	231	3,21
Novembre	11,5	136	106	16,3
Décembre	1,21	72,5	24,1	17

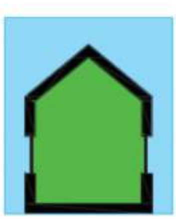
Classification of a city climate by using the concept of "Climatic Seasons"

In order to classify a site from the point of view of bioclimatic strategy we defined three simple situations that represent the broad majority of cases, and imply very different bioclimatic design strategies. These generic situations are described as follows (figure 1):

Situation 1 - It is cold outside, and the vector [temperature, humidity] is unpleasant: users prefer to close doors and windows and reduce exchange with the outside. They try to get as much as possible of sun inside of the house.

Situation 2 - It is temperate outside, cool or warm, the vector [temperature, humidity] is pleasant: users prefer to open doors and windows to generate cross ventilation.

Situation 3 – It is hot outside; the vector [temperature, humidity] is unpleasant: users prefer to close doors and windows and reduce exchange with the outside. The sun-rays are blocked as much as possible.


Too cold to open


It feels nice outside


Too hot to open

Figure 1. Diagrams of “climatic situations”

Several of these three situations can arrive during one same day, making appear different day-types: 1-1, 1-2, 2-2, 1-2-3, 2-3, and 3-3. The designer will then need a passive strategy for different day-type. The impression of cold, cool, warm and hot, can vary a lot depending on cultures. We chose the most common international range of 19ºC to 26ºC, but it could be adapted to any culture just by modifying the values. We define a new concept named “CLIMATIC SEASON”, which are periods that can last several months with the passive strategy remains the same (figure 2)

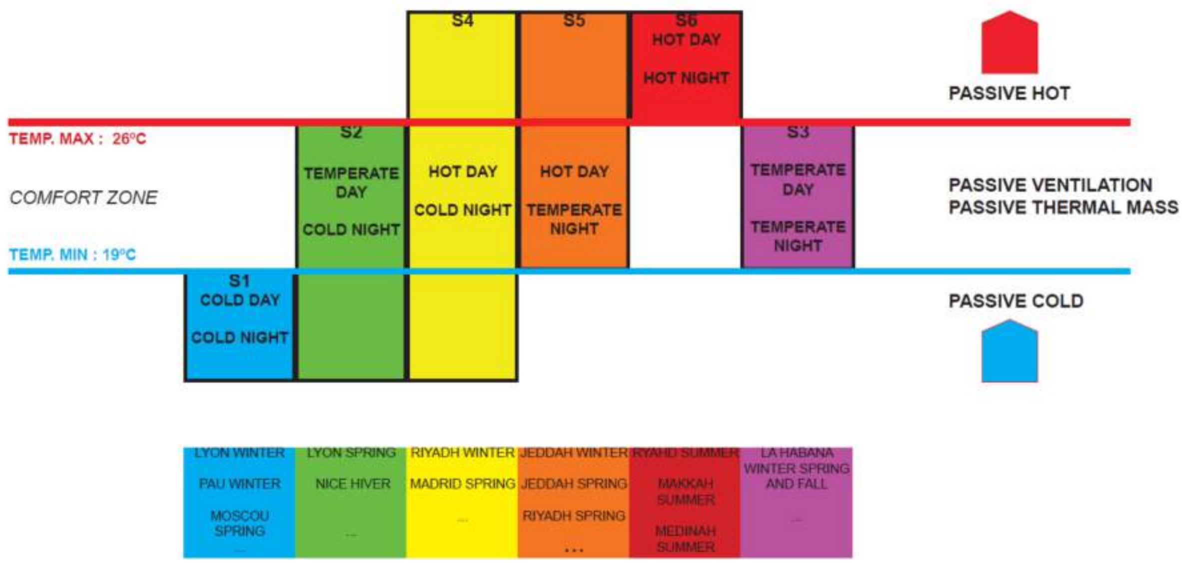


Figure 2. Diagram of “climatic seasons” with some examples of cities and their seasons.

These “climatic seasons” are defined as follows:

Climatic Season S1: cold days and cold nights. This season is the coldest of all, and it is characteristic of many cities in Northern Europe during winter.

Climatic Season S2: cool days and cold nights. This season combines daily temperatures that are comfortable to be outside and open the windows. At night time temperatures that are below the comfort threshold and windows should be closed.

Climatic Season S3: temperate days and nights. This season is always comfortable to be outside day and night, the house can be open during all periods.

Climatic Season S4: hot days and cold nights. Daily maximum temperatures are above the upper threshold of comfort and the daily minimum temperatures are below the low threshold of comfort. An important part of the day temperatures are comfortable but at peak hours we either feel too hot or too cold.

Climatic Season S5: hot days and warm nights. Daily maximum temperatures are above the upper threshold of comfort and daily minimum temperatures stay in the range of comfort. A large part of the day exterior conditions are uncomfortable and late in the evening they become confortable for some hours.

Climatic Season S6: hot days and hot nights. This is the hottest season of all, temperatures are high all the time, and even though they may not be extreme they are permanently over the high threshold of comfort temperature. It is characteristic of many cities in the Middle East during spring, summer and fall.

Degrees-days for architectural passive strategy

In order to organize the year of a city in Climatic Seasons we propose to use the values of temperature and relative humidity in order to find the equivalent of classical degree-day values but by using degree-hour with a transformation by Humidex table to find equivalent resented temperatures. We will use two values associated with the high temperature threshold of 26ºC: HDD26 and CDD26, and two values associated with the low temperature threshold of 19ºC: HDD19 and CDD19.

In order to determine to which Climatic Season (S1, S2,... S6) belongs a particular month of the year of a city, we need to establish criteria based on an established threshold:

Season 1: HDD19>0 CDD19=0	heating- no air conditioning- no exterior
Season 2: HDD19>0 CDD26=0	heating- no air conditioning- some exterior
Season 3: HDD19=0 CDD26=0	no heating- no air conditioning- lots of exterior
Season 4: HDD19>0 CDD26>0	heating- air conditioning- some exterior
Season 5: HDD19=0 CDD26>0	no heating- air conditioning- some exterior
Season 6: HDD26=0 CDD26>0	no heating- air conditioning- no exterior

However we need to allow a certain overtaking on these values to dismiss extreme values: it will be enough in a very cold day (S1) with an outside temperature of one degree over the comfort level to consider it as a temperate-cold season (S2). To allow this over threshold we will use a percentage of 10% of the “thermal Stress” value (YUSTA and al 2018):

STh [XY]ºC = /DJCXºC/ + /DJRYºC/
With,
X : low resented temperature of comfort range
and
Y : low resented temperature of comfort range

We will consider that if the DD value divided by thermal stress value is less than 5%, it will be consider as 0 in terms of Climatic Seasons classification.

Figure 3 shows the Climatic Season classification by using the humidex resented temperature of Dubai 2005 climate data, the result shows that from May to October the temperatures are too high to open the windows at night time, as shows the Season 6 with the “Climatic Season” method. In January, the temperatures are low, especially at night time, so a Season 2 strategy can be carried out.

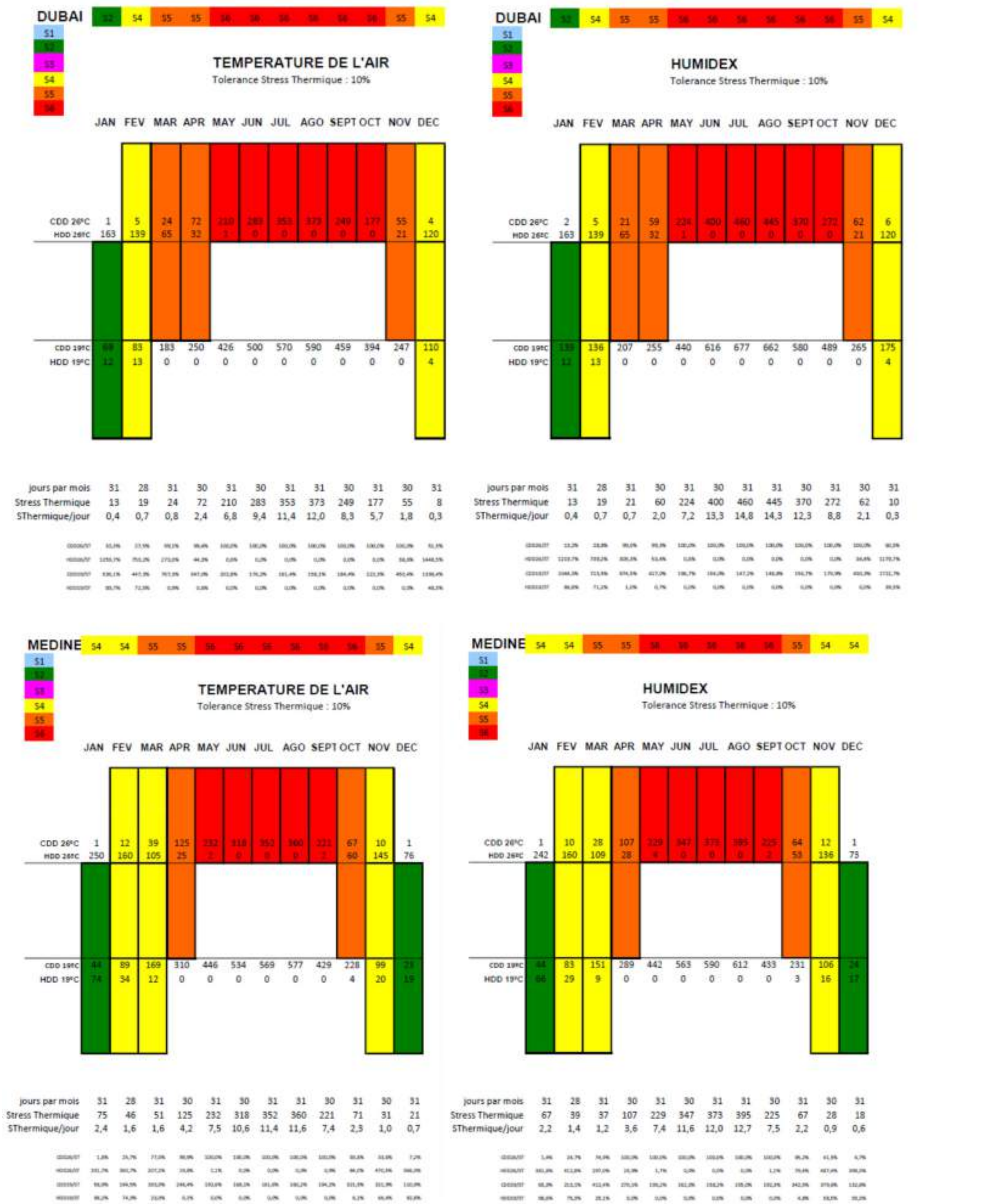


Figure 3. Comparison of Climatic Season method using dry air temperature, Heat Index equivalent and Humidex equivalent. 2005 climates values.

The climatic year

The combination of the Climatic Seasons of a particular city over a year is named 'Climatic Year', the diagram in figure 4 shows all the different combinations of climatic seasons for different cities. This classification allows designers to easily understand the challenges on bioclimatic and passive design and include exterior zones to allow strategies on cross ventilation when needed for 2 to 5 climatic seasons.

The weight of Thermal stress on the climatic year

On a low energy consumption objective, the climatic year should be modified by the weight of the thermal stress (TS) coefficient per month. This would give more presence to the months with higher TS, so with higher intensity on extreme temperatures, and so it would modify the profile of the year so that designers could reevaluate the needs of external spaces and cross ventilation strategies (YUSTA 2018).

	JAN	FEV	MAR	APR	MAY	JUN	JUL	AGO	SEPT	OCT	NOV	DEC
EDINBURGH	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1
PARIS	S1	S1	S1	S1	S1	S2	S4	S2	S2	S1	S1	S1
BORDEAUX	S1	S1	S1	S2	S2	S4	S4	S4	S2	S2	S1	S1
MADRID	S1	S1	S1	S2	S4	S4	S5	S5	S4	S2	S1	S1
JERICHO	S1	S1	S2	S2	S4	S5	S5	S5	S5	S4	S1	S1
VALENCIA	S1	S1	S2	S2	S4	S5	S5	S5	S5	S2	S2	S1
SEVILLA	S1	S1	S2	S2	S4	S5	S5	S5	S5	S2	S2	S1
RIYAD	S2	S2	S4	S5	S6	S6	S6	S6	S6	S5	S2	S2
DOHA	S2	S2	S4	S5	S6	S6	S6	S6	S6	S5	S4	S2
MEDINA	S2	S4	S4	S5	S6	S6	S6	S6	S6	S5	S4	S2
DUBAI	S2	S4	S4	S5	S6	S6	S6	S6	S6	S6	S5	S4
JEHDDA	S5	S5	S5	S5	S6	S6	S6	S6	S6	S6	S5	S5
MAKKA	S5	S5	S5	S6	S6	S6	S6	S6	S6	S6	S5	S5

Figure 4. Climatic year of different cities by combination of climatic seasons

Architectural strategy based on Climatic Seasons

Both, hot/cold, bioclimatic strategies have similar approaches organized in five general axes:

1-External hot/cold protection
2-Inner heat management
3-Heat evacuation/capture
4-Cold/heat production
5-Heat/cold adaptation

These main strategies are formalized by designers by applying different Architectural Actions. An Architectural Action is a decision taken by the designer having an impact on the architectural shape of the building to bring down the energy consumption of the building.
We will now analyze the architectural actions proposed by designers on Solar Decathlon Middle East (SDME) competition and their impact on the behavior of the prototypes.

The SDME climatic and geographic context

The competition took place by the Mohamed Bin Rashim Al-Maktoum Solar Plant from 19th October to 28th Nov 2018. The site was more than 40km from the coast (figure 5).

Figure 5. Location of the SDME 2018 site. View of the solar site during the competition

During this period the lowest temperature was 15ºC and the highest 36ºC, with a mean temperature of 23,1ºC and. The lowest and highest values for relative humidity were 10% and 92% with a mean humidity of 62% (table 3). These conditions do not represent the real harsh climate of the region but could nevertheless be useful for many Mediterranean and coastal hot weather, which is particularly interesting in terms of international projection.

Table 3. Minimum, maximum and 5%, 50%, 95% centiles of exterior Temperature and Humidity during the competition

	Min	Centile 5%	Centile 50%	Centile 95%	Max
Exterior dry air temperature (ºC)	15	16,7	23,1	32,3	36
Exterior Relative Humidity (%RH)	10	16,4	62,0	88,3	92

Temperatures went lowest at dawn, about 6h, making relative humidity go to their daily maximum (figure 7). During day time temperatures went high reaching their maximum in between 13h-14h and at this point the humidity reached its minimum (figure 6). During the competition the climatic seasons S4 (cold nights and hot days) and S5 (cool nights and hot days) were the only represented.

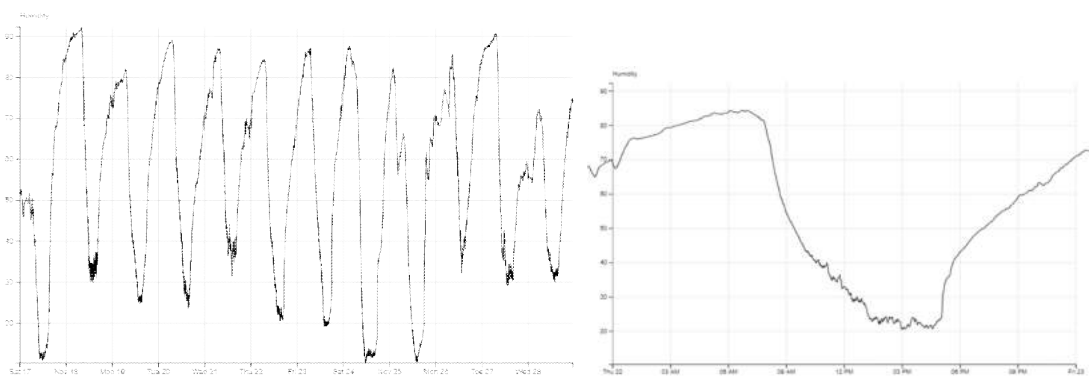


Figure 6. Graphic of exterior relative humidity during the contest period and a zoom on one intermediate journey of 22th November 2018.

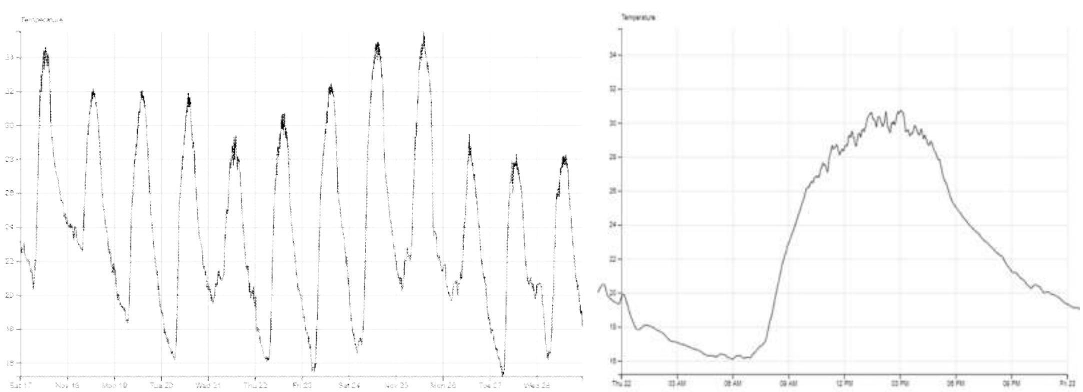


Figure 7. Graphic of exterior dry air temperature during the contest period and a zoom on one intermediate journey of 22th November 2018.

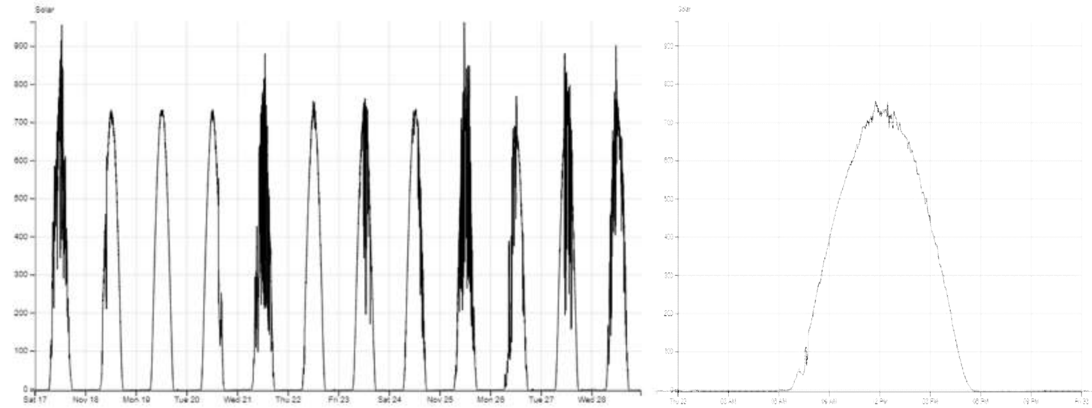


Figure 8. Graphic of exterior solar radiation by pyranometer (W/m2) during the contest period and a zoom on one intermediate journey of 22th November 2018.

The solar radiation can be evaluated with the values of the pyrometer during the journey reached its highest point at 12h with a value of 750 W/m2 (figure 8). The landscape around the site was a desert one: no trees, very little vegetation and sand dunes all around.

The SDME comfort rules and thresholds

As the organizers describe it, the Solar Decathlon is an international competition created by the U.S. Department of Energy in which universities from all over the world meet to design, build and operate sustainable and high energy efficiency grid-connected solar powered houses. During the final phase of the competition, participating teams assemble their houses in an expo area, open to the general public, while undergoing the ten contests of the competition, reason for which this event is called Decathlon (SDME Rules – Introduction- page 4). The house and all site components on a team's lot must stay within the solar envelope. The solar envelope shape is a truncated pyramid whose base measures 20 m x 20 m and whose top plane is located at the height of 7 m and measures 10 m x 10 m.
The measurable area defined below shall be at least 45.00 m2, but shall not exceed 90 m2 for single floor housing unit and 110.00 m2 for multi-story housing units. In order to obtain full points the inner black globe temperatures (radiation and convention) must stay in between 23ºC and 25ºC. This narrow temperature zone is needed to fairly compare the performances of the prototypes.

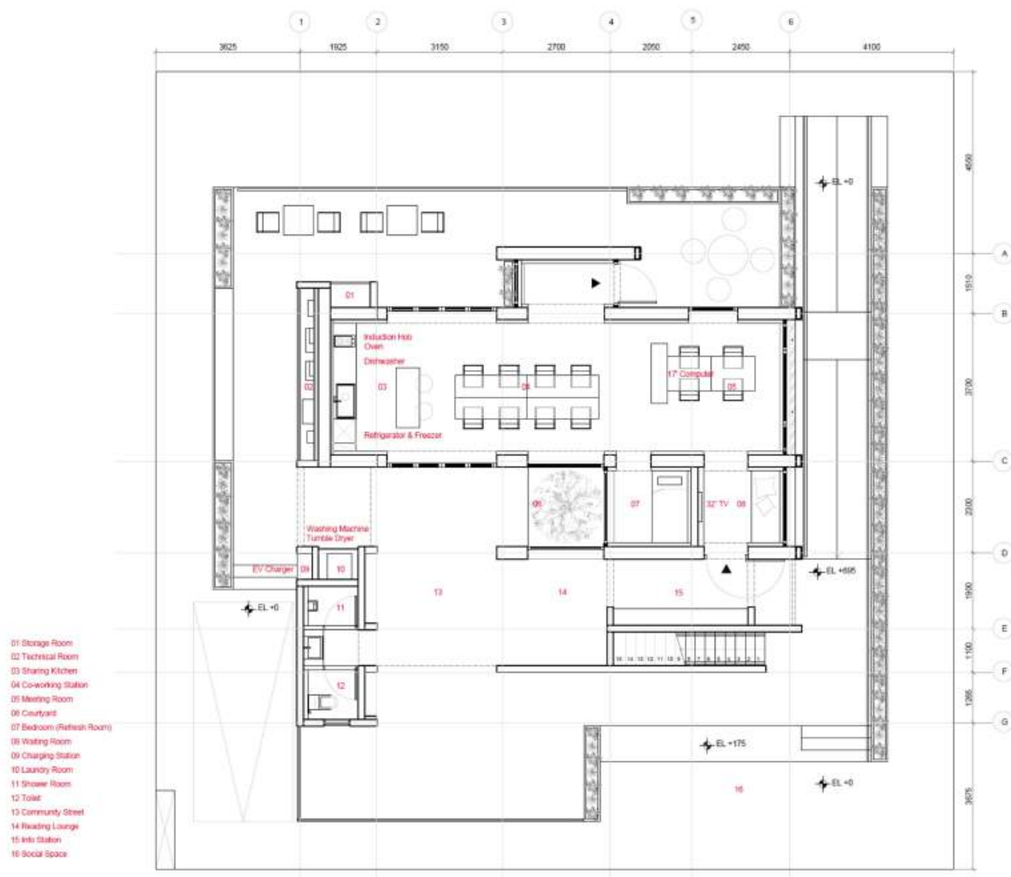
The prototypes and their proposals

The fifteen prototypes, only 14 could open to public. The teams and the main concepts were:

101-TDIS-Taiwan- National Chiao Tung University

Ultra-high insulation wooden walls filled with foam glass with vacuum cavities, an interior shaded court and a self-protected terrace. Inside the comfort is managed by a cooling panels ceiling and a heating floor. The inner surface was the smallest of all the competition with 49m2 on the ground floor and some interesting shaded outer spaces in the ground level and on the roof, protected by the solar panels. They had the most performing envelop on walls roof and floor : a R=15m2K/W. This was achieved by a VIP (Vacuum Insulation Panels) on Glass foam crystalized on void conditions, and a λ=0,02W/mK. No windows neither to the open south, nor to the west and main windows to the north. The Technical room was outside of the house on a red volume and their proposal was to mutualize these red technical zones among several houses. No especial measure was implemented to increase air tightness even if a heat recovery system was coupled with their system of air renewal by a double flow forced ventilation system.

Photo 1- TDIS-Taiwan South facade - National Chiao Tung University. Credit FYusta



Plan 1- TDIS-Taiwan- National Chiao Tung University. Credit : TDIS team

102-knowHouse-Italy- Ferrara University and Univesity of Sharjah

A textile exterior protection walls, wooden structure and an exterior sun protected peripheral terraces. This was the only proposal with a two level house. The proposal combined a poor insulated envelop, R=4m2K/W, with a white textile skin. No heat recovery system, nor particular attention to air tightness features with low performance windows (R=1,66 m2K/W) since using horizontal sliding system.

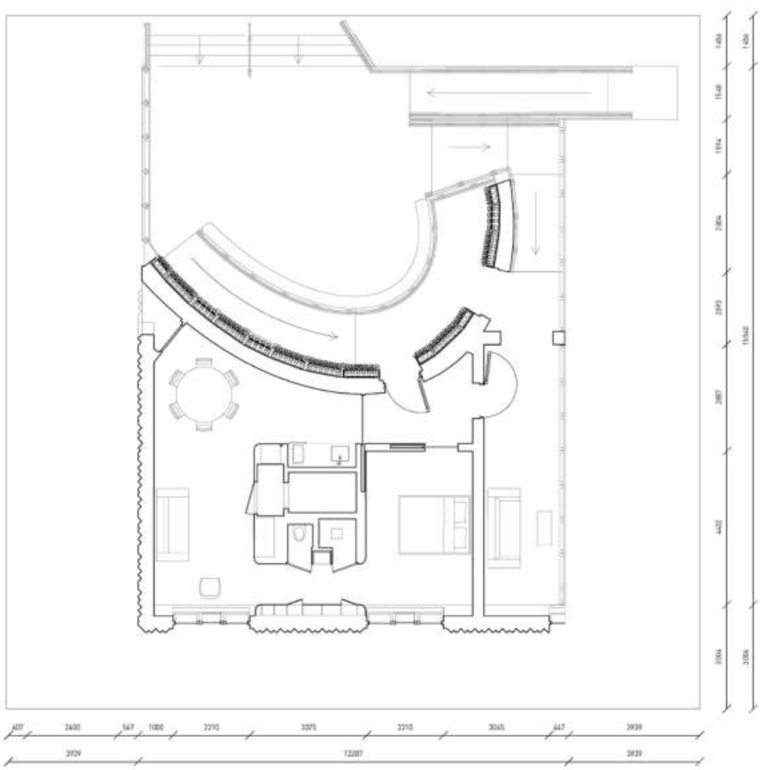
Photo 2- knowHouse-Italy- Ferrara University and Univesity of Sharjah. Credit FYusta

Plan 2- knowHouse-Italy- Ferrara University and Univesity of Sharjah. Credit KnowHouse.

103-Virtue-Netherlands- University of Eindhoven

The prototype represented the upper part of a collective building. The insulation levels of the envelop were among the best of the competition, R=7m2K/W with high insolated XPS inside of a wooden structure. The details shows a good care on air tightness. The southern façade was vertically inclined to avoid direct sun radiation in summer time and a self-ventilated mineral façade protected the W side from storing sun heat. No heat recovery system was installed on the prototype and the plants installed on the northern entry were not useful to the energy performance.

Photo 3- *Virtue-Netherlands- University of Eindhoven. This part represents an unachieved apartment next to the real prototype (behind) as if it was on a collective building*. Credit FYusta



Plan 3- *Virtue-Netherlands- University of Eindhoven, the right part represents an unachieved apartment next to the real prototype as if it was on a collective building*. Credit *Virtue team.*

104-MizanHome-Malaysia- Universiti of Teknologi of Malaysia

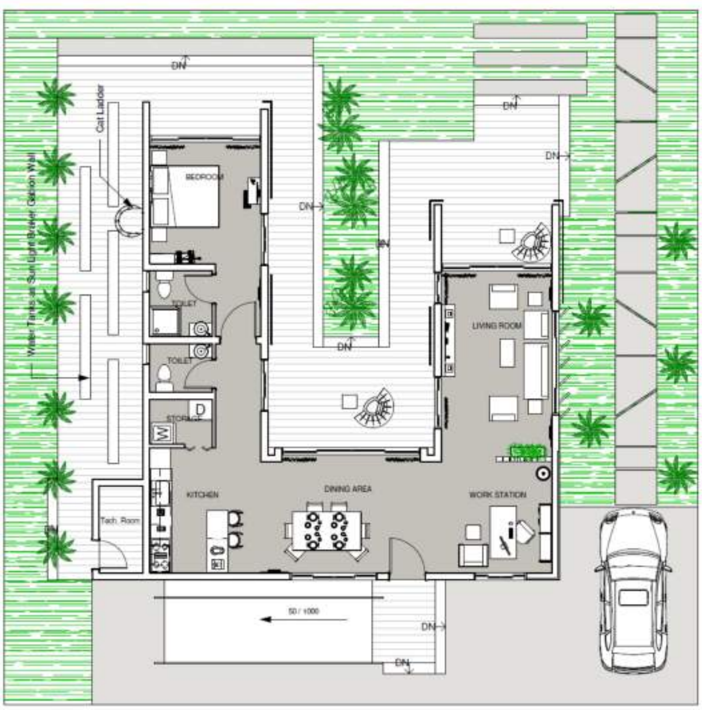
Light cold steel structure supporting insulation and a plywood panel from each side, interior and exterior. The interior distribution allows high cross-ventilation strategies. With a low thermal performance envelop, R=3,4m2K/W, and casement windows with standard values of insulation for a double layer glass windows. Poor air tightness and many thermal bridges existed due to design choices and construction methods, as cold steel and regular steel construction. No heat recovery system was installed on the prototype and the plants installed around the courtyard could have a lowering effect on temperatures near to the envelope. The construction of the house was achieved after the beginning of the measurement period, so the available data on energy consumption cannot be compared to the other prototypes. We will not take it into consideration on our analysis.

Photo 4- *MizanHome-Malaysia- Universiti of Teknologi of Malaysia*. Credit Fyusta

105-KSU-Saudi Arabia- king Saud University

An U shape towards the north and a highly protected interior yard by PV roof panels. Poor insulation made of recycled palm leafs, this was an interesting experiment but the level of insulation reached the lowest of all the prototypes, R=2,4m2K/W. Poor air tightness and many thermal bridges due to construction methods mixing concrete and steel beams. The shape and the concept were interesting and allowed to have generous openings to the inner court yard without direct solar radiation. The inner court and the roof of the house were highly protected by the shadow of solar panels. No heat recovery system or any other high performance system of ventilation were used.

Photo 5- *KSU-Saudi Arabia- king Saud University*. Credit FYusta

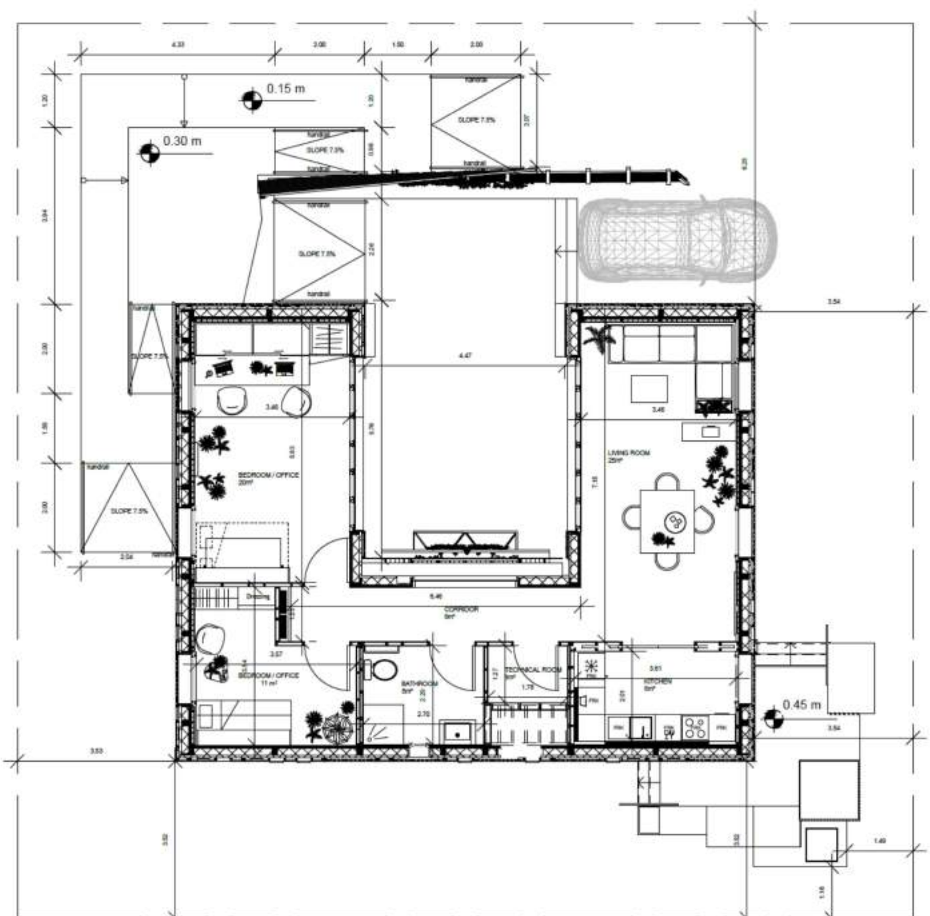


Plan 5- *KSU-Saudi Arabia- king Saud University*. Credit *KSU*

201-Baitykool-France- University of Bordeaux

A U shape oriented north, a complex layered skin supported by a high insulated wooden structure, R=6,8 m2K/W. Interior thermal inertia is obtained by natural clay bricks and concrete inner slab. The sun is filtered by pierced concrete panels in front of outside windows. Aluminum vapor barrier helps to reflect the infrared radiation getting through the piercings and from the mass of concrete panels. The inner patio is covered by a retractable PV pergola and a green roof and green walls contribute to low down the temperature. Cross ventilation facilities. A heat recovery system was coupled with their system of air renewal by a double flow forced ventilation system. The air intake zone was pre-cooled down by plants and vegetal roof.

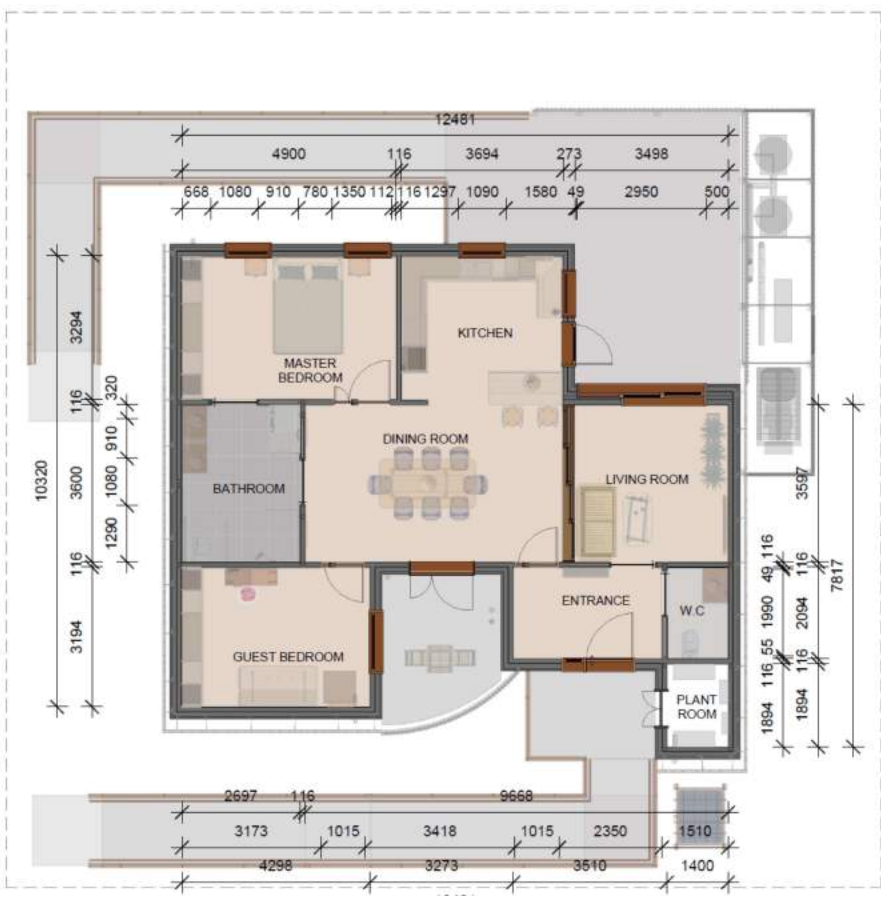
Photo 6- *Baitykool-France- University of Bordeaux*. Credit FYusta



Plan 6- *Baitykool-France- University of Bordeaux*. Credit *Baitykool team*

202-UOW-Australia- University of Wollongong

A wooden structure with high performance skin with a double air tightness barrier and no thermal bridges was used, even if overall insulation level was not among the highest, R=5,8 m2K/W. The main volume has big dimensions to keep hot air on top. This volume is ventilated on top recreating a wind chimney and vertical cross ventilation. Inside, the finishing materials reports little thermal inertia. Nevertheless, the ventilation system uses phase change materials to compensate. The PCM tanks act as a 35 kWh liquid thermal store that is cooled at night, increasing the coefficient of performance of the heat pump. The thermal store is then used to drive the fan coil units instead of using the heat pump. This drastically reduces the amount of energy used by the HVAC system during peak load. The windows have a special treatment against sun radiation with micro shading included in the double glass layer. The roof has PV panels combined with solar water heating panels. The north side hosts the main terrace which is partially covered on it east end. No windows on West or East side as they are the hardest to protect. A heat recovery system was coupled with their system of air renewal by a double flow forced ventilation system an air-to-water heat pump as the primary source of cooling within the home. A humidity controlled system was also coupled with the air treatment equipment, which uses desiccant crystals coupled with a heat pump to dehumidify the incoming air from the outdoor environment before it reaches the fan coil units. This allows maintaining the right levels of moisture comfort without getting a very low air temperature.



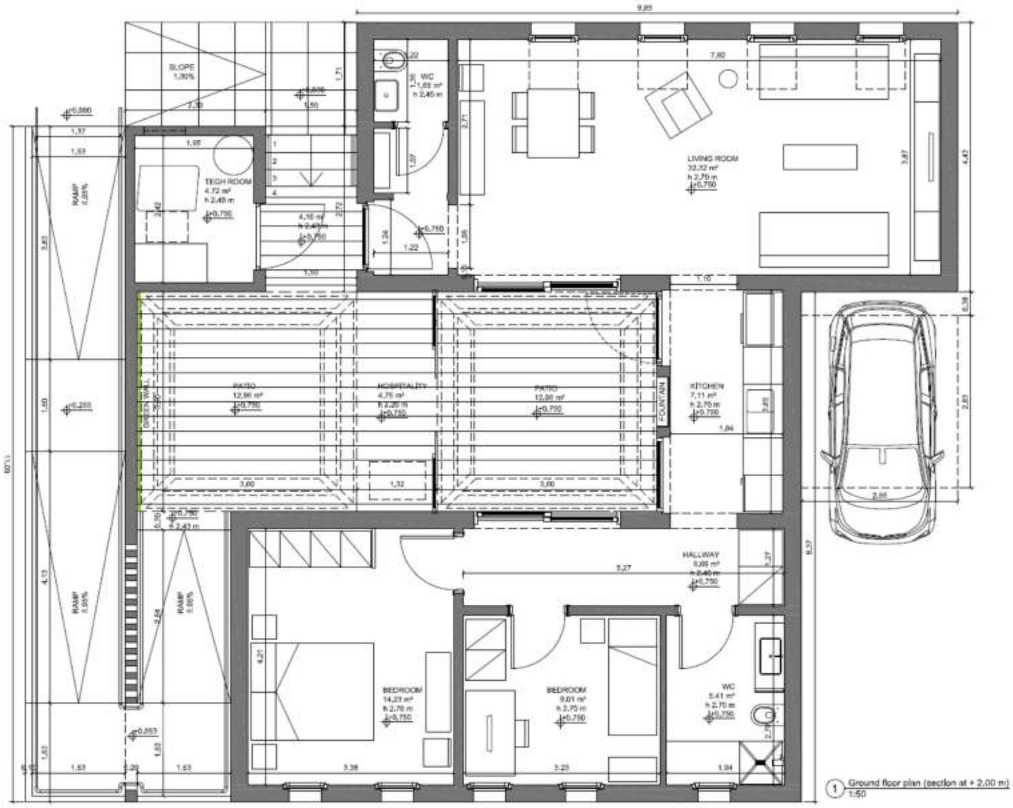
Plan 7- *UOW-Australia- University of Wollongong*. Credit *UOW team*

Photo 7- *UOW-Australia- University of Wollongong*. Credit Fyusta

204-Smart- Italy- Sapienza University of Rome

A Heavy massif wooden structure with high insulated nano-gel materials are used to create the outside and inside of the wooden skin of the envelope. The level of insulation was acceptable but not among the highest, R=5,6 m2K/W. An aluminum vapor barrier is set up under the outside finishing layer of precast cement panels. The U shape of the house was orientated towards the west. Exterior solar protection by textiles blinds. Inner court protected by textile overhead protection. The main volume had double height towards the north. No heat recovery system was installed on the prototype.

Photo 8- *Smart- Italy- Sapienza University of Rome*. Credit Fyusta



Plan 8- *Smart- Italy- Sapienza University of Rome*. Credit Smart team

205-AquaGreen-UAE- Ajman University

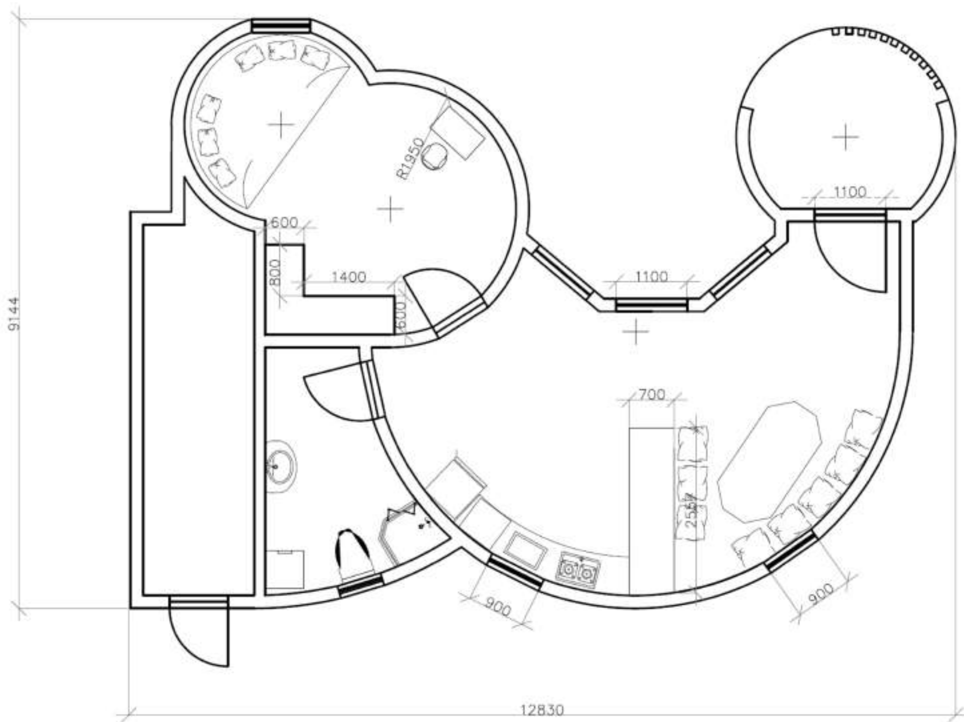
A heavy thermal mass construction type. It was composed by concrete hollow walls, a concrete hollow roof and a concrete beam floor. The voids on the walls are used to canalize an indirect adiabatic cooling system. The outer parts are protected from the sun either by solar panels or by shaded veranda. The over all thermal quality of the envelope was very low despite the adiabatic technology, R=3,1 m2K/W, since roof and floor were poorly insulated.

Photo 9- *AquaGreen-UAE- Ajman University*. Credit FYusta

301-JEEL-UAE- American University Dubai

A heavy concrete structure with precast roof, beams and columns, and site-cast concrete floor. However the walls are made of insulated panels with gypsum inside and cement plaster outside. The level of insulation of the envelope was lower than the average, , R=3,5m2K/W The ceiling is insulated and the floor is covered with carpet layer. This construction proposal gives little thermal inertia to the house. Simple air extractor and a AC split simple flow represents the cooling system. No windows to East and West directions. The construction of the house was achieved after the beginning of the measurement period, so the available data on energy consumption cannot be compared to the other prototypes. We will not take it into consideration on our analysis.

Photo 10- *JEEL-UAE- American University Dubai*. Credit FYusta



Plan 10- *JEEL-UAE- American University Dubai*. Credit *JEEL team*

302-ORA-UAE- Heriot Watt University of Dubai

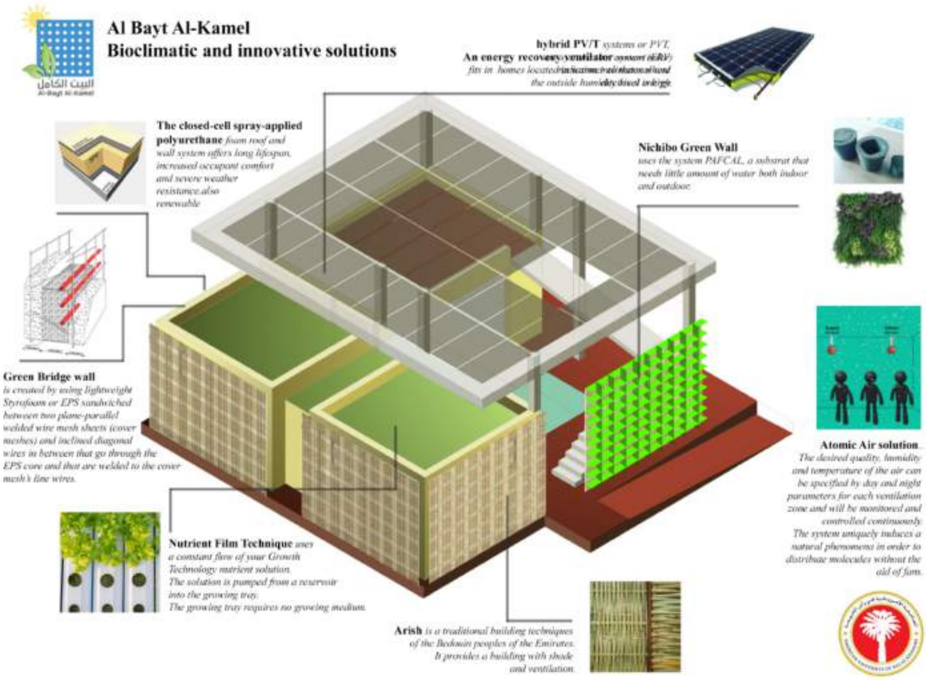
A extremely light weight construction house made of cool steel structure with insulation in between bars, plaster panels inside and polycarbonate over plywood panels outside. This house has very important air permeability due to a lack of glass on windows of the upper part of the house: only a metal adjustable blinds bloc partially the air coming through the house.

Photo 11- *ORA-UAE- Heriot Watt University of Dubai*. Credit FYusta

303-Aurak-UAE- American University of Ras Al Khamiah

L shape house open to north and east. Light steel columns structure with walls made of sandwich cement plaster and insulation panels, floor made of cement mortar over insulation panels, and the roof made of plaster under thermal insulation panels and a green roof structure with very few plants.

Photo 12- *Aurak-UAE- American University of Ras Al Khamiah*. Credit FYusta

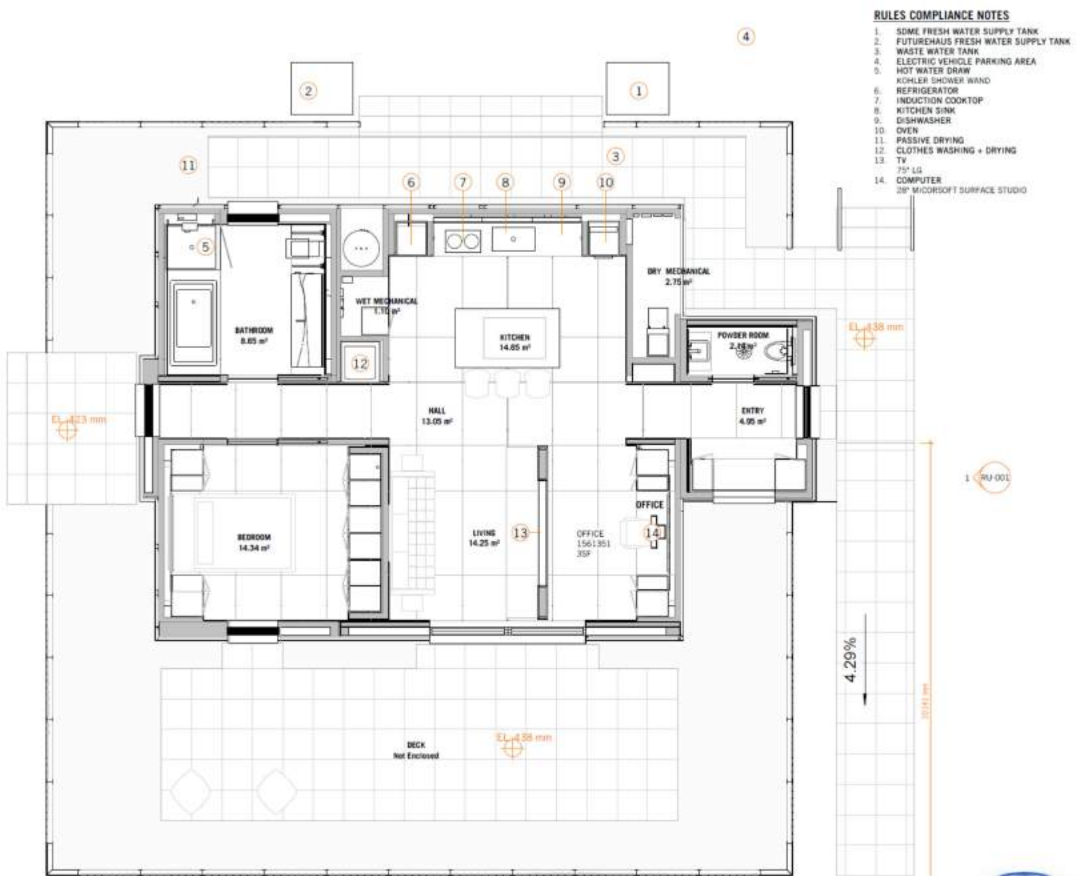


Plan 12- *Aurak-UAE- American University of Ras Al Khamiah*. Credit *Aurak team*

304-Virginia Tech-USA- Virginia Tech University

Light wooden structure made of Structural Insulated Panels (SIP) with an exterior layer made of back painted glass. The windows have a double window complex and both of the window have a double glass system with vacuum inside instead of classical argon filling reaching R:8m2K/W per windows, so R:16m2K/W when all closed, which is more performing than external walls. The outer window has a polished glass treatment. A large overhang detached roof protects the house from direct solar radiation on summer time but not during the month of November when competition took place, in fact less than one third of the south windows were shaded during noon period. However the roof protected the rest of the volume from direct sun radiation and easy evacuated the heat stored under the roof. The HVAC system is using double flow heat recovery, a moisture controller and a phase change material for heat (cold) storage.

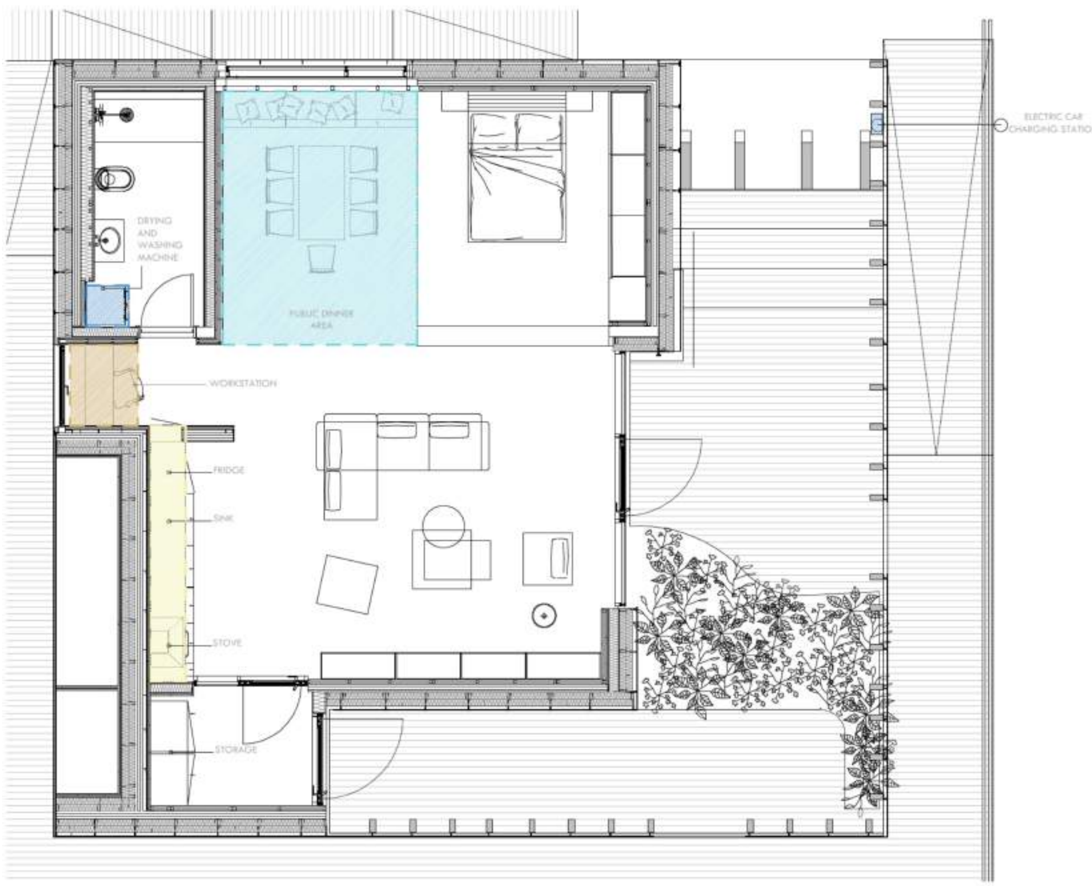
Photo 13- *Virginia Tech-USA- Virginia Tech University*. Credit SDME



Plan 13- *Virginia Tech-USA- Virginia Tech University*. Credit *Virginia Tech team*

305-EFdeN-Romania- University of Bucharest

Wooden wall structure with a XPS insulation on the exterior side, a plywood, a vapor barrier and finally an aluminum perforated outer skin. The roof has inversed the same principle and insulation layer is in the inner side of the house. The house has an extremely effective shaded outer zone: highly protected and full of vegetation it creates a microclimate around the house that reduces the thermal stress on insulated skin. The entry of the house has a double airlock system to avoid the entrance hot air in the house. Two zones are double height to allow the hot air evacuation by natural chimney effect.



Plan 14- *EFdeN-Romania- University of Bucharest*. Credit *EFdeN team*

Photo 14- *EFdeN-Romania- University of Bucharest*. Credit FYusta

The main geometrical and strategic features

The characteristics and architectural actions can be summarized below (table 4).

	Exposed Windows 0 :non / 1 :yes				Air tightness -1 :bad / 0 :middle / 1 :good	R value m2K/W				windows Uw value W/m2K	Thermal Inertia 0 :low / 1 :high	Phase Change Material 0 :non / 1 :yes	air heat recovery 0 :non / 1 :yes	Moisture treatement 0 :non / 1 :yes	Shape	main architectural action
TEAM	N	S	E	O		floor	wall	roof	mean	%	%	%	%			
101-TDIS	1		1			14	18	13	**14,9**	1,5			1		U shape West	insulation
102-knowHouse	1	1		1		3,8	4,8	3,5	**4,0**	1,66			1		Square	textile white walls
103-Virtue		1			1	7,5	7,6	8	**7,7**	1,5					Square	inclined South wall
104-MizanHome	1	1	1	1	-1	3,2	3,5	3,5	**3,4**	1,6					Square	natural ventilation
105-KSU		1			-1	0,9	5	1,3	**2,4**	2					U shape North	over roof protection
201-Baitykool						5,7	8,2	6,8	**6,9**	1,4	1		1		U shape North	high inner mass/green cooling
202-UOW	1	1			1	6,2	6,2	5	**5,8**	0,96		1	1	1	Square	HVAC/air tightness
204-Smart	1	1				3,6	5,6	7,7	**5,6**	1					U shape West	Sun protection textile & white
205-AquaGreen	1	1				2,2	3,5	3,6	**3,1**	2	1				Square	indirect adiabatic wall
301-JEEL-UAE	1	1				1,8	5,6	3,3	**3,5**	2,1					Square	over roof protection
302-ORA	1			1	-1	3,2	3,2	3,2	**3,2**	2					Square	High inner ventilation
303-Aurak	1	1	1	1	-1	4,9	4,9	4,9	**4,9**	1,2	1				L shape	high inner mass
304-Virginia Tech		1			1	5,1	3,5	8,8	**5,8**	0,125	1	1	1	1	Square	over roof protection
305-EFdeN	1	1	1	1		5,3	7,9	7,9	**7,0**	0,7			1		Square	sun protection/green cooling

Table 4. Main architectural features of Solar Decathlon Middle East Prototypes

The capacity of the prototypes to stay in the established comfort zones can be summarized below (Table 5). We can notice that teams 102,104 and 202 were out of the established zones, so less energy consumed should be expected for these teams:

	INTERIOR TEMP.			RELATIVE HUMIDITY			AIR QUALITY		
TEAM	TEMP LR Cntl 5%	TEMP LR Cntl 50%	TEMP LR Cntl 95%	HR LR Cntl 5%	HR LR Cntl 50%	HR LR Cntl 95%	CO2 LR Cntl 5%	CO2 LR Cntl 50%	CO2 LR Cntl 95%
101-TDIS	22,4	24,1	26,3	51	65	74	407	508	891
102-knowHouse	20,7	24,7	27,8	41	61	72	344	417	684
103-Virtue	21,9	24,6	26,3	44	56	70	400	469	1046
104-MizanHome	19,5	23,7	29,6	36	63	74	370	444	537
105-KSU	21,8	23,3	25,7	46	63	72	364	453	869
201-Baitykool	23,2	24,4	25,4	56	62	69	402	536	1144
202-UOW	23,7	24,4	27,2	47	58	64	405	672	1263
204-Smart	22,5	24,1	26,7	49	62	73	373	430	771
205-AquaGreen	21,0	24,0	26,2	42	61	70	278	419	729
301-JEEL-UAE	22,6	23,9	25,8	52	64	75	336	495	894
302-ORA	18,1	22,4	25,5	47	70	82	235	349	817
303-Aurak	22,2	23,8	25,8	44	59	75	383	609	1419
304-Virginia Tech	23,8	24,7	25,5	47	55	63	426	488	1201
305-EFdeN	21,9	23,7	25,8	43	54	62	459	654	1289

Table 5. Inside comfort conditions and performances of prototypes from 18nov to 27nov, with centiles of 5% and 95% to show the capacity to stay under thresholds.

Performances of the SDME prototypes

The 15 prototypes went through several contests, however only the following contests went under real measurement procedures on energy saving:

1-Energy Management Contest

The sub-contests having an interest on energy saving measures were:

-Load consumption per surface area for heating, cooling, ventilation and lighting

-Load consumption per surface area for other appliances

-Net electrical PV production sent to grid

-Net electrical energy drawn from the grid

2-Confort Conditions Contest

The sub-contests having an interest on energy saving measures were:

-Interior temperature

-Relative Humidity

-Air quality (CO2 ppm)

General performances through the measurement period

Table 5 summarizes the comfort conditions that the prototypes had during the period from 18nov to 27nov: dry air temperature, relative humidity and air quality expressed by the 5%, 50% and 95% centiles. All the prototypes were around 24ºC and only two had an exceptional high 95% centiles: prototypes number 102 and 104. In terms of relative humidity all were around 60%RH and only one had an exceptional high 82%RH of 95% centiles: prototype number 302. In the other hand, table 6 shows as well the performances in terms of energy consumption and solar energy production.

	ENERGY CONSOMPTION			SOLAR PRODUCTION		
	E h+c+v+l	E autres	**E Total**	sent to grid	drawn from grid	**Total balance**
TEAM	kWh	kWh	**kWh**	kWh	kWh	**kWh**
101-TDIS	152	102	**255**	272	103	**168**
102-knowHouse	232	131	**362**	147	224	**-77**
103-Virtue	182	119	**301**	64	144	**-80**
104-MizanHome	123	169	**292**	3	341	**-338**
105-KSU	196	214	**410**	250	117	**133**
201-Baitykool	146	157	**303**	62	66	**-4**
202-UOW	222	143	**365**	87	95	**-9**
204-Smart	189	154	**344**	91	37	**54**
205-AquaGreen	109	119	**228**	295	114	**181**
301-JEEL-UAE	110	125	**235**	236	15	**221**
302-ORA	500	48	**548**	135	362	**-227**
303-Aurak	80	248	**328**	178	228	**-50**
304-Virginia Tech	179	146	**325**	152	27	**125**
305-EFdeN	35	221	**256**	78	97	**-19**

Table 6. Energy performances and solar production of prototypes from 18nov to 27nov

	Exposed Windows	Exposed Windows	Air tightness	R value m2K/W	windows Uw value W/m2K	Thermal Inertia	Phase Change Material	air heat recovery	Moisture treatement	Shape	main architectural action	Total Energy consumed	Total ground surface	Total Energy per surface pour 10 days competition	Total Energy per surface for a year on constant conditions
TEAM	E	O			%	%	%	%				kWh	m2	kWh/m2	kWh/m2year
101-TDIS	1			14,9	1,5			1		U shape West	insulation	255	49	5,2	190
102-knowHouse		1		4,0	1,66			1		Square	textile white walls	362	70	5,2	189
103-Virtue			1	7,7	1,5					Square	inclined South wall	301	63	4,8	175
105-KSU			-1	2,4	2					U shape North	over roof protection	410	85	4,8	176
201-Baitykool				6,9	1,4	1		1		U shape North	high inner mass/green cooling	303	78	3,9	142
202-UOW			1	5,8	0,96		1	1	1	Square	HVAC/air tightness	365	85	4,3	157
204-Smart				5,6	1					U shape West	Sun protection textile & white	344	79	4,3	159
205-AquaGreen				3,1	2	1				Square	indirect adiabatic wall	228	65	3,5	128
302-ORA		1	-1	3,2	2					Square	High inner ventilation	548	70	7,8	286
303-Aurak	1	1	-1	4,9	1,2	1				L shape	high inner mass	328	55	6,0	218
304-Virginia Tech			1	5,8	0,125	1	1	1	1	Square	over roof protection	325	87	3,7	136
305-EFdeN	1	1		7,0	0,7			1		Square	sun protection/green cooling	256	72	3,6	131

Table 7. Architectural Actions and the associated energy performances of prototypes from 18nov to 27nov with the ration per square meter and the projection for a year (unreal) under the same weather conditions existing during competition

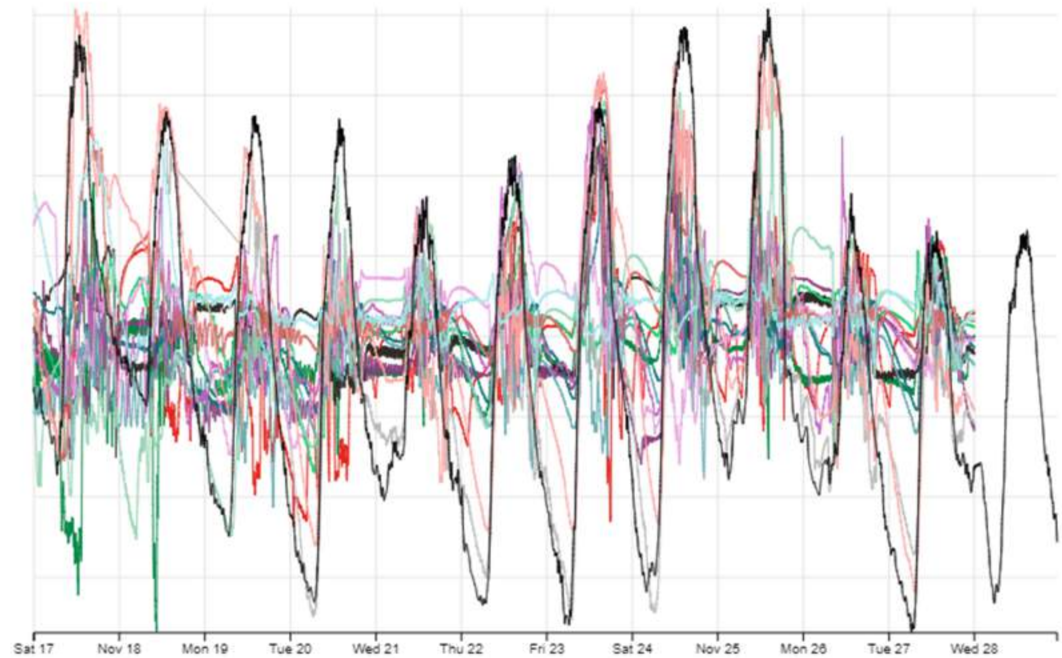


Figure 9. Inside globe temperatures of prototypes from 18nov to 27nov

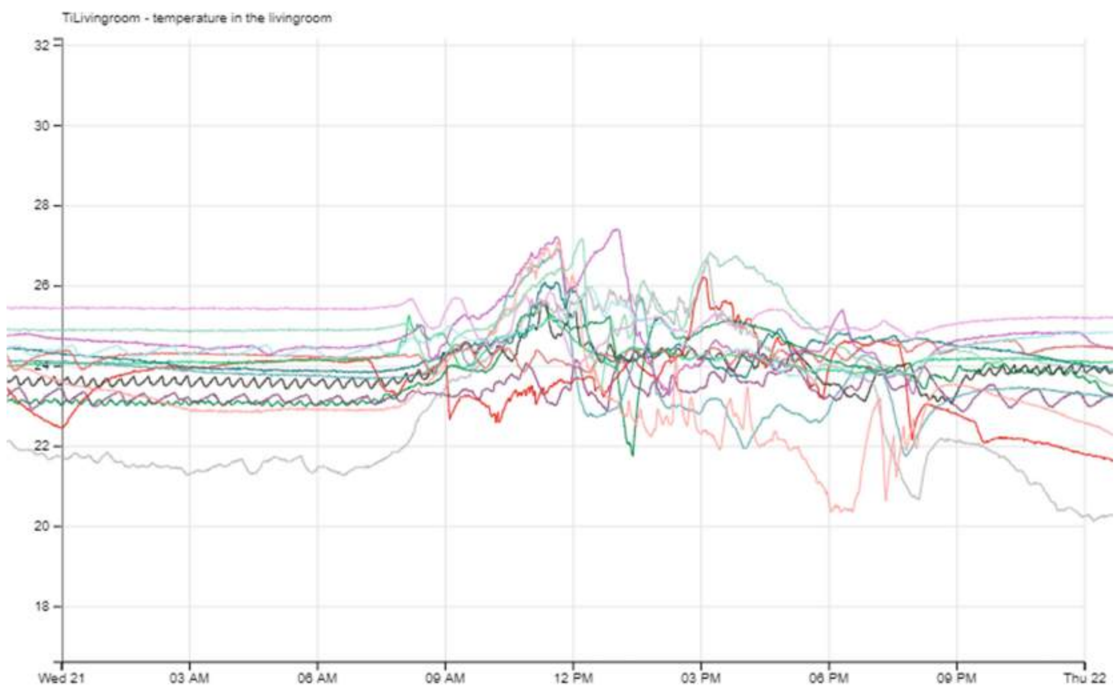


Figure 10. Inside globe temperatures of prototypes during 24h. This table shows that period 0h-9h prototypes are quite regular, then from 9h to 12h the variations are important (from 23ºC to 28ºC) and during period 12 to 21h the variations of temperature witness the human activity in the house (houses tasks) imposed by the organization but stays in the imposed confort zone (23ºC to 25ºC) except for few teams.

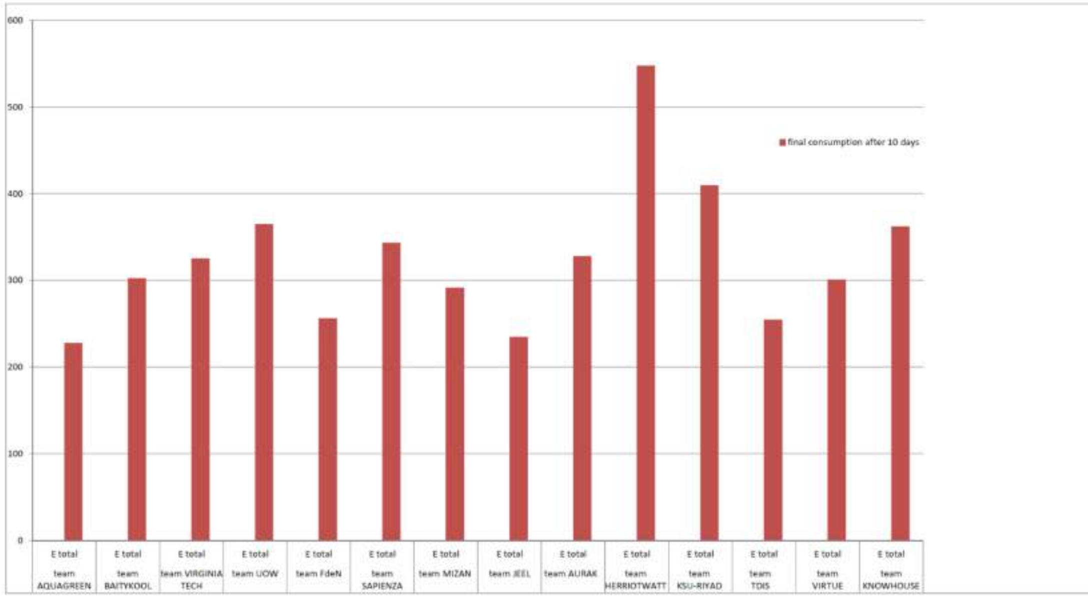


Figure 11. Energy consumed at the end by Solar Decathlon Middle East Prototypes

Analyses of daily performances through the measurement period

In order to better understand the behavior of prototypes during different days periods we have studied two periods:
-A constant temperature period to evaluate the energy needed to maintain this levels of inner comfort, and
-A zero energy period to evaluate how houses react to heat without electrical assistance.

1-Constant temperature period
The constant temperature periods occurred mainly during night time until the visits of public and in the afternoon after the visits (Figures 9 and 10). Based on the general temperature table, table 7, we chose three days, 21, 25 and 27 November, and two periods of 9h, 0h to 9h and 12h to 21h. During these periods the house shows different features:
-from 0h to 9h the house is already cool and outside temperatures are inside of comfort range, therefore the consumed energy is used to bring down relative humidity to acceptable values and to cool down the thermal mass of the house
-from 12h to 21h after the visits the house will use the thermal inertia to better behave during the afternoon warmest hours.

Table 7, and Figures 12 and 13 show the performances of houses during these two periods. We can see that during the day period and with similar inner comfort conditions, the heaviest houses, Aquagreen, Jeel and Aurak works much better than light houses as Ora. On the other side, during night period the light houses show a better behavior, only Aquagreen, the heaviest finishing prototype stays as a low energy consuming reference. However these performances should be re-evaluated by taking in consideration the net floor area in order to better compare the performance between prototypes.

ENERGY CONSUMPTION (Constant TEMPERATURE)	team AQUAGREEN	team BAITYKOOL	team VIRGINIA TECH	team UOW	team FdeN	team SAPIENZA	team MIZAN	team JEEL	team AURAK	team HERRIOTWATT	team KSU-RIYAD	team TDIS	team VIRTUE	team KNOWHOUSE
	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh
MEAN NIGHT CONSUMPTION	1,6	4,5	4,1	3,0	2,8	2,0	1,3	3,6	9,1	3,6	4,8	3,8	1,2	1,9
MEAN AFTERNOON CONSUMPTION	13,3	20,3	19,7	26,5	19,2	21,6	18,6	16,7	18,8	37,6	26,6	16,8	15,0	22,3
Consumption of 2 days type S4 (22-23)	27	46	61	42	39	61	32	22	45	67	97	52	51	17
Consumption of 2 days type S5 (25-26)	35	61	61	57	46	62	54	45	62	110	68	47	50	63

Table 7. Mean values energy consumed on a 9h period of 21st, 25th and 27th November of Solar Decathlon Middle East Prototypes. The NIGHT CONSUMPTION from 0h to 9h and THE AFTERNOON CONSUMPTION from 12h-21h

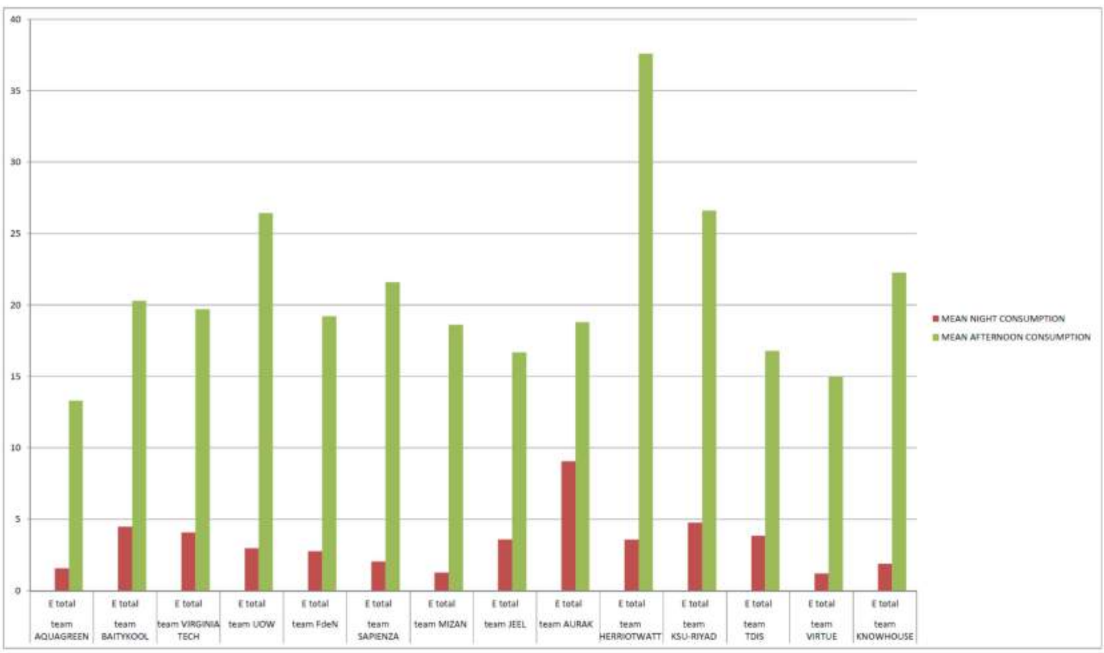


Figure 12. Mean values energy on a 9h period of 21st, 25th and 27th November from 0h to 9h and 12h-21h of Solar Decathlon Middle East Prototypes

1-Constant near Zero energy period

We studied the 23rd because it is a Friday, day of praying and few people were up to visits. Then most of the houses were running on natural passive behavior. After measuring the energy loads during this period, only few prototypes have near to zero energy consumption. This shows that few made the choice of not running on air conditioning during this day. Table 8 shows the consumptions of all prototypes during from 9h-18h, 9h-15h and 9h-14h on the

23rd of November.

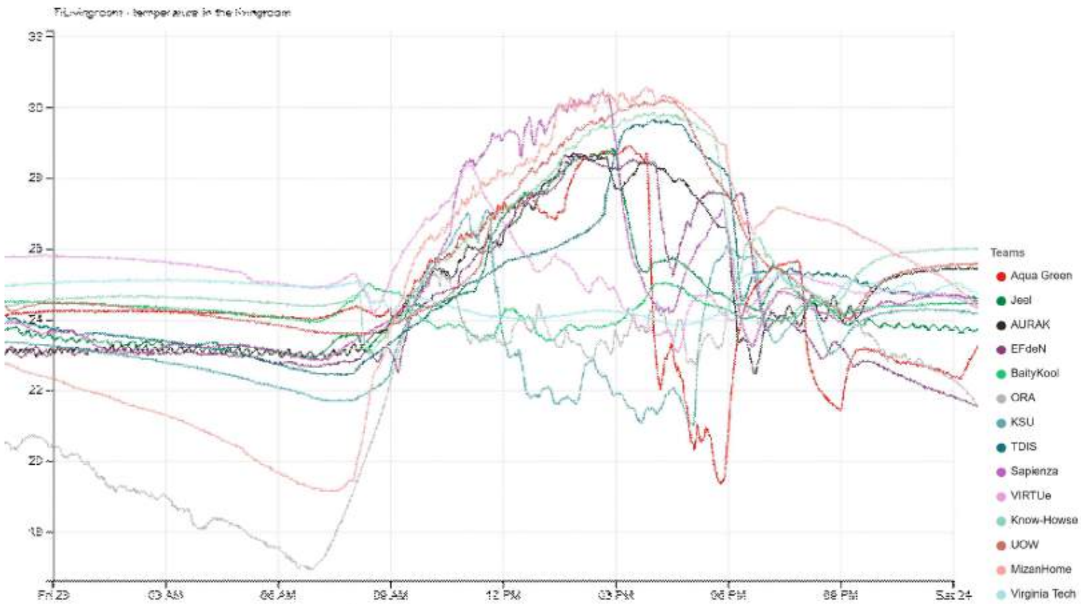


Figure 13. Temperatures during the 23rd of November

Figures 13 and 14 show the energy loads during this period, 9h to 18h of Friday nov23rd, we can see that the only teams close to zero energy are FdeN, Knowhouse, and Jeel. With less energy, all the three prototypes have better temperature response than a light and air permeable construction as team "Mizan home". The team know-house with wooden structure reacts better than Jeel with a "heavy-yet-covered" structure, with means that even by using heavy structure, the fact of using inner insulation on walls and roof or floor carpets has an important lack of performance compared to massive wood, that might not be as heavy but it stays more accessible for heat transfer with interior volumes.

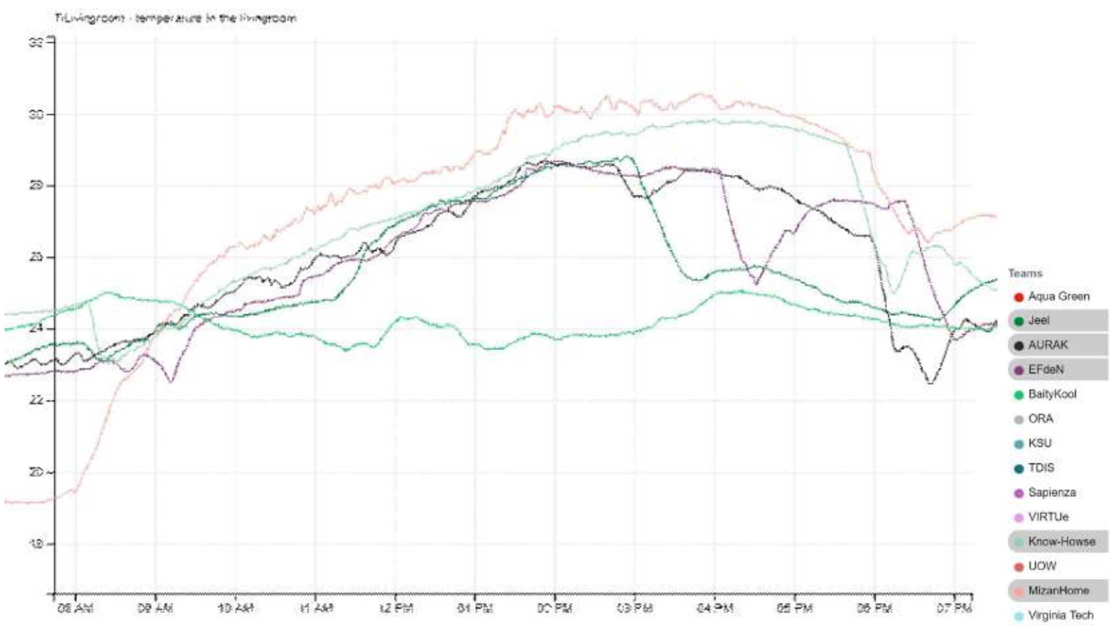


Figure 14. Temperatures of 5 near zero energy houses during the 23rd of November, and the comparison with a non-zero during this period: baitykool.

Response of prototypes during two different climatic seasons S4 and S5

Certain architectural actions can work better on different climatic seasons. To explore how prototypes behave during different climatic seasons, we chose two days, the 22nd and 23rd, with lower night temperatures that represents a S4 climatic season. We also chose two days, the 25nd and 26rd, with higher night temperatures that can represent a S5 climatic season (figure 15). Most prototypes had higher energy consumption during a S5 period as expected, but certain had the same, as team Virginia Tech, and even lower energy consumption during the S5 as teams KSU, TDIS and Virtue. The higher consumptions of team ORA (HerriotWatt) during S5 can be related to the weak air tightness of the building that on S4 helps cooling down the building but during S5 does not help to evacuate heat, whereas the higher consumptions of KSU team during S4 could be related to the important thermal bridges existing all around the structure that might have needed to heat up the house during cold nights or because of not creating cross ventilation since the exterior temperatures where too cold and could penalize the scoring if they came in.

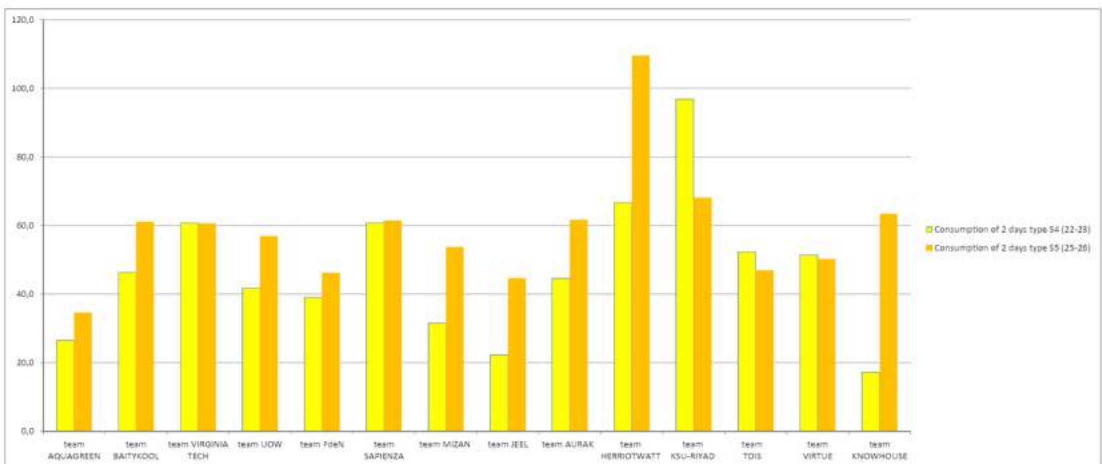


Figure 15. Energy consumption on the climatic seasons S4 and S5. For two days periods of 22nd-23rd and 25th to 26th November from 0h to 24h

Conclusion

The 15 prototypes went through several contests showing in all the cases, when solar energy form PV panels is integrated to the house, that the building can produce more energy that it spends.

The solar panels were not at that point visible and disturbing so a Zero Energy Architecture is possible by relying on solar bioclimatic architecture. Heavy construction prototypes have better response to energy saving strategies than light ones, however even by using heavy structure, the fact of using inner insulation on walls and roof or floor carpets has an important lack of performance compared to massive wood.

The most effective architectural actions during the contest period were:

-No windows on West or East Sides

-Good air-tight performances

-Phase change material as energy storage system

-Moisture regulating system as independent equipment in order to dissociate Tª and humidity regulations.

-Heavy internal mass accessible for heat exchanges

-Wide roof protection from sun radiation
-Indirect adiabatic systems during day time
-Technical rooms out of the house thermal envelop

The contest period can be classified on the S4 and S5 climatic seasons. These seasons are not the ones that represents the most a climatic year in Dubai, as S6 represents much bigger energy saving potential. The further behavior of prototypes during a S6 season should be evaluated in order to get the right strategies for house construction in the region.

Acknowledgements

We want to sincerely thank the Dubai Energy and Water Authority, DEWA, for organizing the Solar Decathlon Middle East 2018 that will become a main reference in terms of research in hot climate architecture. Our research team wants to thank as well French authorities: Ministère de la Culture et de la Communication, Region de Nouvelle Aquitaine and the "Id'Ex program" from Bordeaux University, since they have done this research project possible for our team.

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Monitoring, Evaluating and Optimizing the Energy Supply of a Photovoltaic System of a Zero-Energy-Building in Oman: Case Study of the GUtech EcoHaus

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Abstract: Extreme climates are a challenge as well as an opportunity for creating energy-efficient buildings. In the very hot climate of Oman, the intense solar radiation is the cause for a high demand for cooling energy, but also the reason for a potentially high supply of solar energy. This paper is a case study of the energy supply from a photovoltaic system (PV) for a zero-energy-building, the GUtech EcoHaus in Oman. It reports the performance of the PV system over three 12-month periods as well as soiling problems and cleaning practices. It concludes that the performance is as expected and maintenance is within the range of reasonable effort. This is in fact a very important message in a region where despite excellent conditions of solar irradiance the wide-spread application of PV systems, e.g. in residential units, is still hindered by the long-held assumption that this technology would underperform under the extreme climatic conditions, especially heat and dust. Further, the study looks into ways to optimize the performance through space-efficiency, tilt angle, capacity factor and tariff structure. The results are recommendations for the installation of PV systems on new and existing buildings (retrofit). The paper gives an outlook on policies for promoting PV systems in Oman to reduce energy subsidies as well as developing job opportunities for local small-and-medium enterprises (SMEs).

Keywords: photovoltaics, Oman, optimization, soiling, tilt angle

1. Introduction

The Sultanate of Oman experiences an increasing demand of energy due to ongoing demographic growth (4.67% from 2007-17 (Statista, 2018)) and economic growth (average of 4.23% from 2000-17 (Tradingeconomics, 2018)). To meet this demand, the country's electricity production grew by 240% from 2005 to 2017 to an overall output of 32.3 TWh and is forecast to reach 40TWh in 2024 (AER, 2017,1). However, despite the proven and vast potential for the use of renewable energy in the country (AER-COWI, 2008), the fuels for electricity generation are still pre-dominantly non-renewable (AER, 2017,1) and virtually no electricity generated from renewable sources is fed into the grid.

While currently a few large-scale power plants fuelled by wind and solar power are in planning or will be implemented soon, the application of small-scale on-site energy generation, e.g. through photovoltaic systems on residential units, has not taken off yet despite recent initiatives to promote such projects (AER-Sahim, 2017,2). This is even more surprising when looking at the fact that private customers account for about half of the demanded electricity in the country (AER, 2017,1) and consume electricity at prices that are supported with unsustainably high subsidies. Thus a huge economic and ecological savings potential lies in the transition of the energy supply for residential units from fossil fuel to renewable energy.

The purpose of this study is to gather, interpret and share the findings about the performance of one of the first fully operational and continuously monitored PV systems of a residential unit in Oman in order to provide evidence and recommendations for policies to promote the energy transition in the country that is currently in the making.

The three research questions of this study are:

- How has the PV system performed? (monitoring)
- Has it performed to expectations? (simulation, benchmarking, evaluation)
- How could the performance be enhanced? (optimizing)

Surprisingly, these rather straightforward questions were so far not explored comprehensively in one and the same project in Oman or the region. Studies range from either focussing only on monitoring (e.g. Kazem, & Khatib 2013), or only on simulation (e.g. Al Ali & Emziane 2013), or on both but without further discussions of optimization (e.g. Bhattacharya 2016). With a slowly, but steadily rising number of small-scale energy-efficient residential units equipped with PV systems in the region that are under construction or just being completed, this study could serve as a precedent for applying these basic research questions to achieve comparable outputs, for example, from the Solar Decathlon Middle East houses in Dubai (SDME 2018), the first "Solar Home" in Bahrain (TradeArabia 2018), a proposed "Eco House" in Kuwait (Darroch 2018) as well as from the the Passiv House in Qatar from 2013 or the other four eco houses built in Oman in 2014.

2. Conditions

The following conditions need to be described: climate conditions; building design and location; PV system components; and the operations schedule.

2.1. Climate

Oman's macro climate is categorized as an arid and hot desert according to Koeppen-Geiger's classification (Wikipedia, 2018). However, the meso climate in the coastal region of Muscat shows significant differences from a typical arid and hot desert climate. While summer temperatures are always uncomfortable and can rise up to a maximum of 49°C, winter temperatures are within a pleasant range of 20-30°C. Precipitation is very low with only 100ml per year. But, because of the coastal location and in contrast to a typical arid and hot desert climate the humidity ratio is very high and always above the comfort threshold of 11.5 g/kg. The diurnal difference is often not more than 5°C and thus rather low. This means that in Muscat the climate is humid but it almost never rains, and it is hot but it does not cool down at night. This limits the effectiveness of passive design strategies that can usually be applied for cooling buildings during the summer months in a typical desert climate, such as, for example, cross ventilation and night purge. Rather, the climatic conditions make the use of active cooling technologies imperative for many months of the year. Cooling buildings and, especially, dehumidifying indoor air cause a high demand for energy.

But Oman is also one of the locations in the world that has the best conditions for using solar power as a renewable source of energy (EIPA, ; AER-COWI, 2008). The published values for Global Horizontal Irradiance (GHI), which is a key parameter for the design of a PV system, differ slightly, but, for example, a value of 2,189 kWh/m2/y for Muscat (World Bank, 2019), indicates the great potential for a high supply of energy from solar power.

Thus the climatic conditions in Muscat are on the one hand the cause for a high demand of energy but they are also the reason for a potentially high supply of energy from solar power that can be used for cooling buildings.

2.2. The GUtech EcoHaus

The EcoHaus (Figure 1) is the German University of Technology's (GUtech) contribution to the nationwide Oman Eco House Design Competition (EHDC) that was initiated and funded by

The Research Council (TRC) to design, build and monitor prototype zero-energy buildings at five university campuses in the country. The GUtech EcoHaus was built on campus in Halban, which lies on the outskirts of Muscat (23°38'0.61''N 58°02'50.3''E). The two storey, three-bedroom house has a cylindrical shape with a diameter of 16m and a net indoor area of 257m2. The design and construction demonstrate passive design strategies to minimize heat gains such as a compact volume, optimal orientation, high-performance envelope with mainly natural and local materials, natural ventilation and thermal zoning. The active strategies to optimize the provision of cooling are a hydronic radiant cooling system coupled with a minimized energy-recovering air-handling-unit as well as other efficient appliances. Furniture is made from recycled or recyclable materials. The details of these design decisions, selected construction materials and technological components are reported in a separate paper (Knebel et al., 2014) and are not in the focus of this study, which is on the performance of the house's PV system.

Figure 1. View from the north to the EcoHaus on the GUtech campus

2.3. The PV System

The PV system is on the roof and is surrounded by a 60cm high parapet and the roof surface is with white cement tiles. The building is free-standing; there are neither adjacent buildings nor trees of significant height around that would shade the roof of the house at any time.

The PV system consists of a roof-mounted, 12.426 kW DC, 38-module PV array and a three- phase, 15 kW AC inverter. The system is grid-tied without local battery storage. The SunPower SPR-E20-327-COM monocrystalline modules each have a rated power output of 327 W DC and a rated efficiency of 20.3%. They are mounted in rows on ballasted roof racking that is tilted to 25° and oriented due south (180° azimuth). The KLNE Solartec D 15000 inverter has a rated max efficiency of 98% (Figure 2).

The reasons for installing a PV system with these characteristics was threefold. First, due to delays in the competition schedule, it was unclear in which month of the year the contest for achieving net zero energy balance would be held. Tilting the modules made sense because tilted modules would yield a sufficient amount of energy regardless of the timing of the contest. Second, with a view toward maximizing annual energy generation, the modules were installed at the optimal tilt of 25°. This optimal tilt was determined with the aid of PV-modelling software. And third, the limited budget did not allow for a large coverage of the roof area with PV panels. Therefore, a smaller array with tilted panels was designed out of necessity.

Figure 2. The roof-mounted PV system with ballasted racking

2.4. Operations

The PV system is maintained by GUtech's facility management team (Figure 3). Since the completion of installation and start of operation in November 2014, the modules have been cleaned at the beginning of every month. Cleaning is a manual process that involves hosing off the modules and then wiping them dry with a cloth. The cleaning of the entire system takes two workers less than 1.5 hours, or three man-hours per month. The most notable exception to the monthly cleaning frequency was during the EHDC1 competition period from 18th of November through the 17th of December 2014, during which the modules were cleaned every other day (Al Othmani, 2018). Other exceptions have been the few occasions when the usual four- to five-week intervals between cleaning days were stretched to seven weeks (June/July 2017) or reduced to two weeks (July/August 2017). The maintenance team started keeping logs of their cleaning works in July 2015.

Figure 3. The maintenance team at work cleaning the PV modules

3. Monitoring Performance

The first research question is: "How has the PV system performed?"

The performance of the PV system is recorded through a data acquisition system (DAS) and selected data from discrete study periods is extracted for further evaluation.

3.1. The Data Acquisition System

A Campbell Scientific CR1000-based DAS was installed to measure the house's electricity demand, interior thermal comfort, exterior weather conditions, and the electricity supplied by the PV system. The data sets include data for three measures that were particularly relevant to the assessment of PV system performance: inverter output, outside dry bulb temperature, and global horizontal solar irradiance. The available data sets include data for other measures, such as wind speed, that may have second-order effects on PV system performance. However, those second-order measures were deemed to be outside the scope of this study and were, therefore, excluded from consideration. Other possible second-order variables, such as wind direction, were not measured and were, therefore, unavailable in the data sets.

3.2. Study Periods, Reporting Intervals and Values

Since its installation, the DAS has not operated continuously, but data from the following three study periods of twelve contiguous months are available:

- Study Period #1: November 2014 to October 2015
- Study Period #2: November 2015 to October 2016
- Study Period #3: May 2017 to April 2018

A one-month reporting interval was chosen for this study for several reasons. First, a monthly reporting interval is convenient because the DAS generates one CSV file for each month. Second, a monthly data resolution is appropriate for identifying seasonal trends and year-to-year variations because it dilutes the effect of short-term weather systems and other anomalies. Finally, PVWatts, one of the tools described below, summarizes simulated PV system performance data on a monthly basis.

The following values were calculated for each month and reported in the summary Microsoft Excel workbook file: inverter generation (kWh), extrapolated inverter generation (kWh), daily average inverter generation (kWh/day), adjusted average outside temperature (°C), adjusted average solar irradiance (W/m2), total solar insolation (kWh/m2), daily average solar insolation (kWh/m2-day).

3.3. Results

The measured annual inverter generation for the three year-long study periods are (Figure 4):

- Study Period #1: 22,298 kWh
- Study Period #2: 22,631 kWh
- Study Period #3: 20,703 kWh

4. Evaluating Performance

The second research question is: " Has the PV system performed to expectations?"

The raw measured performance data and the calculated summary values derived from the raw data are not sufficient by themselves to answer this research question. For this, the performance data must be compared to a benchmark that quantifies the performance expectations. Because the performance of a PV system is so dependent upon its unique installation configuration and local climate, it is not possible to simply look up the benchmark performance in a publication. Instead, a simulation tool that models the performance of the system by taking into account the system’s installation configuration, local climate, and other relevant parameters must be used.

4.1. Benchmarking Through Simulation

Various simulation tools for planning the dimensions and specifications of PV systems are available. For this study the web application PVWatts (Version 5.3.8) was chosen as a tool to estimate the expected system output through an hour-by-hour simulation over a period of one year to estimate the expected monthly and annual electricity production. PVWatts is a respected PV modelling tool backed by the U.S. Department of Energy and National

Renewable Energy laboratory. Its user-friendly online interface belies its rigorous technical underpinnings, as documented in the technical manual (PVWatts). For the purpose of this study - to benchmark the recorded with the expected yield of a PV system - this choice seems reasonable. However, using PVWatts required several significant assumptions regarding the location-specific input data for irradiance, meteorological data as well as default settings for module type and system losses. Refer to the Final EcoHaus Project Report (Knebel 2018) for additional discussion and justification regarding the PVWatts model assumptions.

4.2. Comparison

The simulated annual inverter generation for a year-long study period is (Figure 4):

- Simulated Year: 22,745 kWh

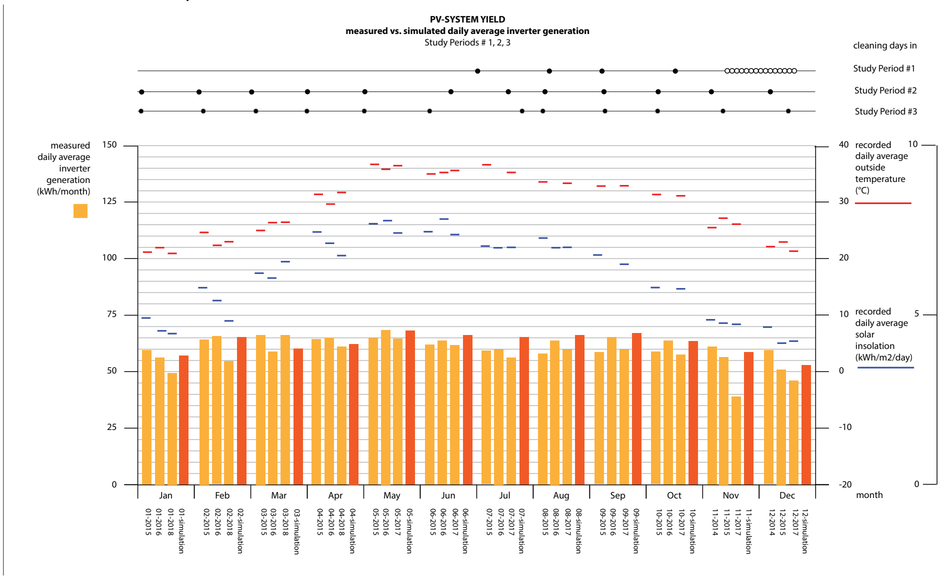

Figure 4. Average daily measured and simulated PV system yield; average daily measured solar insolation; and average daily measured outside temperature over Study Periods #1, #2, and #3

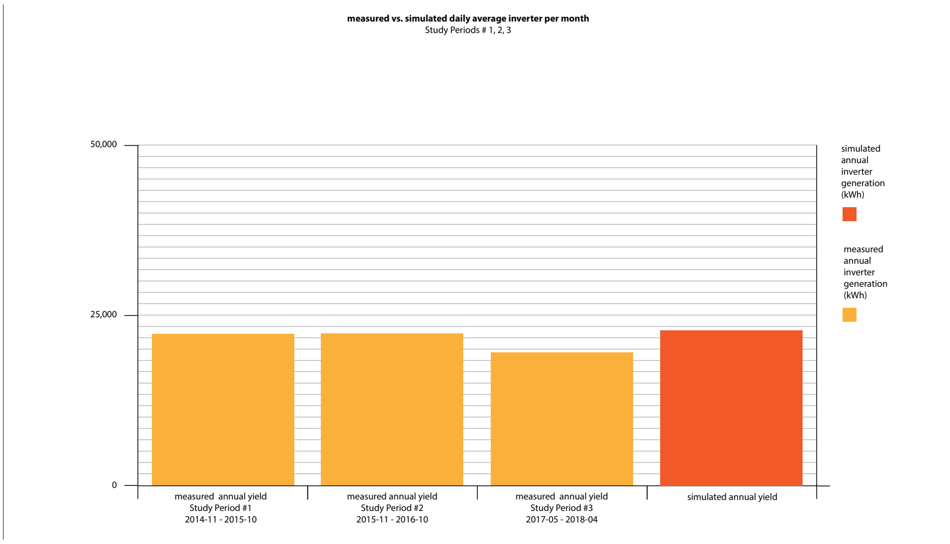

Figure 5. Comparison of measured and simulated annual PV system generation

4.3. Discussion

The percent difference between measured annual inverter generation and simulated annual generation is (Figure 5):

- Study Period #1: -2.0%
- Study Period #2: -0.5%
- Study Period #3: -9.0%

The multi-year average percent difference over the three study periods is -3.8%. The negative sign before the percent difference value indicates that the actual generation was less than the simulated generation.

Although actual generation was slightly less than simulated generation in all three periods of study (see Figure 5), the percent differences were well within ±10% error stated by the simulation programme (PVWatts). Therefore, the answer to the second research question is “yes”—the PV system has performed to expectations since installation.

Despite the overall satisfactory performance of the PV system over the three study periods, the -9.0% difference between measured and simulated annual inverter generation in Study Period #3 is worth investigating further. This leads to the question: If the system has over- or underperformed, what are the reasons for this?

A cursory review of the weather data shows that the conditions in Study Period #3 were not significantly different than conditions in Study Period #s 1 or 2. However, this tentative conclusion requires validation via a more rigorous process. A review of the maintenance logs shows that the frequency of module cleaning was relatively uniform among the three study periods. With weather and operations ruled out as likely culprits for the Study Period #3 performance drop-off, system availability emerges as the likely reason for the discrepancy between recorded and simulated/expected yield.

System Availability Problems

As stated earlier, several reasonable but ultimately incorrect assumptions probably account for the small, acceptable differences between the measured generation and the simulated generation during Study Period #s 1 and 2. On many projects such as this one, the extra work required to refine these assumptions is not worth the effort required. Study Period #3, however, it noteworthy because it has, by far, the largest percent difference. Although the measured generation for Study Period #3 is still within PVWatts’s ±10% error tolerance, there were known system availability issues that occurred during Study Period #3. These issues certainly account for most of the -9.0% difference.

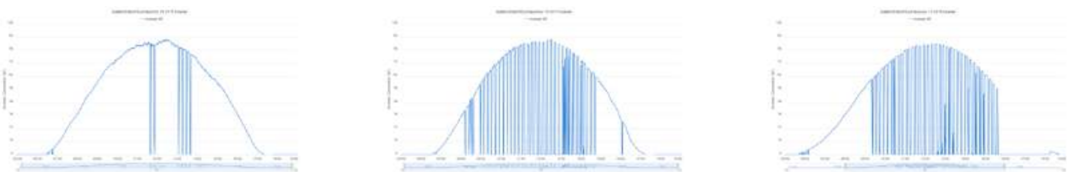

Figure 6. Inverter generation profile for a typical day in October 2017, November 2017, June 2018 (left to right)

An online data dashboard and visualization service called Eagle.io was used to inspect the daily generation profiles in months during which the measured generation was significantly less than the simulated generation (see Figure 4 for monthly generation comparisons). Figure 6 shows the profiles for three typical days in the months of October 2017, November 2017, and June 2018. These profiles clearly illustrate two things. First, the decreased generation values in Study Period #3 and beyond are caused by system availability problems, not partial or gradual system degradation problems. In other words, the inverter appears to repeatedly cycle on and off throughout the day. Second, the system outage events have generally increased in frequency over time. This is particularly evident in Figure 4, which illustrates that measured generation began to lag simulated generation in mid-2017 and that the problem became particularly severe in mid-2018 (Figure 6).

PVWatts assumes a 3% annual energy generation loss due to availability problems. In reality, losses due to availability problems in Study Period #3 and beyond were probably closer to 8%, assuming that the system otherwise performed similarly to Study Period #s 1 and 2.

As of this writing, the cause of the system availability problems is still unknown. However, an answer to the above-mentioned question can already be stated: System availability problems are the reason for the below-expectation performance in Study Period #3. Possible measures to solve these problems are being actively investigated.

5. Optimizing Performance

The third research question is: "How could the performance of the PV system be enhanced?"

For this, two aspects are studied: optimization through maintenance and optimization through design.

5.1. Optimization through Maintenance

In general, the performance of PV systems can be enhanced through maintenance, i.e. cleaning the panels regularly. The questions here are twofold: 1) How much effort is reasonable for a small, free-standing residential array like the one on the GUtech EcoHaus?; and 2) How much energy can be "recovered," i.e., not lost, as a consequence of regular cleaning and can the soiling effect be quantified in a model?

An effort of three man-hours per month was invested into cleaning the GUtech EcoHaus PV array once per month. The frequency interval of once per month was chosen because this interval seems reasonable for a private residence. The time investment per cleaning event is a function of the size of the array, the accessibility of the roof, the accessibility of the PV modules on the roof, the availability of pressurized/unpressurized water, the availability of specialized cleaning tools, the efficiency of the cleaners and cleaning tools, and the desired degree of cleanliness.

For the GUtech EcoHaus case study, three man-hours were required to get the array clean with just a hose from a pressurized water source, wet rags, and a drying cloth. The EcoHaus roof and array are both easily accessible.

Development of a model to predict the effect of soiling/cleaning on PV yields

Given this cleaning interval and level of effort, the research team used measured data from a 16-month monitoring period to develop a simple empirical model to predict the approximate effect of soiling (and cleaning) on system output.

PV system owners and operators in the Muscat area can use this model to quickly and easily estimate the time-dependent effect of soiling on PV system output as they develop an operations and maintenance (O&M) plan for their system(s). They should weigh the incremental cost of automatic cleaning systems and/or manual cleaning procedures against the incremental benefit of additional PV system generation that regular cleaning yields.

Figure 7 shows the percent power generation decrease as a function of days since the last array cleaning event. The slope of the linear curve fit, 0.146%, is the percent decrease per day since last cleaning. For example, the power generation 100 days after the last cleaning event is estimated to be 0.146%/day × 100 days = 14.6% less than power generation on a cleaning day, assuming identical weather.

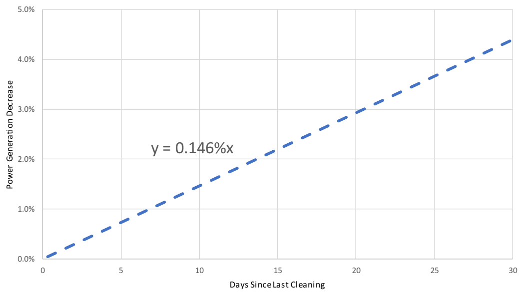

Figure 7: PV system power decrease as a function of days since last cleaning

The simple linear regression model discussed above is based on 16 months of accurate PV system generation data and cleaning log data. Because the model is based on only 16 months of data from a single residential PV system, there is an opportunity to refine the model with additional data collected from this and other sites. In the future, the logs should include times as well as dates. Logs should also include the dates, times, durations, and qualitative descriptions of precipitation events. As the quantity and level of detail of the data increase, it is possible that an improved, non-linear regression model may be developed to replace the linear regression model proposed herein.

The measured data, available at 20-second intervals, were aggregated to produce daily energy generation data in units of kWh per day. The period in which measurements and recordings of both factors, the PV system output and the cleaning log, have suitable data for this analysis is from 01 July 2015 to 31 October 2016. There were 16 cleaning events during this period. The cleaning interval ranged from 17 days to 45 days, but was generally about 30 days, i.e., monthly.

Figure 8 shows the frequency distribution of all days during that period as a function of the number of days since the last cleaning event. Figure 9 shows the relationship between the daily PV system generation and the number of days since the last cleaning event. Each data point in Figure 8 is the average of all seasonally-adjusted (see Knebel 2018 for more detail) daily generation values for days in which the number of days since the last cleaning event equal a particular value on the x-axis. For example, there were 16 days in the data set that occurred 5 days after a cleaning event. The average generation among those 16 days was slightly less than 60 kWh.

Note the shaded region in Figure 8. Only the values for days that fall within this region are plotted in Figure 9. Cleaning days ("Days Since Last Cleaning = 0") were excluded because the time of cleaning was not recorded in the logs. Without the time information, we do not know the soiling status (clean or dirty) of the array during the energy-generating hours of cleaning days. Days that occur more than 27 days after the last cleaning event were also excluded because the sample size drops off considerably beyond this point. Data beyond this point could be disproportionately influenced by short-term weather changes.

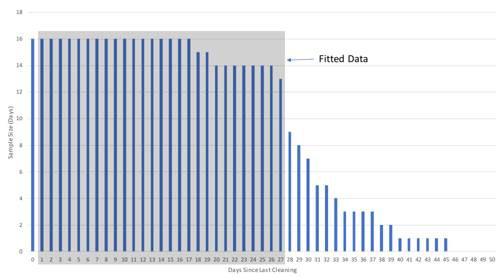

Figure 8: Sample size frequency of measured days as a function of days since last cleaning

A linear curve fit through the data points in Figure 9 yields an equation that shows the incremental loss of generation due to soiling is 0.0913 kWh per day (the slope of the linear curve fit). For example, the generation loss due to soiling on a day 100 days after the last cleaning event is estimated as 100 days × 0.0913 kWh/day = 9.13 kWh. Figure 7 presents the Figure 9 curve fit in a normalized, reciprocal form, which is suggested for broader use by PV system owners and operators.

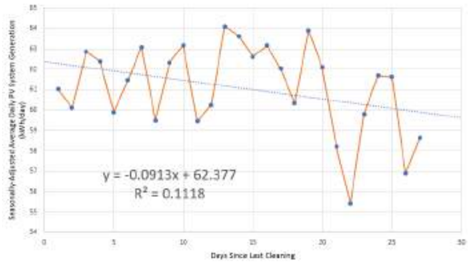

Figure 9: Linear curve fit to seasonally-adjusted average daily PV system generation as a function of days since last cleaning

5.2. Yield Optimization Through Design

Whereas the regular cleaning of PV panels as described above is a general measure to enhance the performance of a PV system, the design of the parameters of the system is a more specific approach to optimization. The question is: What to optimize for? Is the aim to either achieve energy autonomy or cost neutrality or energy neutrality? The aim of energy autonomy - an off-grid, stand-alone solution with an energy storage - was not pursued because the GUtech EcoHaus could be connected to a reliable electricity grid on campus. The aim of cost neutrality - the financial balance of electricity that is sold to and bought from the provider - was not pursued further because at the time of the design of the system Oman still had a flat-rate tariff structure which made such optimization unattractive. Thus, energy neutrality - the numerical balance of on-site energy supply and demand over a defined period of time, e.g. one year, - was pursued as the aim for the design of the GUtech EcoHaus's PV system.

However, since the completion of the GUtech Ecohaus in 2014 the tariff structure for electricity supply to residential units in Oman changed from flat-rate to seasonal-specific electricity costs (MZEC, 2019). Thus, the aim for optimizing the PV system changed from energy neutrality - achieving the highest annual yield - to cost-neutrality - matching on-site energy supply and demand so that their respective peaks are concurrent. Even though the PV array is already installed with a 25° tilt angle it is worth studying an optimization scenario with the tilt angle of the panels as the design parameter.

Two options with different tilt angles for the PV panels were studied. For both options the DC system size is 12.426 KW from 38 panels (see GUtech Ecohaus PV system description above):

- Option 1:
the energy-neutral Ecohaus (as-built) (Figure 10)
a roof-mounted, tilted PV system with an array tilt of 25° and an array azimuth of 180°
- Option 2:
the cost-neutral EcoHaus (optimized) (Figure 11)

a lifted-off-the-roof, flat PV system with an array of 0° and an array azimuth of 180°

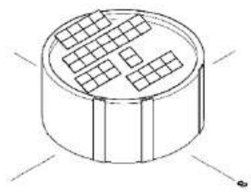

Figure 10. Axonometry of the GUtech EcoHaus with array of 25° tilt angle PV panels, as-built (Option 1)

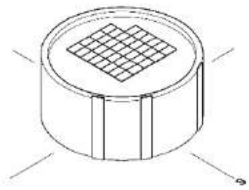

Figure 11. Axonometry of the GUtech EcoHaus with array of 0° tilt angle PV panels, optimized (Option 2)

The comparison is based on a simulation of the yields with the software PVWatts. As described above, the simulated yields from this software are very close to the recorded yields (within a margin of 3-4% over three years) and the application of this method for this purpose therefore seems reasonable.

Further, the two options were studied under two scenarios with different balancing periods based on two different tariff structures:

- Scenario 1:
a flat tariff structure with one balancing period from January to December
- Scenario 2:
a seasonal-specific tariff structure
with differentiated balancing periods reflecting the current tariff structure in Muscat ("winter": Jan - Mar & Nov - Dec, "shoulder seasons": Apr & Oct,
peak summer": May - Jul, "off-season summer": Aug-Sep) (MZEC, 2019)

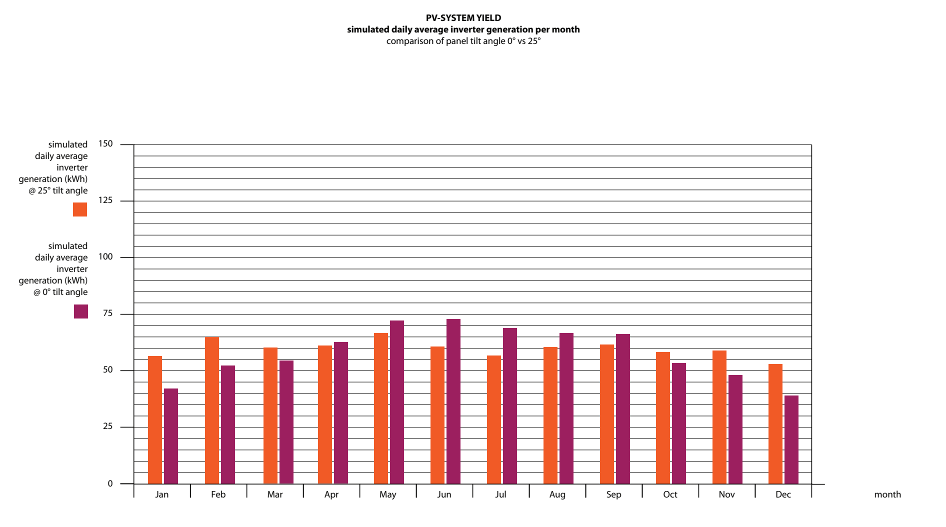

Figure 12. Comparison of the simulated daily average inverter generation per month with PV panel tilt angle 0° vs. 25°

As a result, the simulation shows that in Scenario 1 the annual yield for Option 1 is 22,745 kWh and for Option 2 it is 20,954 kWh; which means that the flat PV array yields 8% less than the tilted PV array over the period of one whole year (Figure 12).

However, in Scenario 2 the result is more differentiated. During the five "winter" months, when outside temperatures and tariffs are low and active cooling is not required, Option 1 yields 8,832 kWh while Option 2 only yields 5,246 kWh, which is 41% less. But during the three "peak summer" months, when the outside temperatures are very high, active cooling is essential and electricity rates spike up, Option 1 only yields 6,013 kWh while Option 2 yields 6,559 kWh, which is 9% more. During the "shoulder seasons" and the "off peak summer" months the yields are more or less similar.

It can thus be concluded that a PV system with an array tilt of 25° is beneficial to reach the more abstract goal of energy neutrality over one year, while the more concrete optimization goal of cost neutrality, for example, under the current season-specific tariff structure, can best be reached with a PV system with an array tilt of 0°.

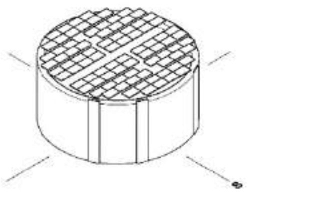

Figure 13. Axonometry of the GUtech EcoHaus with maximum array size of 0° tilt angle PV panels

Besides being more demand-specific, there are other, secondary benefits from a PV system with an array tilt of 0°. First, a flat installation of the panels is much more space-efficient because keeping a distance between the panels to avoid mutual shading is no longer required. Thus much more area of panels can be installed per area of roof surface. For the case of the GUtech Ecohaus the PV array could be enlarged from the current 38 tilted panels to 86 flat panels covering the full roof surface, which would increase the yield from 22,745 kWh to 47,483 kWh (Figure 13). Second, the flat system of panels can be installed such that it is lifted off the roof surface and serve as a shading device for the house itself. In the ventilated and shaded area under this "double roof" devices like the fresh water tank or the split-AC chillers which are usually placed on the roof and are unprotected from the sun can be installed and thus their hygiene (avoiding the danger of legionella in water) and efficiency (providing better re-cooling conditions) would increase. Third, the flat system is much more compatible with the designs of existing buildings, which are predominantly flat-roofed. Retrofitting these buildings with PV panels for direct energy supply is a simple and effective measure to reducing the growth strains on the electricity providers as well as transitioning to renewable energy sources on a wide-range.

6. Summary

The main findings from this research are:

- Monitoring and evaluation of the GUtech EcoHaus's PV system performance shows that it works as expected when comparing recorded annual yields with simulated annual yields.
- Periods of underperformance were due to technical issues (system availability problems).
- Optimization through maintenance requires little effort and is effective.
- The maintenance efforts are within tolerable limits (three man hours per month for manual cleaning).
- The maintenance effectiveness can be assessed through a model for calculating the power generation decrease as a function of days since the last cleaning event that is introduced.
- Optimization through design is focussed on the array's tilt angle.
- A 0° tilt angle is the optimal design of the PV panels to match peak demand and supply during the hot summer months. The 25° tilt angle - as it is installed on the GUtech EcoHaus - is optimal for the initial goal of energy-neutrality, but not for the new goal of cost-neutrality as set by the newly issued season-specific tariff system.
- Secondary effects of a 0° PV system in which the panels serve as a "double roof" of the building are beneficial for a range of situations (shading of roof surface, shading of MEP equipment, compatibility with retrofit).

7. Outlook

Since the purpose of this study is to gather, interpret and share the findings about the performance of one of the first fully operational and monitored PV systems on a residential unit in Oman in order to provide evidence and recommendations for the policies to promote the energy transition in the country that are currently in the making, the findings from this study need to be seen in the bigger picture of achieving a more energy-efficient architecture and urban environment in Oman.

Since the decrease of state revenues through a drop of the oil price on the world market in 2015, the topic of PV-sourced electricity supply to residential units in Oman is on the public stage. Policies and initiatives with different agendas were launched.

The "Sahim"-initiative was launched by the Authority for Electricity Regulation in May 2017 to promote the installation of small photovoltaic systems in Oman (AER, 2017,2). So far, first projects on commercial and educational buildings are under way, but not on residential units yet. The reason that this initiative does not yet reach to residential consumers are the still very low electricity prices for the private consumer and the still relatively high costs for PV-systems in Oman.

The "Ishraq"-initiative was launched in 2018 by a private PV-company (Shams Global Solutions) together with a vocational training institute (Maharat) and the country's electricity holding (Nama Holding Company / Institute) to facilitate the training of local PV-experts that can implement the expected demand for services around the "distribution, development, inspection, installation, maintenance, monitoring and end-of-life waste management" of PV-systems in Oman. Given that in the PV-industry "downstream-from-manufacturing jobs account for 75% of all new jobs" (Tsang, 2018) and can be offered "across the country" this industry lends itself for the promotion of small-and-medium enterprises (SME's); a structure that fits with the overall economic and social development aims of the government of Oman (Tanfeedh, 2017; Riyadaa, 2018). The initiative developed a 24-month training programme to become a "Certified Junior PV Professional", but has not started yet. The estimate is that between 300 and 700 jobs could be created in this market (Tsang, 2018).

As shown in this case study of the GUtech EcoHaus, installing a rooftop PV system is an effective means of supplying renewable energy to a residential unit in the extreme climatic conditions in Muscat, Oman. It is simple to design, install, maintain and monitor. The paths to a further roll-out is thus now no longer a question of technological feasibility, but of capacity building and policies.

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Responsiveness and resilience of existing dwellings in warm-humid climate zone to changing climate

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Abstract: Vernacular building designs have evolved over time to appropriately regulate comfortable indoor conditions in response to outdoor conditions. While climate change is imminent, the specific changes in climatic conditions are uncertain for any given location. The climatic response of vernacular dwellings thus needs to be studied for possible climate change variations, and their ability to still maintain comfort. Progressive nations such as India are characterized by more than 60% vernacular dwellings. However, the occupants in these dwellings are increasingly aspiring for a modern life. This is evident in their adoption to modern materials and building typologies and the dependence on electro-mechanical appliances to maintain indoor thermal comfort.

Inhabitants of vernacular dwellings relied on their physiological resilience to withstand a wide temperature range. This narrows down with exposure to conditioned indoor environments, and is evident with increasing energy consumption to maintain comfort. The current study aims to evaluate the ability of vernacular dwellings to respond to possible climate change variations and maintain comfortable conditions in the ensuing indoor environments. This study also investigates the climate responsiveness and thermal performance of dwellings that are undergoing modern transitions, based on a real-time and simulation assessment of a vernacular habitation in Suggenahalli village, India.

Keywords: Climate change, climate responsiveness, resilience, thermal comfort, transitions

1. Introduction

Climate change is considered one of the greatest threats to development, with growing concern for the environment, human health and economy (de Wilde and Coley, 2012). Building sector has thus far inadequately introspected on its role in changing climate and examining its preparedness to face the consequences of climate change. Greenhouse gas (GHG) emissions from the building sector have doubled between 1970 and 2010, representing 19% of the global 2010 GHG emission (Lucon *et al.*, 2014). The indoor thermal environment, normally perceived as thermal comfort, is the result of the interaction between the building envelope and the climate to which it is exposed to. Any change in the climate will have direct impact on the thermal comfort within the building. The implications of climate change on buildings range from shift in operational energy use, increase in discomfort hours, mechanical damage, to extreme events like flooding (de Wilde and Coley, 2012). Thus, it becomes imperative to analyse the resilience of the existing buildings to changing climate.

Vernacular buildings are time-tested climate-responsive designs that have ensured comfortable indoor conditions to the occupants in response to the surrounding climatic conditions. The buildings constructed with local materials have greater resilience against extremities in climate (Singh, et.al., 2009; Shastry, et.al., 2012). With increased access to transport, electricity and exposure to western lifestyles through media, an increasing trend to modernize not only one's lifestyle but also homes can be witnessed. Modernizing built environment involves construction practices that uses energy intensive materials like cement, glass and steel and are insensitive to the climate of the region. Such a practice results in buildings that compromise thermal comfort of the occupants in the building. Various studies have reported that vernacular buildings provide better comfort as against modern buildings (Shanthi Priya, et.al., 2012; Shastry, et.al., 2012; Agrawal and Singh, 2015). In a vernacular setup, occupants relied on their physiological resilience and behavioural adaptations to improve thermal comfort in response to extreme weather conditions. In modern buildings, occupants resort to active controls for space-conditioning. In 2010, buildings used 32% of the total global final energy use, with space conditioning accounting for 35% of the consumption, which is expected to grow by 79% and 84% in residential and commercial buildings, respectively by 2050 (Lucon *et al.*, 2014). In India, the total electricity consumption by residential sector in 2014 was 50 times that in 1971 (Chunekar *et al.*, 2016). With increased access to electricity and increasing disposable income, the dependence on electric controls for providing comfortable conditions is only likely to increase. Such over-dependence on electric controls for comfort reduces the physical and mental resilience of occupants to unfavourable weather conditions which further increases dependence on electric controls (Patidar and Raghuwanshi, 2016).

The aim of the present study is to evaluate the resilience of vernacular dwellings in maintain comfortable indoor conditions in response to the possible climate change variations. This study also investigates the climate responsiveness and thermal performance of dwellings that are undergoing modern transitions.

2. Methodology

2.1. Case study selection

Suggenahalli (12.816 N and 76.993 E), a village 80km from Bangalore, India, was identified for the purpose of the study, which belongs to warm-humid climate according to the classification of climate zones in National Building Code of India, 2005. Temperatures here range from 14ºC in winter to 36ºC in summer. The community is mostly engaged in agriculture. A field study was conducted as part of the study to understand the type of construction in dwellings in the settlement. The vernacular dwellings were built using local materials like stone for walls with mud plastering, mud flooring, timber, bamboo and clay tiles for roof, thick cob-walls made from local soil enriched with cow dung for internal partitions. The roof is a combination of sloped roof with timber to span the clay tiles and flat roof with timber spans covered with bamboo matting and soil layers. A typical vernacular dwelling is shown in Figure 1. Even though, most of the vernacular houses are well maintained and provide comfortable conditions, there is an increased shift towards adoption of modern materials in construction. The traditional materials were increasingly being replaced by modern materials like burnt brick for wall construction with cement plastering, asbestos sheet and RCC (Reinforced Cement Concrete) for roof. An increase in the use of household appliances was also visible in the community, the role and impact of which is not in the purview of this paper.

One vernacular dwelling in the settlement was identified for the study as representative of the vernacular dwellings in the settlement. The dwelling is a courtyard house with a built-up area of 400 m^2, 450 mm thick rubble masonry walls with mud mortar and mud plastering on the interior walls, a combination of mud roof supported by wooden plank in the south side called Maalige roof and Mangalore tiled roof on timber rafters on all other sides. Main entrance of the dwelling faces north and opens out to the street.

Figure 1. Image of a typical vernacular dwelling in Suggenahalli (Courtesy: IISc Ungra Extension Center 2010)

2.2. Study strategy

The present study extends the work of the current research group (Shastry, et.al., 2012, 2014), that had investigated the thermal performance and thermal comfort of the vernacular dwellings and the effect of changes in wall and roof from vernacular to conventional materials on the thermal comfort of the dwellings. The current study attempts to evaluate the thermal performance of both vernacular dwellings and conventional dwellings (dwellings that have undergone transitions) in the present climatic conditions and possible changes in climate, as India is in the high-risk zone due to climate change according to IPCC, 2014. The foreseeable risks include warmer and/or fewer colder days and nights, heat waves, high precipitation events, increase in intensity of drought and increased incidence of extreme high sea level. For studying the impacts associated with possible changes to the climate, two scenarios are considered, (i) increase in mean monthly temperature and (ii) decrease in mean monthly temperature as discussed by Aysha and Mani, 2017. If the mean monthly temperature increases due to climate change then warm-humid climate zone may become hot-dry climate zone whereas if the mean monthly temperature decreases then the place may fall under temperate climate, as per the study. For the purpose of the study, weather file of Sholapur, Maharashtra, India, is taken as representative weather data for hot-dry climatic zone and that of Bangalore, Karnataka, India for temperate climatic zone.

The study involved real-time monitoring of the thermal performance of the vernacular dwelling along with development of a dynamic simulation model. The real-time monitoring included collection of indoor and outdoor temperatures, relative humidity and dew point temperature every 30 minutes for a period between June-July in 2010 using calibrated Resistance Temperature Detector (RTD) based data loggers (temperature at 0.05°C resolution and ± 1°C accuracy; RH at 0.1% resolution and ± 2% accuracy) installed in the selected dwelling. Location of the data loggers installed inside the dwelling is marked in the plan as shown in Figure 2. Dynamic building simulation was conducted to revalidate the previously done study. It included development of simulation model of the selected dwelling in DesignBuilder (v 3.4), a user-friendly integrated building performance simulation package built over EnergyPlus and integrating the thermal properties of the traditional materials used in construction of the dwelling and using the weather-files for the region. In order to provide a more realistic representation and obtain reliable performance of the dwelling under study, the neighbouring houses have also been integrated into the model (see Figure 3). The hourly weather data for Suggenahalli was generated from METEONORM v6.0. The model was later modified by changing the materials in construction to conventional materials post transition which was observed in the settlement during the field study. The 450mm thick rubble walls are replaced by 230 mm thick burnt brick masonry. The Mangalore tiled roof and Maalige roof are replaced by RCC. The details of the vernacular and conventional dwellings are given in Table 1. The changes in form and orientation are not taken into consideration in this paper, even though these can be witnessed as part of the transitions in Suggenahalli. In this paper, the results of the dynamic building simulation for summer and winter months are discussed to understand the performance of dwellings in extreme climatic conditions in each of the climatic zones.

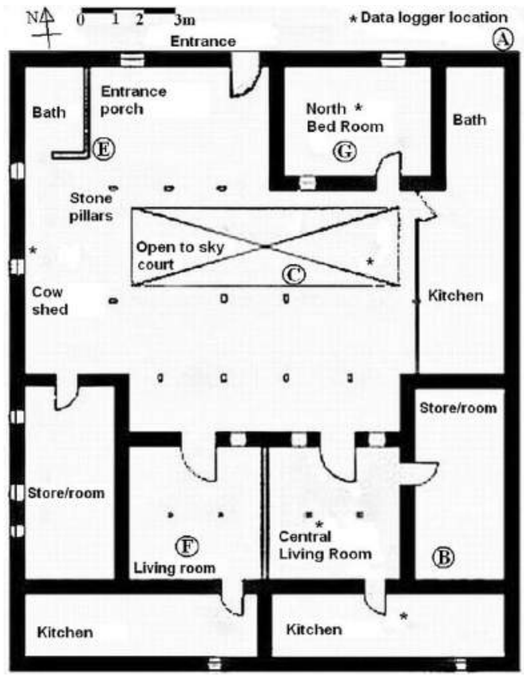

Figure 2. Plan of the house and the location of the data loggers (Shastry, et.al., 2014)

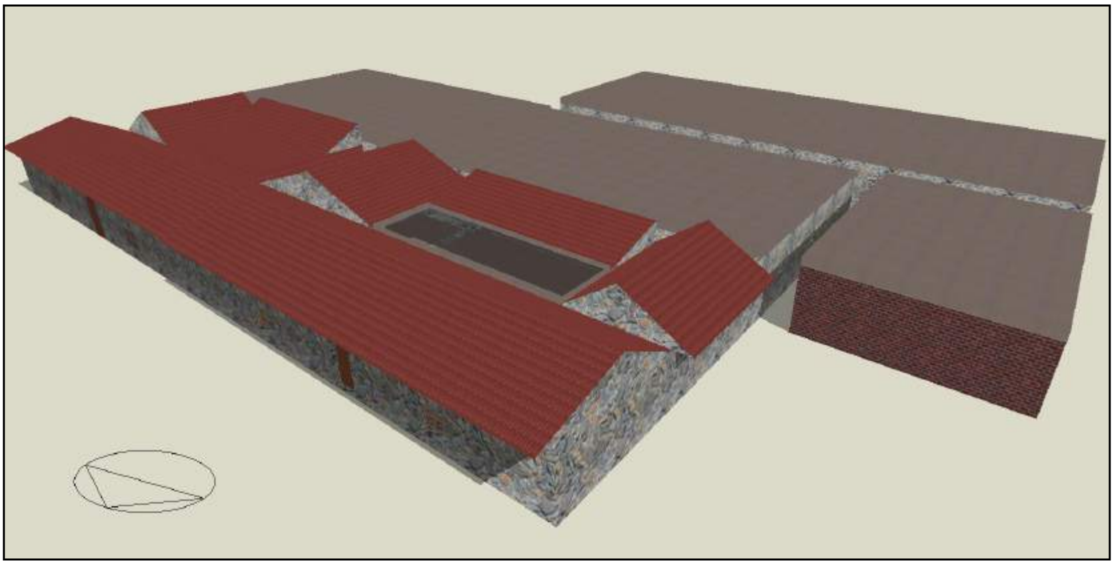

Figure 3. Block-model view of the dwelling under study and the neighbouring buildings (Shastry, et.al., 2014)

Table 1. Details of construction of Vernacular and Conventional dwelling

	Building element	Construction	U-value (W/m²K)
Vernacular Dwelling	Wall	450 mm thick random rubble wall with mud plaster	3.91
	Roof	Mangalore Tile Roof	6.14
		Maalige Roof	2.06
	Flooring	Earth	1.81
Conventional Dwelling (post-transition	Wall	230 mm thick Brick masonry with 12 mm cement plaster	2.14
	Roof	100 mm RCC with 2% reinforcement	4.73
	Flooring	Cast concrete	4.73

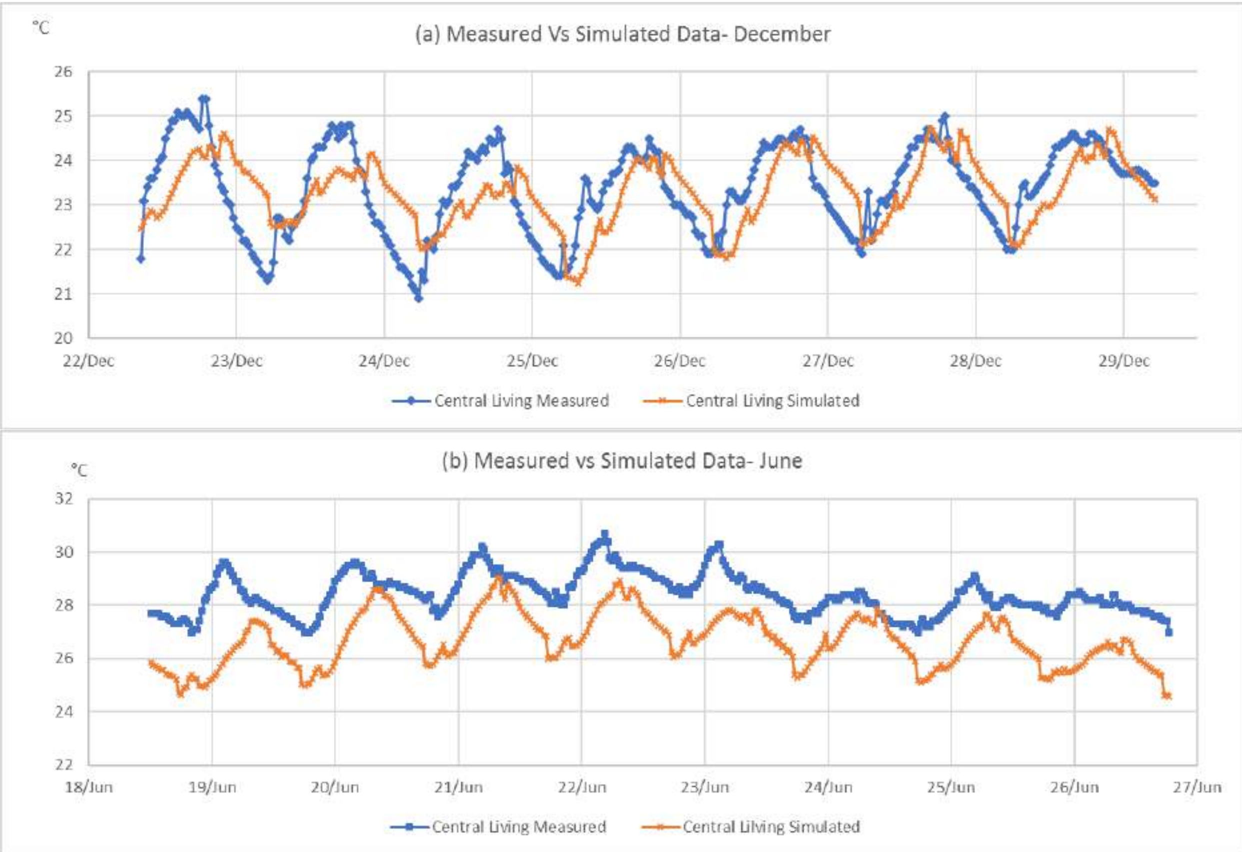

Figure 4. Comparison of simulated and measured (real-time logger data) indoor temperature for a small period in (a) December and (b) June

In order to validate the results of the simulation model, the simulation output was compared with the real-time measurements collected using loggers in different locations in the house. Figure 4 gives the comparison between measured and simulated indoor temperatures in the central living room for a small period in December and June as representative of winter and summer, respectively. Though the simulated data did not show a one-on-one match with the measured data, especially in the summer, it can be considered to be fairly concurrent with the real-time temperature conditions. Mean Bias Error (MBE) and Coefficient of Variation of Root Mean Square Error (CVRMSE) gives an indication of the relative and accumulated discrepancies between measured and simulated values, and have been used to validate space temperatures (Royapoor and Roskilly, 2015). MBE represents the mean difference between measured and simulated data points, while CVRMSE indicates how well the simulated model fits the measured data by capturing offsetting errors between measured and simulated data (Coakley, et.al., 2014). Sub-hourly Mean Bias Error (%) and Coefficient of Variation of Root Mean Square Error (%) for each month, summer and winter seasons and the year were calculated based on the data available, which are summarised in Table 2. Around 90% of the deviations (difference between the measured and simulated value) fell within ±3°C and 74% fell within ±2°C.

Table 2. MBEs and CVRMSEs for each month, summer and winter seasons and whole year

	MBE (%)	**CVRMSE (%)**
January	0.38	6.12
February	1.08	4.29
March	4.06	6.24
April	5.96	7.95
May	No measured data	
June	8.78	10.30
July	8.21	10.52
August	No measured data	
September	No measured data	
October	No measured data	
November	No measured data	
December	1.29	4.23
Summer	**8.58**	**10.14**
Winter	**3.32**	**5.76**
Annual	**4.25**	**7.09**

3. Results and Discussion

The temperatures of the three rooms such as central living room, north bedroom and kitchen from the real time data collected using the data loggers have been plotted along with the outdoor temperature to show the diurnal variation on a typical day, Figure 5. It can be seen that the indoor temperatures are not much affected by the variations in outdoor temperatures, which varies between 21°C and 34°C. Only peaks in the plot seen indoors are in kitchen which is observed to be during the time of cooking. Otherwise the indoor temperature varied from 25°C to 30°C, which can be attributed to the physical characteristics of the building envelope.

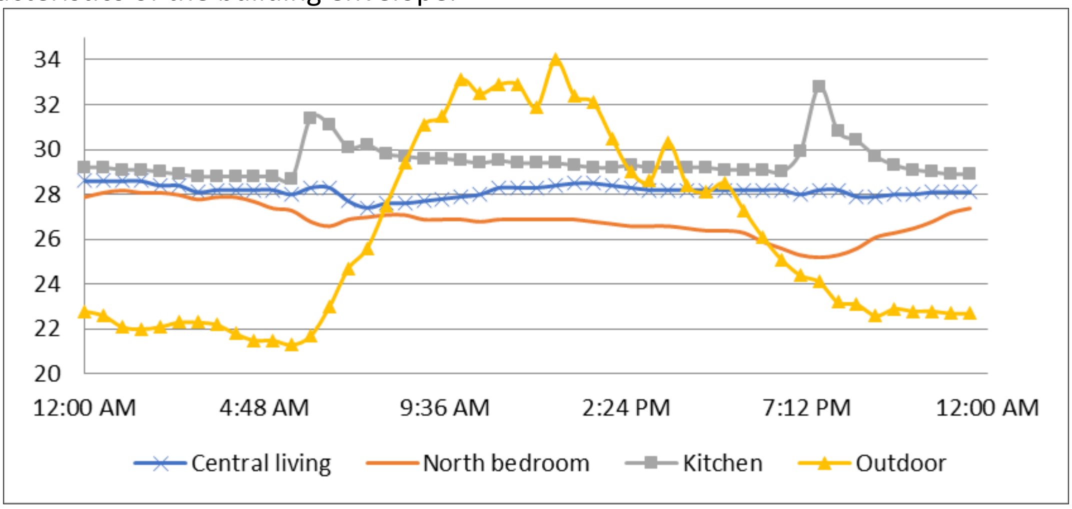

Figure 5. Diurnal variation in indoor and outdoor temperatures in vernacular dwelling

This section is now broadly divided into three; first, the results of the simulation for the vernacular dwelling for the existing climatic condition (warm-humid) and two possible changes in climate (hot-dry and temperate), second, the results of the simulation for the conventional dwelling taking into consideration the changes in materials used in construction due to transitions in the dwellings for existing climatic condition (warm-humid) and two possible changes in climate (hot-dry and temperate), and third, a comparison of the results for both the dwelling types.

3.1. Vernacular Dwelling

A dynamic simulation model for the vernacular dwelling was developed with the given traditional material properties and construction. Dynamic simulation was run for the vernacular dwelling model using the weather file of Suggenahalli, which is in warm-humid climatic zone. By altering the weather file to that of Sholapur and Bengaluru, simulation was run again for the model of the vernacular building to study the behaviour of the dwelling in hot-dry and temperate climate zone. Figures 6 (a), (b) and (c) show the indoor and outdoor temperature variations from the simulation result throughout a year for the vernacular dwelling under warm-humid, hot-dry and temperate climate zone, respectively.

From Figure 6(a), it can be observed that during winter months the vernacular dwelling maintained a comfortable indoor environment at a temperature range of 23ºC - 26ºC when the outdoor temperature was between 19ºC and 26ºC. During summer, the indoor temperature (23ºC -31ºC) was only slightly higher than outdoor (25ºC-31ºC). A similar trend can be observed when the climate zone was altered to hot-dry, but the indoor temperatures were slightly higher especially during summer. In summer, the indoor temperature ranged from 25ºC to 34ºC in response to an outdoor range of 27ºC-35ºC. During winter, the vernacular dwelling maintained an indoor temperature between 23ºC and 28ºC, for an outdoor temperature range of 20ºC-25ºC. When the climate zone was altered to temperate, the indoor air temperature was almost always higher than outdoor temperature but within a range of 21°C and 30°C. Table 3(a) shows the minimum and maximum indoor and outdoor temperatures obtained for winter and summer months for all the three climate zones. In any of the climatic conditions, minimum indoor temperatures do not fall below minimum winter or summer temperatures recommended by American Society of Heating, Refrigerating and Air-Conditioning Engineers, ASHRAE 55, 2010. But the maximum temperature in all the three cases exceeds maximum winter and summer temperature recommended by ASHRAE 55. However, studies conducted in tropical climates including Shastry, et.al., 2014, Indraganti, 2010 and Rajasekar and Ramachandraiah, 2010, have reported that wider comfortable indoor temperature ranges are acceptable by the occupants than that is specified by standards due to behavioural adaptations or their physiological resilience. Traditionally, people are known to adapt buildings and themselves to the variations in weather to stay comfortable through various means like passive strategies or behavioural adaptations (Roaf, et.al., 2009).

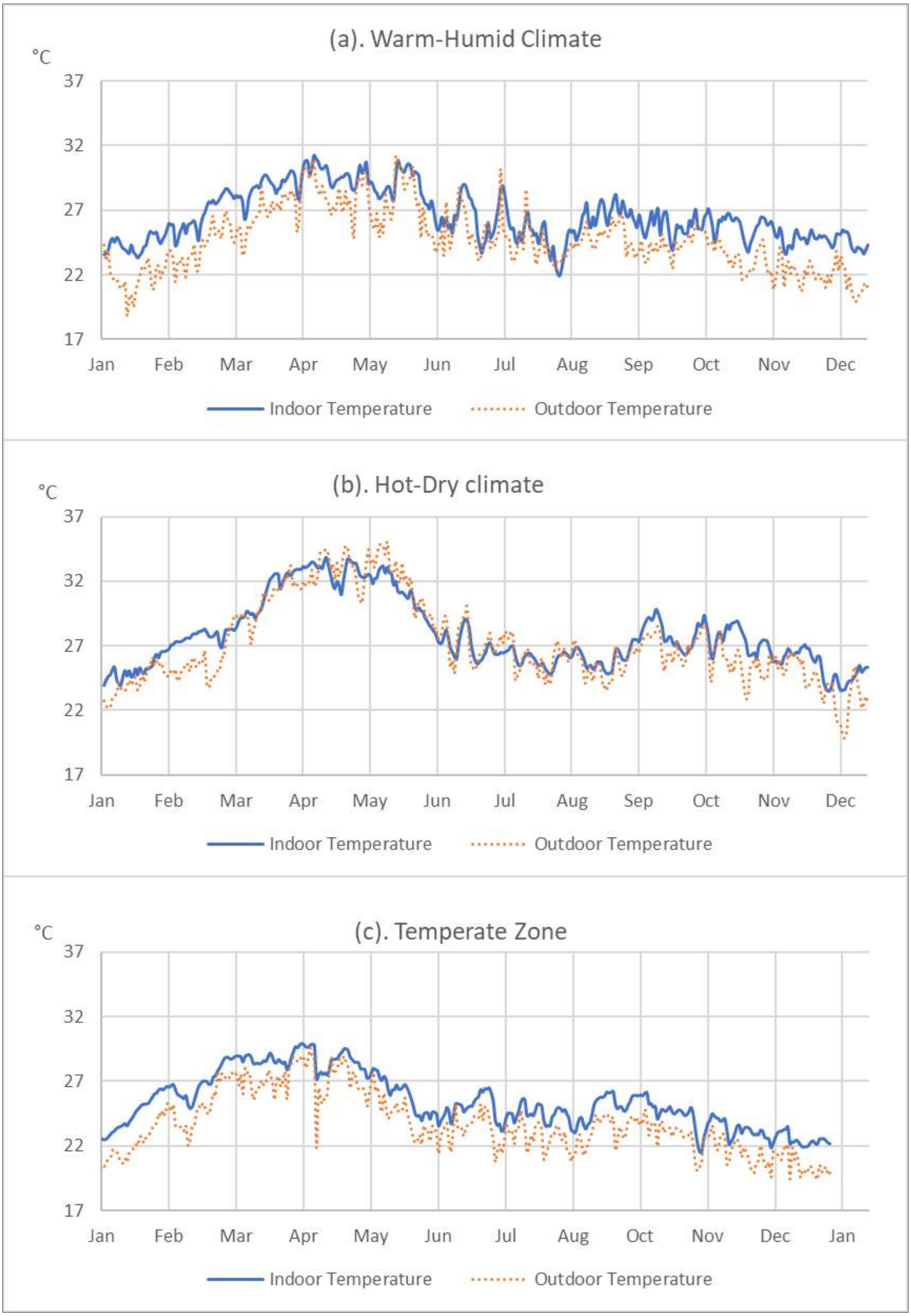

Figure 6. Average daily indoor and outdoor temperatures for vernacular dwelling in (a) Warm-humid, (b) Hot-dry and (c) Temperate climate zone

Table 3. Indoor maximum and minimum temperatures obtained for (a) vernacular dwelling and (b) conventional dwelling in warm-humid, hot-dry and temperate climate zones

	Dwelling type	Climate zone	Indoor Temperatures (°C)						Outdoor Temperatures (°C)	
			Summer		Winter		Overall			
			Min	Max	Min	Max	Min	Max	Min	Max
(a)	Vernacular dwelling	Warm-Humid	23.7	31.2	23.3	26.4	22	31	19	31
		Hot-Dry	25.6	34	23.5	28	23.5	34	20	35
		Temperate	23.6	30	21.5	24.5	21.5	30	19	30
(b)	Conventional dwelling (post material transitions)	Warm-Humid	24	36.3	24.4	29.7	23	36.3	19	31
		Hot-Dry	27.2	39.2	24.8	31	24.8	39.2	20	35
		Temperate	24.5	34.3	22.6	27.7	22.1	34.3	19	30
		ASHRAE 55	22.22	26.66	20	23.33				

The temperature variations in a room provide an indication of the thermal environment inside a building. But thermal comfort is the result of the interaction between the thermal environment inside the building and the physiology and psychology of the occupant. ASHRAE 55, 2010 defines Thermal comfort as “the condition of mind that expresses satisfaction with the thermal environment”. Environmental conditions required for comfort will vary from person to person and so it is difficult to suggest particular thermal environment characteristics that satisfy everyone. Through extensive laboratory and field experiments Fanger devised a tool called Predicted Mean Vote (PMV) for the practical assessment of thermal environments (Fanger, 1973). Fanger’s PMV is an indication of the degree of discomfort using a psychophysical scale ranging from -3 to +3 (where -3 indicates cold, -2 cool, -1 slightly cool, 0 neural, +1 slightly warm, +2 warm and +3 hot environment). This model is based on heat exchange between the occupant and the thermal environment in the room. It considers four environmental (Air Temperature, Radiant Temperature, Air Velocity and Humidity) and two human parameters (Metabolic rate of the occupant and the insulation provided by the clothing). Figure 7 shows the plot of PMV for summer and winter months in a vernacular dwelling. From Figure 7(b), it can be observed that during winter period the PMV values lie between -1 and +1, for all the three climatic zones, indicating comfortable conditions during winter in vernacular dwelling in existing climatic condition and possible increase or decrease in mean monthly temperatures due to climate change. Figure 7(a) shows that during summer period, PMV exceeds +1 especially for warm-humid and hot-dry climate, indicating warmer indoor environment.

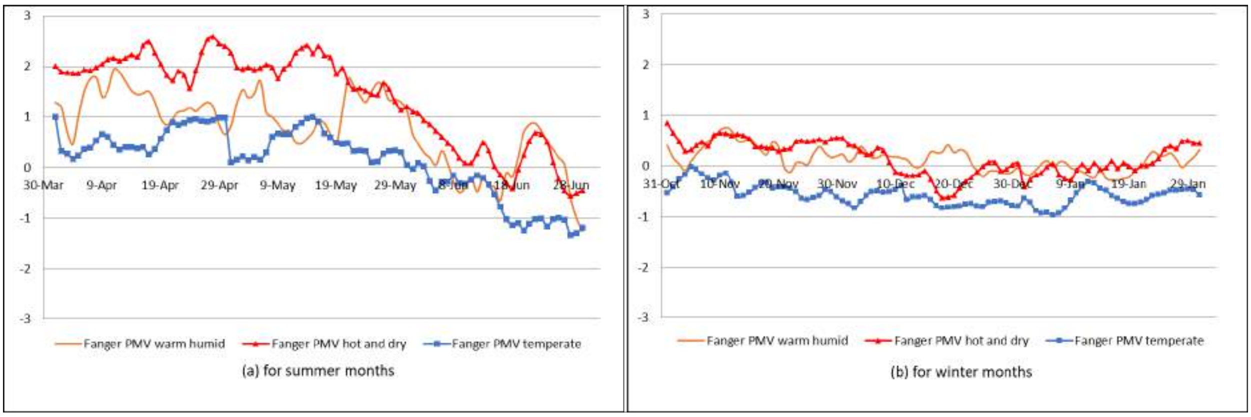

Figure 7. Fanger's PMV plotted for vernacular dwelling for warm-humid, hot-dry and temperate climate zones during (a) summer and (b) winter months

Heat balance models like Fanger's PMV model requires the buildings to maintain a constant thermal environment, like in an air-conditioned building. These may not accurately represent buildings in developing countries, especially rural India, where the dwellings are mostly free-running. These models are also often referred to as 'static' models as these view the occupant as a passive recipient of the thermal environment. Thermal comfort of an individual can also be influenced by factors other than that accounted in the heat balance models like thermal preference of the individual, demographics, cognition etc. On the other hand, Adaptive thermal comfort model considers the individual "as an active agent interacting with the person-environment system via multiple feedback loops" (Brager and de Dear, 1998). A study sponsored by ASHRAE analysed a large database of research results in building comfort studies from around the world indicating a clear dependence of indoor comfort temperatures on outdoor air temperatures in free-running buildings. The study indicated a linear relationship between indoor operative temperature and mean monthly outdoor air temperature (de Dear and Brager, 2002). Figure 8 shows the linear relationship and the acceptable operative temperature ranges for naturally conditioned spaces adapted from ASHRAE 55, 2010. The indoor operative temperatures obtained from the dynamic simulation for the vernacular dwelling in warm-humid, hot-dry and temperate climate zones are marked on Figure 8. From the figure, most of the data points for all the three climatic conditions lie within 80% acceptability limits indicating that the vernacular dwelling provides considerably comfortable conditions indoor in present climatic condition as well as future possible increase or decrease in mean monthly temperature due to climate change.

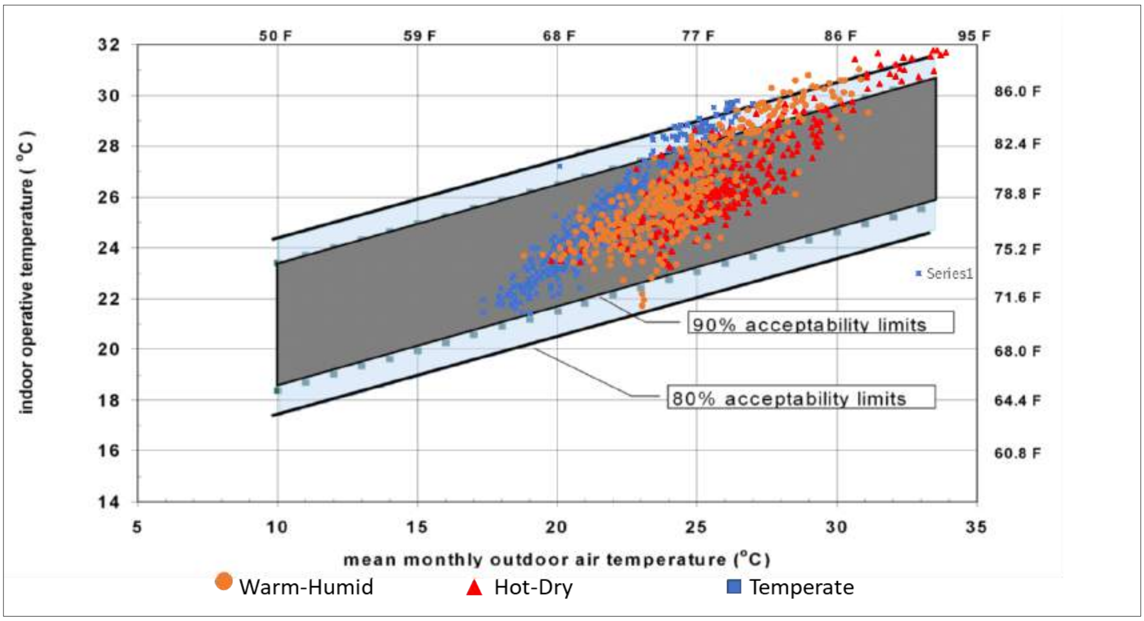

Figure 8. Plot between Indoor operative temperature and mean monthly air temperature for vernacular dwelling for warm-humid, hot- dry and temperate climate zones against Adaptive comfort standard for naturally ventilated spaces

3.2. Conventional Dwelling

The simulation model developed for vernacular dwelling was modified to integrate material transitions in dwellings, as mentioned in section 2.2. Form and orientation of the dwelling is maintained as that of vernacular dwelling, even though the changes in form and orientation are evident in Suggenahalli. Dynamic simulation was run again for the modified building model for three climatic zones: warm-humid (existing climate zone), hot-dry (change in climate zone in case mean monthly temperatures rise due to climate change) and temperate (change in climate zone in case mean monthly temperatures fall due to climate change). Annual variations in indoor and outdoor temperatures for the conventional dwelling in the three climatic zones as obtained from the simulation are shown in Figure 9. It should be noted that in all the three cases the indoor temperatures were almost always above the outdoor air temperatures, indicating that the conventional dwelling almost always resulted in an indoor environment warmer than the outdoors.

In warm-humid climatic conditions (Figure 9(a)), the winter indoors for the conventional dwelling were maintained at a temperature range of 24ºC to 30ºC, for an outdoor temperature range of 19ºC to 25ºC. While in summers, indoors witnessed a warmer environment with a temperature range of 24ºC to 36ºC, for an outdoor temperature range of 24ºC to 35ºC. For a conventional dwelling in hot-dry climatic zone (Figure 9(b), the trend was similar, but the summer indoor temperatures were considerably high from 27ºC up to 39ºC when the outdoor temperature was between 28ºC and 35ºC. In a temperate climate zone (Figure 9(c)), the conventional dwelling resulted in an indoors that was 2-5ºC warmer than the outdoor environment, with an indoor temperature range of 22ºC -28ºC in winter and 24ºC to 34ºC in summer.

Table 3(b) gives the minimum and maximum indoor temperatures for summer and winter months for the conventional dwelling for all the three climatic conditions. Minimum temperature during summer and winter does not fall below the ASHRAE 55 recommended minimum summer and winter indoor temperature for the three climatic zones. But the maximum summer and winter indoor air temperatures exceeds the maximum indoor summer and winter temperatures recommended by ASHRAE 55 in all the three climatic zones indicating a warmer environment inside the conventional dwelling.

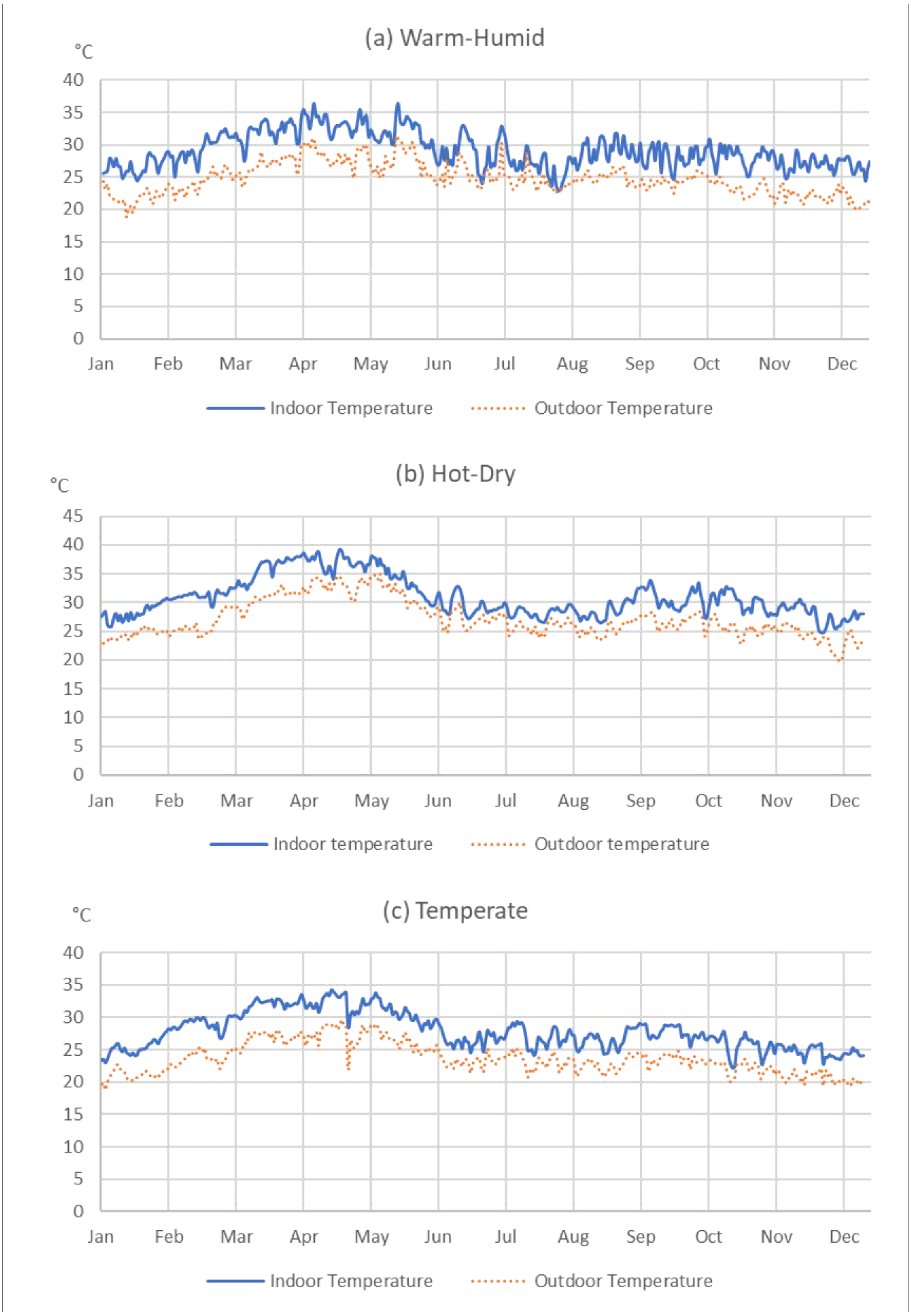

Figure 10. Average daily indoor and outdoor temperatures for conventional dwelling in (a) Warm-humid, (b) Hot-dry and (c) Temperate climate zone

Fanger's PMV is used again for the analysis of thermal environment inside the conventional dwelling. Figure 10 shows the Fanger's PMV plotted for the conventional dwelling under the three climatic conditions as obtained from the simulation output. As observed from the indoor air temperatures Fanger's PMV also indicate a warmer environment inside the conventional dwelling. It also shows that the indoor environment inside the dwelling during summer could be uncomfortably warmer for most of the summer period, especially for warm-humid and hot-dry climatic condition, with PMV values exceeding +2 for most part of the summer period. During winter, temperate zone provides comfortable indoor environment with PMV lying between -1 and +1. In warm-humid and hot-dry climatic zones, even during winters the indoor environment gets slightly warmer, with PMV exceeding +1.

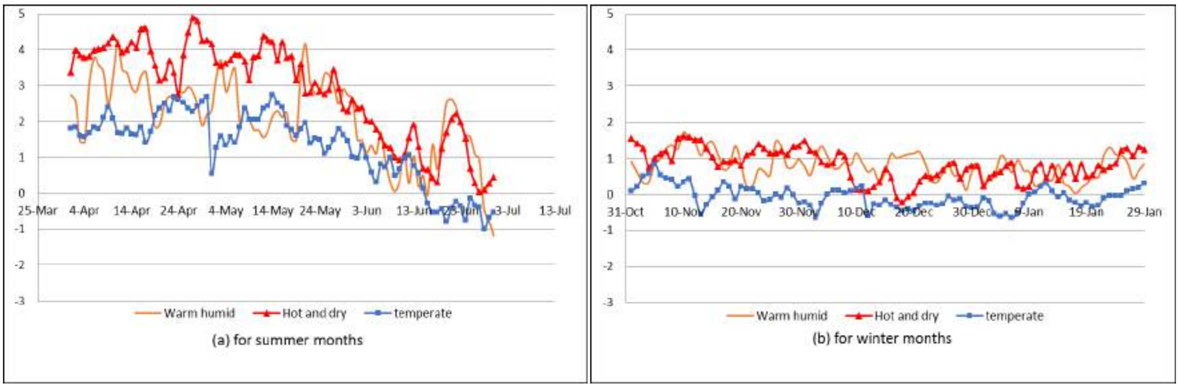

Figure 10. Fanger's PMV plotted for conventional dwelling for warm-humid, hot-dry and temperate climate zones during (a) summer and (b) winter months

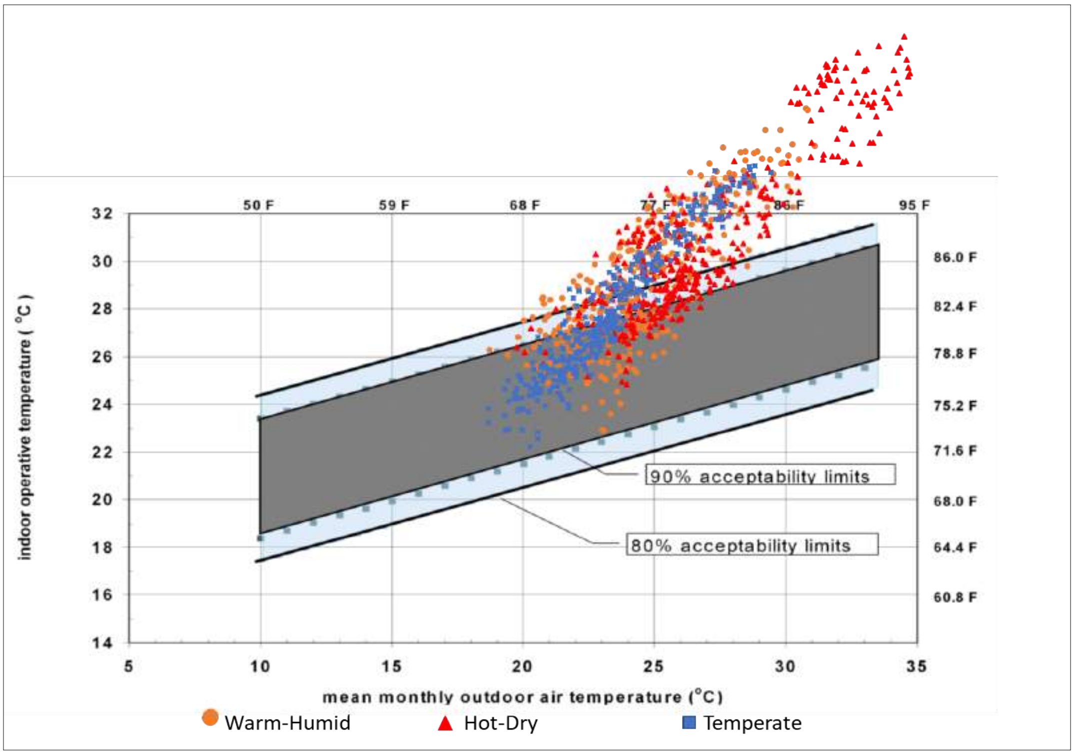

Figure 11. Plot between Indoor operative temperature and mean monthly air temperature for conventional dwelling for warm-humid, hot-dry and temperate climate zones against Adaptive comfort standard for naturally ventilated spaces

Indoor operative temperatures obtained from the simulation was plotted against mean monthly air temperature as shown in Figure 11. From the figure, for the conventional dwelling the operative temperatures exceed the 80% acceptability limit, with majority of the points for all the three climatic zones lying farther away from the preferred temperature band. This shows that the indoor environment can get uncomfortably warmer to hot for a conventional dwelling composed of modern materials.

3.3. Comparison of vernacular and conventional dwelling

Table 3(a) and 3(b) gives the maximum and minimum indoor temperatures during summer and winter months for a vernacular and conventional dwelling in the three climatic zones. A comparison of the values suggests that the conventional dwelling which has the same form and orientation as the vernacular dwelling but consisting of modern materials in the place of local traditional materials make the indoor environment much warmer than that in the vernacular dwelling. A conventional dwelling in warm-humid climate is 0.4°C to 5.5°C warmer than the vernacular dwelling. Similarly, conventional dwelling is 0.8°C to 5.5°C and 0.5°C to 4.4°C warmer than the vernacular dwelling in hot-dry and temperate climate zones respectively. Table 4 gives the percentage change in indoor temperatures with respect to the vernacular dwelling in that climatic zone. The values confirm that material transitions result in warmer indoor with respect to the vernacular dwelling.

Table 4. Percentage change in Indoor temperatures obtained for conventional due to material transitions in comparison to vernacular dwelling

	Percentage change in Indoor Temperatures (%)					
	Summer		Winter		Overall	
	Min	Max	Min	Max	Min	Max
Warm-Humid	1.3	16.3	4.7	12.5	4.5	17.1
Hot-Dry	6.2	15.3	5.5	10.7	5.5	15.3
Temperate	3.8	14.3	5.1	13.1	2.8	14.3

Comparison of Fanger's PMV for vernacular dwelling (Figure 7) and that for conventional dwelling (Figure 10) show that the material transitions in dwellings make the indoors uncomfortably warmer to hot, to the extend that in summers PMV exceeds +2 for most part of summer, especially for warm-humid and hot-dry climatic condition. The plot of indoor operative temperatures and mean monthly temperatures (Figures 8 and 11) also show the conventional dwelling becomes uncomfortable demanding the need for electric controls for providing thermal comfort.

4. Conclusion

The current paper deals with the thermal performance of a vernacular dwelling composed of traditional local materials like clay and timber situated in a village called Suggenahalli near Bangalore, India and studies the effects of changing climate on the thermal performance of the dwelling. The study also investigates the impacts of change in construction materials from traditional to modern materials like cement and concrete due to transitions in the built environment on the thermal performance of the building for the present climate and in case of changes in climate. The vernacular and the conventional dwelling are studied under three climatic conditions: warm-humid (which is the present climatic zone in which the dwelling is located), hot-dry (if the mean monthly temperature is to rise as the effect of climate change) and temperate (if the mean monthly temperature is to drop due to climate change). Results from dynamic simulation from DesignBuilder was studied for the analysis, which was validated with the help of data collected through real-time monitoring using loggers installed in the dwelling under study. Comfort conditions inside the dwellings are assessed using both Fanger's Predicted Mean Vote and Adaptive Thermal comfort model.

Table 5. Percentage change in Indoor and outdoor temperatures obtained for vernacular and conventional dwelling in comparison to base case

	Dwelling Type	Climate zone	Percentage change in Indoor Temperatures						% change in Outdoor Temperatures	
			Summer		Winter		Overall			
			Min	Max	Min	Max	Min	Max	Min	Max
(a)	Vernacular	Hot-Dry	8.0	9.0	0.9	6.1	6.8	9.7	5.3	12.9
		Temperate	-0.4	-3.8	-7.7	-7.2	-2.3	-3.2	0.0	-3.2
(b)	Conventional	Warm-Humid	1.3	16.3	4.7	12.5	4.5	17.1	0.0	0.0
		Hot-Dry	14.8	25.6	6.4	17.4	12.7	26.5	5.3	12.9
		Temperate	3.4	9.9	-3.0	4.9	0.5	10.6	0.0	-3.2

(Note: The base case considered here is the vernacular dwelling in warm-humid climate zone. The two scenarios considered include (a) the same vernacular dwelling when climate zone was altered to Hot-Dry and Temperate and (b) conventional dwelling which is the vernacular dwelling that has undergone material transition in warm-humid, hot-dry and temperate climate zones)

Table 5 gives percentage increase or decrease in temperatures for the scenarios considered in this paper with respect to the base case, which is the vernacular dwelling situated in warm-humid climatic zone. It shows the combined effect of climate change and transitions on built environment. The indoor temperatures increase when the average monthly temperatures increase and when dwellings transition to conventional type, in the given climate as well as possible future climates. In a conventional dwelling exposed to hot-dry climate indoor temperatures tend to increase by 26.5%. There is but a marginal decrease in indoor temperature when the traditional dwelling is exposed to temperate climatic conditions. Once transition in the built environment sets, in the performance of the dwelling gets adversely effected. The modern building, which replaced the 450 mm thick rubble masonry with 230 mm thick brick masonry and the Mangalore and Maalige roof with RCC failed to respond to changes in climate. The dwelling tends to get warmer in all the three climatic conditions studied and performs worst in warm-humid and hot-dry climate, indicating that the building is not designed taking climate into consideration. From the results of the thermal comfort study, in all the three climatic conditions, the vernacular dwelling performed exceptionally providing comfortable indoor environment throughout the year. It can be concluded that the vernacular dwelling can ensure considerably comfortable conditions indoor irrespective of the climatic zone it was in. This further confirms the climatic resilience of vernacular dwelling to perform in adverse climatic conditions. The modern building that suits the modern aspirations of the occupants may not be suitable for the present climate or future possible climatic conditions. The vernacular dwelling has shown to perform in the future like it has in the past, suggesting designers to trust traditional wisdom when it comes to designing buildings for the future.

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An Adaptive Thermal Comfort Model for Residential Buildings in Iraq

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Abstract: In Iraq, the temperature reaches around 0 °C in winter and 50 °C in summer. Aiming at providing thermal comfort for people, studies have been advocating developing innovative thermally responsive designs or adopting traditional architecture's passive design strategies. However, to develop appropriate solutions for the country, it is critical to determine the thermal comfort limits to define the targeted thermal performance of buildings. This research worked on defining Iraqis' thermal comfort limits in residential buildings for two reasons. First, they are the dominant building type in the country. Second, to inform the design of large housing developments Iraq is planning to have to satisfy large housing needs. Exploring previous literature in Iraq or regional countries shows that residential thermal comfort limits for people have not been defined properly. To achieve this aim, the research conducted thermal comfort survey in four Iraqi cities for a year. Nearly 4800 thermal comfort votes were recorded by 90 participants. The results show that the lower thermal comfort Globe temperature in winter is 17 °C and the highest acceptable Globe temperature in summer is 33 °C.

Keywords: Adaptive thermal comfort model, Iraq, Residential buildings.

1. Introduction

Iraq has an extremely long and hot summer and cold winter. The temperature range in Baghdad is between 0 °C in winter and 50 °C in summer (Iraqi Meteorological organization, 2016). 60% to 70% of the total energy consumption in the country is used for air-conditioning purposes (Hasan, 2016). These factors, in addition to the fact of having frequent interruptions in the electricity supply since 1990 (Al-juboori, 2015; Rashid et al., 2018), make it of high importance to develop options to provide thermally comfortable environments for people. Among the main possible options is to develop innovative thermally responsive buildings or to use traditional passive design strategies to have less energy consuming and more thermally comfortable buildings (Holmes and Hacker, 2007; Al-Jawadi, 2011). However, before developing any solution, Iraqis' thermal comfort limits need to be determined. This will help to define the targeted performance for designers and to judge possible alternatives' thermal efficiency. Otherwise, buildings' thermal efficiency might be not correctly determined which might lead to adopting inappropriate solutions for the country.

This research aims to explore and determine Iraqis' thermal comfort limits in residential buildings. This building type was selected for two reasons. First, it is the dominant building type in the country. Second, Iraq has a housing shortage of around 1.5 million housing units. To solve this challenge, the country is planning to have massive housing development in the future (Iraqi Ministry of Construction and Housing, 2017). Having thermal comfort limits for people properly determined might help to inform future residential developments' design.

To achieve this aim, the research explored the subject of thermal comfort, previous thermal comfort studies in Iraq and regional countries, then conducted a thermal comfort survey in Iraq.

2. Thermal comfort

Thermal comfort is defined as '*that condition of mind that expresses satisfaction with the thermal environment*' (ASHRAE, 2005; Enescu, 2017; Höppe, 2002). It affects people comfort in their buildings (Al horr et al., 2016; Frontczak and Wargocki, 2011), in addition to their health (Nicol et al., 2012) and productivity (Freire et al., 2008). It also affects buildings' energy consumption as a large amount of the consumed energy in buildings is directed towards achieving thermal comfort (Yang et al., 2014), which leads to increasing the CO^2 emissions (Elaiab, 2014). Because of these reasons, thermal comfort has been investigated by researchers since the beginning of the 20^{th} century, when air-conditioning systems were first introduced (Fabbri, 2015; Nicol and Roaf, 2017). Since that time many studies have been conducted to determine thermal comfort limits around the world. National and international thermal comfort standards have been established and developed, such as ISO Standard (7730), ASHRAE Standard 55 and CEN Standard EN15251 (Rupp et al., 2015; Nicol et al., 2012; Humphreys et al., 2015b).

To assess and predict people's thermal comfort levels, studies, first, have worked on exploring the factors that affect people's thermal sensation. They have found that they are of two groups: quantitative factors and qualitative factors. The former includes air temperature; air velocity; humidity; Mean Radiant Temperature (radiation); people activity level and people clothes (Reiter and De Herde, 2003; Nikolopoulou, 2011; Setaih et al., 2013). The latter includes not measurable factors such as people's previous experience, thermal expectations, time of exposure to climatic conditions, psychology, available adaptation opportunities, and cultural and social backgrounds (Reiter and De Herde, 2003; Nikolopoulou, 2011; Aljawabra, 2014).

Depending on these factors, two thermal comfort models have been developed to assess and predict thermal comfort: the Static Model and the Adaptive Model (Yao et al., 2009; de Dear and Brager, 2002a). The former was developed by Fanger during the 1970s. It assumes that thermal comfort can be universally defined by determining the impact of the six quantitative factors on the human body's thermal balance. It has been developed by doing thermal comfort surveys in special thermal comfort chambers (de Dear and Brager, 1998; Fanger, 1970). The latter was developed and introduced later by researchers, including Humphreys, Nicole, and de Dear. It states that there are factors that affect people thermal sensation other than the factors of the human body's thermal balance. It argues that people from different places and cultures have different thermal comfort limits and that people adapt themselves to their surrounding climatic conditions (de Dear and Brager, 2002a; Nicol, 2004; Nicol and Humphreys, 2002). This model has been developed through doing thermal comfort surveys in people's actual contexts doing their normal activities (Nicol et al., 2012). It predicts people's thermal sensation by making correlations with outdoor running temperature (Humphreys et al., 2010). Both of these two models have been used to determine people's thermal sensation and comfort limits. However, studies have found that the Static Model overestimates the discomfort of occupants in buildings that depend on natural ventilation (Nicol et al., 2012; Brager and de Dear, 2001). It is also not able to tackle and consider the psychological, social and cultural factors that affect people perception of thermal comfort (Nicol et al., 2012; De Dear and Brager, 2002b).

According to this exploration, this research used the Adaptive Model to determine Iraqis' thermal comfort limits. It offers to explore thermal comfort in a wider range of space types in addition to making a better correlation with countries' local conditions.

3. Thermal comfort limits in Iraq

There are a number of international comfort standards that have developed adaptive models, such as ASHRAE 55 and EN 15251 standards (Rupp et al., 2015; Nicol et al., 2012). However, they cannot be used for Iraq's climates because they have been developed depending on experiments and surveys, in most cases, in moderate climate zones (Nicol et al., 2012). This makes them inaccurate when they are applied to hot regions. The considered mean temperature limits in the ASHRAE 55 standard's model, for instance, is between 10 °C and 33 °C, which different from hot regions' temperature (Farghal and Wagner, 2010; Eltrapolsi, 2016; Indraganti et al., 2014).

Exploring previous studies that have worked on developing an adaptive thermal comfort model for hot regions shows that there has been two comfort studies in Iraq and a number of studies in regional hot countries (Table 1). Although these studies give useful indications about thermal comfort limits for people in hot regions, they do not conclude a complete adaptive thermal comfort model that can be used to determine Iraqis' thermal comfort limits in residential buildings. They are either in non-residential buildings, which makes them not accurate for residential buildings, or in residential buildings but of limited time frame. This study aims to address this research gap by conducting a thorough thermal comfort survey in Iraq to develop an inclusive thermal comfort model for residential buildings in the country.

Table 1. Previous thermal comfort studies in hot regions

The study	Country	Outdoor Ta (°C) during studies	Indoor Tem. (Ta/Tg)		Building type/ Vent. mode	Study period	No. of comfort votes	Results (thermal comfort range) Ta/Tg	
			Min	Max				Min	Max
(Rashid et al., 2018)	Baghdad, Iraq	0.0 – 50.0	Ta 14.0	Ta 37.0	MM. Class-rooms	Dec., Jan., Aug.	530	Ta 19.0	Ta 29.0
(Alshaikh, 2016)	Damam, KSA	5.0 – 40.0	Ta 15.5	Ta 38.5	MM. Houses	Jan., Aug.	561	Ta 18.0	Ta 29.7
(Indraganti and Boussaa, 2016)	Doha, Qatar	18.0 – 37.0	Tg 22.0	Tg 25.0	AC. Offices	13 months	3742	Tg 24.0	Tg 25.0
(Farghal and Wagner, 2010)	Cairo, Egypt	16 .0– 35.0	Ta 20.5	Ta 34.3	NV. Class-rooms	Feb. – Dec.	2689	Ta 21.0	Ta 33.0
(Heidari, 2008)	Tehran, Iran	2.0 – 37.0	---	---	NV. Offices	July	631	---	Ta 26.2
(Heidari and Sharples, 2002)	Ilam, Iran	2.0 – 40.0	Ta 15.4	Ta 32.7	NV. Offices	One year	3819	Ta 21.7	Ta 26.7
					NV. Houses	Aug., Dec.	891	Ta 20.8	Ta 28.4
(Webb, 1964)	Baghdad,	----	-----		MM.	Jun.,	1284	---	Tg

	Iraq			Houses	Jul.			32.0

Ta: Air temperature – Tg: Globe temperature – AC: Air conditioned spaces, NV: naturally ventilated spaces – MM: Mix-mode ventilation spaces

4. Research methodology

This research worked on developing an adaptive thermal comfort model for Iraq to be used to determine Iraqis' thermal comfort limits. To achieve this objective, the research conducted a thermal comfort survey for a year from October 2017 to October 2018. The survey was conducted following exploring a number of similar thermal comfort studies and with considering (Nicol et al., 2012) guide to conduct thermal comfort surveys.

- Study sample: To extend the research's results reliability and representativeness, this research considered targeting a sample size and thermal votes threshold suggested by (Nicol et al., 2012), which is twenty participants giving around 2000 thermal comfort votes. For the same purpose, the research also considered having participants from different regions in the country. Eight households from four cities accepted to participate in the study. Three households were in Erbil, three in Mosul, two in Baghdad and one in Ramadi. They all constitute more than 70 participants. Although they might not represent the whole country, the participated cities are still from different regions and can give useful results about the overall thermal comfort limits in the country. All of the participating households' houses were mix mode ventilation buildings.
  It is important to state here that participants were selected using the convenience sampling technique. It was not possible to select participants randomly due to the nature and conditions of the survey which required having committed and motivated participants.
- Survey: A survey form was developed following exploring previous literature and (Nicol et al., 2012) thermal comfort survey guide. In preparing the survey forms, it was considered to make it as easy and simple as possible to encourage participants to record as many readings as possible. The survey form included asking participants to record thermal conditions measurements, define used approaches to control the spaces' environments, and record their thermal sensation on a seven-point scale from very cold to very hot (Figure 1). Participants were asked to take the measurements and record their thermal comfort votes on the survey form simultaneously. They were informed to fill the survey while doing their normal daily activities.
- Assessing people' thermal sensation: This research used the Globe Temperature (Tg) to assess Iraqis' thermal sensation. It combines the impact of air temperature, air velocity and radiation in its value, which makes it of an inclusive measurement. Studies have found that it represents an appropriate index to represent people's actual thermal sensation (Humphreys et al., 2015).
- Instrument: The measuring instrument was selected to be able to measure the Tg directly. For this reason, Calibrated Extech HT30 Heat Stress WBGT (Wet Bulb Globe Temperature) meters were purchased and delivered to the participants in Iraq (Figure 2). This instrument is manufacturer calibrated, easy to use, with acceptable accuracy and measures all the required factors. A limitation of this instrument that needs to be stated is that it does not allow the assessment of the cooling effect of air movement.

However, this was not considered a problem in this study for two reasons. First, the main focus of this study is only to measure Tg. Second, in indoor spaces, in most cases, there is no or limited air movement.

ENVIRONMENTAL BUILDING WITH PLYMOUTH UNIVERSITY

استبيان تعريف حدود الراحة الحرارية في العراق

Thermal comfort limits survey in Iraq

وصف الاستبيان

يهدف هذا الاستبيان الى تحديد حدود الراحة الحرارية في العراق وتغيرها على مدار السنة.
يرجى من حضرتكم ملىء المعلومات في الجدول ادنها بالاستعانة بجهاز قياس الظروف الحرارية المرسل اليكم.
يرجى من كل مشارك ملىء المعلومات الخاصة به ثلاث مرات على الاقل في الاسبوع في اي وقت واي فضاء سكني.
للحصول على نتائج صحيحة, يرجى من حضرتكم قراءات تعليمات الجهاز و الملاحظات التالية:

	المشارك The participant	الوقت و التاريخ Date & time		الظروف الحرارية Thermal conditions				نظام التكييف / التهوية (في حالة الفضاء الداخلي) Air-conditioning / ventilation system (Indoor spaces)					وصف الفضاء Space description		الاحساس الحراري Thermal sensation						
		التاريخ Date	الوقت Time	الاجهاد الحراري WBGT Heat stress (WBGT) (C°)	درجة حرارة مركبة TG Tg (C°)	درجة حرارة الهواء TA Ta (C°)	الرطوبة النسبية Humidity (%)	جهاز تكييف Air-condition	مبردة Evaporative cooler	مروحة Fan	مدفأة Heater	تهوية طبيعية Natural ventilation	فضاء داخلي Indoor space	فضاء خارجي Outdoor space	حار جدا Very Hot	حار Hot	حار قليلا Slightly hot	مريح Comfortable	بارد قليلا Slightly cold	بارد Cold	بارد جدا Very cold
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لارسال القياسات والتواصل مع الباحث, يرجى استخدام عناوين الاتصال التالية:

Figure 1. The survey form

Specification s	Range	Accuracy
Black Globe Temperature (Tg)	0 °C -80°C	2°C
Air Temperature (Ta)	0 °C -50°C	1°C
Relative humidity	0 to 100%	3%
The ball size	40mm diameter, 35mm high	

Figure2. The used instrument to measure the Globe Temperature

5. Results analysis and discussion

More than 90 people participated in the survey. 73 of them recorded their votes on a regular basis. The rest were irregular participants who participated in the survey a few times while visiting the survey hosting households. The total number of the properly recorded thermal comfort votes were 4797.

The results show that the monthly average indoor Globe Temperature ranges between 19 °C and 30 °C (Figure 3). The heating period is five months: during the months of January to March and November to December. The cooling period is nine months: between March and November. Within the cold period, people sometimes do not use heating systems and satisfy with closing their windows. The peak use of heating systems is in January, and the peak use of cooling systems is between July and August. The period in which they mostly use neither cooling nor heating systems is in March and November. The use of air-conditioning systems enabled participants to have a temperature difference in indoor spaces of up to 16°C comparing to outdoor temperature (Figure 4).

Month	Av. In. Tg	Av. Out. Ta
Jan	19.3	9.0
Feb	19.1	12.1
Mar	23.2	15.4
Apr	25.0	20.8
May	27.4	27.3
Jun	28.2	32.7
Jul	28.6	36
Aug	29.1	35.7
Sep	27.7	31.1
Oct	26.3	24.7
Nov	21.6	15.8
Dec	19.5	9.8

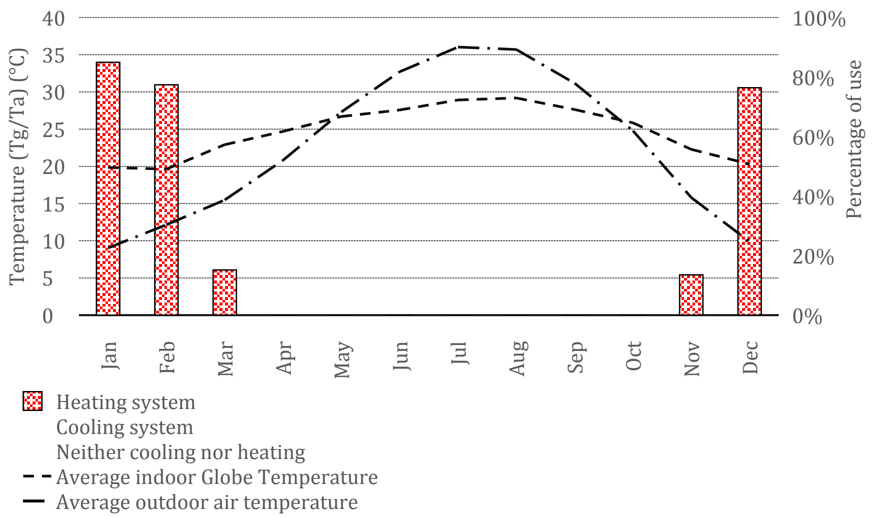

Figure 3. The measured Globe Temperature (°C) and use of heat and cooling systems (%)

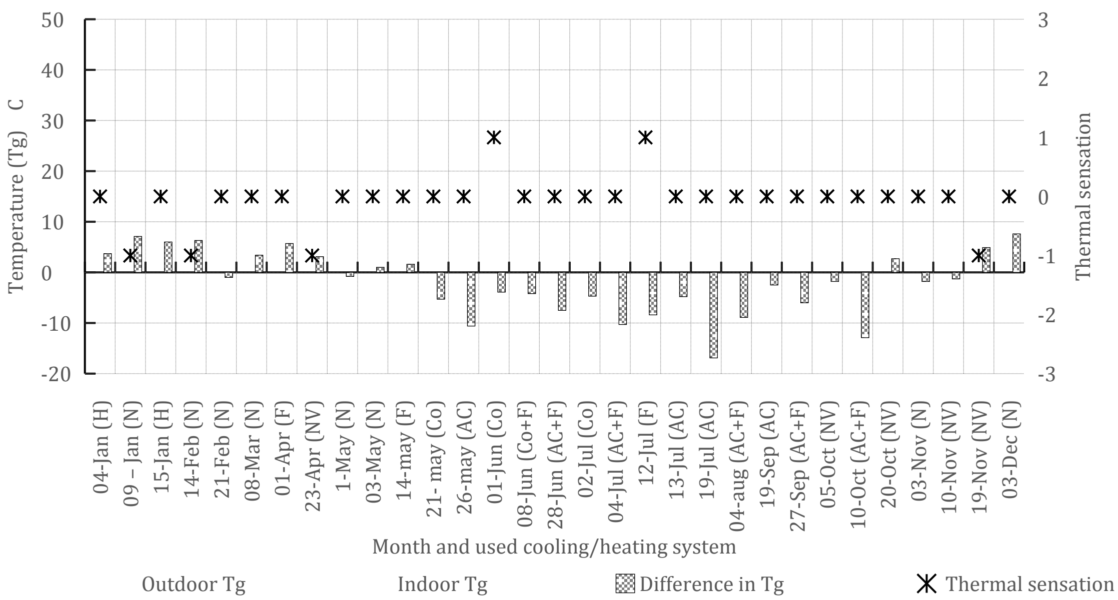

Figure 4. The impact of the used air-conditioning systems on indoor spaces' temperature

Analysing the correlation between indoor Globe Temperature and participants' thermal sensation shows that the upper comfort limit is 32 °C and the lower comfort limit is between 12°C and 14°C. The graph in (Figure 5) shows Tg in indoor spaces in the cases of being naturally ventilated (NV) and air-conditioned (AC). It can be seen that there are cases in which participants kept spaces naturally ventilated even though that spaces were highly out of the comfortable temperature. Another related interesting result is that, for the same Tg, people tend to feel more comfortable in NV spaces than in AC ones. The graph in (Figure 5) shows that participants' thermal sensation is 1.5 when Tg is 35 °C. In AC spaces, for the same temperature, participants' thermal sensation is at 2.0 level. A possible reason behind this is that the electricity supply interruptions obstruct using available air-conditioning systems (Al-juboori, 2015; Rashid et al., 2018). As a result, participants became more tolerated with their environments as they did not have high control over their thermal conditions (Brager and de Dear, 2001).

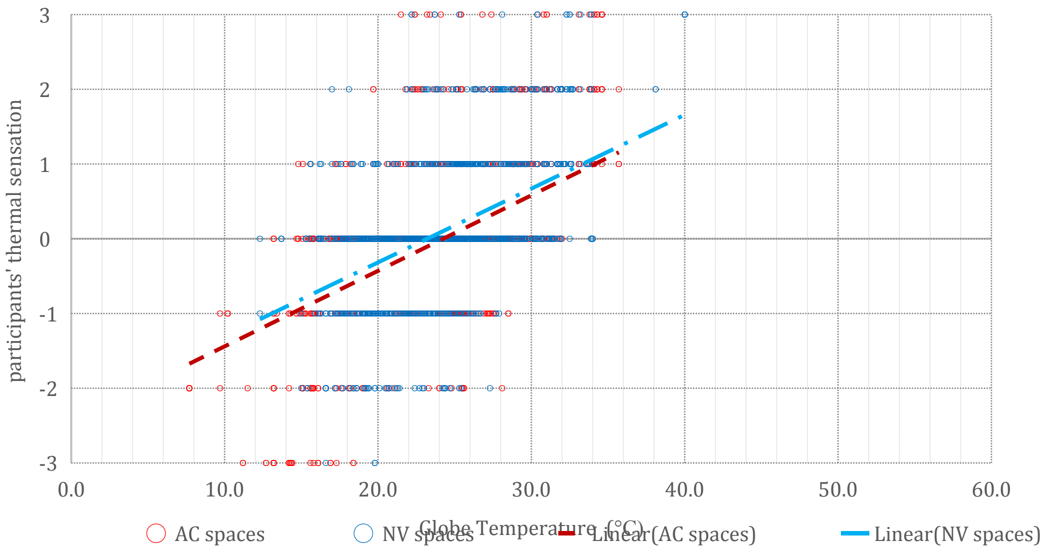

Figure5. The correlation between the measured Globe Temperature and participants' thermal sensation in AC and NV spaces

To develop an adaptive model to determine Iraqis' thermal comfort limits, this research conducted a regression analysis to correlate the running mean outdoor air temperature and indoor Globe temperature and participants' thermal sensation (Figure 6). The average running outdoor air temperature was calculated for a year for the four cities depending on temperature data from the Iraqi Meteorological Organization and online temperature records (www.accuweather.com, 2019). The analysis shows that the lowest comfortable Globe temperature for Iraqis is 17 °C when the running mean outdoor air temperature is 8 °C. The highest acceptable Globe temperature is 33 °C when the running mean outdoor air temperature is 38 °C. The perfect comfortable Globe temperature is 19 °C and 30 °C when the running mean outdoor air temperature is 8°C and 38°C, respectively.

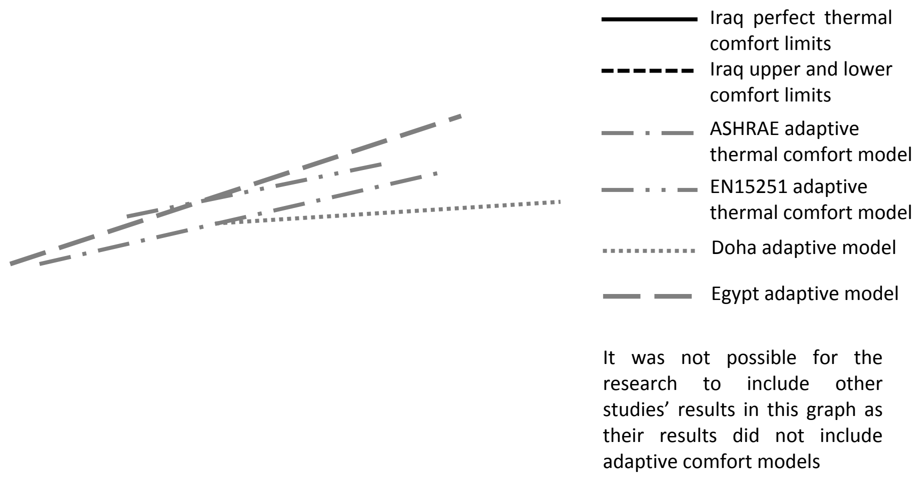

Figure6. The proposed adaptive thermal comfort model for Iraq

Comparing these results with other studies shows some similarities and differences (Figure 4). They are similar to the determined comfort limits by (Webb, 1964) in Baghdad around fifty years ago. Assuming that Ta is similar to Tg in indoor spaces, the upper comfort limit in the study of Egypt is also similar to the upper comfort limit determined by the current study. The similarity between this study's results and Webb's study might be reasonable as both studies are in the same context. But, it is interesting to have the same upper limit while there is a difference of around 15 °C between Iraq and Egypt. This similarity can be resulted from that the study in Egypt was conducted in naturally ventilated buildings. This might lead to extending occupants' comfort range so that it becomes similar to Iraqis' comfort range in mixed mode ventilation buildings. Studies have shown that people's tolerance with thermal conditions increases by decreasing their control over their environments (Brager and de Dear, 2001). Clear differences can be seen when comparing this study's determined comfort limits and the ones determined by (Rashid et al., 2018) in Baghdad, (Alshaikh, 2016) in Saudi Arabia and by (Heidari and Sharples, 2002) in Iran. The upper comfort limit determined in the current study is around 4°C higher than limits determined by these studies. The lower comfort limit is around 2°C less than these studies. The difference between the current study and the Iraqi study can be traced back to the difference between the functions of the surveyed buildings. People have fewer adaptation opportunities in classrooms than houses, which narrows their thermal comfort range. Regarding the differences with studies in Iran and Saudi Arabia, they can be traced back to two reasons. The first one is the climatic differences between the tested cities in Iraq, Iran and Saudi Arabia. The latter two cases' highest air temperature is 10°C less than Iraq's highest temperature. The second reason is related to occupants' tolerance and control over their environments. The electricity stability in both of these studies enables occupants to have a higher level of control over their environments than the present study's participants. This study's participants used air-conditioning to reduce the temperature by around 16°C in July (Figure 4), which was, for sure, disturbed at some points by the electricity supply interruption. The impact of this factor can be further clearly seen when comparing the current study's results with the study of Qatar's results. The determined comfort limit range in the current study is of 16k, whilst it is only 2k in the study of Qatar. This difference is also because of the three reasons stated above. But, the most important factor is that the conducted study in Qatar was in air-conditioned offices for the whole year. Three out of ten surveyed buildings were even without operable windows. This gives occupants very high control over their environments, which leads to having occupants of very limited tolerance with having changes in thermal conditions. Finally, comparing the results with ASHRAE and EN15251 standards' adaptive models shows that the lower comfort temperature in the present study is less than the lower comfort temperature defined by both of these two standards. The upper comfort temperature determined by this study is above the one defined by both of them as well. This difference results from the three discussed reasons above, including the difference between the Iraqi climate and the climate of the countries where the two international standards have been developed.

6. Conclusions

This study conducted a thermal comfort survey to develop an adaptive thermal comfort model to determine Iraqis' thermal comfort limits in residential buildings. The results show that the upper comfortable Globe temperature in summer is 33 °C and the lower Globe temperature in winter is 17 °C. These are the overall thermal comfort limits for Iraq and they are applicable to mixed mode ventilation residential buildings. The results discussion shows that they are different from the comfort limits defined by international standards' adaptive models. They are also different from thermal comfort limits in naturally ventilated and air-conditioned buildings in regional hot countries. People's thermal comfort range is affected by their contextual climatic conditions, adaptation options and control over their environments' conditions. For the same context, they become more tolerated with thermal conditions in naturally ventilated buildings than in air-conditioned ones. This means that designers can still develop thermally comfortable buildings without having to totally depend on energy consuming air-conditioning system. It also implies that buildings' design and thermal efficiency need to be determined in hot regions in a different way than in regions of a different climate. The determined comfort limits in this study can be used by designers and developers to consider having as much as possible thermally comfortable and energy efficient residential buildings in Iraq or countries of similar climate and culture.

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Comfort, ventilation and health issues in dwellings of Ho Chi Minh City

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Abstract: Ho Chi Minh City, Vietnam is a location in which a number of environmental factors come together in such a way as to create concerns for comfort and health of building occupants. The city is located in a tropical monsoon climate which brings long periods of hot humid weather and there is evidence that climatic extremes have become more prominent in recent years, and these are being exacerbated by urban heat island effects. Ho Chi Minh City has undergone a rapid period of urbanisation and perhaps more importantly densification; this increasing density means that air flow through circulation routes in and around buildings is being compromised. The spaces between buildings are being encroached upon, and opportunities for cross-ventilation and natural cooling are diminishing. Environmental conditions within buildings are often very warm and humid and in addition could harbour and give rise to spread of, harmful bacteria/viruses/fungal intrusions. This paper presents information on typologies of dwellings and potential risks; it includes observations and measurements from a range of dwelling types gained at first hand. Whilst the research does not provide full solutions it indicates where risks exists and thus where future research efforts might be concentrated.

Keywords: ventilation, health, dwellings, comfort, Vietnam

1. Introduction

This paper addresses issues of contemporary importance relevant to many rapidly urbanising and developing cities across the globe, but particularly to those areas which experience hot humid conditions for considerable fractions of the year. Such circumstances tend to give rise to comfort and health problems which are exacerbated when extreme conditions occur. Research is therefore being undertaken focused on microclimate and comfort (Dang and Pitts, 2018a) and increasingly must address how dwellings and urban environments can be designed to reduce risks.

The focus of the paper is on conditions to be experienced in Ho Chi Minh City (HCMC), formerly Saigon, which is the largest city in the south of Vietnam. It experiences a tropical monsoon climate in which historically the annual mean temperature was 28°C and average monthly maximum temperatures were between 31-35°C with humidity ranging from 69-92% (IBST, 2009). Recent experience however shows the climate to be warming (Thuc et al, 2016) with mean temperature increasing by 1.2°C over a 50 year period, and with peak temperatures of 40°C or above occurring in combination with higher rainfall and higher humidity. There is much evidence of earlier onset and more prolonged periods of extreme temperatures in recent years too, with several reports identifying vulnerabilities to flooding, drought, and temperature rise (Asia Development Bank, 2013) (Schmidt-Thomé, et al., 2015) (The World Bank, 2011).

At the same time the population of the city has increased rapidly, doubling since 1999 to over 9 million at the present time, but with projections to reach 13.9 million by 2025 (Storch and Downes, 2011). City centre house prices are amongst some of the highest in the world and the built upon area has expanded to cover 750km^2. In a number of places the traditional street patterns together with those aspects of urban design which encouraged air flow and ventilation through housing schemes have been lost, and there is much development of remaining infill sites. Recent conditions of high temperatures have given rise to concerns with heat wave death rates in the city being linked to heat island impacts and lack of green space (Dang et al, 2018). Higher temperatures have led to increased demand for air conditioning and the availability of electronic consumer products has also caused a sustained increase in demand for electricity; and both factors stretch the capacity of current electricity supply systems.

The conditions to be found within buildings is concerning from a comfort and heat stress point of view, but as in other areas of S.E. Asia there are additional issues associated more broadly with health and the potential for incubation and spread of airborne diseases. Cooking and some other activities still rely on use of bottled gas and its burning within confined spaces also adds to air quality health worries.

Taking all these factors together there is clear impetus for the consideration of how urban areas, buildings, and in particular dwellings, can be designed/re-designed to help reduce discomfort and health risks in extreme ambient environmental conditions. At the same time there should encouragement for adoption of energy efficient practices. In the following sections further information is provided in order to help define the current and future problems and to suggest ways to help understand and engineer future solutions.

2. Urban form and building typologies

Over 90% of global urbanisation is occurring the developing world (UN Habitat, 2006), and in Asia the population has increased from 1.9 billion in 1970 to 4.4 billion in 2014. Urbanisation is also occurring rapidly in Vietnam, with an estimated 57% of the population expected to be living in cities by 2050 by comparison to only 20% in 1990 (VCAP and CAI-Asia, 2008). This has put strain on HCMC land resources, producing overcrowding, a level of uncontrolled development in some areas, and redesign of existing properties to maximise use of any available space to meet the urgent need for accommodation.

HCMC is normally considered to divide into four zones: a core central area; a historically defined inner zone; a second newly developed inner zone; and then a wider suburban zone. Whilst initial pressures for more accommodation were in the central area this is now spreading to others and traffic travel times and pollution levels are increasing.

A number of research groups have investigated the development of the city and have also considered potential adaptation to global temperature rise. As part of one such study, Downes and Storch (2014) carried out large scale and valuable data acquisition exercise leading to evaluation of the urban structure and housing types to be found. Mapping tools combined with fieldwork identified 82 city structure typologies covering over 16,000 of the city's urban blocks.

There are three main types of housing within the city: 'shophouses', villas, and apartments. Shophouses are single properties forming the major part of the most common type of dwelling: a single unit in either detached or terrace form, which accounts for 96% of the properties in the city. At the present time these shophouses are the predominant type of dwelling and as the name indicates they consist of two components: a shop or commercial function together with accommodation for residents. They typically exist as rows of connected properties, sometimes very straight, regular, and formal in nature; but sometime much more varied with informal layouts. Shophouses were initially introduced from about 1850 onwards during the French colonial period in Vietnam (for history and context see the work of Le, 1999). As a type they have extended across the country into other cities and settlements, and also into a number of other states in the region. Any study of house type and urban form must therefore focus on this style of housing which is the case in this paper.

Shophouses are typically from 3m to 5m in width across their plot and from 10 to 100m in depth (more often 10-20m), and have typically 2 to 5 floors. When originally constructed they would have had space around and within the development compound, including open sides to blocks that would have allowed greater air movement than is now the case. Twelve urban structure types were assigned to shophouses (Downes and Storch, 2014) and these are listed in table 1. A simplified cross-sectional drawing of a typical shophouse is shown in Figure 1.

Table 1. Urban Structure Types for Shophouse Dwellings (source Downes and Storch, 2014)

Type	Shophouse Category	No. of blocks
1	Regular new community	62
2	Regular new	100
3	Regular with narrow street	592
4	Irregular high density	45
5	Irregular with yards	794
6	Shophouse regular and irregular	23
7	Regular with yards	153
8	Irregular clustered	7411
9	Irregular scattered	815
10	Irregular with large gardens	2342
11	Irregular temporary	-
12	Shophouse with industry	22

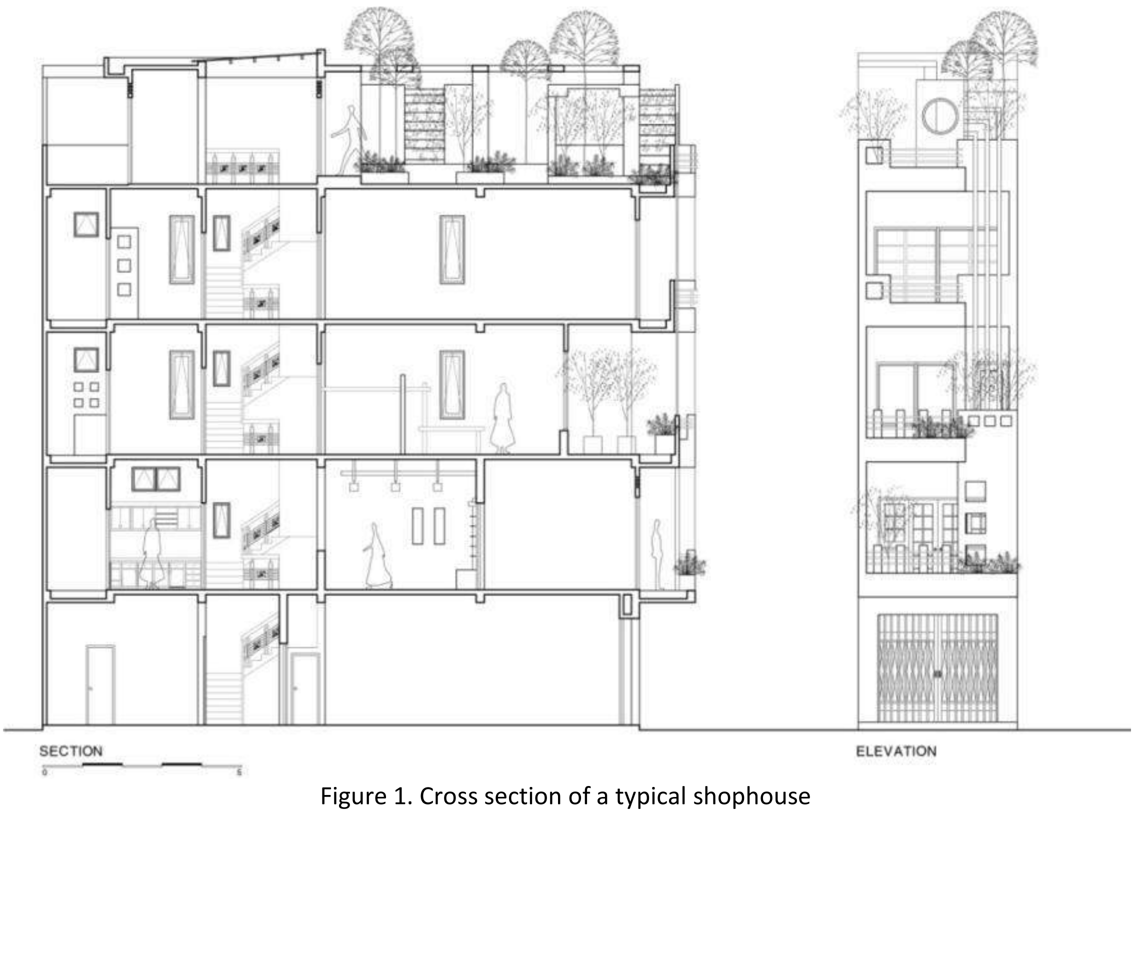

Figure 1. Cross section of a typical shophouse

The type of urban structure plays a part in determining the potential for air movement and this information together with more detailed analysis of predominant sub-types provided the basis for identifying some of the properties to be examined in more detail and which are included later in the paper.

3. Comfort and Health Issues

As already stated above, ambient temperatures in the external climate of HCMC have been rising in recent years and this is further exaggerated by the urban heat island effect. These raised temperatures impact upon internal environments raising the thermal impact up to and beyond the thresholds of discomfort even allowing for a substantial degree of adaptation amongst the local population.

The authors have undertaken measurements in areas of the city adjacent to dwellings for which comfort studies have been carried out, and the data analysed and reported for the 117 sets of records that were acquired. The main results are summarised in Table 2, indicating the high internal and external temperatures and the modest availability of internal air flows for natural cooling.

Table 2. Measured Summer Indoor and Outdoor Conditions HCMC (source: Dang and Pitts, 2018b)

	Indoor				Outdoor			
	Mean	S.D.	Max.	Min.	Mean	S.D.	Max.	Min.
Air temperature (°C)	31.9	1.18	34.6	29.1	32.8	1.74	37.8	29.5
Relative humidity (%)	61.9	7.29	76.9	44.9	59.5	8.30	79.0	41.0
Mean radiant temperature (°C)	32.0	1.35	35.5	29.0				
Operative temperature (°C)	31.9	1.24	34.8	29.1				
Air velocity (ms^{-1})	0.14	0.10	0.55	0.01	0.32	0.22	1.00	0.77

In addition to the challenging indoor and outdoor thermal environments rapid industrialisation in HCMC has resulted in densely populated urban areas that are polluted with a variety of airborne contaminants, including particulate matter (PM10 and PM2.5), sulphur dioxide, nitrogen oxides, volatile organic compounds (VOCs), black carbon, carbon monoxide, and methane (VCAP and CAI-Asia, 2008). Approximately 98% of Vietnam's population is exposed to PM2.5 at levels above guidelines set out by the WHO (2015), with the majority of urban air pollution occurring as a result of traffic, industrial processes, and domestic cooking. An estimated 70% of the air pollution in cities is as a result of vehicle emissions, which are linked to many of the airborne pollutants found in the environment. The increasing economic growth in Vietnam is reflected in the increase in number of vehicles, with, in particular, the number of motorbikes increasing by over 400% between 1996 and 2006 (VCAP and CAI-Asia, 2008).

Air pollution can cause or aggravate a variety of health conditions, including asthma, allergies, bronchitis, and lung cancer. These illnesses linked to air pollution have resulted in economic losses of up to USD$20 million in Hanoi (the largest city in Vietnam) and USD$50 million in HCMC (Labour Health and Environmental Hygiene Institute as reported by Hung, 2010). These diseases are also responsible for a 20% reduction in earned incomes in Hanoi; a study of 2,200 households determining that 73% had had illnesses due to air pollution (Pham, 2007), and it is likely a similar situation exists in HCMC.

Added to the general air pollution, further specific diseases can also increase risks to health, for instance: Legionnaires Disease which thrives in warm moist conditions; Severe Acute Respiratory Syndrome (SARS); and Avian Influenza (commonly referred to as 'Bird

Flu’). These last two diseases have had significant health impacts in many parts of Asia and in Hong Kong led to research or urban ventilation and changes in planning advice and regulation (Ng, 2009).

The range of worsening comfort issues combined with very real health risks means that a better understanding of urban environments, and particularly those within and around dwellings, is an urgent task for HCMC and similar locations.

4. Research methodologies

This paper presents a selection of data and findings that relate to an extended and developing research project with additional detail provided in other publications such as Dang and Pitts (2017). The requirements for appropriate research techniques for HCMC are defined by the different types of information and data needed for suitable analysis. The following subsections identify areas of interest and the methods used to investigate.

4.1. Ambient Environment

There is a need to determine the ambient environmental conditions which exist in different dwelling types, particularly those which by their design and layout, can either contribute to, or alleviate, sensations of discomfort and heat stress. Measurements of temperatures and humidities in dwellings as part of longitudinal and transverse surveys of environmental parameters have been used to identify and clarify experienced environments for dwelling occupants. Occupant reactions in terms of comfort surveys are also important to understand current potential for adaptation and risks.

4.2. Ventilation

In Vietnam air conditioning equipment is available for use in dwellings but this is often used sparingly due to running costs and the limitations of the electrical supply network. As a result natural ventilation and room fans are utilised for significant fractions of time. Measurements of air flow velocities using hot wire probes, has been carried out in short term surveys of 59 properties and also in longer term surveys of a smaller number.

4.3. Dwelling design and use

In order to understand better the combined impacts of comfort and health risks, observations of dwelling design and utilisation by occupants in practice has value. In this case visits were made by a multidisciplinary team to a range of dwelling types and styles.

- Buildings 1 and 2 served as small family accommodation with no formal commercial function: the front of the ground floor being used as an arrival and storage area.
- Buildings 3 and 5 both provided shop-fronts for businesses leading on to the street, though dwelling 3 was much larger than dwelling 5.
- Buildings 4 and 10 were larger family houses; building 4 had limited commercial function whereas building 10 gave almost the whole of the ground floor for retail and associated activities.
- Building 6 was a multi-family dwelling with no real commercial function other than the letting of individual rooms in the rear block. Its main feature was the absence of air conditioning.
- Buildings 9 and 11 were apartments above ground level: building 9 was compact and above a shop, building 11 was a large high floor penthouse apartment.
- Buildings 7 and 8 were hostel accommodation. Building 7 was being converted at the time of the visit and was substantial in size; building 8 was in-use and busy with bar/food service on the ground floor.

4.4. Health issues

At the current stage of the research programme active data collection and monitoring was not possible due to concerns over use of potentially intrusive equipment and collection and storage of biological samples. However during and after the visits to the individual properties mentioned in 4.3 above, observations were recorded and form the basis for future research.

5. Measured environmental conditions

Extensive transverse and longitudinal environmental measurement surveys have been carried out in a number of dwellings in both cool and warm seasons of HCMC. The main findings are reported elsewhere (see for instance Dang and Pitts, 2018a). Therefore in this paper a selection of key concerns are identified.

Data from 59 external measurement points around the city were collected during the warm months of April and May 2017. Average air temperature was 32.6°C and air velocity $0.32ms^{-1}$; peak values were 38°C and $0.9ms^{-1}$. These figures can be compared with the threshold limit for comfort (29.5°C) set by the Ministry of Construction (MOC, 2004) and there is strong evidence that microclimatic conditions in the city will lead to discomfort.

Comparisons of recorded conditions inside dwellings from which Operative Temperature was determined alongside collection of thermal sensation votes by occupants showed neural temperature to be 28.5°C and indicated the upper limit of the normal comfort range as approximately 31.5°C. This is illustrated in Figure 2.

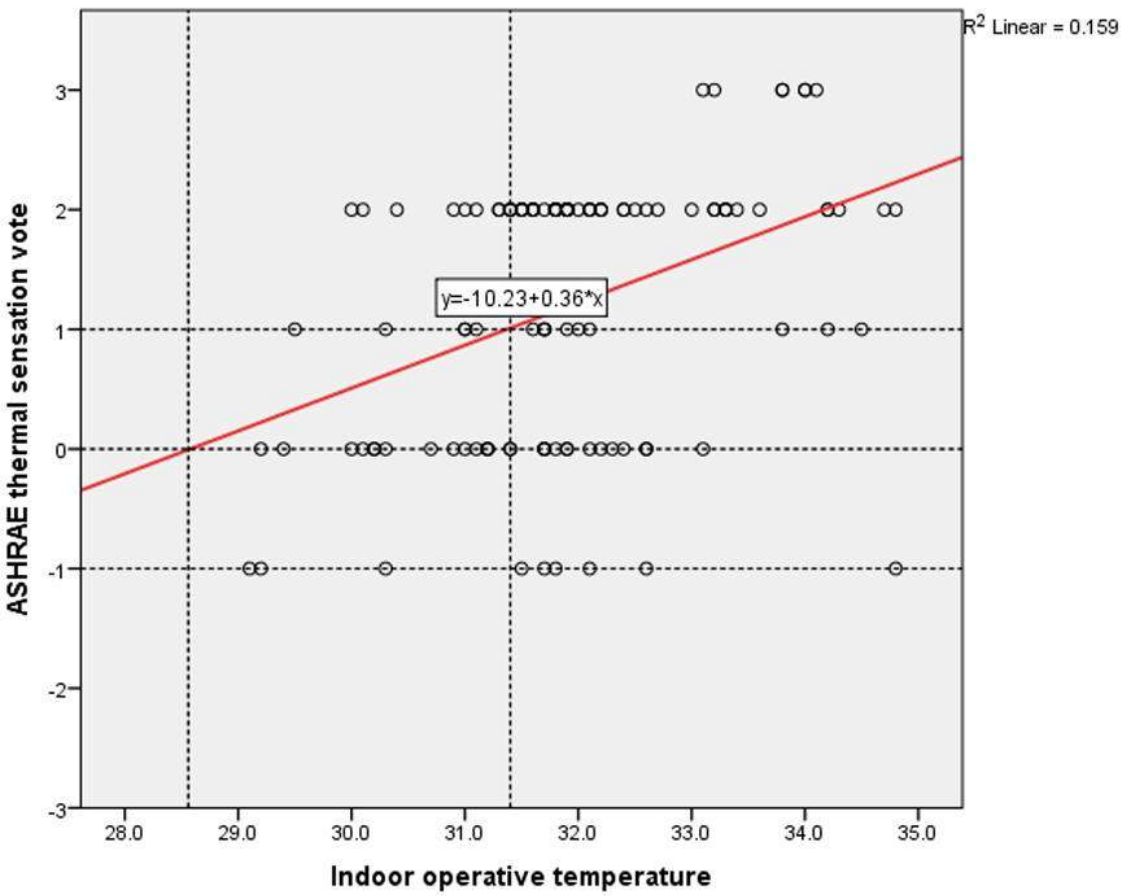

Figure 2. Linear regression of Operative Temperature and Sensation Vote (Dang and Pitts, 2018b)

The conditions measured indicate a substantial level of discomfort despite the apparently high level of toleration for hot conditions; 65% or measured values were above the upper limit of comfort and 95% of respondents requested cooler conditions (Dang and Pitts, 2018b).

6. Ventilation

In Vietnam and in HCMC in particular natural air movement and wind flows have the potential to alleviate heat discomfort. In 2016 and 2017 a wide range of buildings and dwellings were visited to examine how to develop the potential for exploitation of naturally induced air flow. From the initial sample of 59, 16 were chosen for further study, and within that group 4 examples were selected for long term measurements using permanently installed hot wire probes in key locations within those dwellings. The hot wire probes were checked and calibrated before installation and were regularly checked on site and also remotely (as measurements could be collected using the internet). Any unexpected variations in measured values could be checked and equipment replaced if necessary.

The design and layout of several dwellings suggests that any heat generated might not be easily dispersed causing higher temperatures in some rooms, elevating the heat stress risks further. In many of the dwellings there is little separation of the heat and moisture producing activities (such as kitchens and bathrooms) from the rest of the property.

An important influence on internal air circulation is the amount of air flow outside the building. In the summer months of 2017 recorded values varied between 0.1 and $0.9ms^{-1}$; internal air speeds where however rather lower and inconsistent. Investigations were carried out to determine reasons: externally there was some relationship to the urban pattern but internally a number of additional issues were identified. Residents had a tendency to keep external openings closed even when beneficial draughts might be encouraged: this seems to have been associated with a need to keep external air pollution from vehicles and construction activities, as well as intrusive noise, outside of the dwelling.

Other factors influencing internal air flows were the frequent use of hanging drying racks inside the building and in external areas adjacent to ventilation openings. Planting of shrubs and vegetables in close proximity to some of the dwellings whilst providing a more natural and pleasing landscape also reduces the air flow potential in some cases which might otherwise aid air circulation near to the building perimeter.

7. Dwelling observational studies

During the autumn of 2018 an intensive tour was undertaken within HCMC in order to visit and observe multiple dwelling types and their internal conditions. The properties ranged from small family houses, almost hidden at the end of twisting narrow streets, to larger shophouses and also penthouse style apartments. The purpose of the visits was to observe the comparative exemplars of the dwelling types and to consider features that could give rise to better or worse performance from comfort, ventilation and air quality points of view. Whilst it is recognised that such visits are unavoidably subjective, the presence of three different experts and with the potential to discuss the context with the dwelling occupants allowed some valid observations to be made.

A total of 9 individual dwellings were visited within HCMC along with 2 group hostel accommodation buildings. The visiting evaluation team consisted of an architect familiar with sustainable design practices, a specialist in environmental design and comfort research, and a trained microbiologist with expertise in health issues. The key features are noted below. Figures 3-13 show views of each building to provide an overall impression.

- Building 1 – simple layout; limited circulation within dwelling; kitchen adjacent to a toilet at rear of ground floor; limited air circulation mainly single-sided from front; in a dense built-up neighbourhood but along relatively quiet but narrow road/path.
- Building 2 – small end of terrace property; some potential for air flow from side access but mainly single-sided ventilation from front; toilet adjacent to kitchen; limited ventilation in kitchen area; in a dense built-up neighbourhood but along relatively quiet but narrow road/path.
- Building 3 – a true modern shophouse; located in a modern street row; owners' design business operating from ground floor; substantial potential for air flow both front to back and also bottom to top; some animals present; road with modest level of traffic; under airport flight path.
- Building 4 – family house on several floors; each room with good window; wide staircase; adjustments to layout made by owners to facilitate lifestyle; open space to one side allows for some cross- ventilation options; plants being grown on roof; road with some traffic.
- Building 5 – medium size property; front of ground floor used for architect/designer business; area to rear and above has restricted opportunities for ventilation – mainly single sided ventilation and some areas quite deep; used by enlarged family group.
- Building 6 – multiple family residence and with rentable rooms in rear block; complex shape offers many opportunities for natural ventilation; no air conditioning installed – occupants report ability to cope with heat in hot weather; located in dense urban area narrow road with some traffic; depth of house removes occupants from proximity to road.
- Building 7 – currently being converted to an up-market hostel in back-packer area by heritage design company; in dense urban block with another building in front but with wide busy road beyond that; some cross ventilation potential as building is narrow; new design incorporates a number of environmental design features including water.
- Building 8 – new good quality hostel close to public market; multiple opportunities for air flow through central areas open to sky; entrance opens to busy street at front; water used as a feature within property public areas.
- Building 9 – upper floor dwelling above restaurant; small volume space efficiently redesigned by occupant/architect; many interconnected spaces; uses mainly wood finishes; some areas difficult for air circulation (mainly single sided); situated alongside a busy main road.
- Building 10 – substantial building within dense urban area; dwelling has entrance at back of retail/food store; extends upwards over 5/6 floors; front opens to busy main road but quieter towards rear; some opportunities for cross ventilation and also ventilation through substantial stairwell.
- Building 11 – this dwelling is an apartment towards the top of a multi-storey block (apartment blocks are still a modest part of the overall market share); this penthouse style has opportunities for good single-side ventilation as well as cross-ventilation; the proximity to fields/marshy ground means insects can be a problem; located on busy road but raised well above it.

Figure 3: Building 1 view of entrance

Figure 4: Building 2 view of entrance

Figure 5: Building 3 view of Shophouse front

Figure 6: Building 4 view of front façade

Figure 7: Building 5 interior view looking to street

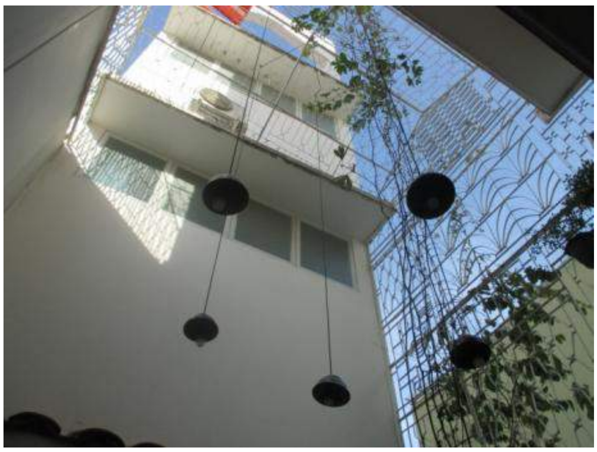

Figure 8: Building 6 view through gap in structure

Figure 9: Building 7 view from adjacent building

Figure 10: Building 8 view of model

Figure 11: Building 9 internal view of workspace

Figure 12: Building 8 view front facade

Figure 12: Building 11 view from balcony of apartment block

8. Health risk factors

With regard to health issues, the key points observed from the visits are noted below:

The temperatures and humidities in HCMC are in the ideal range to permit growth and transmission of bacteria. In areas with cramped conditions and houses situated close together, the transmission of disease is increased. Figures 13 and 14 illustrate the congestion and consequent reduction in ventilation potential in external and internal spaces respectively.

Figure 13: Poorly ventilated external space

Figure 14: Restricted flow paths for internal ventilation

Many of the kitchen areas observed had little or no ventilation; this impacts on the burning process for gas and on the effective dispersion of combustion products. It is likely in some of the more limited kitchen areas towards the back of dwellings that pollution from cooking could have health impacts. Bathrooms were also often next to the kitchen with inadequate separation of the two areas. Figure 15 shows the ground floor plan of building 2 and illustrates how tightly different activities are packed into this small house. Figure 16 shows the tight design and proximity of kitchen and bathroom in building 1.

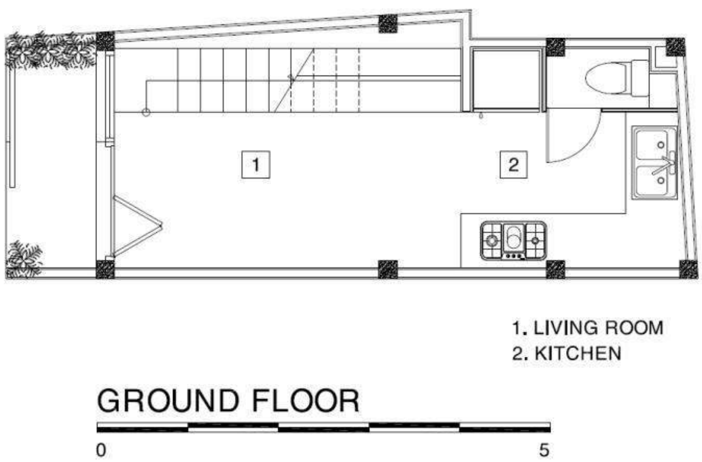

Figure 15: Limited space and proximity of functions on ground floor of building 2.

Smoking often take place indoors and with external doors closed restricting dilution of harmful airborne material. The closure of doors is attributed to the use of smoking for relaxation which is interrupted by external noise and pollution ingress

Chickens were kept in close proximity to humans, living on balconies or in gardens, increasing the risk of diseases from these sources.

Water was often used as an architectural feature (see figure 17); however this water if untreated could be a reservoir for disease vectors such as mosquitoes. The use of fountains also creates aerosols that may contribute to the spread of disease.

Figure 16: Proximity of functions in building 1.

Figure 17: Water used as a design feature in building 8.

9. Discussion

The evidence presented above draws together a number of different fields of interest in relation to extreme environments. In different parts of the world what might be considered 'extreme' varies; in terms of temperatures the highest risk is associated with regions already predicted to reach or exceed the limits of human existence in natural outdoor environments (Pitts, 2015), whilst the concerns might be different elsewhere.

The combination of high temperature and high humidities is perhaps a more pressing issue which is beginning to have impacts now. In these circumstances, cities such as HCMC are at the forefront of concern as the outlook embodies not just high heat stress from temperature and humidity but also additional threats posed by other health issues associated with pollution and diseases.

Whilst in HCMC the occupants of buildings displayed good tolerance for warm conditions currently experienced (see figure 2), even here there was substantial reporting of discomfort. It is in the extension of such conditions and taking account of potential future global temperature increases that most research attention should now be focused; this establishes a need even whilst there is some ability to adapt to comfort at the extremes, it is not a situation that should be accepted.

Research of the broader spectrum of issues is appropriate taking account of: building design; climate at macro and micro levels; urban design and building design; thermal discomfort evaluation and prediction; opportunities for encouragement of natural ventilation; knowledge of air pollution and environmental health risks and the means to mitigate them; and of course occupant expectations and understandings.

A research programme is already underway led by the authors to investigate some of the issues in more detail, but this will need further extension and to draw together multiple stakeholders and knowledge bases.

In relation to HCMC although buildings can be classified into broad typological groups, it seems that even within those groups there are substantial variations between examples as shown from the gathered evidence from the dwelling visits process. To address these concerns requires some holistic thinking and approaches to research and also to the use of the outputs of the research. These are discussed in the following section.

10. Challenges and future research development

This section is written in order to focus on the issues of 'Comfort at the Extremes' and the first important consideration is the need to take a broader view than simply comfort or discomfort, or indeed thermal stress. Heat stress is often more difficult to deal with than cold stress because it can be associated with additional environmental issues as evidenced in this paper. The following list identifies the research challenges going forward.

- Research into understanding air flow at urban/city level is needed with results produced in a format that can be adapted for use by building designers, urban planners and other stakeholders.
- A further level of building typological research is needed in order to evolve and build upon the databases currently available. This might well be incorporated into 3d modelling of the urban environment in HCMC with superimposed levels of information.
- A better understanding of the reactions of local inhabitants to more extreme conditions is needed; this should incorporate a process to more fully appreciate adaptation issues within the general public.
- A systematic and coordinated programme is needed to understand better the range of health problems associated with increasing temperature and other climate change issues (such as rising sea levels and increased precipitation).
- Information on building ventilation performance in a variety of circumstances differentiated by type of building and also by surroundings is needed. This may well require coordination between real world and computer simulated analysis tools.
- An assessment tool is required which can incorporate not just temperature predictions for typical building configurations, but knowledge of health risks from ambient issues and possible sources of disease and pollution. This might use as start points some of the public domain simulation and analysis programmes currently available.
- Design tools for use by urban and building designers are required; these could range from simplified rule-of-thumb approaches to moderate complexity.
- Information for dwelling occupants ought to be more readily available to guide when building redevelopment/renovation is being considered.
- Research efforts might reasonable be coordinated with other regions and countries in which thermal stress, ventilation and air quality issues similar to HCMC are experienced.
- Research should be led by Government at various levels as both the most important organisations able to enact regulation and as the most important organisations that can utilise the outcomes.

The significance of research in this area for comfort and well-being is enormous. Heat stresses combined with other health problems such as infectious diseases poses a large future risk which is made worse as ambient conditions approach those most favourable to pathogenic microbial growth. Environments such as exist in many humid tropical cities and in which much urban development is taking place also increase densities of living and further promote potential for infection. Issues identified here form the basis for further research and analysis of health in context which is very much needed.

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Austrian Pavillon in EXPO 2020, Dubai: A New Vernacular?

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Abstract:

Austria's pavilion at EXPO 2020, Dubai is designed as a low-tech and eco-friendly building. The building offers comfortable indoor conditions with minimum use of mechanical climate control. The concept of natural air conditioning applies principles of traditional Arabic architecture and interprets them in a contemporary way; *Night ventilation* together with thermal mass, with the truncated cones serving as wind-towers, utilizing stack effect ventilation during the nights; *Subsoil cooling:* During the day, outdoor air for hygienic air quality is supplied via air ducts beneath the concrete floor, taken from the shady courtyard; *Comfort ventilation:* The outdoor air brought in via inlet vents and deliberately designed "Breeze Towers" which deliberately create a constant air movement within the pavilion in the range of up to 1 m/s; *Shading:* The queuing-zone in front of the building as well as the public courtyard will be shaded from plants and equipped with mist nozzles, offering adiabatic cooling together with the shadows from the plants; *Local and temporal active cooling* is supplied by means of a highly efficient solar-assisted chiller. The chiller supplies specialised "Breeze Towers", which combine the performance of displacement ventilation fan coils with the benefits of comfort ventilation and a *grid connected PV-system* delivers green electricity, not at least supporting the chiller.

Keywords: Vernacular design, bioclimatic design, climate design, energy sufficiency

1 Introduction: Building with a Mission

Within an open architectural competition, the team around *querkraft architects*, Vienna, succeeded with their proposal of the Austrian pavilion in EXPO 2020, Dubai. Their building consists of 47 truncated cones of heights up to 15 m. The pavilion will host the Austrian exhibition during the EXPO, from Oct 2020 until April 2021. The mission of the building is to demonstrate true sustainability, including beauty, simplicity, and last but not least a respectful use of resources. It is also an example of a building conceived to be *energy sufficient* rather than just energy efficient. This means that it is designed to make the most of the environmental energy that can be exploited directly by the using the physics of the building itself in its unique context and site. To achieve this it builds on a full dialogue between its location, first class passive design of form details and materials to respond, as much as possible, to the energy needs within the building, typically required to provide comfort and a sense of wellbeing for its occupants. The design builds on the traditional tenets of the Passive and Low Energy Architecture movement and goes beyond to create a structure resilient not only in the setting of the extreme climate of the Gulf region but also one developed to cope with the increasingly extreme weather events resulting from the warming climate there (Santos et al., 2018).

Figure 1: Rendering of the pavilion at competition state. credits: querkraft

2 Traditional indoor comfort engineering, newly interpreted

Together with their climate-engineering team, IPJ Ingenieurbüro P. Jung, Vienna, the architects developed a building, which offers comfortable indoor conditions with a minimum use of mechanical climate control and a minimum of carbon emissions. The engineering team built their design upon many years of experience in low-tech comfort consultancy, not at least tested in hot countries like Israel, Jordan, Greece and others.

The pavilion relies on mainly natural and passive cooling strategies, supported only by local and temporal active solar cooling.

The concept of natural air conditioning applies principles of traditional Arabic architecture and interprets them in a contemporary way, tested and optimized by the means of dynamic multi-zonal building energy modelling.

a. The first mean of passive cooling is night ventilation together with thermal mass: During the nights, the towers serve as wind-towers, utilizing stack effect ventilation during the nights, extracting warm air from the pavilion and effectively cooling down the thermal mass of the building. Thermal mass, precooled by night ventilation, during the days serves as a mean of regenerative heat exchange and forms an effective heat sink.

b. The second mean of passive cooling is subsoil cooling: During the day, outdoor air for hygienic air quality is supplied via air ducts beneath the concrete floor, taken from the shady courtyard. By these passive means only, supply temperature will be reduced by 2 to 3 K against outside temperature.

c. The third mean of passive cooling is comfort ventilation: The outdoor air brought in via inlet vents and deliberately designed “Breeze Towers” which deliberately create a constant air movement within the pavilion in the range of up to 1 m/s. This air movement improves conductive and evaporative heat extraction from the body and thus lowers the sensed temperature by another 3 K.

d. A fourth passive cooling measure is taken towards outside comfort: The queuing-zone in front of the building as well as the public courtyard will be shaded from plants and equipped with mist nozzles, offering adiabatic cooling together with the shadows from the plants.

e. Finally, reacting to the specifically high internal loads within the pavilion, local and temporal active cooling is supplied by means of a highly efficient solar-assisted chiller. The chiller supplies deliberately designed “Breeze Towers”, which combine the performance of displacement ventilation fan coils with the benefits of comfort ventilation at elevated air-movement.

f. A grid connected PV-system delivers green electricity, not at least supporting the chiller, which is controlled in a way to maximize the on-site use of PV-production.

3 Outdoor Climate

Dubai is located within the BWh climate zone, according to Koeppen-Geiger classification, which is the hot desert climate. Still, westerly wind from the Gulf cause elevated levels of humidity. Since the EXPO takes place from mid of October to mid of April, only the climate of this part of the year is relevant to the bioclimatic design of the building.

Our comfort calculations are based on Dubai hourly climate data of one full reference year, derived from the international climate database METEONORM. Climate data include temperature, humidity, radiation, cloud cover, wind and precipitation.

The following charts show exemplary characteristics of climate data over the sequence of one year. The opening period of the EXPO 2020 is indicated within the charts.

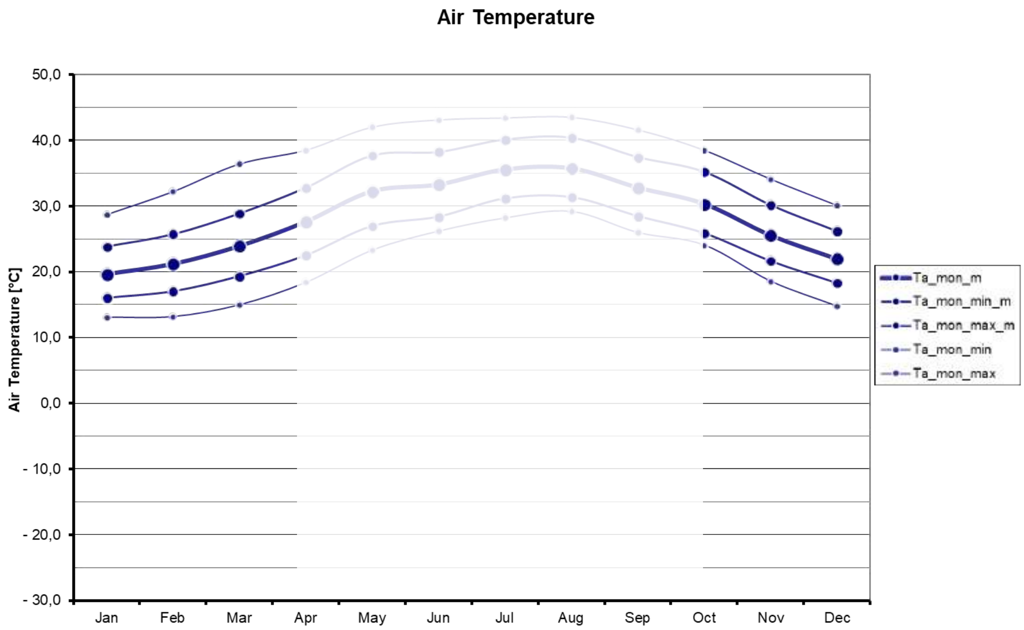

Figure 2: Monthly temperature at Dubai, from METEONORM database, credits: IPJ

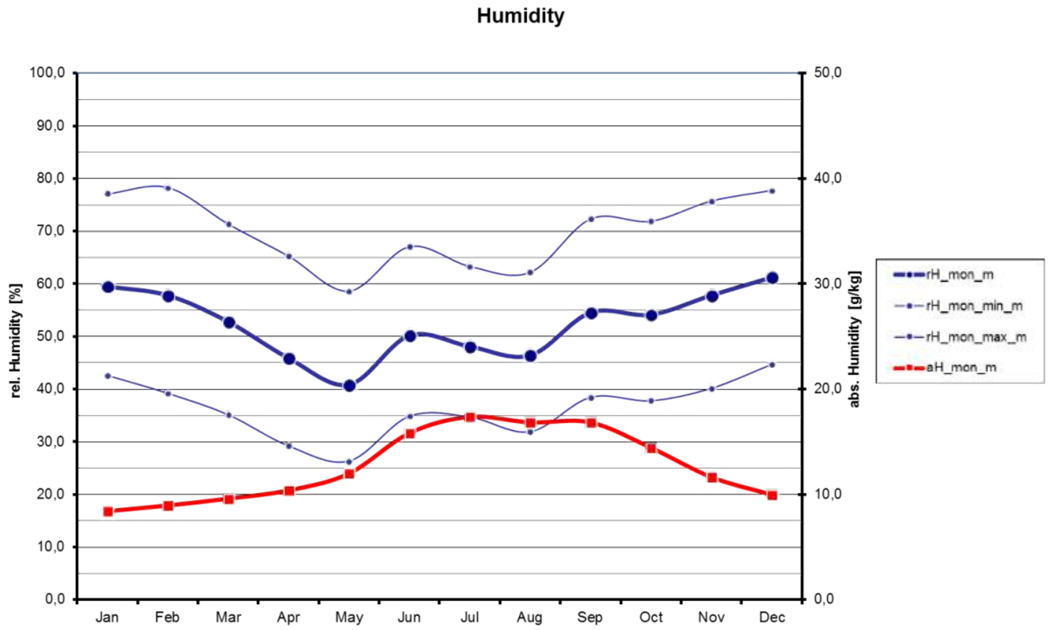

Figure 3: Monthly humidity at Dubai, from METEONORM database, credits: IPJ

4 Comfort Goals

Originally, the EXPO requires strict general comfort limits according to ASHRAE 55 (2010) for AC mode. We claimed the building to be a hybrid one, which was accepted. Still, we promised keeping the ASHRAE 55 comfort standards. Mean monthly outdoor temperatures during EXPO 2020 range from 21°C to 28°C. Thus, comfortable operative temperature during EXPO 2020, according to adaptive comfort model, range from 22°C to 29°C. This does not include the effect of elevated air speed. If elevated air speed is applied, the comfort range may be extended by another 3 K. We guarantee keeping these comfort limits without exception during full occupation of the pavilion.

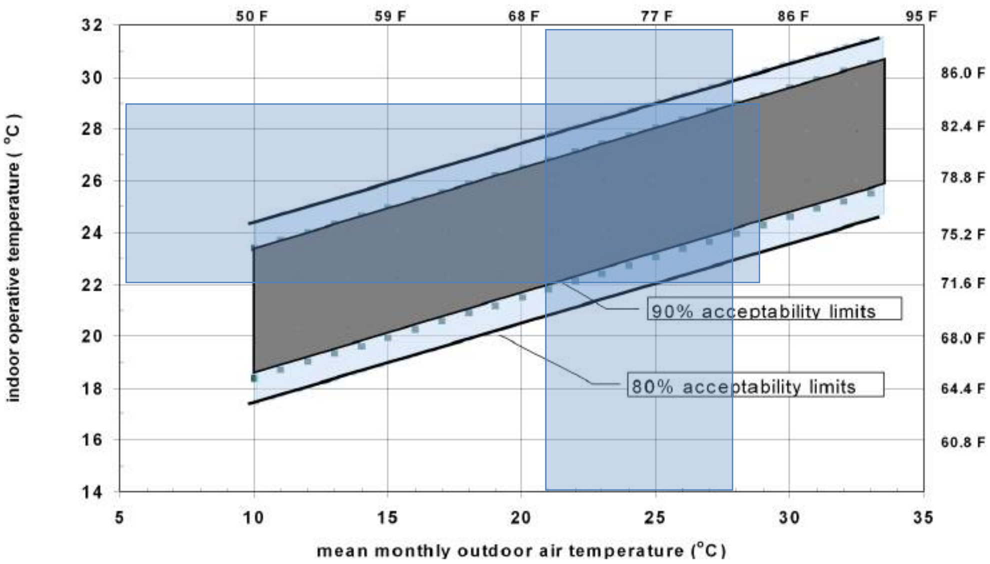

Figure 4: adaptive comfort limits at Dubai, according to ASHRAE 55 (2010), credits: IPJ

In rooms such as the café, the office and VIP zone, during periods of additional technical cooling, the building will be perceived as an AC building. Again, we applied ASHRAE 55 (2010): The summer comfort zone allows operative temperature in the range of 27°C (for met 1.1 and clo 0,5), but may be extended up to 30°C, if elevated air speed is applied. Comfort design of the Austrian pavilion will keep these general comfort limits with only very view exceptions, lower than 50 hours during the full EXPO period, as shown in figure 5.

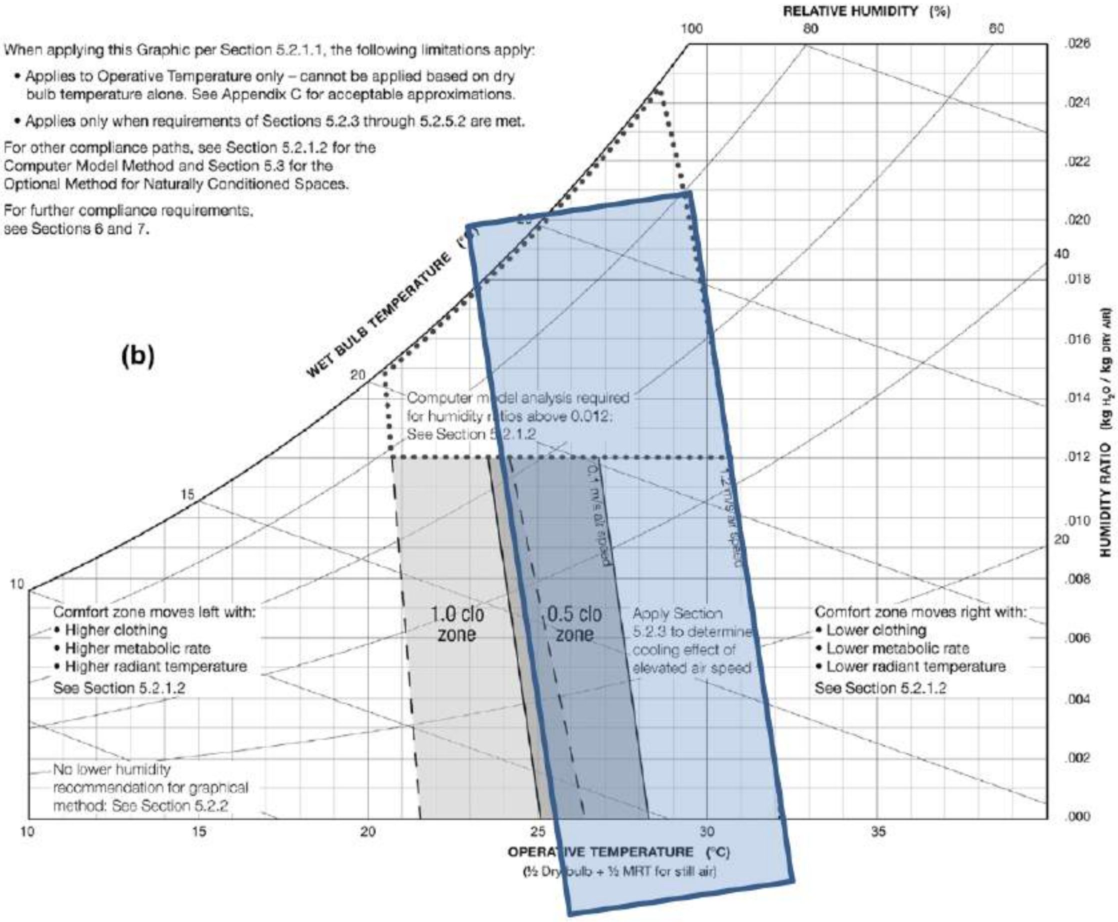

Figure 5: general comfort limits, according to ASHRAE 55 (2010), credits: IPJ

5 Thermally Relevant Construction Parameters

In accordance with the passive cooling design, the building envelope is optimised towards diurnal thermal mass activation. Considering the elevated indoor air temperature, the static U-value is no more the crucial key-figure as regards energy demand and indoor comfort, as it would be in AC-controlled buildings.

Our calculations, based on dynamic Building Energy Modelling, prove that lowering the U-value of the building envelope would have no significant positive effect on the energy demand and the indoor comfort. The Table 1 shows a summary of both the construction type and U-value of the building shell.

Type	Construction	U-value W/m² K	g-value	comment
Walls	15cm prefab concrete 5cm interior clay plaster	3.5		high exterior reflectance r =0.7 (white coloured)
Floor	5cm cement screed 15cm gravel 30cm reinforced concrete	1.72		
Roof	15cm prefab concrete 5cm interior clay plaster	3.92		high exterior reflectance r =0.7 (white coloured)
Glass wall	Laminated safety glass	5.5	76%	
Rooflights	PVC skylights	4	78%	

Table 1: Building constructions, credits: IPJ

6 Usage Assumptions

The indoor climate building design is based on comprehensive dynamic heat flow calculations. In this chapter, we describe the usage assumptions and bordering conditions, which form the basis of our calculations of comfort and energy demand.

6.1 People

Occupancy: We assume the Austrian pavilion to be crowded by visitors. In the exhibition hall, we design for a maximum number of 250 visitors. In the café, we design for another 100 guests. We assume operating hours from 8 am to 10 pm.

We developed characteristic occupancy schedules, relative to the absolute visitor-maximum. The schedules are derived from visitor-analyses of the EXPO 2017 in Astana, Kazakhstan ac-cording to Google Maps and adapted to Muslim weekends (Friday-Saturday).

In our comfort calculations, we apply the occupancy schedules to the zones of exhibition, café, lab, VIP and service. In the office, we assume a constant occupancy of 10 people, from 8 am to 10 pm. The following charts show those occupancy schedules, one for Mon-Wed, one for Thu, one for Fri, one for Sat-Sun.

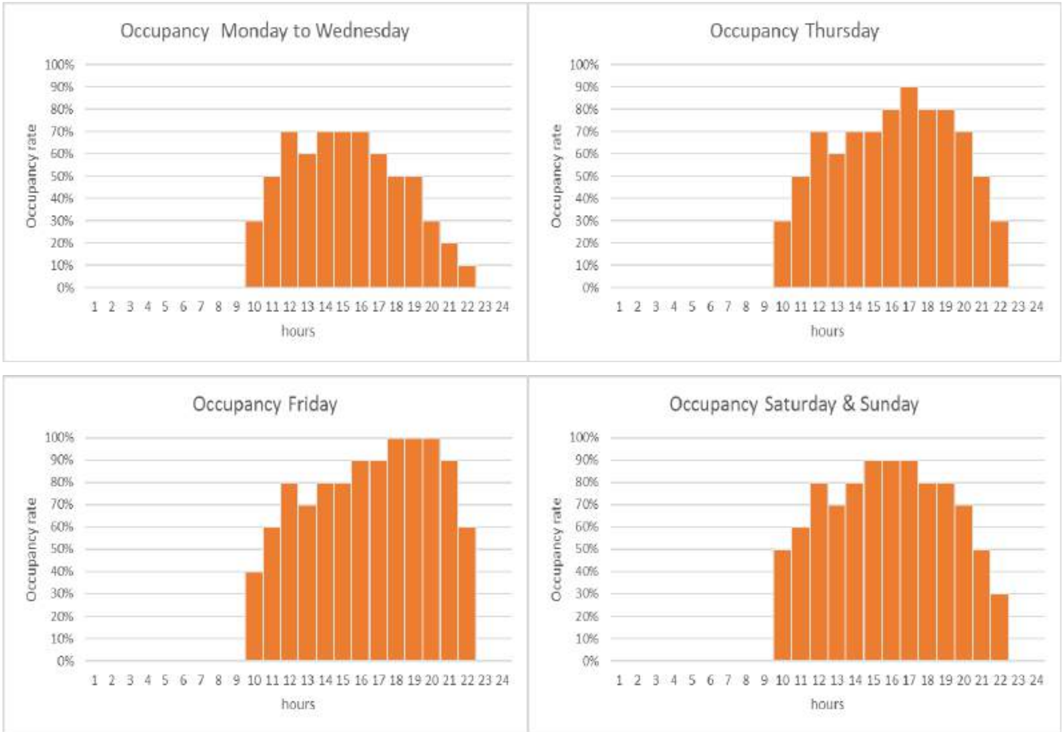

Figure 6: Occupancy schedules, credits: IPJ

Heat gains: Sensible heat gains from people depend from their level of activity and from the indoor air temperature. In our calculations we consider people in the exhibition and the kitchen area with an activity level of 1.3 met (W_{sen} 64 W, W_{lat} 83 W), while in the lab, office, VIP and café areas we consider people with an activity level of 1.2 met (Wsen 60 W, Wlat 65 W). Note: 1.2 met equals sedentary work, according to the internationals "comfort standard" ISO 7730.

For the purpose of comfort calculation, we relate the heat gains of people to the floor area of the specific zone. The Table 2 shows the heat gains from people, specifically for the different zones, related to the floor area, and classified in sensible and latent heat gains.

Space	Number of people	Sensible load (W/m²)	Latent load (W/m²)
Exhibition	250	30	38
Cafe	100	39	43
Lab	20	13	14
Office	10	10	6
VIP	50	32	35
Service	15	15	20

Table 2: Occupancy schedules, credits: IPJ

6.2 Lighting and Equipment

We model internal gains from lighting with 5 W/m² from 8 am to 10 pm. We model equipment loads with 2.5 W/m² for the lab, office and VIP areas, again from 8 am to 10 pm. In the kitchen area we model another 15 W/m², again from 8 am to 10 pm.

7 Detailed Design Solutions

7.1 Night Ventilation

Night ventilation is applied to the main exhibition and to the café. During the nights, the covers of the higher cones (13m and 15m) will open automatically, what forms air outlets. At the same time, openable strip curtains provide air inlets. The stack effect drives significant airflow. Our calculations by dynamic Building Energy Modelling prove induced air exchange rates in the range of 10 air changes per hour, still conservatively calculating only stack effect without wind enhancement. From calculation results, we recommend to operate night ventilation from 6 pm to 8 am. BMS should enable to alter the schedule for night ventilation easily. An emergency shutdown of night ventilation protects the building in cases of sand storms. We recommend orienting the openable covers alternating facing and averting the prevailing wind direction, thus serving as both wind scoops and wind towers. Night ventilation cools down the building's thermal mass, providing a significant passive cooling effect during the day.

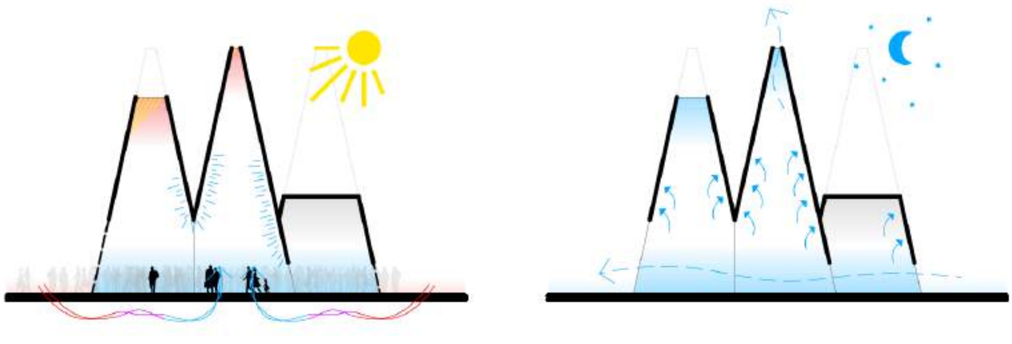

Figure 7: Subsoil cooling and Night flush ventilation, credits: querkraft

7.2 Subsoil Cooling

Supply air is guided through a grid of subsoil concrete ducts, forming a geothermal collector, utilizing the extended thermal mass of the soil beneath the pavilion's foundation plate, with the exception of the courtyard. From external studies, we assumed the undisturbed soil temperature with 29.5°C at a depth of 2 m below surface. Note: The subsoil heat exchanger performs as a diurnal heat storage. Thus, its temperature is much more dominated by the day-night-swing of the outdoor temperature than it is by the undisturbed soil temperature. Subsoil cooling together with night ventilation already reaches the comfort goals in six out of seven months of the EXPO period. Additional technical cooling will be needed only for the first and for the last two weeks of the EXPO. See chapter 8 for calculation results.

7.3 Mechanical Ventilation

During the day, the supply of fresh air will be secured by the central Air Handling Unit. The Supply Air (SUP) inlets will be designed as floor inlets, evenly distributed in the rooms.

Preliminary flow rate design is based on a hygienic specific Outdoor Air (ODA) demand of 35 $m^3/(pers.h)$. It will be detailed in the next design step. At this design stage, the full airflow rate is modelled from 8 am to 10 pm. In the next design step, we will test the effect of part load operation of the mechanical ventilation, linked to the occupancy schedule.

Within the exhibition hall and the café the air inlets will specifically be designed to create a constant air movement, using the effect of offsetting elevated air temperatures by elevated air speed, according to ASHRAE 55 (2010), chapter 5.2. See Figure 5 in this report.

Space	Volumetric flow rate (m^3/h)
Exhibition	6,250
Cafe	3,700
Lab	1,750
Office	350
VIP	1,450
Service	1,150
Total	**14,650**

Table 3: Occupancy schedules, credits: IPJ

7.4 Solar assisted Cooling via Breeze Towers

As a temporary supplement to the passive cooling, active cooling is provided from a central chiller. Building Energy Modelling proofs that the need for technical cooling will be limited to few weeks in Oct.-Nov. and Mar.-Apr.

A grid-connected PV-system on the top of selected cones produces the electricity consumed by the chiller. Low-tech local cooling with circulating air ensures the necessary comfort when this is not provided solely by the passive measures. This is realized with strategically placed breeze towers. Breeze towers are cone-shaped components, supplied with an integrated fan for circulating air, which is cooled with an integrated cooling coil by up to 6 K. Utilising the induction ventilation principle, i.e. the ability to entrain the room air, they comprise groups of small holes on their surface resulting in an induction of room air around them, assuring comfort.

8 Comfort Calculation Results

The following figures present preliminary results of the comfort calculations of the exhibition hall, derived from dynamic building simulation, using the BEM software tool of *Tas* (Thermal Analysis Systems) by EDSL (Environmental Design Solutions Ltd.).

8.1 Comfort with Passive Cooling Only

In free running mode, with only utilizing passive cooling from night ventilation and subsoil cooling, the comfort target of max. 30°C operative temperature together with elevated air speed will be met during May to October, but will be failed by up to 4 K during April and November. Figure 8 illustrates this.

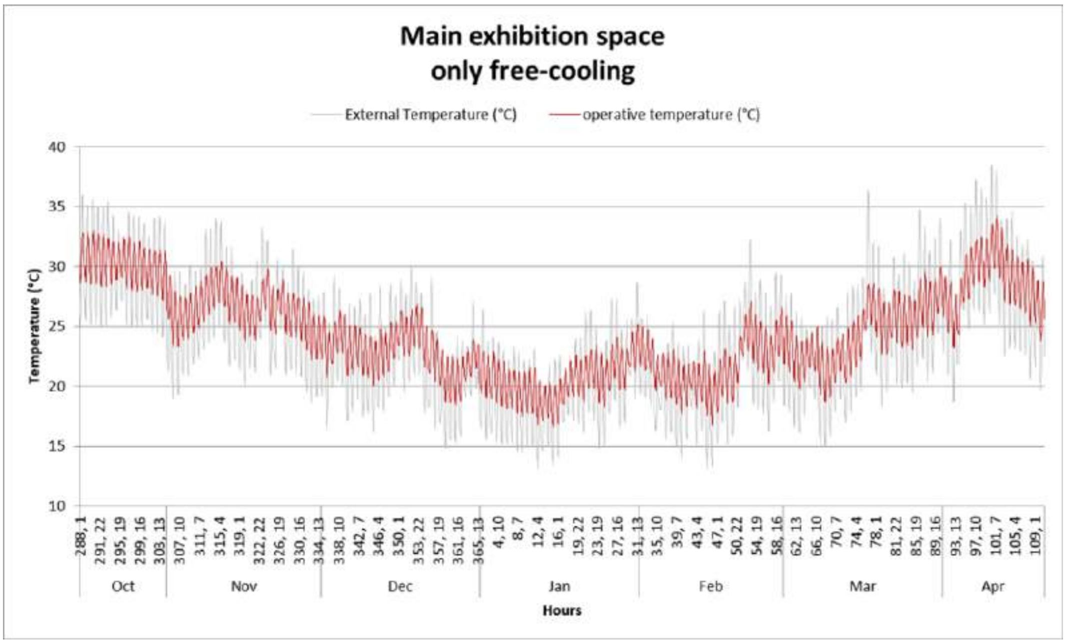

Figure 8: Indoor operative temperature in the exhibition hall with passive cooling only. credits: IPJ

8.2 Comfort with Passive Cooling plus Solar Assisted Active Cooling

Figure 9 shows the combined effect of passive cooling plus Active Cooling via Breeze Towers. In our model, the cooling capacity to the exhibition hall of 530 m² net floor area is limited to 20 kW, equalling 40 W/m². The SUP flow rate within the exhibition hall is modelled with 6 250 m³/h.

Still, in some days in April and November, the operative temperature (red line) exceeds the acceptable limit of 30°C. Note: 30°C is acceptable according to ASHRAE 55 (2010) if elevated air speed is used to offset the elevated indoor resultant temperature. This happens rarely and it happens only on days with very high outdoor temperatures.

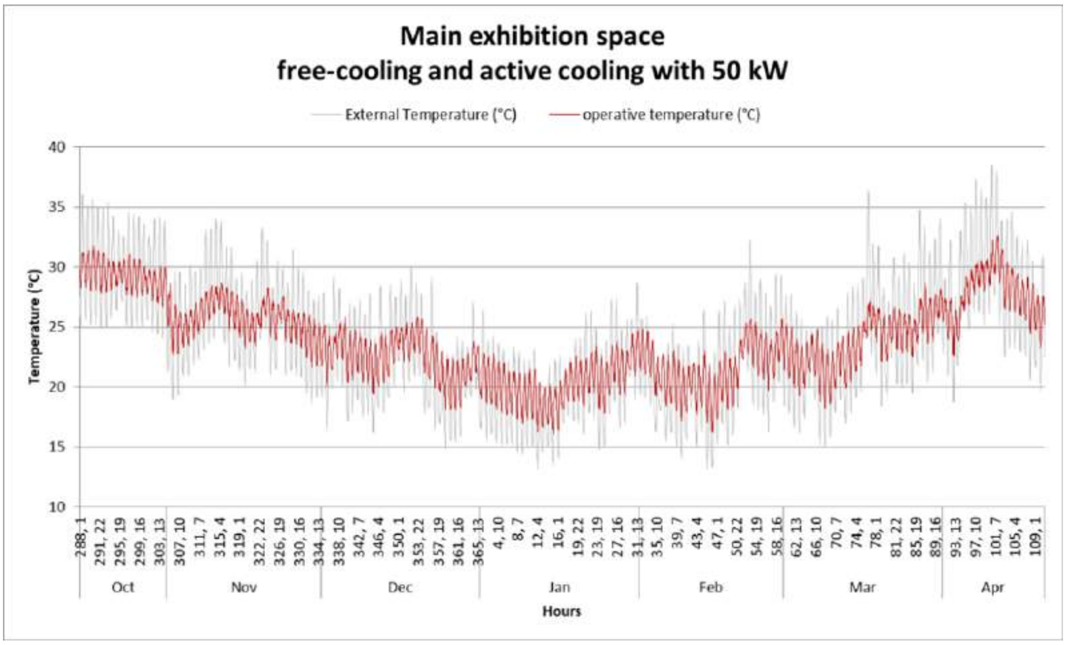

Figure 9: Indoor operative temperature in exhibition with passive cooling plus technical cooling

9 Conclusions

The Austrian Pavilion at EXPO 2020, Dubai, has been designed as an exemplar of a 'sufficient' building design approach. With its hybrid comfort concept it relies mostly on means of bioclimatic architecture, with only temporal and local active and solar assisted cooling. The design is based upon new interpretations of elements of Arabic building traditions, such as wind towers, wind scoops and qanats.

Comprehensive design studies have been carried out, using multi zonal, dynamic building energy and comfort modelling. Given the opening time of the EXPO, which is from the middle of October to mid of April, the building will offer sufficiently good comfort with a minimum of energy use.

Reference:

Santos, H., P. Samani and E. de Oliveira Fernanded (2018). Energy sufficiency in buildings, a synonym for passive and low energy architecture (PLEA), *Architectural Science Review*, 61-5, pp.292-297. Accessed on 18/03/2019 at: https://www.tandfonline.com/doi/abs/10.1080/00038628.2018.1505332?journalCode=tasr20

American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (2010) ANSI/ASHRAE Standard 55-2010, Thermal Environmental Conditions for Human Occupancy

Extreme Design: Lessons from Antarctica

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Abstract:

The warming global climate is triggering ever more extreme weather events with records being broken year on year for flooding, heat and cold waves and wind strengths. Consequently, more buildings are failing in the face of such weather events. In order to build structures that can withstand ever greater climate challenges in which people and populations can 'bounce forwards' to remain safe in them, even in worse weather conditions, we need to upgrade our approach to the climatic design of buildings around the world. A recent project to design a tent to stand for twelve months at Collins Bay, Antarctica, emphasised that it is difficult to approach more 'extreme design' without actually experiencing the extreme conditions they may be required to operate in. This paper outlines what was learnt in that project about designing for extremely cold and windy environments. Lessons learnt were often unanticipated and included new insights into the form, materials, design, construction and siting of the tent at both its design, its fabrication and its building stages. This paper outlines the main steps in that design learning. The project clearly demonstrated the complexity of the issues involved in making sure the tent was optimally designed and built for and in its location, with a view to ensuring it would not fail in local conditions which include minus 30^{0}C during winter and locally recorded winds of up to 200pmh. It provides valuable lessons on the underlying process of how to design more generally for more extreme weather futures.

Keywords: Extreme Design, Antarctic, Global Warming, Resilience, Tent,

1. Introduction

All around us buildings are currently failing in for two main climatic reasons (Roaf, 2018a):

a) They were built in the wrong place (too hot, cold, wet or windy).
b) They are wrongly built there to keep people comfortable or safe in current climates

The growing risks of ignoring climate change are visible all around us but many who know of the risks still build the wrong buildings and in the wrong places, for either a) short term cost/benefit gains or b) they suffer from a fantasy reality gap that 'that' could not happen to 'them'. Who would build in the wrong place? Many Councils in the UK are still allowing building on land that has already flooded. Many 'wrong places' have nice views of a river, ocean or mountains and appear ostensibly to be prime locations until the wind starts blowing, it rains or the ocean invade a coastline. In some countries they are even promoting the making of new land out in the ocean to build on that will inevitably flood in the future in the face of already predicted rising sea levels and increasingly high storm surges (Roaf et al., 2009). The 'resilience' refrain of wanting to shore up systems so that they can 'bounce back' to their former state after catastrophic events appears to ignore the prescient science that warns of very different future climates. when what may hit next time is much worse than what destroyed the system in the first place. Where better to see this than in the stranded luxury homes of

Tuckerton, New Jersey, USA, flooded by Hurricane Sandy in 2012, where today many mansions have been re-built to 'higher standards', still in the wrong place. It is difficult for any local or central authority to deal with the need for 'managed retreat' from areas that will inevitably be even more catastrophically inundated in the future.

a)  b) 

Figure 1a) Flooded homes in Tuckerton, N.J. on 30th October 2012 the day after Hurricane Sandy Hit (US Coast Guard, via AFP/Getty Images); 1b) Some buildings survive better than others. People shelter in the strong house in Buzi, Central Mozambique after Cyclone Idai hit on the 18th March 2019 (Source: AFP).

Weather records around the world are being broken, often on an annual basis. The recent International Panel on Climate Change report (IPCC, 2019) on limiting global temperature rises to 1.5^{0}C claims that adaptation and mitigation actions are already occurring. However, the fact that they are ineffective is highlighted in the recent International Energy Agency report (IEA, 2019) on the latest trends in global energy use and CO_2 emissions states:

> *Driven by higher energy demand in 2018, global energy-related CO2 emissions rose 1.7% to a historic high of 33.1 Gt CO2…. Coal use in power alone surpassed 10 Gt CO2, mostly in Asia. China, India, and the United States accounted for 85% of the net increase in emissions, while emissions declined for Germany, Japan, Mexico, France and the United Kingdom.*

The IPCC report shows clearly the range of climate dangers we face in the built environment including those resulting from more extreme weather events and heat related morbidity and mortality. A critical pathway to a safe future in buildings and cities is to build and refurbish structures and infra-structures that can withstand ever greater climate challenges. Many buildings in which people and populations can 'bounce forwards' (Roaf, 2018a) to remain safe, even in worse weather and climate conditions, will need to upgraded in their performance. In the 1990s the idea of robust and climate-ready design was experimented with, for instance in the Oxford Ecohouse (Roaf et al., 2012) for which a wide range of adaptive features were designed in and have subsequently been proved to work well in the most extreme climate events experienced to date. When the scale of the increasingly extreme climate events was beginning to become apparent authors began to write about how to systematically prepared to keep people safe in buildings and communities during them (Roaf, 2009), and also how to transform markets to ensure that both mitigation and adaptation could occur to make necessary changes happen (Roaf, 2010). However, in the face of ever more extreme climate and weather events and impacts the need for much more 'resilient design' has become increasingly apparent over the past decade (Roaf 2018a).

In order to go well beyond ideas of adaptation and resilience an 'extreme lodge' project has been developed by the authors of this paper to develop designs that can survive intact in extreme weather conditions (www.extremelodge.org), be they hot, cold, wet, dry or windy. To explore how far habitable buildings can be pushed beyond our current design limits, the first Polar Lodge, a traditional yurt (PL1), was built Antarctica in 2016 but failed during an extreme storm just weeks after it was erected (Cantuária et al., 2016 and 2017). In February 2019 a second, innovative yurt tent (PL2) was erected on the same to withstand twelve months extreme cold and windy weather at Collins Bay, Antarctica. This exercise brought home to the team that it is difficult to approach ‘extreme design’ without actually interweaving premeditated and onsite design insights into the continually evolving development, construction and use of the structure in an ongoing ‘evolutionary process’.

This paper provides an overview of the activities and findings resulting from the designing and building the tent and outlines the main steps followed in that process. A range of numerical simulations were made during the design and building of the tent and in the paper useful ways of integrating a disparate range of insolation and wind pressure models are discussed, with a view to improving the location, orientation and physical integrity of the tent on its remote site on King George Island, Antarctica.

The project clearly demonstrated the complexity of the issues involved in making sure the tent was optimally designed and built for, and in, its location, with a view to ensuring it would not fail in local conditions which include minus 30^{0}C during winter and locally recorded winds of up to 200pmh. The process described may provide useful lessons on how to design more generally for more extreme weather futures. This project history is also covered in several referenced publications.

2. The Collin’s Bay Yurt 2019: site and function

PL2 was erected on the same site as PL1 in 2016 for the reasons outlined in Pinelo et al. (2019). The site is located beside a remote research outpost around five nautical miles away from Escudero, the main Chilean research station. PL2 was design as a sleeping and work base for using that facility. This factor influenced the need to design a tent in which one could walk and stand, not one in which researchers simply sleep. The primary aim of the project was to provide a tent in which its occupants can remain thermally safe both during the night and day during the November to March research season at the station. To ensure its structural reliability during those months it was felt that if it could remain intact during the winter months it should be able also to survive in anything the summer season might throw at it.

a) b)


Figure 2. View of the Polar Lodge looking a) South East and b) North East towards the Collins Bay glacier

3. Extreme Design features

During the design, construction and occupation of the tent a number of 'Hot Topics' arose and were hotly debated. these took designers well beyond the everyday concerns of designers of usual structures. Here the idea of extreme design features emerged:

Extreme design features *- included to ensure the integrity of the structure in situ and the safety of its occupants in extreme climate locations and events.*

3.1 Tent Form

The initial decision on the form of the tent was taken back on 2015 when the PL1 team chose to build a Mongolian yurt tent. This round tent form evolved in the extreme cold of the Mongolian winters to which it is suited having a minimum surface area to volume ratio so reducing heat loss through its envelope. Design inspiration, for instance for the secondary guy system – we named the gher net, was sought from the classic texts and illustrations of yurts in many cultures by Peter Alford Andrews (1997 and 1999).

Two clear lessons here were that a) a very good place to start the design of a locally appropriate building is by looking at vernacular architypes in similar climates around the world. A previous study by Meir and Roaf (2005) in a hot dry climate demonstrated the importance of then using simulation to develop and improve an original set of vernacular design features to optimise them for the particular environmental requirement of the new extreme design context. Vernacular designers did not have the benefit of modelling.

Such a modification example is roof slope. PL1, that failed, was made in Portugal and had a high angle to its roof which performed less well in high winds than a lower angled room. Early simulations were performed by Martin Oude at Mode Ltd in Oxford. His background is super-yacht hull design and construction was invaluable and using the ALTAIR Hyperworks simulation tool he was able to iteratively improvement the form to optimise its performance under extremely high wind conditions. He lowered the roof slope to the wind pressure optimum shown in Figure 3a. The structure here was modelled as a bio-composite structure.

a) b)

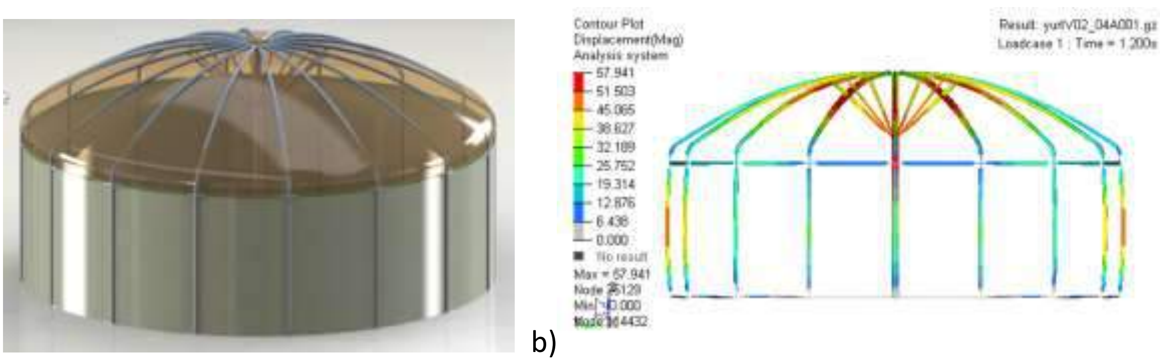

Figure 3. a) Optimised Yurt form with central structural column; b) Model in bio-composite members tested under different windspeeds to explore weak points (Mode ltd.)

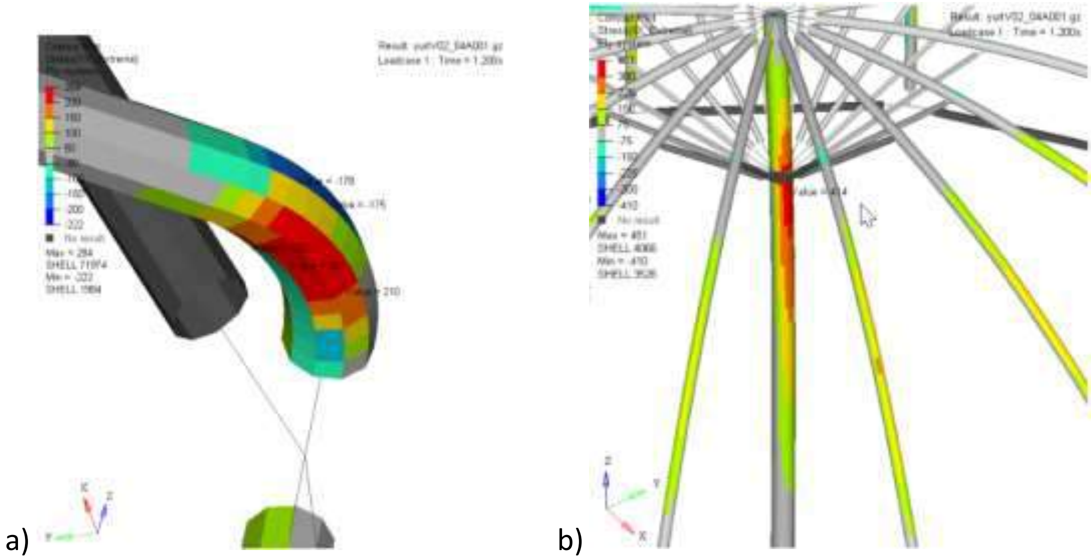

Figure 4. Ply stress details of Carbon Components within the structure a) of the roof member and b) as distributed around the central support column (Modet Ltd.)

Extensive simulations were performed to look at loadings on individual members to identify potential failure points in the bio-composit structure as shown in Figures 3b and 4a and 4b.

In the end the project could not raise the forty three thousand euros that the bio-composite structure would have cost and due to pressure of time we comissioned Henry Dowell at Yurtmaker (www.yurtmaker.co.uk) to make the PL2 structure out of steam bent Ashwood and reducing the roof slope from the PL1 version, lowering the wall trellis height to 1.4m from 1.8m, reducing the diameter to 3.55m, reducing significantly the internal volume to be heated when necessary. A central support system was an innovation from PL1 to PL2. The originally simulated central pole was finally replace in practice by two uprights supporting the crown.

Simulation of the structural performance in high winds continues throughout the project on site (Guedes et al., 2019b) to validate intuative design decisions being felt, interpreted, discussed and made in response to the live conditions experienced on site. But also critical decisions were made based on in-depth deliberations assited by pencil and paper sketches.

In future, the overall tent height may be reduced, moving towards the optimised form, also making attachment of the internal envelope onto the structure possible with out a step ladder. The internal height of the space inside is key for the consevation and harvesting of heat internally. The difference between the occupied, heated temperatures at night were recorded as c. 16^{0}C at sitting height and 19^{0}C at the apex of the tent. Reducing the overall height would keep heat closer to the occupants. Snow loads are key and further work will be done looking structural performance and snow. The fundamental form is obviously absolutely key to both its structural and thermal success or failure (Gueddes et al. 2019a and b).

3.2 Door Orientation

Hotly debated on site the choice of door orientation was key, taking into account wind ingress into the tent; snow ingress and dumping around the tent; maximisation of solar access, water run-off from the hill above; etc. The wind and solar modelling informing most of the discussions but not all. This is a critical decision for the design. As with most PL2 design modelling was a key decision making tool (Pinelo, 2019), but so was the ‘feel’ of the site.

a)  b) 

Figure 5. The erected for of a) PL1 in 2016 and b) PL2 in 2019.

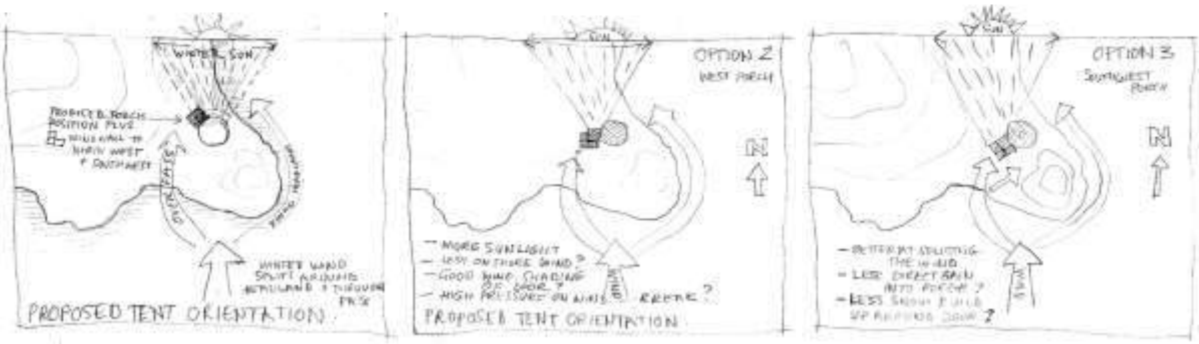

Figure 6. Options for the door location were expanded and explored. Finally, Option 3 was adopted.

3.3 The Envelope

PL1 failed badly in terms of its envelope for a number of reasons: The felt, when wet, became heavy and difficult to dry; the canvass outer envelope was in two pieces, walls and roof that were poorly joined leading to flapping and failure in the wind; the two external envelopes attached to the timber structure led to significant cold bridging visible in the thermal images in figure 7. In light of this he choice was made to use a triple envelope with two leaves outside the structure with a) an external skin to be lightweight, strong to take the guy strain and keep out wind and rain, b) a second external skin to provide thermal insulation and c) an internal a third envelope suspended from the structure to eliminate cold bridging as far as possible[1].

It was necessary to test the proposed materials for PL2 and during August 2018 two sets of tests in the proposed material ORV8 and the envelope structures were field tested in a cold store facility in Hull (Roaf et al. 2019). Important lessons were learnt then on the effectiveness of the double envelope in eliminating cold bridging, the importance of understanding the potentials of harvesting heat from the thermal stratification within the occupied tent and the importance of the floor in the internal temperatures in the tent. Tests showed cold bridging was also almost eliminated by using the envelopes internal and external to the structure. It also highlighted the key role of the floor in shaping the thermal landscape in the tent.

[1] The decision to use a third internal layer was inspired in Roaf by finding how much hotter tea remained when a second tea cosy was added that eliminated the cold bridging in the spout and handle. Does this constitute bio-mimicry?

a) b)

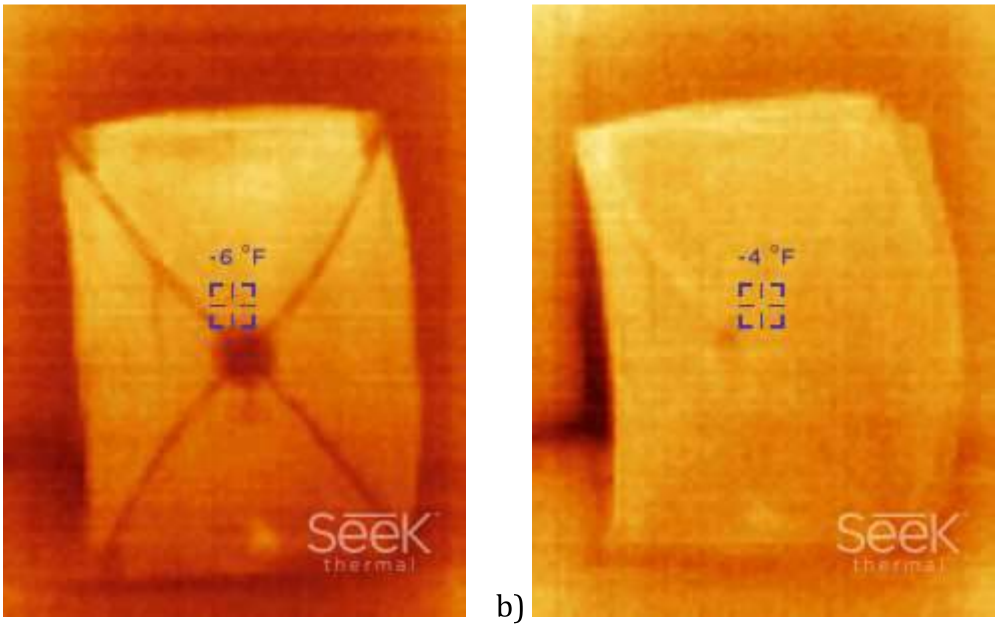

Figure 7 External thermal image of the Sheerspeed ice fishing tent with a) no inner lining showing the cold bridging and b) the suspended inner lining almost eliminating cold bridging

a) b)

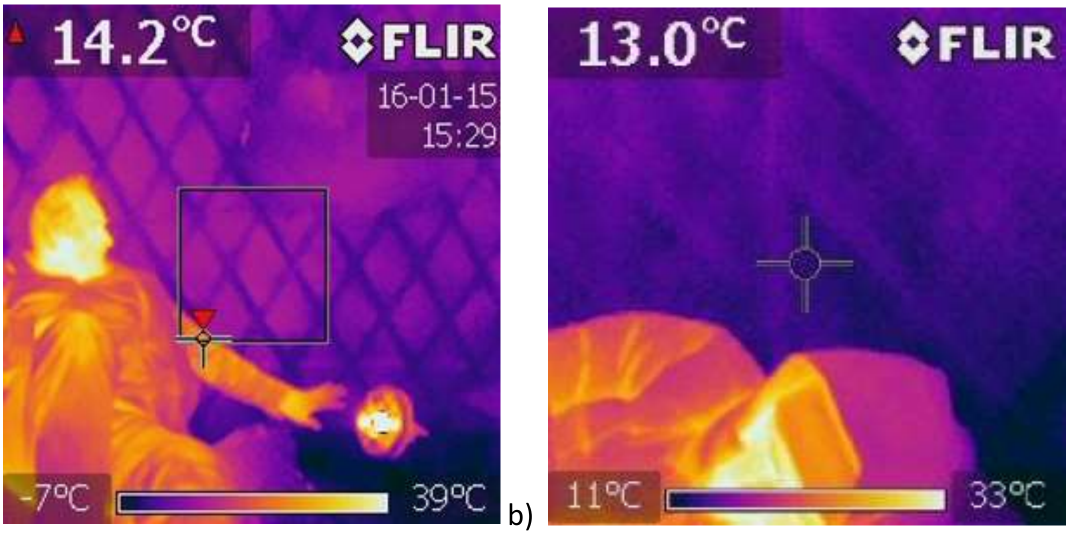

Figure 8. Internal thermal images showing a) 2016 clear cold bridging without internal lining and b) 2019 muted thermal impact of cold bridging inside the tent with inner lining.

At this stage the general design notions were in place but it was essential that they should then be run past the experts we had assembled for the project: Dave Arksey at ORVEC – could we make enough of the fabric for the project? Stainton Reid – could he make the triple envelopes out of the provided materials in time? Fiona Bruce at Northsails – could we get a Dyneema racing sails for the outer envelope in time; Henry Dowell – could he make the specified structure in time and to the design? Each added vital advice and expertise to us.

3.4 The guying strategy for the tent

This is a critical area for further research. For PL2 there was a heated discussion that is captured in the project blog (www.extremelodge.org/home/app) in which early advice from from the tent makers who advised guying very closely to the tent to avoid potentially catastrophic flapping of the guy ropes in the wind was disputed in light of the structural calculations of optimal guy configuration angles for the specified wind loads for the site. Here again we suffer from the limitations of modelling where usual structural calculations may not keep a tent on the ground in 200mph winds. This really is an area for more work. Here again resorting to a wide variety of vernacular solutions can also provide new thinking.

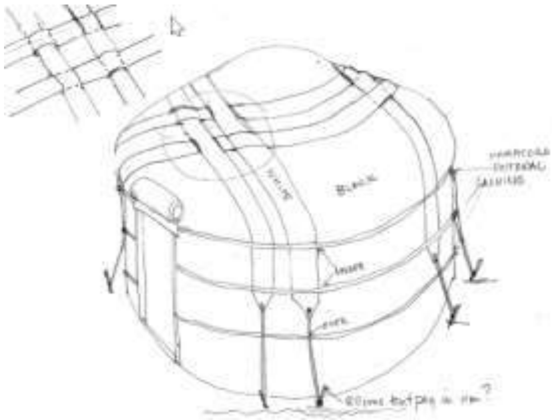

Figure 9 a) Ideas and strapping sketches from Peter Andrews tent book (1997), and b) useful tips on strapping, anchoring and fluing tents from Mongolia (Source: Wouter van Markaken Lichtenbelt).

3.5 The flue design for the tent

A great deal of thought was given to what is the best path for the flue pipe to effectively channel air out of the tent? What is the best material for the flue and how best to re-use the heat from the flue gasses not only in the inner envelope of the tent? Where there is spare energy extra degrees of heat may not matter but where every calorie of heat is precious this is a critical decision to be made. Initial think in the early prototype tent development covered issues like how much of the heat produced internally could be retained within the tent space through intelligent design of the flue. The key issues here concern the thermodynamics of heat movement through height and space, the conductive, conductive, reflective and storage capacities of the flue materials and the integration of any flue system within the context of the tent construction itself. Suffice it to say these discussions have not been resolved for PL2.

3.6 To daylight or not to daylight.

The tent is designed for the most extreme storms in Antarctica and is like an igloo inside a yurt inside a raincoat, and as such it does not let in the light. So discussions ensue as to how best to get natural light into the structure when available: A solar chandelier for use when the sun shines? A plastic window set into one of the doors that may provide a heat collectors in summer if properly oriented? See Pinelo et al., (2019) for the modelling of solar gain with different door orientations. A real question is what is a window for? view? light? Ventilation? connection with God? And the structural and thermal integrity of the tent? Many choices.

3.7 Rock walls: wind shadowing, heat retention, wind shaping?

Many questions on the relationship between the tent and the site climates resulted from the building of the wind wall. What will the thermal function of the wall be adjacent to the tent? Simulations show the wind flows around the structure (Guedes et al. 2019b) but do not answer questions like ‘will the wall be a source of cold or a heat retainer in the winter months’? How will the wind wall shape the wind patterns around the tent? But also what will that do to its thermal context over a day or month or year? Theoretically the Polar Lodge will only be used by researchers in the summer months. In summer when the air temperature during the day rises about night time temperatures will a large rock wall act as a heat source, store or sink? Ultimately is its primary function simply to stop the wind?

4. Conclusions

By taking one simple structure, a tent, and placing it in an extreme climate - Antarctica, the extraordinary complexity of the range and depth of design decisions necessary to create a functionally successful, simple, design solution there have been revealed. Because of the potentially life-saving value of each unit of extra beneficial energy that can be harvested in that extreme climate, and stored, or every iota of damage avoided simply by correctly designing and siting a structure, the fundamental architecture of a shelter there becomes critical to its success or failure, and the life and death of its occupants. The language one uses to describe the structure and its function also become critical. Thermal performance must be measured, for instance both in air temperatures and radiant temperatures that, if ignored, may hide extra degrees of warmth that prove vital to its safe performance. The ultimate measure of the success of this structure lies not necessarily in the comfort of its occupants, but in the degree of physical and thermal protection that it provides in that extreme climate.

This project has highlighted that simulation alone offers a very limited approach to the design and construction of safe structures in extreme climates. This project has highlighted the usefulness of empirical learning and field testing in the development of the necessary insights and understanding to produce safe and comfortable structures at the extremes. Table 1. proposes a series of steps that might usefully be followed during an extreme design project.

1	Source and study and appropriate vernacular archetype
2	Simulate improvements to the structure in the context of the proposed site
3	Explore innovative material solutions building on the advice of product experts
4	Field test structures and materials in an appropriate local test facility
5	Proposed draft structural and envelope design
6	Build and transport final design to site for testing
7	Continually measure conditions on site and refine structure to reflect local conditions
8	Monitor structure over a year to record good and bad points and then improve the design

Table 1. A simple staged process for exploring, developing, testing and building an extreme design.

The above might provide a good process for a student design project as well as a live design. What is important here is that it should be designed and built for an extreme environment, n current or future climates, to push the limits of a designer's understanding to new heights. Once achieved then that designer will never again think in the same way about how to go about the climatic design of any building and hopefully will henceforth build the need and the tools for more resilient design into their everyday working practices.

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Evaluation of psychological and physiological response to transient comfort conditions in Singapore

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Abstract: Microclimate has among further key factors a fundamental influence on how people occupy and use public spaces in dense urban environments. Comfort evaluation of outdoor spaces is essential since they accommodate daily pedestrian traffic and various outdoor activities, also they contribute largely to urban liveability and vitality.
In the wider context of adapting our cities to assure human comfort, the present study investigates individuals´ subjective and physiological responses to sudden and unexpected changes that urban microclimates generate.
The objective is to verify correspondences between physiological and psychological response to varying environmental condition in Singapore´s outdoor spaces, focusing on the transient conditions from outdoor to indoor (conditioned and non-conditioned), shaded and mechanically ventilated spaces.
Significant changes in thermal sensation votes were found when transiting between indoor (air conditioned) and outdoor spaces. Our results showed that exposure to high temperature causes thermal stress. Although the subjects expressed cool sensation when transiting from outdoor into indoor, such heat stress is not relieved by short-term exposure to cooler environment and will amplify the increase in hot sensation once the subjects were back into the outdoor space. In addition, thermal comfort under transient conditions is strongly affected by the sky condition and air temperature.

Keywords: outdoor comfort, physiology, transient comfort, heat stress, walkability.

1. Introduction

Climate is the primary factor that allows the use of public spaces. In particular, microclimate describes the conditions that human beings continuously experience through their senses. Microclimate most drastically affects cities and has a fundamental influence in giving quality to the urban experience. Cities are walkable - healthy, safe and vital - if they give the experience of being comfortable. In fact, particularly citizens are affected by the consequences of discomfort in urban spaces, resulting in a high amount of challenges for the city dwellers and having serious impacts on the everyday life and well-being of hundreds of millions of people around the globe, with different impacts from place to place. In high-density cities like Singapore, pedestrians experience highly variable microclimatic conditions within short distances of daily walk and are frequently exposed to extreme conditions. An initial study confirmed the high variability in thermal comfort conditions and showed that subjective thermal pleasure and sensation also exhibited considerable variations over time (Lau et al., 2017). The choice of walking routes under different urban geometrical settings also was found to have a great influence on thermal comfort. This study aims at setting up a framework to give a more comprehensive answer to determine the dynamic/non-steady-state human thermal comfort model. The experiment relates human thermal sensation and the built environment in tropical high-density urban environment, with the final goal of determining the dynamic thresholds of microclimatic conditions which pedestrians may find comfortable when moving. The study employs multiple sensing techniques across 1) physical urban climates, 2) pedestrian physiological responses to transient urban climatic exposures and 3) pedestrian subjective perception.

1.1. Previous work

The experiment follows up a series of so called *Climatewalks* we have been carrying on in several locations (Munich, Hong-Kong, Rome, Seville, Barcelona and Genova). The *Climatewalk* experiment is designed to measure environmental factors and human thermal behavior in urban spaces by relating individual and subjective responses to environmental conditions adaptation. The objective of the ongoing research, is to provide thermal understanding of the responses of pedestrians when walking in outdoor environment using a georeferenced method for monitoring and mapping of microclimate (Chokhachian et al., 2018) and a longitudinal survey to obtain the thermal responses of pedestrians, for improving the “climatic knowledge” of the urban context. The study is relevant to the topic of urban density and outdoor comfort understanding the mutual impacts and bringing the human factor to the center of attention.

Neutral temperatures are often defined as a standard for outdoor thermal comfort and microclimate that contributes to a more sustainable outdoor environment (Johansson and Emmanuel, 2006; Lin et al., 2011). However, most of these studies emphasize on outdoor comfort as a “static” phenomenon, which is determined by buildings and other urban structures. Transient conditions are experienced when people move between spaces and are situated in spaces with a wide range of environmental conditions (Hensen, 1990) including step changes, temperature drifts, and cyclic variations influence thermal sensation and comfort. The transient nature of thermal comfort has been widely discussed in indoor studies (Fiala et al., 2003; Arens et al., 2006). However, such understandings in outdoor environments are generally lacking. Pedestrians tend to adjust their behavior or walking routes in order to achieve better thermal comfort (Brager and de Dear, 1998). Höppe (2002) discussed the fundamental differences between steady and non-steady state conditions of outdoor thermal comfort. There are currently no internationally accepted non-steady state indices for the assessment of outdoor thermal comfort, implying the difficulty in establishing certain standards for achieving a thermally comfortable environment for pedestrians. In addition, dynamic or non-steady state models are able to provide additional information about temporal courses of thermophysiological parameters such as skin and core temperature, which are more relevant to human thermal sensation (de Dear, 2011).

1.2. Influences of variations in thermal comfort and physiology

Urban environments generate sequences of microclimates that elicit thermal experiences in the pedestrian that are vastly more complex than they would be under steady-state microclimatic exposures. Because of their material diversity and complex morphology, urban areas are characterized by varied microclimates across very small spatial and temporal scales. Furthermore, in public spaces, people are exposed to varying conditions due to their navigation across the spaces. Particularly in the transition from and to conditioned spaces, thermophysiological regulation mechanisms set in to maintain a stable body temperature, and people experience continuous substantial changes in terms of thermal sensation and thermal comfort. In dense urban environments in tropical climates, this circumstance becomes even more explicit because all indoor spaces are fully conditioned and often even public spaces are equipped with devices such as fans, to increase comfort in open spaces. In these locations, urban environments are even more complex from a microclimatic point of view, and providing thermal pleasure is particularly compound matter. As it has been suggested earlier by Cabanac (1992) and Parkinson et al (2012) that a perception of thermal pleasure does predominantly occur in transient states, the study proposes a research design that allows to highlight the relationship between mean skin temperature (Tmeanskin), UTCI and subjective thermal pleasure during environmental transients. Displeasure must occur in order to experience pleasure (Parkinson et al., 2012).

2. Methods

During this specific experiment in Singapore, the previous *Climatewalk* setup has been combined with physiological measures, through precise and continuous skin temperature measurements. The experiment was designed to understand interdependencies of microclimate conditions within varied range of daily activities integrating the topic of adaptation in outdoor spaces. Figure 1 illustrates the workflow of the experiment.

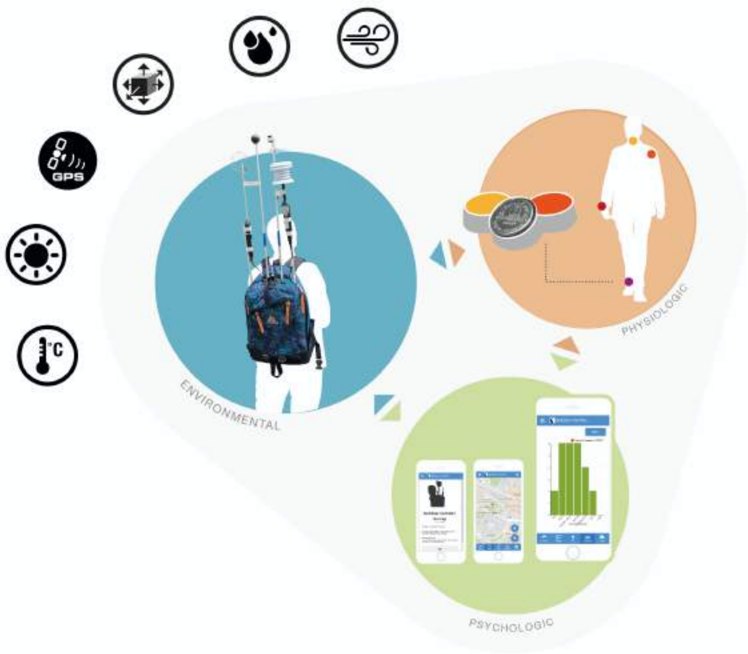

Figure 1. The Workflow of the experiment setup, merging sensing domains of Environmental, Physiological and Psychological data

2.1. Research design

The novelty of the present study is the amalgamation of three different measures in an outdoor environment:

- Microclimate georeferenced field measurements at the human scale assessed with the UTCI;

- Subjective thermal perception, recorded by an individual survey with designed App;
- Physiological response assessed by skin temperature measurements with iButtons.

The experiment was conducted in Singapore on July 25th and 26th 2018 and started at 11 a.m. and ended at 1 p.m. The days had different climatic conditions: the 25th was a cloudy day with reoccurring rain and showers (maximum air temperature during the walk: 30.9 °C), the 26th a sunny hot day without cloud coverage and precipitation (maximum air temperature during the walk: 34.9 °C). The participants were exposed to varying outdoor conditions in a dense urban context, simulating a common life experience, when moving from conditioned indoor spaces to outdoor public spaces and then again into conditioned commercial spaces. Subjects met in a Subway station where they were equipped with wireless skin temperature sensors, while they were exposed to a 30-minute 23°C preconditioning period (65% RH) at the beginning of each experiment. Following this, the walk started. Every 10 minutes the subjects were asked to do a survey about thermal perception. The walk had a moderate speed and ended around 1 hour after in an outdoor / indoor exchange environments. The experiments were conducted during consecutive mornings. This was done in consideration of circadian rhythms in core temperature, as well as the influence of prevailing weather on expectations and adaptation.

2.2. Path

The walks were done in the center of Singapore, starting at the Esplanade underground station´s mall. The path was chosen to simulate an everyday life experience and started from a conditioned space (Shopping mall) to outdoor exposed conditions. The path included segments that were fully exposed, covered paths, underground conditioned spaces, indoor fully conditioned spaces and indoor non-conditioned but ventilated spaces (fans). The path passed also through green spaces and along the river and ended on the Marina Bay waterfront boulevard.

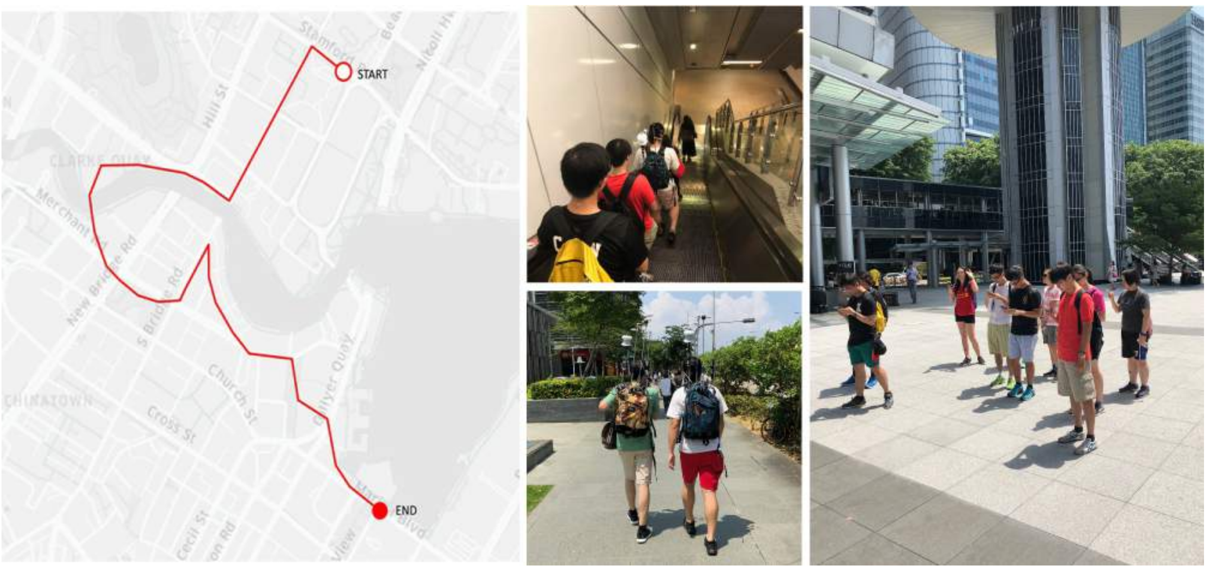

Figure 2. Path through downtown Singapore (left), Indoor and outdoor transition (right)

2.3. Subjects

The experiment was conducted with a group of five healthy female and five healthy male, subjects (average age of 22,3 years) that were tested individually. All subjects were photographed to document their clothing factor. They wore light summer clothing consisting of a cotton t-shirt, athletic shorts, sneakers with anklet socks and their own underwear. The isolative value of this clothing type was estimated to be 0.25 clo.

2.4. Thermal perception

Thermal comfort, regardless of environmental parameters and energy balance, is still largely a state of mind. However, this perception is definitely influenced by environmental, heat and mass transfer variables. In most of the thermal comfort studies, the general approach is to confront numerical thermal comfort estimations with psychological metrics. In these methods, the level of comfort is often characterized by thermal sensation and thermal pleasure scales. In this study, we used 7-point ASHRAE thermal sensation scales to assess subjective responses of the objects. The responds are collected with designed app on the predefined locations embedded with GPS trackers to trigger exact locations of the survey through the route.

Figure 3. App interface for subjective votes

2.5. Physical and skin temperature measurements

The mobile meteorological station with sensors listed in Table 1 was used to collect microclimate data with 1 second intervals during the experiment campaigns. The equipment setup contains three different loggers with different functionalities. The first set is a TESTO480 Digital Microclimatic Sensor kit for the measurements of air temperature (T_a), Relative Humidity (*RH*), instantaneous wind speed (*v*) and Globe Temperature (T_g), Type K thermocouple, class 1. The second set is LI-COR LI-1500 light sensor logger kit with embedded GPS tagging and LI-200R Pyranometer for solar radiation records. The third logger is HOBO Pendant sensor able to measure tilt angle of the instrument package. This data is used to correct radiation values based on sun vector on every specific hour and tilt vector of the backpack.

To measure Tmeanskin, wireless skin temperature sensors (iButton, Maxim Integrated Products, California, USA) were used for each subject at four body sites (neck, shoulder, hand, shin) for continuous and synchronized sampling of data from different logger domains. Skin temperature was sampled every 5 seconds at these 4 sites across the body in order to calculate mean skin temperature according to the formula in Hardy & duBois (1937). The iButtons, have been used in the same application in many other (thermophysiological) studies and considered to be sufficiently low in thermal mass for skin thermometry (Harper Smith et al, 2010; van Marken Lichtenbelt et al, 2006). The sampling was set every 5 seconds to generate a data that has the same resolution as the collected

UTCI measures. Table 1 summarizes the details of the equipment including their sensor type and accuracy ranges.

Table 1: Technical details of the experiment instruments

Logger	Parameter	Sensor	Model	Accuracy
TESTO 480	Air Temperature	Testo Air Temperature Probe	0628 0143	+/- 0.5 °C
	Wind Speed	Testo Air Flow Probe	0628 0143	+/- 0.03 m/s
	Relative Humidity	Testo Humidity Probe	0636 9743	+/- 1.0 %
	Globe Temperature	Adjusted Ping Pong ball Globe Thermometer (D = 40 mm, E = 0.95)	0602 0743	+/- 1 °C
LI-COR	Global Solar Radiation	Pyranometer	LI-200R	0.183 w/m^2
	GPS	RADIONOVA	RF Antenna	2.5 m
HOBO	Tilt	Pendant G Data Logger	UA-004-64	± 0.105 g; 1.03 m/s² from -20°C to 70°C
Maxim	Skin Temperature	iButtons	DS1922L-F5	±0.5°C from -40°C to +85°C

3. Data processing

3.1. Geo locating of the monitored data

One of the main challenges of this study was to match different data sets and post process them to thermal comfort metrics. The recording interval was initially 1 second and averaged to 5 seconds to keep same interval for all data sets listed in Table 1. It is important to note on the GPS data that at some points, depending on the visibility of the satellites and sky view factor the signal was not available and those points were removed through the post processing to match the number of nodes for mapping equality. Parallel to data cleaning process, the based maps are extracted with shape files of the region from Open Street Map. This data was used to match georeferenced tags with the estimated location on the streets and also create the figure ground of the buildings and landscape features. All the procedure of data post processing and mapping was done in Grasshopper (visual programming interface) where the user can bring all the process under a single umbrella.

Transient comfort experiments are relatively complex and due to unstable conditions of the sensors kit over the walking activity. This instability can cause several errors in the measured data specifically on solar radiation because of varying tilt angles walking through the path. In order to enhance the problem, the sensors kit is equipped with pendant gravity acceleration data logger to measure the tilt angle over the time. The logger uses an internal three-axis accelerometer based on micro-machined silicon sensors consisting of beams that deflect with acceleration with logging sequence of 1 second. Tilt angle is not measured directly by the logger, but is processed using the formula:

Tilt Angle of the sensor kit = 180° – ArcCos (Acceleration in Axis)

Taking the tilt vector for every second of the measurement and calculating sun vector for every hour of the tour depending on the accurate location of the subject using GPS data logger, made it possible to calculate adjusted solar radiation taking into account the tilt angle of the device and location with this formula

Adjusted Solar radiation = Incident Solar Radiation × Sin (sun vector + tilt vector)

The adjusted solar radiation is used to calculate mean radiant temperature with the method explained in Chokhachian et al., (2018).

3.2. **Skin Temperature**

Tmeanskin data of the four different skin sites were combined using the following equation, as recommended by above mentioned ISO-standard 9886:2004:

T_{skin} mean= $0.28t_{shoulder} + 0.28t_{neck} + 0.28t_{leg} + 0.18t_{hand}$

Tmeanskin data is presented for men and women separately.

4. Results

4.1. Microclimatic measurements and skin temperature

The collected processed data were matched into the charts presented in figure 5 and 6. The graphs show the UTCI plots, described as equivalent temperature in degree C, the mean skin temperature of the male and female subjects separately and the direct radiation, to highlight covered or closed spaces. The graphs illustrate the effects of transitions both on UTCI and on the average of the mean skin temperature. On the cooler day, the UTCI values are almost always corresponding to moderate heat stress. In some locations, the indoor conditions register higher equivalent temperature than outdoor spaces. On the hotter day, conditions are drastically different: the equivalent temperature difference between indoor and outdoor is high (up to 7 K) contributing to a higher fluctuation of the mean T_{skin}. In tropical climate, clear sky conditions contribute to a higher influence of the built environment, since the variations of direct radiation highly affect the UTCI values. While with overcast conditions, the contribution of the variation of the urban environment is less relevant on the UTCI values. In general, the most evident phenomenon we could recognize is that on the cooler day (July 25th) the mean skin temperature of women is higher, and on the warmer day (26th) it is lower than the male subjects´ average.

Figure 4. Climatewalk path with georeferenced UTCI mapping

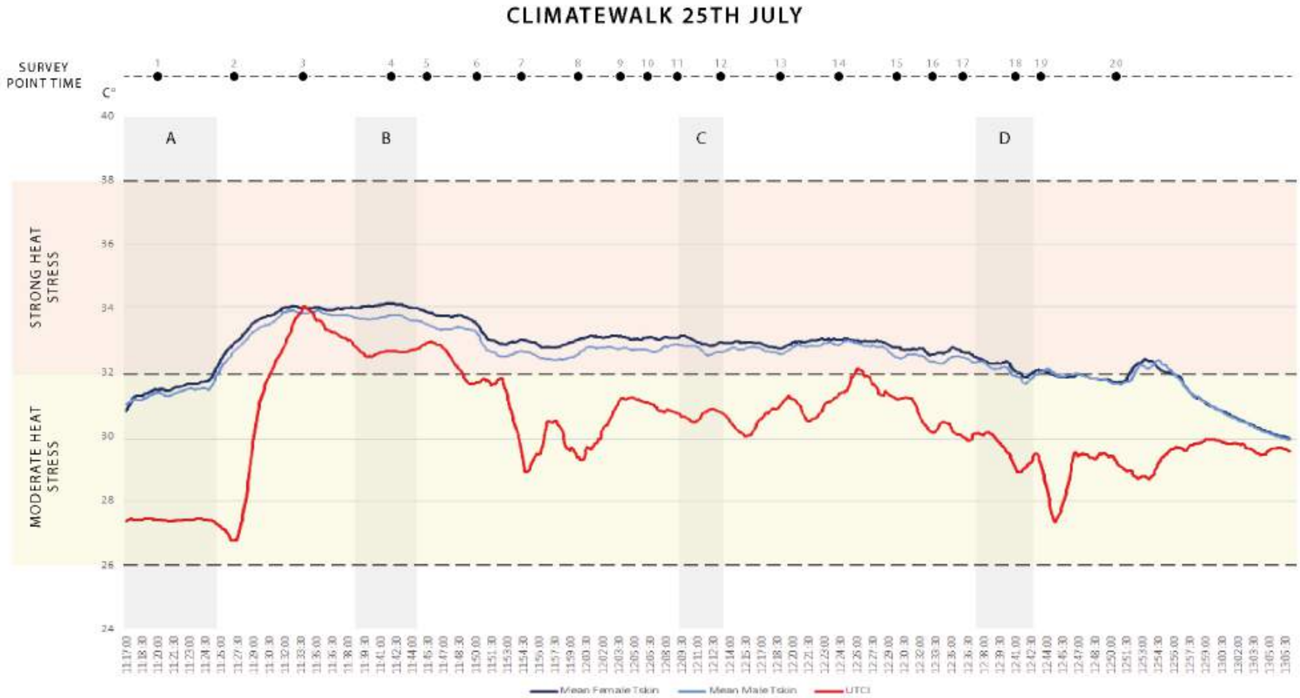

Figure 5. Radiation, UTCI and skin temperature, day 1.

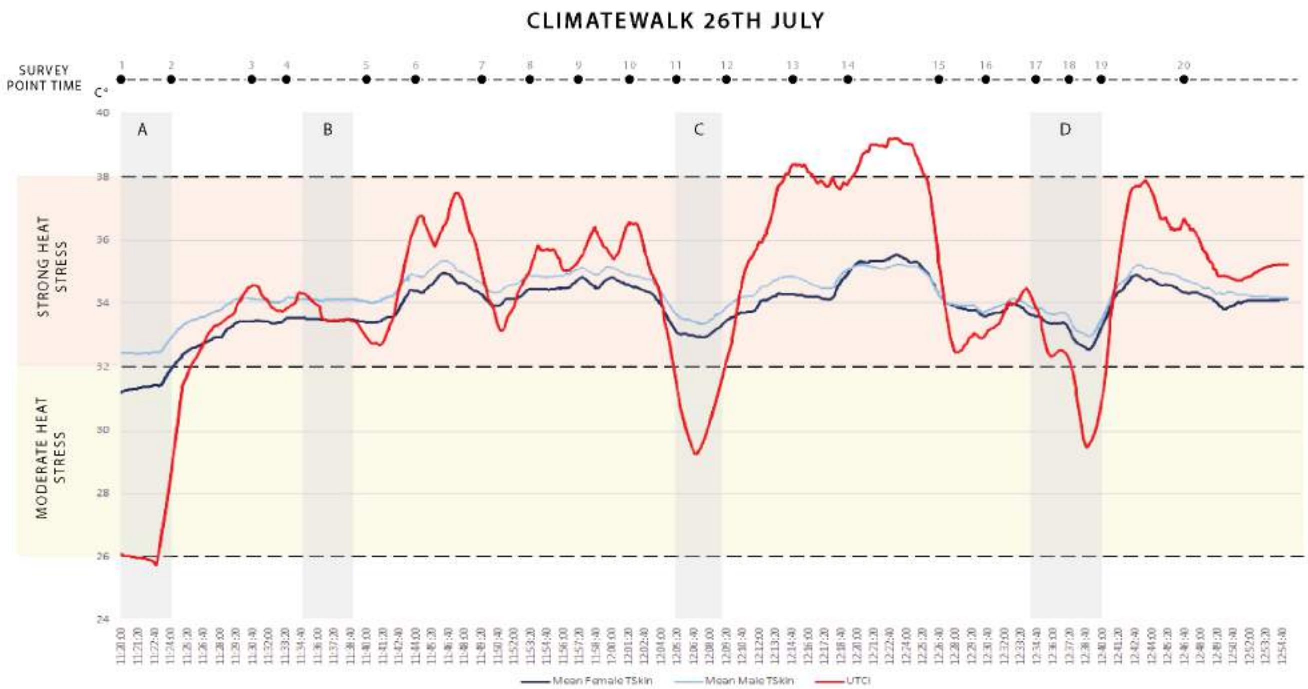

Figure 6. Radiation, UTCI and skin temperature, day 2.

4.2. **Subjective thermal sensation and skin temperature**

Subjective thermal sensation shows a similar trajectory to T_{skin} on a partly cloudy day (Figure 7). Mean T_{skin} increased quickly from 31.3°C (Point 1, indoor air-conditioned environment) to 33.9°C (Point 3, outdoor bus stop on roadside). It started to drop from Point 5 when the subjects reached the riverside and was then stabilised at around 32.8°C from Point 7 onwards. It dropped below 32.5°C after Point 18 as the subjects reached the very exposed waterfront. As the *Climatewalk* was conducted on a partly cloudy day, T_{skin} was less fluctuated and remained relatively stable in outdoor environment. On the other hand, mean TSV varied similarly to T_{skin} when the subjects were under outdoor conditions for a period of time (e.g. from Point 7 onwards). However, when the subjects went from indoor to outdoor environment, mean TSV increased from slightly cool (-1) to slightly warm (about +0.6), with a corresponding increase in UTCI of about 6°C. When there was a decrease in UTCI by 3°C (from Point 4 to 8), mean TSV dropped from +0.5 to -1.7 at Point 6 and later increased back to about -0.7. It suggested that an overshooting of thermal sensation would occur when there are abrupt changes in meteorological conditions.

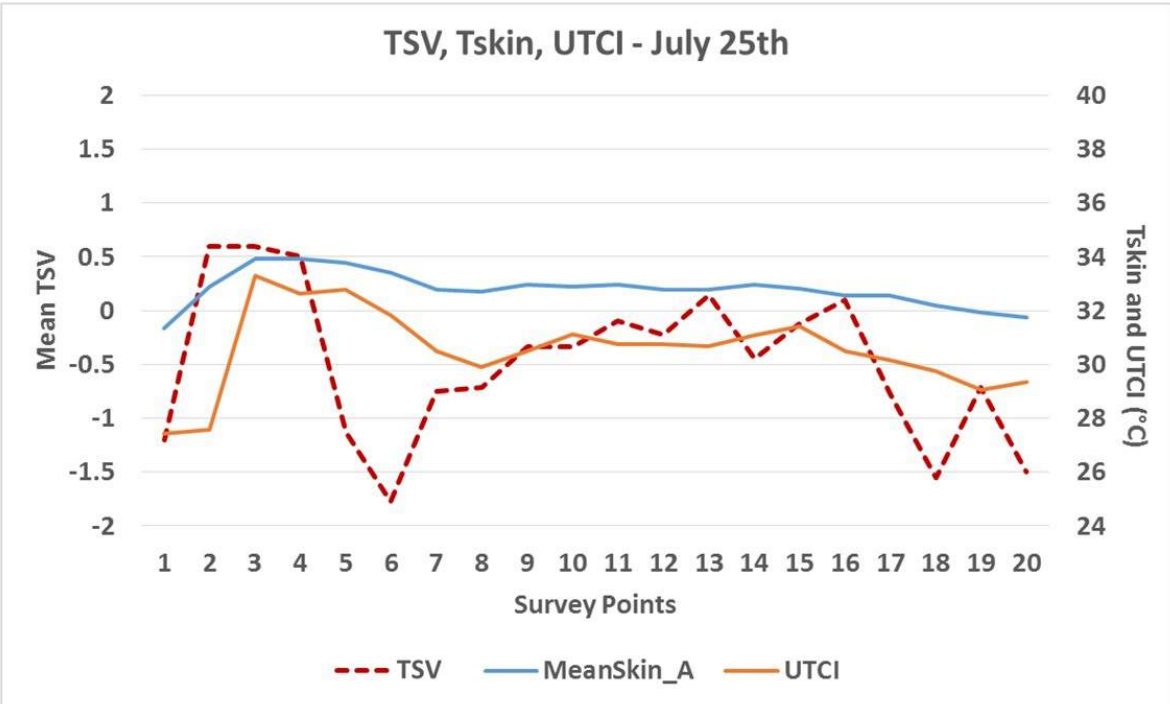

Figure 7. Changes in mean TSV, mean T_{skin} and UTCI for all subjects along the route, day 1.

On a clear day, T_{skin} increased steadily after the subjects entered the outdoor environment and reached up to 34.9°C in the latter half of the walk. The highly variable meteorological conditions due to the complex urban geometry were shown by the fluctuation in UTCI (Figure 8). UTCI was as high as 37.9°C at Point 14 where the subjects passed through a low-rise area without many shading opportunities. Lower UTCI values were observed at Point 12 as the subjects passed through an underground area while it was dropped from 37.5°C to 32.9°C when they entered an air-conditioned passage way. These values also corresponded to the decrease in T_{skin} (33.4°C at Point 12). This close relationship between UTCI and T*skin* was also shown in their correlations (r = 0.840 and 0.964 for partly cloudy and clear day respectively). The fluctuation of TSV generally coincides with that of UTCI while the overshooting of TSV was not observed on clear day. It was likely because the highly variable meteorological conditions did not provide sufficient time for the subjects to get acclimatised under certain conditions.

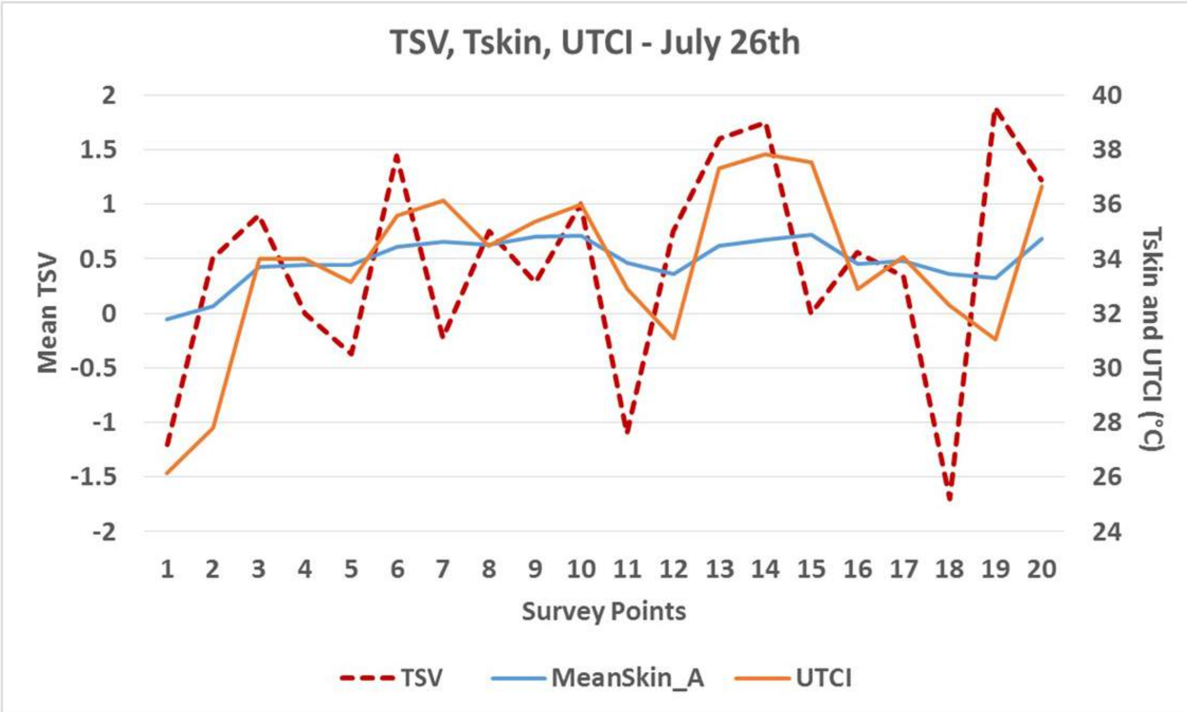

Figure 8. Changes in mean TSV, mean T_{skin} and UTCI for all subjects along the route, day 2.

5. Discussion

The outlined approach uses different measurement domains to frame a methodology for mapping and understanding human transient comfort with a geo-referenced method. The applied workflow was tested in an on-field experiment and its results clearly show the relation between UTCI variation and mean skin temperature in transient status: the dataset granularity allows further analyses and studies on human thermal behaviour in indoor-outdoor transitions. Additionally, distinguishing between the proximal and distal skin temperature alongside with T_{skin} mean, would allow a more detailed determination of the influences of environmental conditions on the skin temperature fluctuations.

The results of this experiment show that after an initial adaptation phase, mean skin temperature stays in a constant range even if major changes in UTCI occur. This phenomenon is supported by the results of the subjective response survey.

The comparison of the two experiment days, July 25th with overcast sky and 26th with clear sky conditions, shows that in tropical climate the moderate heat stress level of UTCI induces more moderate and stabilized skin temperatures. However, with immediate shift in thermal stress level to strong heat stress, the skin temperatures start fluctuating following the same pattern as the UTCI curve. This phenomenon hypothetically can prove that the UTCI thermal perception ranges have strong correlation with the skin temperature. This aspect needs further experiments and evaluations.

In fact, under partly cloudy conditions, subjects reported lower TSV values when they experienced an abrupt drop in UTCI, compared to the same meteorological conditions they were exposed before this abrupt drop. This cold overshoot was first observed by de Dear et al. (1993) in a study of short-duration sensation and comfort overshoot during temperature transient. However, this overshooting phenomenon was not observed under clear conditions. The highly fluctuating meteorological conditions did not provide sufficient time for short-term acclimatization so subjects' thermal sensation was dependent on the changes in meteorological conditions (i.e. UTCI). This suggests that the concept of thermal Alliesthesia, which refers the restoration of thermal comfort status to its original state, is associated with the duration of the subjects' exposition to the conditions prior to changes (de Dear, 2011).

While the challenge of thermal comfort dynamics have been widely discussed in indoor studies, such understandings in more complex outdoor settings where the transients are even more pronounced, allow to formulate indications for designers, city planners and policy makers. This method is based on data integrated approach and can be scaled up to make cumulative outdoor comfort predictions and urban geometry based design solutions.

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ENERGY GENERATED EXTERNAL ENVELOPE
TOWARDS THE METHODOLOGY OF DEVELOPING THE PERFORMANCE OF THE EXTERNAL ENVELOPE TO ACTIVATE SOLAR ENERGY SYSTEMS

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Abstract: The energy consumption in buildings is one of the most important issues in the 21st century. Most of the researches and recommendations focused on using the renewable energies and attempts to develop its technological systems, parallel in the same time with the technological development. Nowadays we can notice the need for making an integrated design for the external building envelope to build an energy generator external façade through an architectural vision.
The paper discusses the problem of the obvious gab between the architectural elements of the external building envelope and the technical elements of the solar energy systems, especially in the existing buildings which are to be supported by solar systems later, which it may not be acceptable to the architectural vision.
The paper aims to develop an applied methodology to improve the design efficiency of the PV systems to be integrated with the building elements as a tool to create a GENERATED PV/ARCHITECTURE building,

Keywords: Solar energy – Renewable energy – Photovoltaic systems – PV/Architecture integrated design.

1. Introduction: Solar Energy:

The general concept of solar energy can be simplified as the energy that can be produced directly from solar radiation, it can be considered as a huge source of clean renewable energy. The studies indicate that only 0.1% of the 75,000 trillion kilowatt hours of solar energy reaching the earth is sufficient to meet the needed energy for the planet. The solar energy can be used through three ways:

- Converting to thermal energy.
- Converting to photovoltaic energy.
- Photosynthesis.

1.1. Thermal energy:

It can be produced from solar collectors, as in figure (1), it had been widely used in many commercial products which depends on solar radiation in its mechanics. Such as cooking machines, water heating systems, drying of agricultural crops, natural materials treatment such as wood and purification of saline water. There are several trials to develop these systems for the service of many commercial and industrial purposes, which contributed in a positive way in the fields of saving electrical energy consumption in the building.

Figure 1. The solar collectors, source: https://nabichinna.files.wordpress.com

1.2. Photovoltaic energy:

In which electricity is produced directly from solar radiation, as in figure (2), its basic idea depends on the solar radiation when it falls on certain substances such as silicon in the stimulation of electrons to pass regular through the wires to be an electric current. The Photovoltaic cell is the basic unit in that system, where its basic composition includes an electron-emitting metals.

Figure 2. The PV cells, source: https://encrypted-tbn0.gstatic.com

1.3. Photosynthesis:

It means the chemical transformation of CO2 and water into carbohydrates using the sunlight and chlorophyll in the plant, as shown in figure (3). It is one of the most efficient methods in nature to transform the solar energy into a storage energy, the experiments and studies have shown that approximately 30% of the light absorbed in plants Turns into chemical energy.

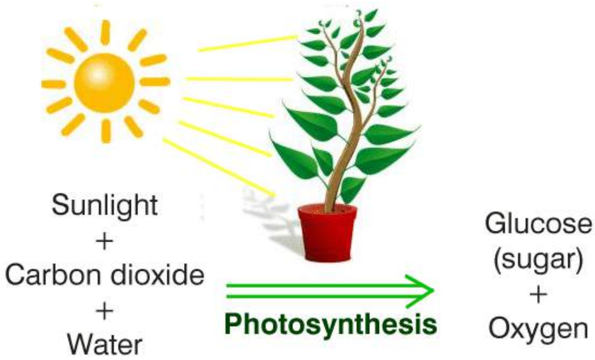


Figure 3. The Photosynthesis, source: https://www.ducksters.com

2. Photovoltaic Cells techniques and systems:

2.1. The concept and historical background:

The conversion of solar energy to electrical energy by PV cells is the most prevalent method of using solar energy, the main concept of its work depends on PV cell which made of semi-conductive materials, mostly made of silicon, which allows passing the electrical current. The PV cell consists of two silicon layers, one containing 3 electrons in the outer orbit of the atom so that it becomes positive side, and the other contains 5 electrons in the outer orbit of the atom so that it becomes negative side. When the sunlight falls on the cell, it absorbs the photons of light and produces energy that allows the release of negative electrons from the atom orbit causing positive gaps, and producing a direct current (DC). The electrical energy can be collected by a certain devices, so that each cell works as a power-generating battery with multiple cells connected straight or parallel, as a figure (4).

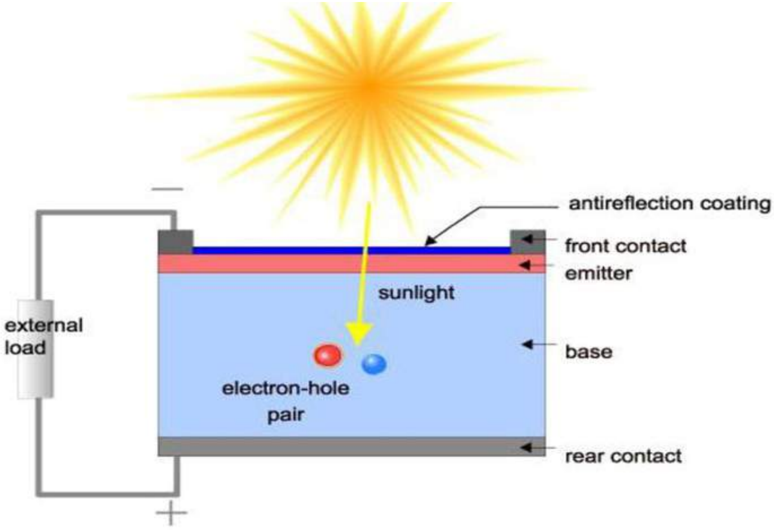


Figure 4. Solar cell structure, source: https://cdn.importantmedia.org

The efficacy of photovoltaic cells are about 15%, which means that it can convert about 15% of solar energy into electricity during its life period which is about 20 years. The physical effect of converting sun light into energy was discovered in the first half of the 19th century in 1839 by The French scientist Alexander Edmund Bekrel, after that many scientists contributed through their research such as Charles Frits and Nikola Tesla on the development of that principle in 1904.

A significant technological development took place in the semiconductor production from the late 1950s to the 1960s and solar cells were exclusively used for producing electricity, and significant progress was discovered in this field during the period 1985:1990, when solar power systems were produced commercially by a specialized companies and has been used to supply buildings with electricity in multiple uses that require limited capabilities such as lighting, water pumping, ……. etc.

These systems have become widely used for its ease of installation, low cost of maintenance, no noise pollution, environmentally pollution prevent, long life and suitability for use especially in distant areas. The only major limitation is the high amount of the system initial cost, however, it is noteworthy that statistics indicate that from 1985 to 2011 there was a decrease in the costs of solar cell systems by 70%, as illustrated by the figure (5). The manufacturing rate of photovoltaic units has increased by 40% in the last years.

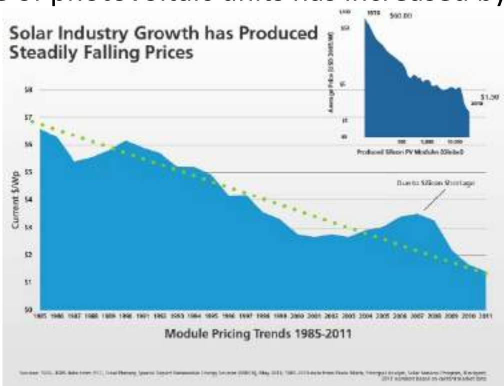


Figure 5. Solar pricing trends 1985-2011, source: Kleinbach, h. (2013)

2.2. **Technical developments of photovoltaic cells:**

Recently, new developments and technologies have been added to photovoltaic cells that have contributed significantly to the development of its material, shape, efficiency and the idea of its work. The prevalence of these products is still limited in comparison with traditional products, as well as the exposure of some of these items under experiments and tests. The table (1) shows the most important types and the technical characteristics of each.

Table 1. Contemporary PV cells, Source: Krebs, F. (2008)

Cell type	Cell properties
Dye sensitized organic	The efficiency of the electrical conversion of the cells increases by 18%.
Nano PV cells	Ultra-compact technical units with double cell efficiency.
Material integrated	Has been compatible with the building materials to be as the natural materials.
Concentrate dots	With overlapping lenses, so the sunlight concentration is added to increase its efficiency from 15:35% to the vertical rays only.
Plastic cells	Less costly than the other types, but is less weak than the traditional type.
Flexible cells	Flexible, which can be combined on multiple surfaces such as cars and bags.
Intelligent cells	The possibility of turning it into a transparent color in cloudy atmosphere to take advantage of natural light.
Dye based	The concept of its work depends on the mechanism of working of the dry batteries.
Hybrid	Merging several semiconductor materials together into a single cell that increases its efficiency by more than 18%.
Spherical cells	Small balls of silicon are affected by solar radiation from all directions.
High performance	With a coarse surface that causes the increasing the absorption and efficiency of the cell to 25%.
Semi-transparent	Can be used with the types of glass in the facades of buildings.
Anti-reflective	Reflective materials support the cell to use an extra amount of solar radiation.
Compacted	Achieving maximum production by using two or three layers of conductive materials.
Carbon pipes	Lighter and more flexible materials.
Concentrated	The use of composite lenses as one unit to produce electricity efficiently from the solar radiation.
Blu-Ray cells	Using nanotechnology optical layers similar to the layer that used in Blu-ray discs that improves the flow of light into the panels then to the batteries.
Transparent	It is available as tinted glass which makes it suitable for the facades of buildings.

2.3. **Techniques for upgrading photovoltaic cells**:

With the technical development in the manufacturing and types of photovoltaic cells, some of the contemporary techniques have also contributed to the development of traditional photovoltaic cells, the most important which can be mentioned in the following:

- Lenses.
- Concentrators.
- Mirrors and reflectors.

2.3.1. Lenses:

It depends on using a square lenses containing small circular protrusions that contribute to the transformation of the sun into a focal point, where the solar cell is installed in this focus, and the most famous lenses in this field are the Fresnel lenses as in figure (6), which work to focus the sunlight on each cell with more than 500 times, which contributes to giving the cell an additional efficiency of 30:39% and sometimes up to 50%. But in this technique must consider the following:

a. Cell design must prevent the cell unit from the damage due to the high temperature that generated from the focus of the sun radiation.
b. The inclined solar radiation is not compatible with the cell due to the lenses which distribute the solar radiation away from the cell.

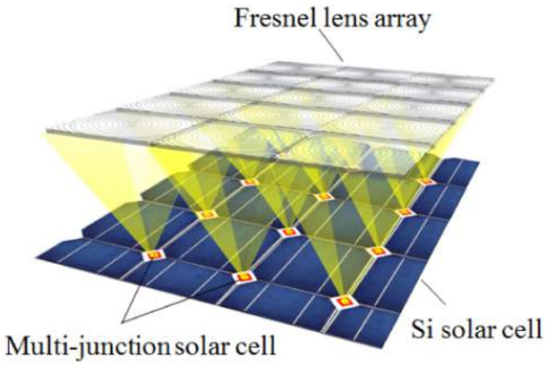


Figure 6. Fresnel lenses, source: Lynn, p. (2010)

2.3.2. Concentrators:

Are used on a large scale and therefore can only be used in the desert or mega lands, where more than 200 matrices are installed with advanced technologies, all of which are designed to increase overall efficiency and can be operated without daily follow-up. One of the most important examples of these centres is the Amonix mega centre concentrator in California as is shown in figure (7).it is noteworthy that that this system does not operate at a radiation rate below than 400w/m².


Figure 7. Amonix concentrators, source: Lynn, p. (2010)

2.3.3. Mirrors and reflectors:

It depends on the concept similar to the work of the lenses mentioned in part (2.3.1) where mirrors work to reverse the solar radiation on the cell indirectly instead of focusing directly on it. We can benefit from this case by avoiding the factor of high temperature caused by the lenses over the cell and the low cost of using the reflectors and mirrors instead of the high cost of using lenses. The figure (8) illustrates the use of two mirror surfaces with the PV cells. The measurements show that the levels of cell efficiency increase from 10:100 times in the case of vertically reflected rays and from 2:10 times in the case of inclined reflected rays.

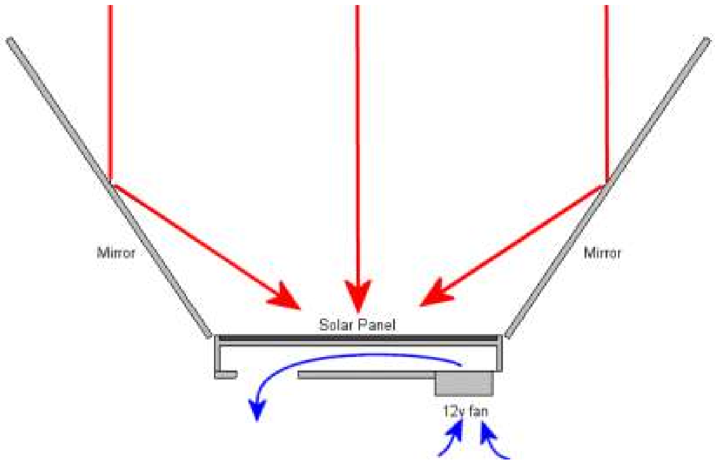


Figure 8. Mirrors in PV systems, source: https://www.thebackshed.com

2.4. **Advantages and disadvantages of photovoltaic cell systems**:

Photovoltaic systems have several advantages that have helped to use it widely as a renewable energy source although there are some disadvantages that are still under technological development to avoid its effects. The main advantages and disadvantages can be mentioned in the following points:

2.4.1. Advantages of Photovoltaic systems:

- One of the most important renewable clean energy sources.
- Widely used due to the availability of its energy sources (solar radiation) in most parts of the world.
- The importance of the environmental and economic positive impacts of the systems.
- The importance of its economics, especially in distant areas where there are no availability of traditional energy sources.
- The possibility of being environmentally used through the components of the external envelope of the building as a second layer allowing the use of the air space between the two layers environmentally.
- Positive environmental effects such as shaded areas below which reduce the direct thermal load on the building.
- Easy installation of these systems and its simple technologies.
- The availability of many styles and forms with many properties and colours which does not make them as an architectural determinant during the design steps and can be used as an architectural item also in the building.
- Some types of cells can be used instead of the glass in external facades.
- Easy to carry out regular maintenance.

2.4.2. Disadvantages of Photovoltaic systems:

- The initial cost of these systems is still high especially in low-economy countries.
- The lack of awareness of the building users about the positive impact of these systems economically especially the running cost of the building.
- Cells are fragile and easy to break so it must be handled with care.
- The average of using cells is 20 years, after that there is a need to be recycled which the needed recycling energy is 80% from the needed production energy, as well as the bad effect of silicon in recycling process on the environment.

- The cells are affected by some climatic factors such as high temperature and the dust.
- Cell efficiency is low and requires technical development to increase its efficiency.
- We must to take into consideration the structural requirements due to the load of photovoltaic cells on the building.

3. The economics of the photovoltaic systems:

Several studies have been done on the economic assessment of solar PV systems, although these economies depends on several factors such as: the nature of consumption, the systems location and the availability of traditional energy.

For example as shown in figure (9) the economics of PV systems are the best in areas with a distance far from the network line between 4:12 km If the required load range are between 1:3 kw. While in the case of distance from the network lines of 10 km and loads up to 10 kW, the costs of PV systems are higher than traditional energy costs, but it becomes the best economical if the distance is more than 40 km.

Therefore there is a necessary economic request for investing in the construction of PV systems in distant and desert areas and relatively distant from traditional energy network. In addition to this economic positive impact there are several advantages that increase the efficiency of the economic importance of PV systems such as:

a. It can be constructed to start producing energy in a short time.
b. It can be applied and constructed in distant areas where it is difficult to get traditional energy systems.
c. It can be considered as a clean and renewable energy source that protects the environment.
d. Low costs of maintenance.
e. The possibility of reducing the cost through the mass production of units with a large amount.
f. The technological positive impact in the development and reducing cost.

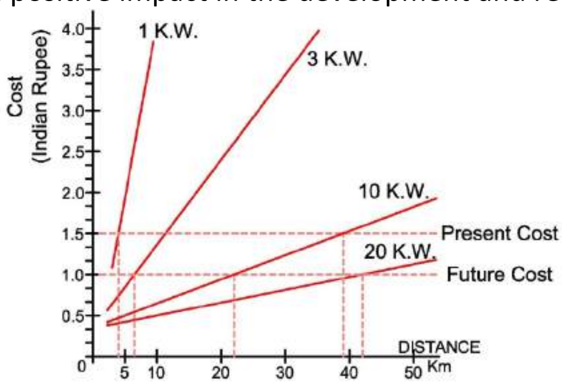


Figure 9. PV economics, source: Shauhan,D.&Srivastava,S., (2006)

4. **Considerations and standards of photovoltaic design:**

This section discusses the design considerations of photovoltaic cells through an architectural vision through a proposed methodology for the integration of PV systems with architectural design to get a generated effective renewable energy building in its all components. It can be divided according to the stages of the building design as follows:

- Pre-design phase.
- The schematic design phase.
- Final design phase.

The impact of each phase and its design considerations can be shown in the proposed methodology for the building design phases as described in the following points.

4.1. Pre-design phase:

This phase includes the basic studies that effects on the design of the PV system. This phase includes two cases, one if there are site alternatives for the project and the other if the site is selected previously. The studies can be shown in the following points:

4.1.1. **Case (1): availability of site alternatives for the project:**

In some projects there are several alternatives to the site such as national projects where the project is identified first and then we choose the suitable site for this project. In this case several economic and social studies can be done and these studies should include all studies that effect on the PV system efficiency including the following:

4.1.1.1 Impact of site topography:

The site topography has a direct impact on the building exposure to solar radiation on its external surfaces with an optimum amount, for example Figure (10) illustrates the topography of the site and its relation to solar radiation impact on the exposed area of the external envelope of the building, and these cases include:

Case (A): Site Topography is in the same direction as solar radiation.

Case (B): Site Topography is in horizontal direction.

Case (C): Site Topography is in a direction opposite the direction of solar radiation.

We can notice that the case (C) is the best case that can give a maximum sun exposure especially as the sloped angle increases.

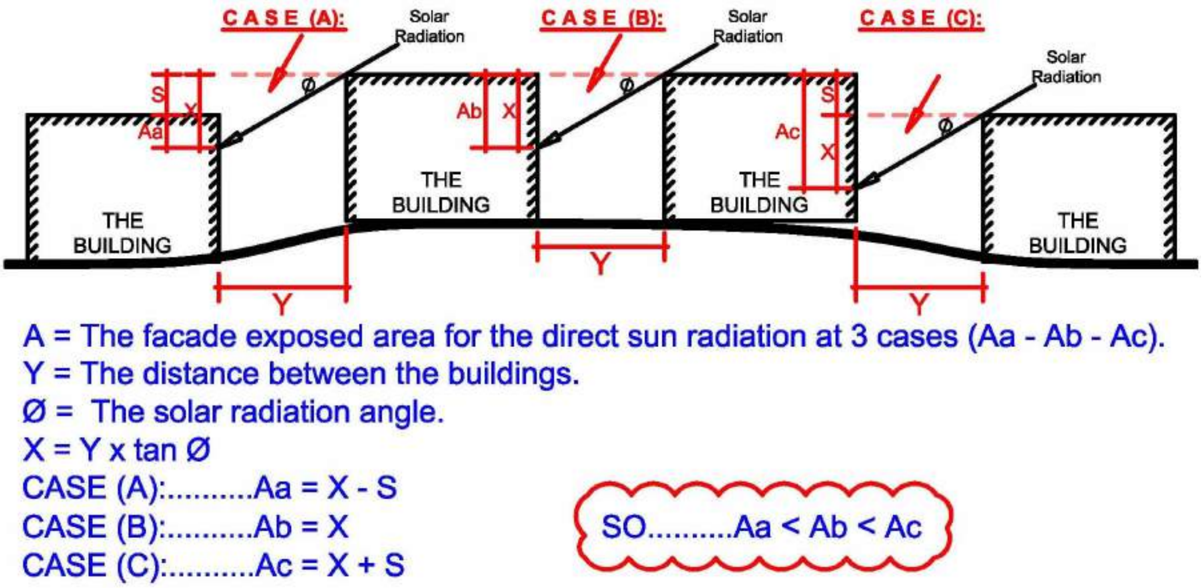


Figure 10. Topography impact, source: Researcher

4.1.1.2 Impact of surrounding buildings and elements:

It has a direct effect on the amount of shade and light on the site, where the total shaded areas is to be determined all of the day through the study of the sun movement. This study can be done through several methods such as:

a. From the simulation programs that draw shadows on the 3d model of the building and the elements surrounding the site, such as Revit-Vasari Beta 3 programs, as in figure (11).

b. Using the solar maps with buildings and surrounding elements through tracking of the shadow and light movement in the site to get the most exposed areas to solar radiation.
c. Studying the land on site using special tools such as the shadow analysis tool as shown in figure (12).

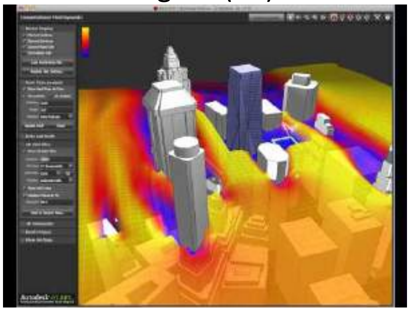


Figure 11. Vasari beta 3, source: https://oliebana.files.wordpress.com

Figure 12. Shadow analysis tool, source: http://azurean.ca/index.php/portfolio/resort-municipality-of-whistler-shadow-study/

4.1.1.3 **Impact of the amount of the solar radiation:**

It can be done by studying the value and amount of solar radiation throughout the day for each location to select the most optimum site with the suitable radiation intensity to optimize the use of PV system.

4.1.1.4 **Impact of the proportions of the site:**

It has a direct effect on the building orientation and thus the area of building envelope exposed to solar radiation, for example as in figure (13) shows the various elevations sun exposure in Btu unit for the in two cases for the same building include cases (A) & (B) in Egypt, we can notice that the overall sun exposure in case (B) is higher than case (A) with about 2% only, so we can conclude that the effect of orientation is almost zero.

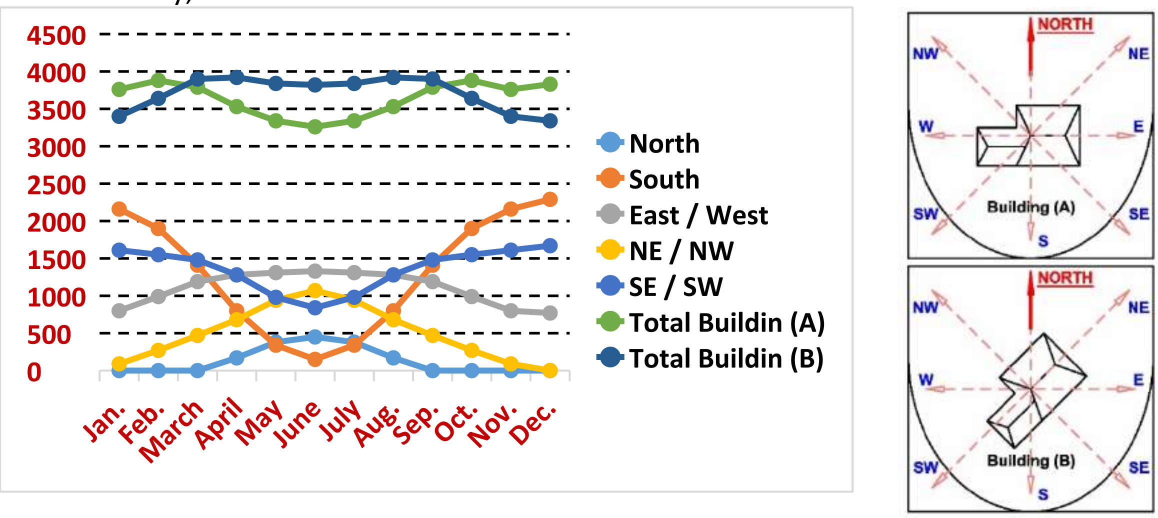


Figure 13. Site proportion impact, source: Researcher

4.1.2. **Case (2): a previously selected project site:**

In this case, the site is selected previously. For that we should to do the studies that have a direct impact on the design of the PV system. These studies include the following:

- The amount of solar radiation.
- The solar radiation angles.
- The impact of the surrounding items and buildings.

- The total hours of solar radiation.
- Shaded areas in the site throughout the day at the site.
- Sun Path Diagram.

4.2. The schematic design phase:

This phase includes the conceptual design of the building according to the requirements and architecture vision. We should to take into our consideration the conceptual steps of the PV system as an integral step with the architectural design, the most important steps of this phase include:

4.2.1. **Energy-saving strategies:**

At this stage, it is necessary to activate the energy saving strategies of the building with its direct impact on the design decision and elements including several items:

4.2.1.1 **The items related to the building:**

Can be achieved by the environmental design techniques and methods by taking into consideration all surrounding environmental items positively in reducing energy consumption to operate the building, especially all items related to external building envelope.

4.2.1.2 **The items related to the technical installations of the building:**

Can be achieved by the selection and use of devices, equipment and systems that are highly efficient in the energy consumption for operation.

4.2.1.3 **The items related to the users of the building:**

Can be achieved from users by following all instruments that lead to energy saving such as the moderate use of technical installations to avoid energy consumption.

4.2.2. **Calculations of the electrical energy required for building operation:**

Energy is consumed within buildings to operate many of the necessary services, for example: artificial lighting, water heating, air conditioning, ventilation and alarm works ………..etc. For example the figure (14) shows the electricity use in U.S. commercial buildings.

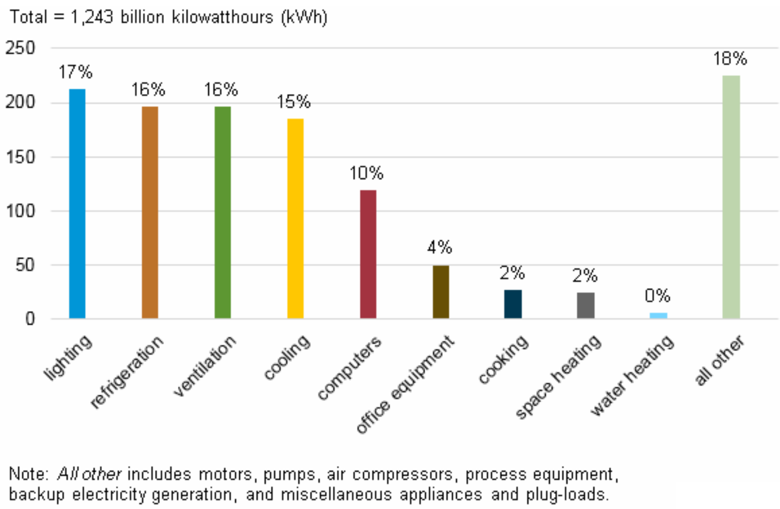


Figure 14. Electricity use in U.S. commercial buildings, source: U.S. energy information administration (2012)

The calculation of the amount of electrical power required for the building is a basic step in the design of the photovoltaic system and its calculations, it is noteworthy that we must to take in our consideration the required power for the both of the expected design of the building and the expected consumption in the future due to the increasing of the electro-mechanical requirements according to the technological development or the future extension of the building. The amount of required power can be calculated in two ways, as follows:

1. **Method (1): the maximum requirement for electrical equipment:**

In this method we calculate the all devices and the electrical requirements for operation and what is expected in the future, and then estimate the electrical loads required for each device with the maximum number of expected operating hours, and calculate the total electricity required daily from the relation:

Total electricity per day =

∑ Equipment's number x electrical load for each x operating hours per day

2. **Method (2): the maximum requirement per square meter of the building:**

This method depends on the rate of consumption of the square meter of the building according to the building function, where the rate differs from the building of another building as well as from one country to another, for example, the table (2) shows the electricity consumption rates per square meter to the buildings in the Arab Republic of Egypt. And we can calculate the total electricity required daily from the relation:

Total electricity per day =

Energy consumption rate of square meter per hour x operating hours x building area

Table 2. Electricity consumption per m2 in Egypt, Source: Egyptian electricity ministry, (2015)

Building type	Elec. K.v.a/100m2	Building type	Elec. K.v.a/100m2	Building type	Elec. K.v.a/100m2
Hotel	10	Hospital	3 : 5	Open Market	4
Commercial	9	Culture	4	Nursery	3
Residential	8	Retail	6	School	1 : 2
Admin.	6 : 9	Store	4	Restaurant	9
Bank	9	Services	4	Mosque	1.5

4.2.3. **Photovoltaic cell types and techniques:**

As mentioned before, there are many types of contemporary photovoltaic cells with different characteristics, although the common use is still traditional cells but there are many trials to use and develop other types. These types can be used according to the design vision, for example:

- The selection of the type that is compatible with the external finish and the different between the glass and the solid surfaces.
- Choosing the available colours according to the building finishes colours.
- Choosing the suitable type according to the required form.
- Taking into consideration the visual effect of photovoltaic systems.
- Choosing the system mechanism such as the choice between fixed or moving cells with sensors that follow the Sun path with a motor that allows movement to get a greater amount of energy, the figure (15) illustrates the idea of the movement of those cells on one axis or two axes, as shown by the figure (16) the difference between the energy produced by the two mechanisms.

There are a generated electricity amount and intensity for each type, which can be considered as a factor in the calculations of the required photovoltaic cells surfaces, for example, the table (3) shows the technical data for a PV cell type that is relied upon in the calculations of the required surfaces of those Cells according to the total amount of electricity required daily.

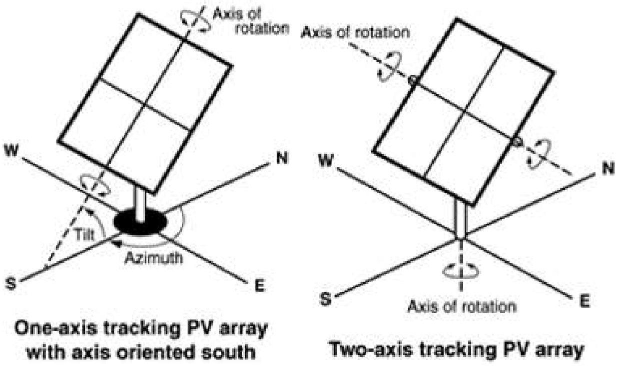


Figure 15. One & two axes PV tracking, source: Dobson,r&prinsloo, (2014)

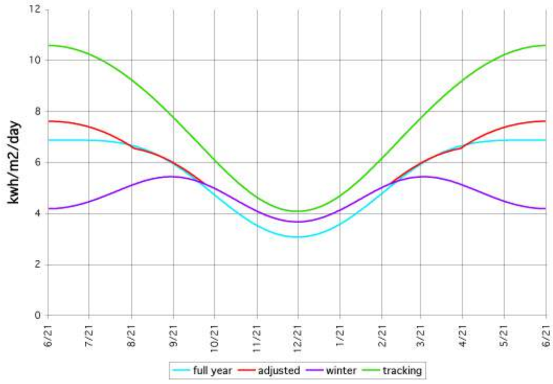


Figure 16. Fixed & tracking PV energy output, source: Dobson,r&prinsloo, (2014)

Table 3. Polycrystalline PV cells technical data, Source: http://www.egreen-eg.com

Item	Unit	Value	Item	Unit	Value
Panel wattage	W	250	Amp	A	8.2
dimensions	mm	1650x992x40	Open voltage	V	37.8
Efficiency	%	15.3	Weight	Kg	19.5
Area	M2	1.6	Suitable work temperature	°C	46 (±2 °c)
Max. voltage	V	30.5			

4.3. The integrated proposed design of photovoltaic cells with architectural elements of the building:

The integrated PV/Architecture design can be proposed in the schematic design phase to get a generated electricity building that contains a combination between the PV cells and the architecture elements. This product can be achieved by the architecture design which can be divided into five levels as follows:

a. The lay out and site level.
b. The building form level.
c. The external envelope level.
d. The openings level.
e. The finishes and materials level.

The next part will review the proposed points for the integrated design and its effect on the PV and building design for each level.

4.3.1. The integrated design for the layout and site level:

- PV cells as light covers such as pergolas or equivalent, figure (17).
- PV cells as covers for parking areas, figure (18).
- PV cells as covers for service buildings attached to the project such as security and electricity rooms.
- Choice of light colours to the exterior finishes surrounding the building to reflect the maximum amount of solar radiation on the PV cells installed on the exterior walls of the building.
- Designing land scape elements in a coordinated vision with the performance of cells.
- Suitable street width between project buildings to allow sun radiation flux as figure (19).

Figure 17. PV as light covers, source: https://www.altenergymag.com.+

Figure 18. PV as parking shade, source: https://solarthermalmagazine.com.

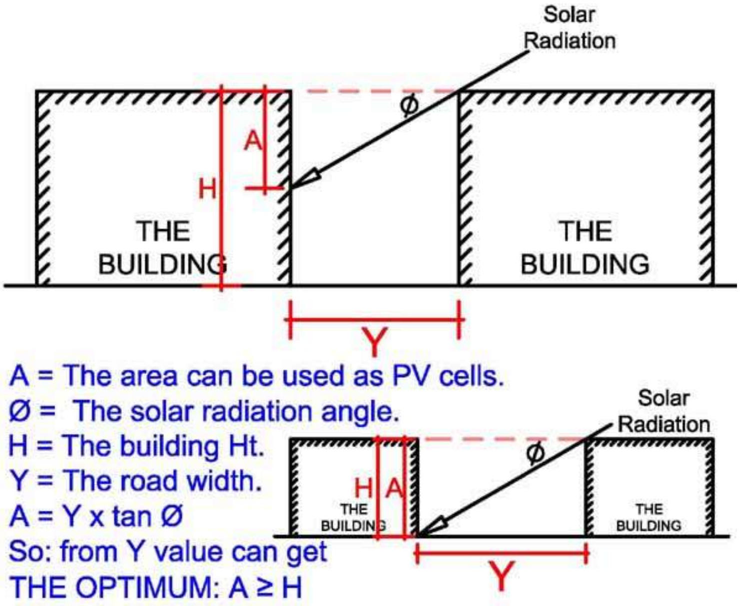


Figure 19. The optimum roads width, source: researcher

4.3.2. The integrated design for the building form level:

- The stepped form in a vertical direction on the direction of solar radiation leads to more exposure areas to the sun which can be used for PV cells, figure (20).
- The ratio and dimensions of internal and external courtyards.
- Taking into consideration the future extension of the building to be horizontal direction instead of vertical direction to enlarge the horizontal surface exposed to solar radiation due to the higher radiation intensity over these surfaces in comparison with the vertical surfaces.

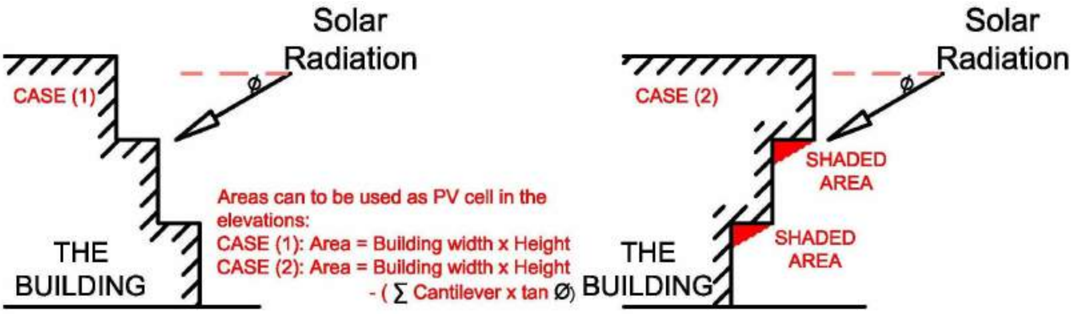


Figure 20. The effect of building stepped form, source: researcher

4.3.3. The integrated design for the building form level:

4.3.3.1 External roofs:

- The sloped roof vertically on the direction of solar radiation is better than the horizontal roof to provide a larger area for the photovoltaic cells placed on it, figure (20).
- The use of cell units as light covers like pergolas on the top of the roof.
- The cell units as the second layer in the double roofing, including the air space with its positive environmental impact of lowering thermal loads over the upper roof in addition to the positive ventilation.
- The use of cell units as a basic element in the sky light.

- In case of stepped roof, it is preferred to be in a vertical direction on the direction of the solar radiation to provide a maximum suitable area for the PV cells.

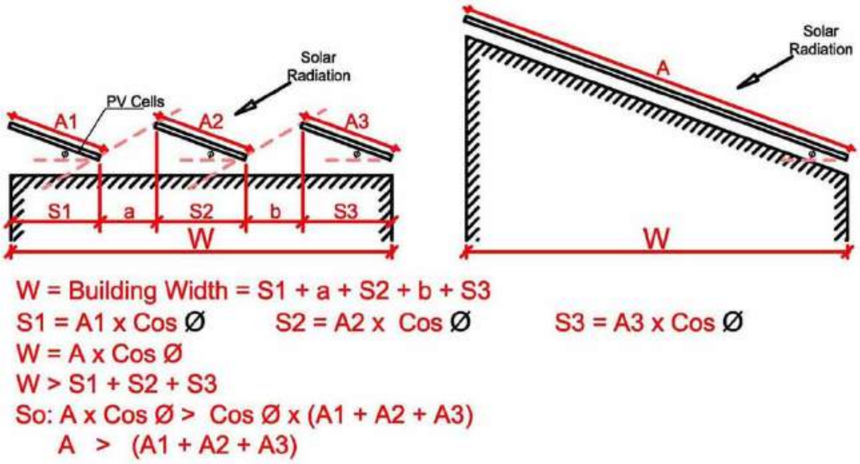


Figure 21. The effect of sloped roof, source: researcher

4.3.3.2 Exterior walls:

- First priority is the utilization of the facades that most exposed to the sun path and has a preference from the other facades.
- The facades that can be designed with a slope angle with the orientation perpendicular to the solar radiation direction to achieve the maximum solar intensity upon the PV cells more than the vertical facades.
- The cell units as the second layer in the double skin, including the air space with its positive environmental impact of lowering thermal loads over the facades in addition to the positive ventilation.

4.3.4. The integrated design for the opening level:

- The use of contemporary cells such as transparent and semi-transparent cells instead of glass in windows to be power generated item.
- The use of cell unit as a basic item in the ventilated double skin in the outer layer.
- The use of cell units attached to the external openings environmentally to be sun breakers in addition to its basic function, figure (22).
- The suitable design of all cantilevers over openings to be an optimum base for PV cells.
- The suitable atrium design as an environmental solution with using PV units in its components.
- The use of contemporary PV cells in the external curtain Wall instead of glass.
- The smart PV as louvers over external openings, figure (23).

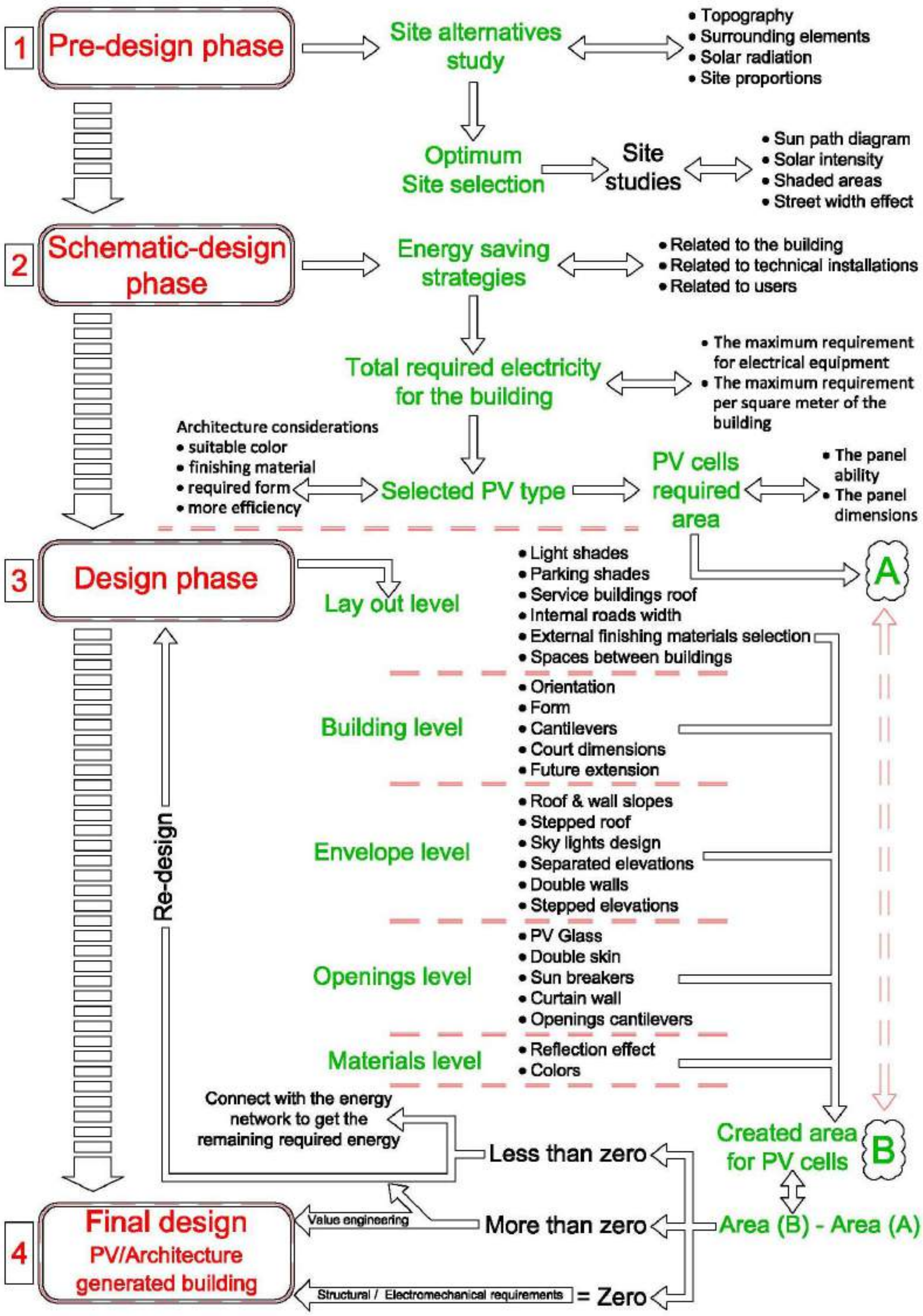

Figure 22. PV cells as sun breakers, source: https://www.gabreport.com


Figure 23. PV cells as smart louvers, source: http://www.wikiwand.com

4.3.5. The integrated design for the finishes and material level:

- Choice of the PV cells Colour and surface from the contemporary types to be compatible with exterior finishes.
- Taking into consideration the visual effect for the photovoltaic cells resulting from the reflection of solar radiation on the protective glass of cells, either by choosing the position of cells away from vision or using contemporary types that prevent the reflection of solar radiation.

5. The proposed methodology for the integrated (PV/Arch.) design of the building:



6. Results:

- The successful (PV/Architecture) integrated design should to be designed from the co-operation between: architectural engineer, structural engineer, urban design engineer, landscape design engineer and electromechanical engineer.
- The urban planner has an important issue in the study of road widths and distances between buildings for its direct effect on the exposed areas for the solar radiation.
- The PV systems installed over the roof are more efficient than the systems installed on the external facades due to its exposure to solar radiation with a great intensity.
- Environmental climatic data are considered to have a direct impact on the efficiency of the photovoltaic system, which include: the solar intensity, clouds, temperature and the solar radiation.
- The surrounding architectural elements have a direct impact on the efficiency of the design of the photovoltaic system.
- The most important constraints in the field of solar energy are the shortage in the technical awareness of the designer and the economics of installation of the photovoltaic system.
- The horizontal future extension for the building has a positive effect more than the vertical extension on the optimum use for the PV units.
- The photovoltaic systems in the buildings does not conflict with the architecture design and can be integrated together.
- The inclined walls and roof are the optimum base for the PV units.
- The separate buildings are better than the attached buildings in the utilization of solar radiation in PV systems.
- The application of photovoltaic systems to buildings during the architectural design phase is better than the modification of the existing buildings and produces an integrated (PV/Architecture) design of an energy generator building.
- The solar radiation angle has a direct effect on the courts design and the spacing between the project buildings.
- The traditional efficiency of photovoltaic cells is about 15% and its life is 20 years.
- A significant progress was discovered in the PV systems during the period 1985:1990.
- The PV systems cost were decreased by 70% during the period from 1985 to 2011.
- New developments for photovoltaic cells occurred during the last years that effect positively on: shape- efficiency-the concept of its work.
- There are many techniques contribute to the development of the traditional photovoltaic systems to be more efficient such as: lenses, concentrators, mirrors and reflectors.
- The economics of photovoltaic systems are based on several factors, such as: the consumption rate, the systems location and the availability of traditional energy.
- There are many factors that contribute to increasing the economic efficiency such as: the short installation time, applicability in distant areas and the low maintenance costs.
- The integrated (PV/Architecture) design steps can be mentioned as follow: applying the energy consumption saving strategies, the calculation of the required electrical loads for the building, selection of the PV cells type, calculation of the required PV units and the proposed ideas for the integrated (PV/Architecture) design.
- The integrated (PV/Architecture) design can be classified to five levels.

- The integrated design at the lay out level includes: shading for the external areas, service building roofing and distance between buildings.
- The integrated design at the building form level includes: the orientation, the form, the cantilevers, internal courts and the future extension.
- The integrated design at the external envelope level includes: sloped roof and walls, double roof and walls, the separate facades location and the upper lighting.
- The integrated design at the openings level includes: types of glass, solar breakers, the double skin and the openings cantilevers.
- The integrated design at the materials level includes: colour selection and reflective glass material.

7. Recommendations:

- Take into consideration the future extension locations for the expected added PV cells according to the expected electromechanical demands in the future.
- The need to activate and use of the contemporary PV cells to get more efficient photovoltaic systems.
- The importance of maximizing the direct and reflected solar radiation on the cells through the right selection to the suitable design and the optimum cell colour.
- The importance of the modifications of the traditional environmental design items such as solar breakers, double roofing, double skin, ………etc. and the use of photovoltaic cells as one of its main components to create an environmental energy generated item to be as a first step in the (PV/Architecture) design.
- There is an important need to activate the workshops to the designers and users to be aware of the importance of PV systems and its advantages.
- The codes and the design standards should to be reviewed by the designers especially the points related to the required dimensions for the streets, courts, buildings height, ……etc. to be suitable for the PV design.
- The new PV technologies should to be used for the required development for the existing PV systems.
- The suitable PV cell selection depends on the architecture design to create an integrated energy generated building.
- The large width of the street and the distances between the buildings lead to the maximum exposure of the building to solar radiation in summer and winter, thus avoiding the shading of the existing photovoltaic cell systems.
- The designer must take into consideration all elements that have a negative impact on the photovoltaic system, especially the items related to the shading and the climatic data.
- The designers can use the photovoltaic cells to produce the electricity from the solar radiation and also to be an environmental design element.
- Innovative design is one of the success factors of the integrated design between the building and the photovoltaic systems.
- The designer must take into consideration all the requirements of the PV system from the first step in the schematic design.
- There is an important need to follow a scientific methodology by the architectural, structural, urban and electromechanical engineers to create the optimum photovoltaic systems.

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Vernacular houses: exemplars of survival and comfort in extremely hot and humid conditions

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Abstract: With rapid urbanisation in the developing world, much of which is occurring in hot climates, methods of providing sustainable thermal comfort without resorting to energy intensive equipment are urgently required. In such climates, most urban buildings are dependent on electrical air-conditioners, leading to increased use of energy to maintain comfortable indoor conditions during the hot season. This results in more emissions of carbon dioxide, which contributes to global warming. As the climate gets warmer, the dependence on electrical air-conditioners increases to avoid the risk of overheating. In these regions, reductions or cutbacks in electrical power are predicted because of problems related to the production of electricity and overuse by consumers. Therefore, if for any reason the electricity fails, urban buildings become overheated, and under extreme conditions, uninhabitable. It is necessary to take steps to prepare for and adapt to such conditions.

For centuries, before electric cooling systems were invented, traditional houses in the hot and humid regions of Jeddah were designed in such a way that the inhabitants were able to cope with extreme climatic conditions. These houses serve as exemplars to demonstrate how extreme temperatures could be managed in the absence of electrical power. But, are these past design solutions still sustainable in present-day environments?

This article identifies the main vernacular strategies and technologies (i.e., natural ventilation, shading, thermal mass, material selection, etc.) that were used in the design of traditional housing in the hot, humid climate of Saudi Arabia. We investigate, through interviews, how they are perceived by their local users and stakeholders. This study was used to generate an understanding of how such technologies might be upgraded to help provide truly sustainable and comfortable buildings under extremely uncomfortable living conditions.

Keywords: extreme climatic conditions, hot and humid, vernacular architecture, passive cooling, material selection

Introduction

With rapid population growth and urbanisation in the developing world, much of which is occurring in hot and warming climates, methods to provide thermal comfort without resorting to energy-intensive equipment are urgently required (Foruzanmehr, 2018). In such climates, most existing buildings are dependent on electrical air-conditioners, which leads to an increase in electricity use to maintain comfortable indoor conditions during the summer. This results in more emissions of carbon dioxide contributing to climate change. According to Nicol (2008), global warming and climate change, along with excessive use of energy and natural resources, are currently threatening the sustainability of life on Earth. Problems, such as water and resources scarcity, increasing energy demands and costs, shrinking fossil fuel reserves, and global warming, have sounded a wakeup call around the world (Hootman, 2012, p.1). In this situation, residential heating and cooling to satisfy people's ever-escalating requirements for home comfort accounts for about one-fifth the earth's total fossil fuel energy production (Chiras, 2002, p.4). Thus, low-energy designs and renewable alternative energy resources in the 21st century are of paramount importance (Chen *et al*., 2010).

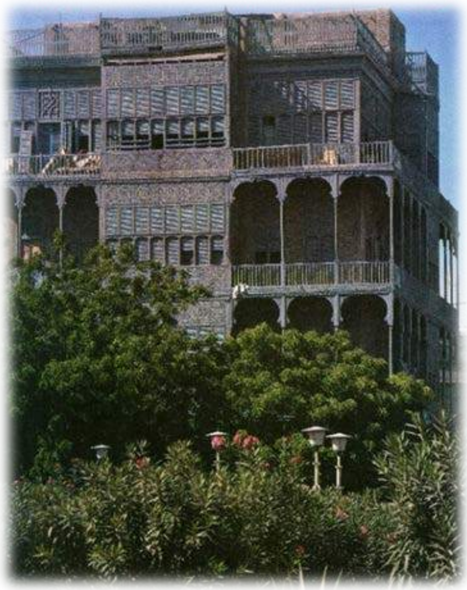
Oil-rich Middle-Eastern countries, such as Saudi Arabia, are claimed to be among the top contributors to air pollution in the world (Reiche, 2010). For several decades, Saudi Arabia has undergone rapid population growth and economic development, which have increased energy demand, and in turn, more power generation is required to meet those demands. In the hot climate of Saudi Arabia, most residential buildings rely on electrical air-conditioning systems to provide comfortable indoor temperatures, and this leads to a high demand for electricity, especially when weather conditions are harsh and extreme (Foruzanmehr, 2010).

The nation's domestic air-conditioning devices consume from 38% to 60% of the total electrical energy used (Choudhury *et al*., 2010), while a huge amount of electricity is also used for lighting in buildings. With a growing number of residential customer connections to the power grid, the surge in electricity demand is projected to continue its growth to reach double its size (in 2011) by the year 2023 (Hepbasli and Alsuhaibani, 2011). Because of overuse by consumers, reductions or cutbacks in electric power are possible (Bahadori *et al.*, 2008). As a result, people will not be able to rely on electro-mechanical cooling systems; thus, will not be able to tolerate the heat in the event of electrical power failures, particularly during the day. (Figure 1).

Figure 1 Overuse of A/C in Saudi Arabia
Source: The Free Thought Project (2015)

For centuries, before electric cooling systems were invented, traditional houses in the hot and humid regions of Jeddah were designed in such a way that the inhabitants could manage the extreme climate. These houses serve as exemplars to show how overheating could be tackled in extreme conditions without any electrical power (Figure 2). But, are these past design solutions still sustainable in the present-day environments? Many of the vernacular architectural features of the past, which were essential for living in hot climates, have been ignored, identified as signs of underdevelopment and replaced by methods that are inappropriate to social, cultural and environmental conditions (Afshar *et al.*, 1975; Singh et al., 2009).

Figure 2 *Mashrabiyah* of a house in Jeddah.
Source: Buchan (1986)



Research aim

This article identifies the main vernacular strategies and technologies used in the traditional housing of hot humid climates of Saudi Arabia, and investigates, through interviews, how they are perceived today. This study generates an understanding of how such technologies could be upgraded and applied to help provide truly sustainable and comfortable buildings under extremely uncomfortable living conditions.

Methodology

The methodology was developed to understand traditional passive cooling systems, particularly the ones used in the hot humid climates of Jeddah, and to gather and analyse data that reflect the attitudes of local professionals in the field of architecture towards traditional passive technologies in the hot humid climates of Saudi Arabia, and to identify potential barriers related to the reimplementation of these technologies.

First, an extensive literature review was carried out to establish the background for the study, and to explore the types of traditional cooling methods that were used in traditional Hijazi houses, i.e., the houses of old Jeddah. Jeddah was selected because there are still a number of intact traditional houses equipped with traditional passive cooling features, such as *rowshans, i.e.,* shaded bay windows or wind-catchers, which facilitate natural ventilation.

In this research, the interview was identified as a suitable method of data collection, and a group of six interviewees, comprising local experts, architects, academics and interior designers with knowledge of Jeddah's architecture, was selected. A list of open questions and topics was compiled from the main research questions, and the literature review. They were framed in a set of 10 optional & open questions, and used as the interview schedule. Interviews were conducted in person, on the phone and via Skype. Each interview lasted for approximately half an hour depending on the flow of information from the interviewee.

Hot humid Jeddah and climate-responsive traditional houses

Jeddah: Geography and Climate

Jeddah, on the eastern coast of the Red Sea, is the second largest city in Saudi Arabia after Riyadh (Figure 3). It is the major urban centre of western Saudi Arabia, the largest city in Mekkah province, and the largest sea port on the Red Sea. It was the stopping place for pilgrims on their way to and from the holy cities of Mecca and Medina. For centuries it has been an important trading centre in the diplomatic capital of the region (Kamal, 2014).

Figure (3) Location of Jeddah in Saudi Arabia.
Source: Ezilon Maps (2015)

Jeddah is extremely humid throughout the year with the average relative humidity of 75 to 80 percent. Humidity reaches its highest levels in summer because of the high temperature of the sea water in near proximity. However, winters are mild with a relatively lower humidity. In summer, the average maximum and minimum temperatures are 37° and 27° C, respectively. During the winter, average maximum and minimum temperatures are 29° and 18° C (BBC, 2016). Generally, the prevailing winds over Jeddah are north-westerly, due to the city's coastal location on the shore of the Red Sea, with a mild to medium wind speed throughout most of the year. Occasional southerly winds, especially during winter months, can give rise to sand, thunder and rain storms. Most of the precipitation is in the form of rain showers, sometimes accompanied by thunderstorms. These usually take place in winter and rarely in spring and autumn.

The climate of Jeddah is harsh, hot and humid, against which the traditional built environment of Jeddah has effectively been responsive. Various climate responsive natural and passive features and techniques have been used to maintain maximum thermal comfort within buildings, particularly during the hot humid hours of the day. The following section introduces these features and techniques, of which some can be adapted and incorporated into the design of contemporary residential architecture of western Saudi Arabia to help in the provision of comfort such an extreme climate.

Traditional buildings in Jeddah

Having historically been a trading port, Jeddah, acted as a cross-cultural point between the trading Middle-Eastern Asian and European nations (Talib, 1984, p.67). This enriched the arts and architecture of Hijaz. Furthermore, the Hajj pilgrims, who came from various parts of the world, brought their skills and exchanged ideas with the local people. In addition, building activities in Egypt across the Red Sea influenced the construction skills of the builders of Hijaz (Kamal, 2014). For example, *mashrabiyas,* or projecting screened windows called *rowshans*, prominent features of Hijaz architecture, originated in Egypt (Figures 4 and 5).

Figure (4) Old Jeddah's historic treasures are in danger of being lost.
Source: Buchan (1986).

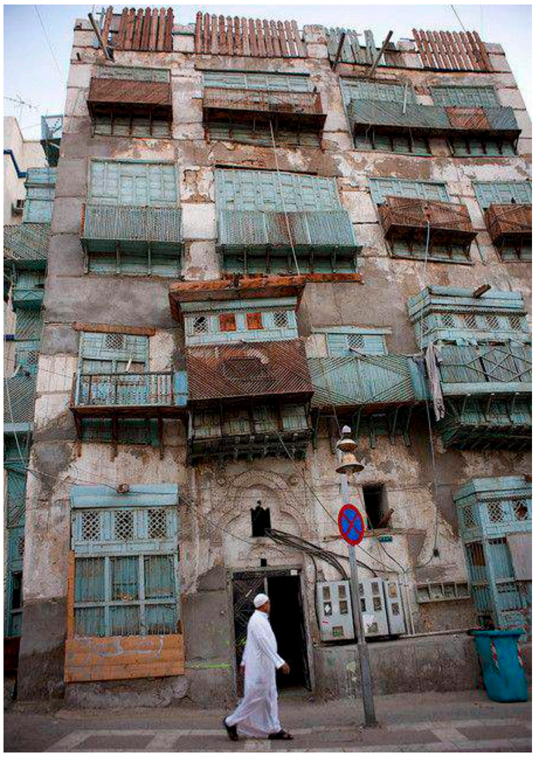


Figure (5) Old Jeddah's historic treasures are in danger of being lost.
Source: Pinterest (2016).

Building materials in Jeddah's traditional buildings

The building materials used in the past in and around Jeddah were superior in quality to those in other regions of Saudi Arabia. Jeddah was an intercontinental trading port for centuries, resided mostly by merchants. The line of trade allowed importation of building materials not available locally such as teak, mahogany and S*isam* wood (Talib, 1984). The wealthy merchant houses were built with expensive wood, and coral stones dug from the Red Sea, by engineers, builders and artisans from distant places such as India, North Africa, Java, Burma, East Africa, and southern Europe (Talib, 1984). Tall, airy and light structures, up to seven stories high, that were built for the rich merchants of Jeddah still stand in their magnificence after two to three hundred years (Figure 6). Intermarriage and intermixing of cultures and of differing technological skills in Hijaz produced architecture that demonstrated a better use of materials and a superior technology.

Figure (6) One of the finest examples of architecture in Old Jeddah, Nassif House, is a large merchant residence. The fretwork, mouldings, *mashrabiyah* and fanlights have been preserved and restored to their original state. **Source:** Buchan (1986).

In Jeddah, buildings were basically framed structures with infill facades of wooden screens called *rowshans*. The main structure was made of coral stones taken from the reefs of the Red Sea, and cemented together with clay from the bed of the Al-Manqabah lagoon (Figure 7).

Figure (7) Ocean rock and coral stone load bearing construction
Source: Kamal (2014)

Hard timber used for the beams was transported from Africa and Indonesia (Pint, 2005), and the ornate balconies and windows were built with wood imported from India or Burma (Llewelly-Jones, 1995). The foundation was constructed using coral stones. According to Kamal (2014), the walls were generally 60-70 cm thick and the thickness was reduced on the upper floors as needed. Gypsum was used as a bonding material in stone construction and as a sealant. Gypsum was also used for plastering and water proofing, and teak, mahogany and *sisam* wood were used for doors and windows (Figure 8).

Figure (8) Timber roof of a typical traditional house
Source: Kamal (2014)

Traditional responses to the hot humid climate

Until 1947, Jeddah was a small town of less than one square kilometre with approximately 35,000 inhabitants living within city walls (Al-Ban, 2016) (Figure 9). After the wall was demolished in 1947, most of the old town remained intact. Today, the remaining parts of the old town form a traditional neighbourhood (called *Al-Balad*) within greater Jeddah (Al-Ban, 2016) (Figure 10). The urban and architectural design of *Al-Balad* shows how people of the past tackled overheating through the design of their settlement.

Figure (9) Jeddah in 1948
Source: www.skyscrapercity.com/showthread.php?t=294912&page=23

Figure (10) Settlement pattern and layout of *Al Balad* - Jeddah
Source: www.maps.google.com

According to Al-Ban (2016), the orientation of the streets in Jeddah corresponded to the north and north-westerly coastal breezes. The streets were wide and well-aligned, whereas, the alleyways were narrow and well shaded (Al-Ban, 2016). Houses were primarily detached or semi-detached units to facilitate the flow of air between buildings and alleyways (Al-Ban, 2016). The orientation of structures and the layout of streets increased air flow and cross-ventilation. In addition, the height and proximity of traditional houses to one another created shade, and protected the streets from direct sun and heat. Because land was scarce within the town walls, houses differed from traditional Islamic courtyard homes in which a two-story structures surrounded a courtyard. Instead, courtyards were replaced by roof terraces (Figure 11), and traditional buildings of old Jeddah were constructed tall, and equipped with *rowshan*s (Al-Ban, 2016). Tall houses caught the sea breeze and channelled it through the entire house. Towards the top of the house, the floor area of each succeeding story was reduced as terraces were created on the roofs of the rooms below. The terraces enabled women to organize outdoor domestic activities, such as drying clothes, while remaining screened from the streets below by balustrades around each terrace. Houses were typically arranged to prevent outsiders from looking in, a reflection of an Islamic sense of politeness and decorum (Al-Ban, 2016).
In some exceptional cases in Jeddah, very large houses were built with courtyards to provide cross-ventilation and to create a large interior space emphasizing the interiority of the Arab house. The courtyard in such situations was highly decorative, and might contain fountains which further enhanced the introverted environment of the houses (Talib, 1984).

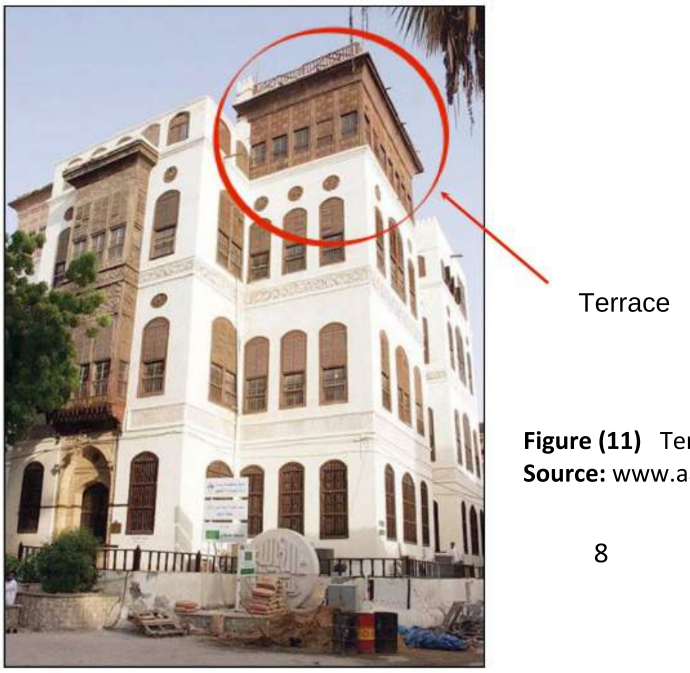


Figure (11) Terrace at Bayt Nassief - Jeddah
Source: www.aawsat.com/2010/07/29/images/ksa-local1.580105.jpg

Talib (1984) has identified the techniques through which traditional settlements of Jeddah responded to the hot-humid climate of the region:

- Wider streets allow passage of air except in the densely built, poorer sections.

Figure (12) Tall houses catch the regular sea breezes and create upward drafts with their temperature differences. The overhanging open-louvered windows filter glare but allow air to circulate freely in the rooms. The streets are intentionally as narrow as possible to provide maximum shade. **Source:** Buchan (1986).

- Construction of tall, airy structures to allow cross-ventilation and better penetration of breezes (Figure 13);

Figure (13) A tall, airy house in Jeddah. **Source:** Buchan (1986).

- Invention of *mashrabiyahs* (*rowshans*) – projected by windows enclosed with decorative wood screens – to provide cross-ventilation as well as privacy (Figure 14);

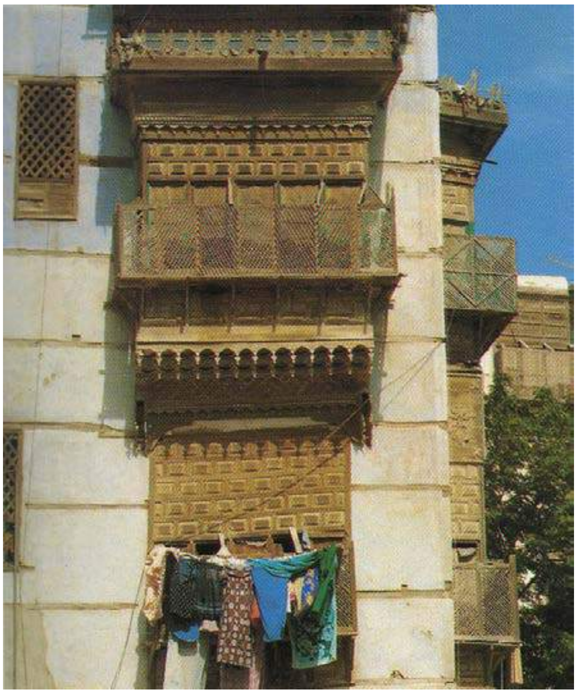


Figure (14) A house with *mashrabiyah* in Jeddah.
Source: Buchan (1986).

- Frame structures with transparent infill facades of wooden screens called *rowshans* (Figure 15);

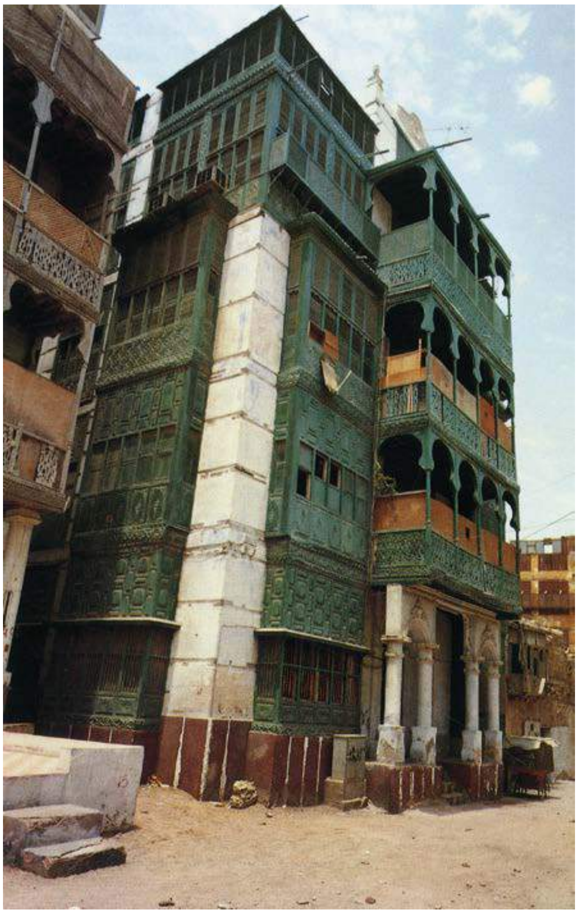


Figure (15) Galleries, balconies and bay windows (rawashin or *mashrabiyah)* ornament a large merchant house in Jeddah.
Source: Buchan (1986).

- A skeletal structure of heavy columns built from coral stones and wood framed floors and roof which allows the building to be bright and well ventilated;

Figure (16) A four-storey house built out of coral in Jeddah with wooden rawasheen. **Source:** Al-Ban (2016).

- The use of coral, and gypsum as a bonding material in stone construction and as a sealant. Gypsum was also used as plaster and for water proofing;

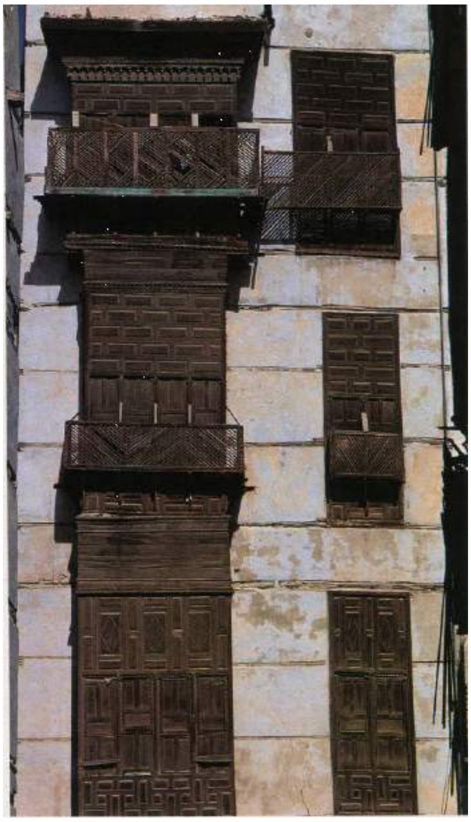


Figure (17) Use of gypsum as plaster and for water proofing.
Source: Buchan (1986).

- An internal plan, which provides cross-ventilation to each room through access to external facades, with sleeping and family rooms on upper floors to take advantage of on-shore and off-shore breezes;

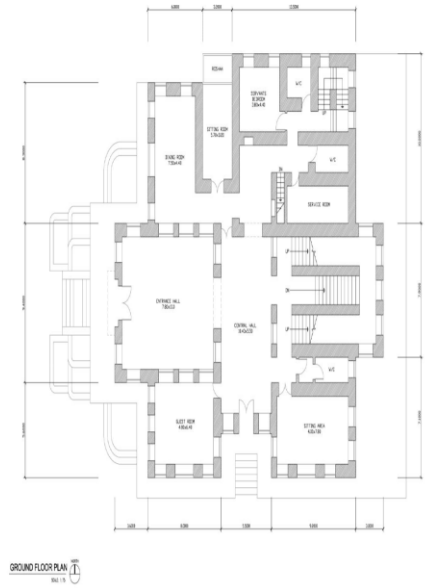


Figure (18) Ground Floor Plan - Bayt Nassief
Source: Al-Ban (2016)

- Buildings were constructed in such a way that air could move freely around them. When this was impossible, such as in congested areas of Jeddah, building facades competed with each other to project as many *rowshans* and screened windows as possible (Figure 19). Sometimes entire streetscapes were composed of dozens of m*ashrabiyahs* (*rowshans*);

Figure (19) In the past, it was the prosperous mercantile community that provided the patronage for the craftsmen to make Jeddah so notable a city. **Source:** Buchan (1986).

Rowshan (or *Mashrabiya*) - functions

The *rowshan* (also *mashrabiya* or *shanshool*) is a term given to a type of projecting window enclosed with carved wood latticework located on the second storey of a building or higher, often lined with stained glass. It was developed in response to the hot-humid climate of the western coast along the Red Sea (Talib, 1984) to fulfil four main functions: to provide shade, ventilation, and privacy and to demonstrate status. The *rowshan* was constructed entirely of cantilevered timber framework and was often installed over the openings after prefabrication with the desired decorations and finish. On most houses, the seasoned wood of *rowshans* was left exposed, but sometimes, it was painted.

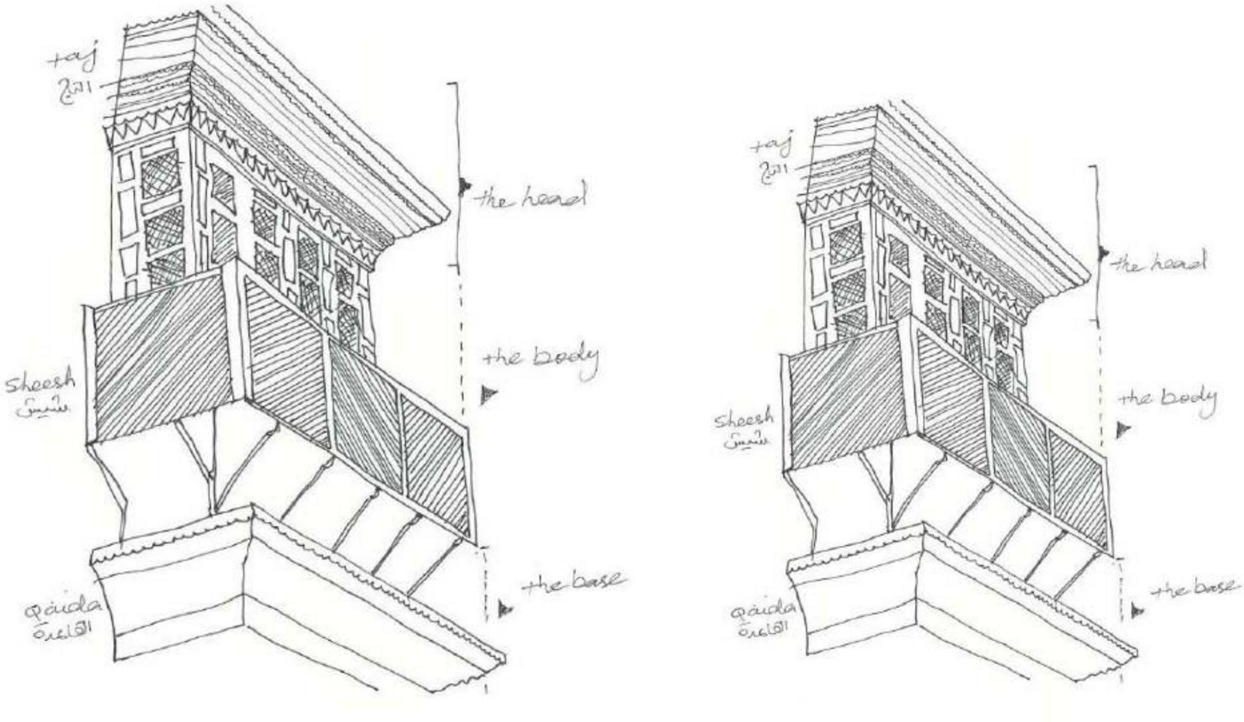


Figure (20) Sketch of Rowshan
Source: Al-Ban (2016).

The wooden screen was designed to provide shade and protection from the hot summer sun while allowing air from outside to flow into the house. Projected *roshans* enabled air from three sides to enter the house. R*oshans* also provided shade to the flat unprotected ground floor windows that often faced the streets.

Mashrabiyas were also designed to provide privacy. Privacy has always been an essential aspect of Arabic culture. The desire for privacy required that large openings, to allow for ventilation in hot humid climates, needed to be screened so that one was able to see out, without being seen from the outside (Figure 21). Such windows are often similar to a single awning window called a magic-eye. According to John Feeney (1974), *mashrabiyas* were veils drawn against the outside world and behind their cool shield of latticework those inside did recline in shaded privacy while gazing out at the tumult of the streets below.

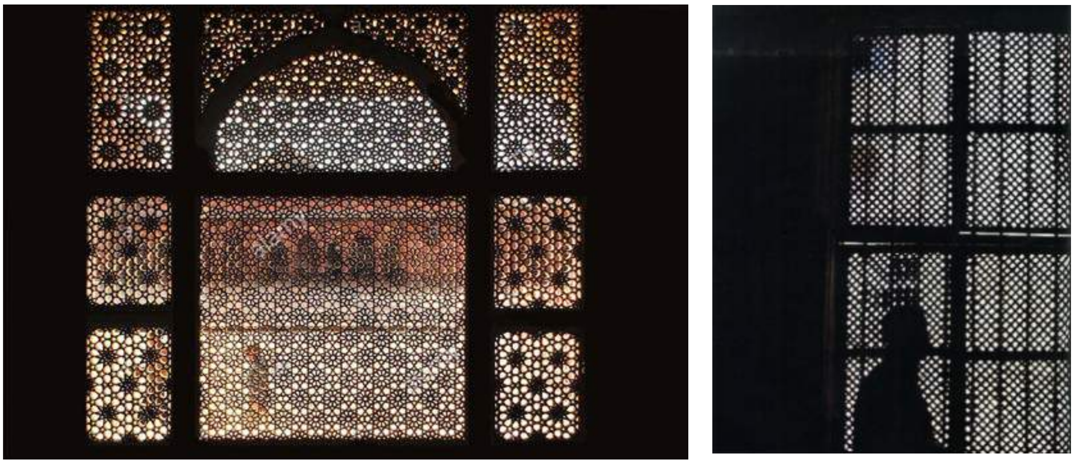


Figure (21) During hot summers, before the days of air conditioning, *mashrabiyas* made life tolerable for Jeddah citizens. **Source:** Buchan (1986).

Mashrabiyas (*rowshan*s) also became decorative elements and acquired popularity because they were indicators of prestige and high status.

Development of *rowshan*

In Egypt, and especially in Cairo, *mashrabiyas* (or *rowshans*) were first built in the 14th century. They were made of wood imported from Lebanon and Asia Minor, to encompass balconies to cool people as well as pots of drinking water (Feeney, 1974). Later, as they were fitted with cushioned beds running the length of the screen, they became comfortable spaces in which the occupants could recline in cool privacy while gazing down at the streets or courtyards below. Because of the high cost of materials, *mashrabiyas* were at first limited to the palaces of rulers and the homes of wealthier merchants as an outward sign of success. Gradually, *mashrabiya* became fairly common in Arab cities. For example, as recently as the late 1900's, entire Cairo street fronts were embellished with row upon row, level upon level of *mashrabiya* (Feeney, 1974). Splendid examples were also to be found in houses surrounding Ezbekiya Lake and the Khalig Canal in Egypt. But, the best examples were found in the great homes of Cairo and Jeddah (Figure 22). As can be seen, in large houses, *mashrabiyas* may adorn the entire façade.

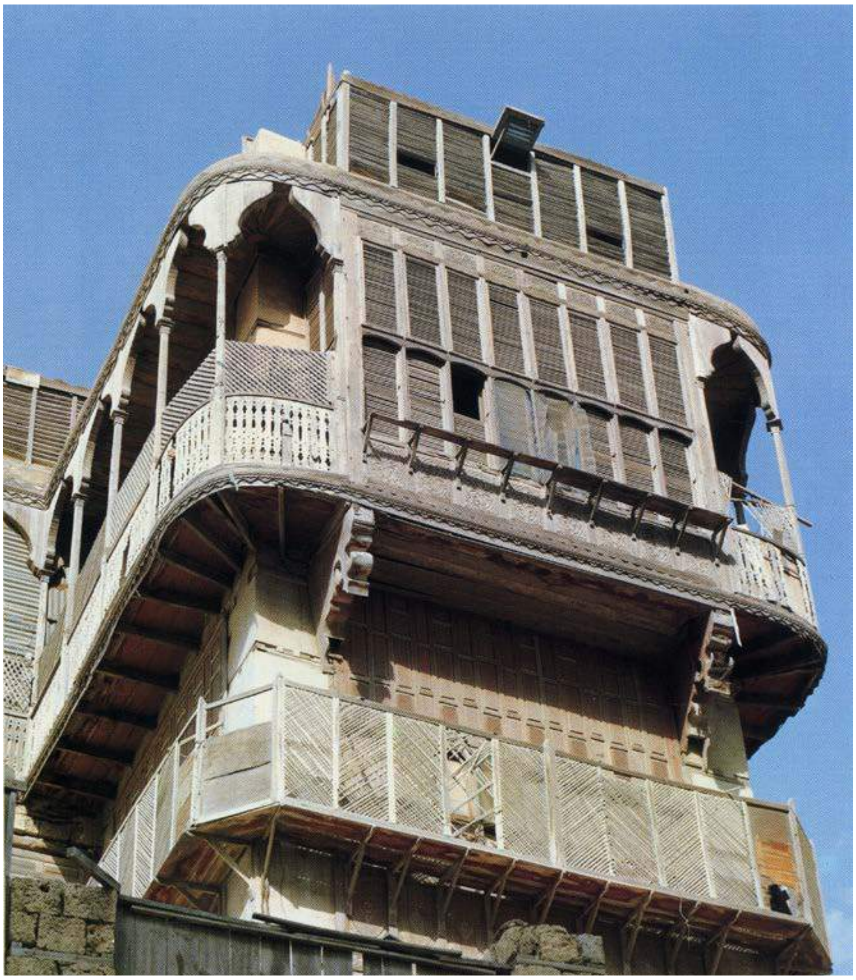


Figure 22 The projecting loggia of the large merchant house – Beit Al-Torki. Suspended six storeys above the street by a complex and carefully calculated sequence of cantilevers and crobels. This striking example of a chamber was where the whole family gathered together to enjoy cool onshore breezes. **Source:** Buchan (1986).

However, *mashrabiyas* had their own shortfalls. They did not stop any bad smells or insects from coming in to the home. They also became a fire hazard. Tinder dry, and crowded along narrow streets, often nearly touching, they could easily catch fire (Feeney, 1974). There are accounts of fires leaping from window to window at frightening speeds. As a result, many were removed, and the practice of building *mashrabiyas* declined.

Interviews outcomes

Most of the interviewees perceived the incorporation of natural cooling into the design of buildings in Saudi Arabia to be important because of its positive effects on the environment and energy resources. However, some found passive design techniques impractical compared to conventional cooling technologies.

The interviewees mentioned that *mashrabiya*s, large courtyards within houses, high interior room ceilings, and narrow and open networks of alleyways around buildings were the primary traditional passive cooling methods, or design features, in the hot humid climate of Jeddah. In this regard, the main aspects liked about traditional *mashrabiya*s was said to be their 'aesthetically pleasing' appearance, and the 'provision of an intermediate space within the room' with 'high levels of privacy required by the culture. The overuse of non-functional *mashrabiya*-like patterns, as a sign of identity, was disliked by one of the interviewees. He believed that there were other and better ways to achieve this goal.

The reduction of external heat gains was identified as the most important method of passive design in hot climates; and the use of shading devices was considered the best solution to reduce external heat gains. The interviewees claimed that they would consider natural ventilation as an important factor and would take it into account in the design if they wanted to purge built-up heat from indoor spaces.

The respondents agreed that the biggest possible problem they faced when putting natural cooling measures (including vernacular ones) into practice in Saudi Arabia was that these measures were not required or supported by clients, and therefore, were not funded and incorporated into the design.

Three of the interviewees expected 'natural cooling' to become less important for them and their potential clients in the future, whereas two had the opposite opinion. Cheap electricity, the availability of convenient cooling systems, and the scarcity of appropriate and affordable building materials for vernacular design (i.e., traditional *mashrabiya*s) have turned the attention of the investors and developers away from natural cooling to electric air-conditioning systems. In addition, most of the developers were not convinced that natural cooling systems could provide the residents with adequate cooling. These were the main reasons why passive design features were considered less important in Saudi Arabia.

Furthermore, the interviewees believed that traditional architectural features and their role in creating the identity of towns and cities, in this case Jeddah, were not highly regarded by investors, developers, and architects.

Conclusion

Findings from the interviews in this study indicate that natural cooling techniques and design features in Saudi Arabia are important, especially in academic communities. With respect to practical applications, there is generally a lack of awareness and little support from the investors and building developers. Thus, natural cooling, including vernacular and traditional techniques, become undervalued, and they are not incorporated into contemporary construction.

There is huge potential for implementing passive cooling strategies into the design of residential buildings in Jeddah. This could not only add to the values of the building aesthetically and environmentally by using passive cooling strategies, local architectural designers could also revitalise cultural and historical values and traditional features through new and innovative designs. Although there currently appears to be little demand for this from developers and investors, they could gradually be educated on the subject by architects and academics and those involved in the field of building design and construction through conferences, workshops and similar events or through media.

The economic, social, cultural, environmental and physical significance of traditional building design necessitates their conservation, rehabilitation and regeneration and calls for understanding the methods by which they are conserved, rehabilitated and regenerated. Incorporation and re-application of vernacular cooling strategies to design naturally cooled modern buildings could reduce the costs associated with cooling loads, which at a larger urban and regional scale could considerably reduce the use of fossil fuels and production of air pollutants.

The authors believe that a lack of appropriate and affordable building materials is a bottleneck to take advantage of this type of vernacular architecture. Therefore, the development of sustainable building materials using local natural resources may pave the way for traditional *mashrabiya*s to return to the construction market and promote sustainable vernacular architecture.

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Thermal Comfort in Higher Educational Buildings: Different Classroom Types

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Abstract: Thermal comfort in learning environments influences the students' attention, concentration and learning productivity. Due to the impact of the thermal environment on students' thermal comfort and consequently their productivity in line with the impact on energy consumption, this topic has attracted substantial attention among researchers in the recent years. This study aims to evaluate thermal comfort of the students in different classroom types in the UK higher learning environments. Thermal comfort zone, comfort temperature and thermal acceptance are evaluated under Free running, Cooling and Heating modes. Simultaneous environmental measurements and questionnaire survey were conducted in the classrooms under each mode. 2046 students participated in the surveys in a university building in Coventry, United Kingdom, between October 2017 and March 2018. Results present thermal comfort zone between 21°C and 25°C and comfort temperature of around 23°C in the classrooms under each operation mode. The research output helps to expand the existing environmental guidelines for higher educational buildings to have more reliable and energy efficient standards.

Keywords: Thermal comfort, Higher education buildings, Comfort temperature, Energy efficiency

1. Introduction

Thermal comfort in learning environments influences the students' attention, concentration and learning productivity [1–4]. Both higher and lower temperatures than the comfort zone tend to reduce students' performance and ability to grasp instruction. Warm environment affects students' productivity and cold temperatures reduces manual dexterity and speed [7, 8]. Due to the influence of the thermal environment on students' thermal comfort and productivity in line with the impact on energy consumption, this topic has attracted huge attention among researchers in the recent years. So far, studies have been conducted on thermal comfort in educational buildings in *primary schools* in the UK [7, 8, 11, 12], Italy [11], Netherlands [7, 14] and Taiwan [13], *secondary schools* in Italy [16, 17], Portugal [16] and Cyprus [17] and *university buildings* in Italy [5, 20], Netherlands [19], Japan [22, 23], Brazil [22] and India [25, 26]. Vargas [27, 28] conducted two studies in Sheffield University in the UK evaluating the impact of HVAC technologies on environmental diversity along with examining the role of transitional lobby spaces on the occupants' thermal comfort in interior spaces. However, there are only limited studies carried out to investigate thermal comfort in the UK higher educational buildings [30, 31]. Existing guidelines such as CIBSE-A [29] and ASHRAE 55 [30] recommend general environmental standards for educational buildings, however, no detail information provided based on the educational levels. There is no specific standard for the higher learning environments where providing comfort for the occupants is quite challenging mainly due to the students' different climatic background, various subjects and exposed classroom types. Students in higher learning environments are typically from different disciplines and studying in disparate topics. They are exposed to dissimilar environmental conditions, in different classroom types, with variable occupancy periods and different levels of freedom for adaptive behaviour. For example, students in art-based subjects may spend four or five hours in studios with high levels of freedom for adaptive behaviour. While, students, mostly in science-based subjects, tend to occupy the lecture rooms for one to two hours or PC labs for two to three hours with low or medium levels of freedom. This study aims to evaluate the comfort temperature for students in different disciplines, art- based and science- based subjects, attending the studios and lecture rooms/ PC labs classroom types respectively.

2. Methodology

Field experiments were conducted through simultaneous environmental evaluation, questionnaire survey and observation in the four university buildings in Coventry, England. Mean annual temperature in Coventry is 12°C [31]. Relative humidity and mean annual air velocity is around 85% and 2 m/s respectively. Data collection took place between October and November 2017; and between January and April 2018. Experiments were conducted in the classrooms in four different mixed- mode buildings. All classrooms were equipped with HVAC systems and operated on changeover or concurrent mixed-mode [32]. Based on the indoor ambient environment, free running (FR, neither heating nor cooling), cooling (CL) or heating (HT) mode were preferred by occupants in those spaces.

Field measurements included recording of indoor air temperature (T_{in}), relative humidity (RH), air velocity (V_i) and mean radiant temperature (T_{mr}) in each classroom. Relative humidity, air velocity and mean radiant temperature were recorded using Multi purposes SWEMA 3000 instrument working based on ISO 7730 with time interval of 5 minutes. Probes included in SWEMA kit were positioned at the occupants' head height to reflect all subjects' thermal sensation. Thermometer placed on 1.1m above the floor level, as recommended by EN ISO 7726 [33], anemometer and humidity probe were placed above and below the thermometer. SWEMA kit and one temperature and RH logger were placed in the middle of the room, away from heat or cool sources.

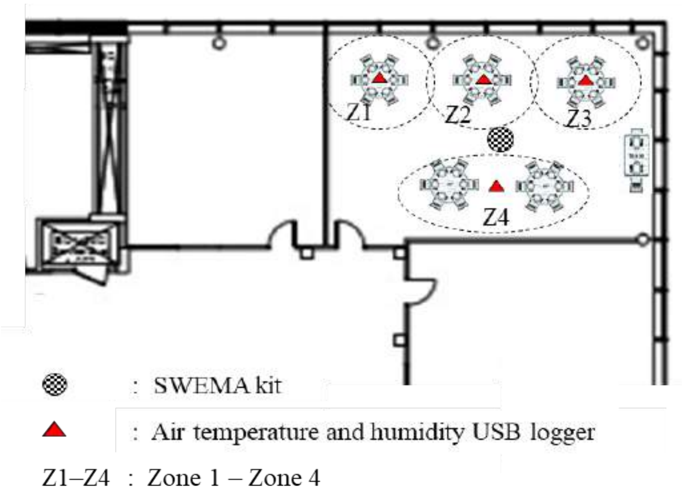


Figure 1. architectural plan of one of the surveyed classrooms

Classrooms were divided into 4 or 5 zones (Figure 1), based on the physical shape, and each temperature and RH logger were located in each zone to have nearest environmental data on the students' sensations. Operative temperature, which is generally worked within this study, was calculated as the mean of radiant temperature and indoor air temperature [34]. Outdoor air temperature data was obtained from the UK meteorological office [31]. Cross-sectional questionnaire survey was conducted on students in studios, PC labs and lecture rooms after obtaining ethical approval from both universities.

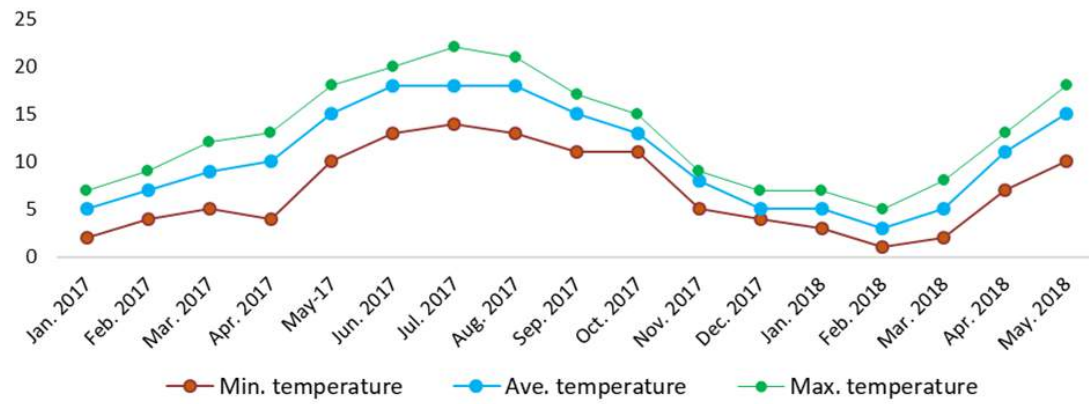
The duration of each lecture was around 1 or 2 hours while the students were seated listening to the lecturer. However, in studios they were involved in activities such as making samples and drawing which took almost half a day with couple of breaks in between. According to CIBSE-A [35], metabolic rate was considered 1.4 met for students in lecture rooms and PC labs and 1.8 in studios (workshop). Occupants' clothing level were evaluated based on the introduced clo value in EN ISO 7730 [36].

Table 1. Thermal comfort scales

Scale	−3	−2	−1	0	1	2	3
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 sensation vote (TSV) was examined based on the ASHRAE 7 point scale. A similar 7-point scale was used for thermal preferences (TP), Table 1. The questionnaires were distributed in the last 15 minutes of each class, after at least 1-hour that students had sat in the classrooms. It is mentioned in the previous studies that 15 minutes is enough to eliminate the influence of metabolism on thermal sensation votes [53, 54]. All participants were asked to complete the questionnaires at the same time to make sure the recorded environmental variables correspond to all the collected thermal sensation votes. Overall, 2046 students, 1247 in lecture rooms, 408 in studios and 391 in PC labs participated in the survey. Each student participated once in the survey. Participants were in both genders and in average aged between 18 and 25 years. Collected data were statistically analysed to estimate the comfort temperature in which majority of students are thermally satisfied.

3.



Results

3.1. Outdoor and indoor environment

Figure 2 shows the outdoor air fluctuations in 2017 – 2018 in Coventry. Minimum, average and maximum air temperature equals to 1, 7 and 15°C respectively within the survey period (October 2017- March 2018). Results for the indoor and outdoor environmental parameters are presented in Table 2. Mean indoor air temperature, mean radiant temperature and operative temperature approximately equals to 22.9°C, 22.6 °C and 22.8°C respectively. Mean operative temperature is higher in studios than the other classrooms by 1°C under FR mode and 2°C under HT mode. In the PC labs, it is 1°C higher than lecture rooms under both FR and CL modes.

Table 2. Summary of the indoor and outdoor environmental parameters

Classroom type	Mode	Items	T_{out} (°C)	T_{air} (°C)	T_{mr} (°C)	T_{op} (°C)	V_i (m/s)	RH_{in} (%)
Lecture room	FR	Mean	12.7	22.6	22.7	22.6	0.08	51
		SD	2.6	1.3	1.4	1.3	0.35	9
	CL	Mean	10.3	22.7	22.0	22.4	0.07	38
		SD	4.8	2.1	1.7	1.9	0.24	9
	HT	Mean	3.8	21.2	20.3	20.8	0.06	24
		SD	2.7	1.5	1.2	1.2	0.29	5
Studio	FR	Mean	14.0	24.0	23.8	23.9	0.07	60
		SD	2.2	1.0	1.1	0.9	0.04	7
	CL	Mean	-	-	-	-	-	-
		SD	-	-	-	-	-	-
	HT	Mean	9	23.3	23.2	23.2	0.03	41
		SD	0	0.6	0.7	0.6	0.01	4
PC lab	FR	Mean	11.3	23.3	23.5	23.4	0.03	44
		SD	2.0	0.9	0.8	0.8	0.02	7
	CL	Mean	13.1	23.5	23.1	23.3	0.08	49
		SD	1.8	0.5	0.7	0.6	0.05	5
	HT	Mean	-	-	-	-	-	-
		SD	-	-	-	-	-	-

T_{out} : Outdoor air temperature (°C), T_{air}: Indoor air temperature (°C), T_{mr}: Indoor mean radiant temperature (°C) , T_{op}: Operative temperature (°C), Vi: Indoor air velocity (m/s)

3.2. Subjective evaluation

Table 3 presents the summary of the subjective parameters collected during the survey. Mean thermal sensation votes (MTSVs) in all classroom types in both locations fell between -1 and 1. The negative value of MTSV in lecture rooms, -0.26, indicate cold thermal sensation of students in such spaces. However, MTSV in studios and PC labs equals to 0.20 and 0.12 respectively showing that students feel warmer than neutral in these environments. Thermal preference votes are toward warmer thermal environment in the lecture rooms and cooler environment in studios and PC labs, which is consistent with thermal sensation votes. Mean clothing value is in the range of 0.85 to 0.91 clo in all classroom types.

Table 3. Summary of subjective evaluations

Classroom	Modes	Items	TSV	TP	Clothing

types					(clo)
Lecture room	FR	Mean	-0.20	0.13	0.87
		SD	1.22	1.11	0.32
	CL	Mean	-0.23	0.11	0.85
		SD	1.20	1.12	0.31
	HT	Mean	-0.54	0.32	0.96
		SD	1.17	1.14	0.32
Studio	FR	Mean	0.18	-0.19	0.90
		SD	1.15	1.13	0.29
	CL	Mean	-	-	-
		SD	-	-	-
	HT	Mean	0.27	-0.12	0.87
		SD	1.14	1.05	0.30
PC lab	FR	Mean	0.19	-0.17	0.86
		SD	1.09	0.99	0.31
	CL	Mean	0.05	0.06	0.87
		SD	1.21	1.03	0.32
	HT	Mean	-	-	-
		SD	-	-	-

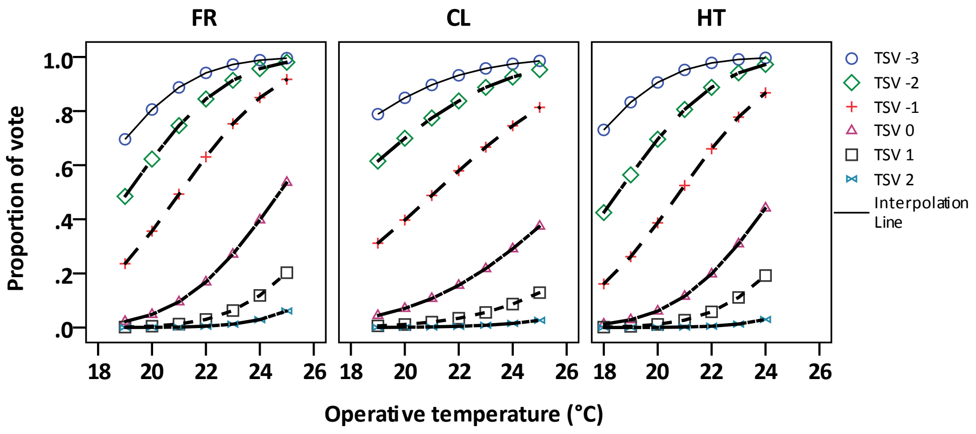
- : No data available

3.3. Comfort zone

To identify the comfort zone for the students under each operation mode, probit regression analysis is applied for thermal sensation votes and operative temperature. This analysis was conducted by applying probit regression as the link function and operative temperature as covariate [39].

The first line (highest) in Figures 3 (a) shows the proportion of TSVs of "-3 cold" and last line (lowest) indicates the proportion of TSV of "2 warm". The neutral temperature, between line TSV -1 and TSV 1, with probability of 0.5 is around 23°C in FR and HT modes and 24°C in CL mode. Optimum temperature with high proportion of occupants' satisfaction equals to 24°C under FR and CL and 22°C under HT mode. Considering standard of minimum 80% acceptability as recommended in regulatory documents such as ASHRAE - 55 [34], comfort zone equals to 22- 25°C under FR and CL and 21- 24°C under HT mode (Figure 3b).

(a)
(b)



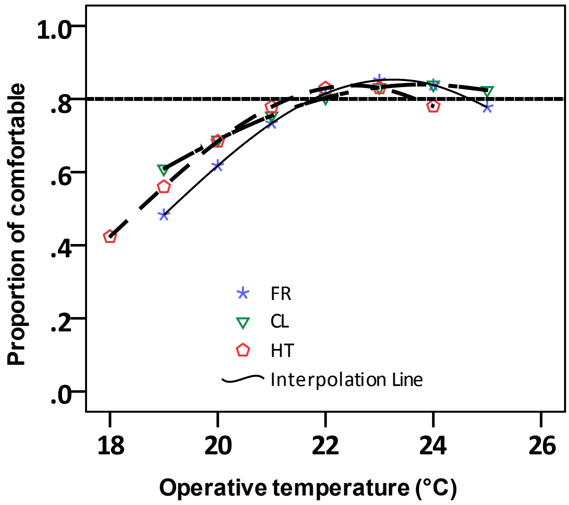


Figure 3. Comfort temperature in the classrooms in each mode

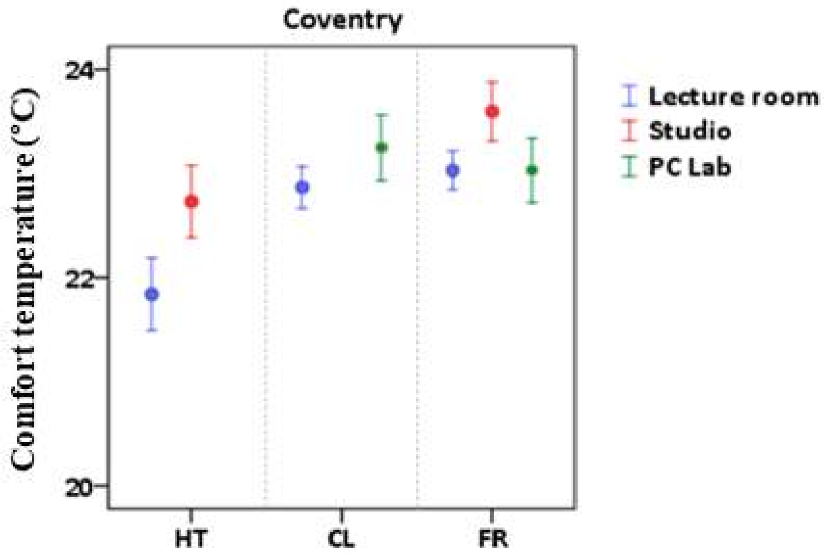
3.4. Comfort temperature

Griffiths' method is applied to estimate comfort temperature in each classroom type under FR, CL and HT modes. Results presented in Figure 4, shows statistically significant difference between comfort temperature in studios and lecture rooms under FR and HT modes in Coventry. There is approximately 1°C higher comfort temperature in studios compared to the lecture rooms in both operation modes. However, it is similar in the lecture rooms and PC labs under FR and CL modes.

According to Gail, et.al. [47], high levels of freedom and control over the space can lead to 1.5°C higher comfort temperature for the occupants compared to a group with limited control in a same environment. Therefore, higher comfort temperature in the studios is resulted from the students' higher levels of freedom and control in such spaces than the other classroom types.

Furthermore, according to Tables 2 and Figure 4, students' comfort temperature is very close to the actual experienced operative temperature in the studios. This similarity happens due to the students' thermal adaptation to the studios as they spend long enough time there to thermally adapt to the environment. Apart from physiological thermal adaptation which happens to maintain the constant internal body temperature and proved in some previous studies [34, 60, 61], psychological thermal adaptation plays an important role on students' thermal comfort in studios. Occupants' thermal assessment and mental benchmark during initial occupancy results from their thermal history, not current environmental condition [28, 31, 55, 56]. However, after extended period of occupancy they change the set benchmark according to the current thermal experience not previous environments [46].

Consequently, higher levels of freedom and control over the space as well as long occupancy period and thermal adaptation in the studios, is the main reason for higher comfort temperature in such spaces than the lecture rooms and PC labs.



3.5. Thermal acceptability in the lecture rooms, studios and PC labs

Figure 5 shows the thermal acceptability votes in the lecture rooms, studios and PC labs. As the common operative temperature range in all classroom types is from 22°C to 25°C, the evaluation of thermal acceptability is completed in this temperature range to get more reliable comparison results. Overall, 90% of the students voted for acceptable thermal environment and only 10% of them thermally evaluate the classrooms as unacceptable.

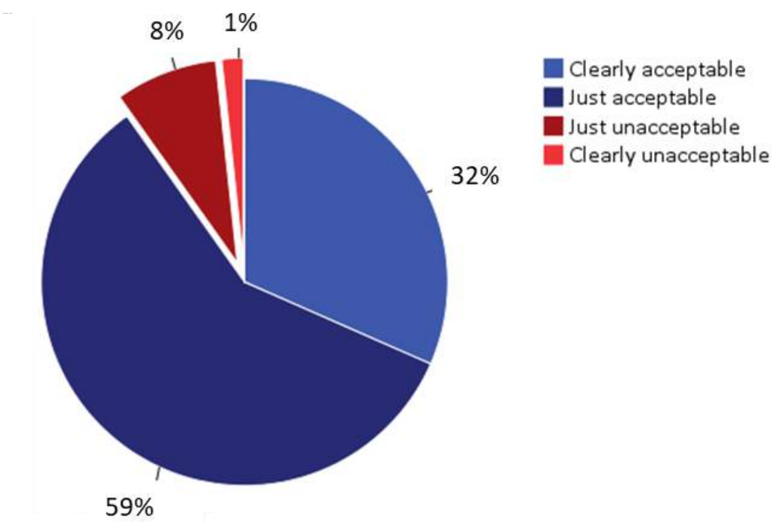
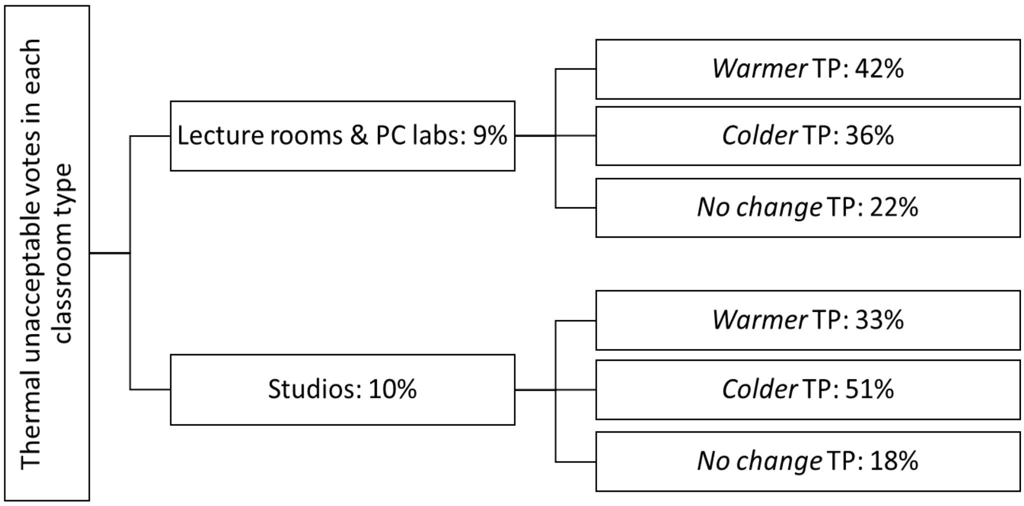


Figure 5. Thermal acceptance in the classrooms

Figure 6 illustrates the percentage of thermal unacceptable votes in each classroom type. As there is a similar environmental conditions and teaching style in the surveyed lecture rooms and PC labs, thermal acceptability votes in these two spaces are considered as the same group. Among all the students in the lecture rooms/ PC labs and studios, only around 10% of them vote for unacceptable thermal conditions. A detailed look at the thermal unacceptable and preferred votes at the same time to some extent shows a reason of the unacceptable votes. Students in the lecture rooms and PC labs prefer *warmer* thermal environments, while in the studios *colder* thermal environment is preferred by almost half of the students. Despite the higher comfort temperature in studios than lecture rooms and PC labs, cooler thermal condition is preferred in studios. In fact, higher level of activity in the studios (making samples and drawing) than lecture rooms and PC labs, may not directly affect the comfort temperature but affects the occupants' thermal preferences and, as a result, their thermal acceptability.



4. Conclusion

This study evaluates thermal comfort in the lecture rooms, studios and PC labs in higher learning environments in Coventry, United Kingdom. Investigation was conducted through environmental measurements, questionnaire surveys and observations. Total, 2046 undergraduate and postgraduate students participated in this study inside the classrooms.

Considering standard of minimum 80% acceptability as recommended in regulatory documents, thermal comfort zone, evaluated by probit regression analysis, is wider in the lecture rooms than studios and PC labs. The main reason is due to the students' wider exposure temperature range in the lecture rooms than studios and PC labs.

Also, it is revealed that the comfort temperature calculated by Griffiths' method tends to be 1°C higher in the studios than the lecture rooms and PC labs as a result of higher operative temperature in the studios that the other classroom types.

Proximity of the comfort and operative temperature in the studios shows the occupants' thermal adaptation to the thermal environments due to the long occupancy period and high level of freedom/control over the space. In fact, thermal adaptation tends to both physiologically and psychologically overcome the influence of higher metabolism on the occupants' thermal comfort in the studios.

The output of this work helps to expand the existing environmental guidelines for higher educational buildings to not only improve the students' thermal comfortable and consequently productivity, but also minimize energy consumption and such buildings running costs.

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Monitoring the performance of a passive downdraught evaporative cooling (PDEC) system – a case study of a library in Saudi Arabia

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Abstract: This paper presents field measurements and analysis from the performance monitoring of a Passive Downdraught Evaporative Cooling (PDEC) building in Saudi Arabia. Summer temperatures in Saudi Arabia frequently exceeding 45°C, and daytime relative humidities can be below 20% during the same period. The case study building, Dar Al-Rahmaniah, is a small public library located in the central region of Saudi Arabia. The library consists of three main parts, which include separate sections for men, women and children, and an auditorium. The men's section was chosen for the monitoring process as it represents the largest part of the library. Two PDEC towers are used to cool the large open space of the library. Central and leeward clerestory openings in the roof exhaust the stale air, allowing the evaporatively cooled air coming down the towers to circulate within the space. The primary aim of this study was to investigate the applicability and effectiveness of the PDEC system in the hot and arid climate of Saudi Arabia. For over 70 days during the summer of 2018, a range of data loggers were installed in the case study building to collect data. Different types of data loggers were used to record various parameters inside and outside the towers and the building, including external and internal dry-bulb temperatures, wet-bulb temperatures, relative humidity and external wind speed and wind directions. The case study provided detailed information about the performance of the PDEC tower in the climate of Saudi Arabia. The results indicated that PDEC Towers can achieve significant cooling for most of the time, but that their effectiveness was influenced by changes in wind direction and wind speed. Some reasons for this loss of effectiveness are discussed.

Keywords: Passive cooling; cooling Tower; PDEC systems.

1. Introduction

In Saudi Arabia, buildings use around 75% of the country's total electricity generation, with air conditioning being responsible for most of that consumption (Abuhussain et al, 2018). The majority of electric power generation comes from the direct burning of crude oil, with up to 900,000 barrels per day being used during the summer months (EIA, 2017). If air conditioning use in buildings might be reduced by substituting passive cooling systems, then this could have a significant impact on Saudi Arabia's energy consumption and greenhouse gas emissions. This study investigated one such cooling system – the Passive Downdraught Evaporative Cooling (PDEC) tower – by monitoring the performance of the system in a real building. The analysis of collected data revealed that this passive system did provide cooling, although the system's performance was negatively affected by the wind.

2. Literature and Background

The term 'passive cooling' describes a process that relies on a natural environmental heat sink to achieve cooling. Passive cooling strategies can be classified to four major types based on the natural heat sinks: (i) Natural ventilation (night ventilation), (ii) night sky radiation, (iii) ground cooling, (iv) evaporative cooling (Lechner, 2009). Passive Downdraught Evaporative Cooling (PDEC) towers are categorized as a direct evaporative cooling technique. When hot, dry air passes through a water medium, the evaporation of the water occurs as sensible heat is converted into latent heat, and the air temperature decreases as the relative humidity level increases. A PDEC tower consists of a wind catcher at the top of a tower, an evaporative/water medium, and a shaft to deliver the caught, cooled air to an occupied space via openings at the bottom of the tower. Hot and arid climatic regions provide an ideal environment for PDEC systems, and an up to 80% reduction of wet bulb depression (WBD) can be produced, which would ultimately lead to a significant reduction in cooling energy consumption (Alshenaifi et al, 2018). Contemporary applications of PDEC towers can be classified as four different types based on the evaporation method (Ford et al, 2010):

- Shower Towers (large droplets of spray)
- PDEC with wetted porous ceramic
- Cool Towers (wetted pads).
- Misting Towers (misting nozzles)

2.1. PDEC case study with wetted pads

Zion National Park's Visitors' Centre in south-west Utah, USA has two cooling towers incorporated in to the building, and air is cooled naturally by evaporation using four wet pads at the top of the towers. The outdoor summer daytime temperatures range between 35°C and 37°C. Clerestories are designed in the roof to maximise daylighting and improve the air movement with the cooling towers. The building envelope is well insulated to minimise heating and cooling loads. The building was assessed over two years (Torcellini et al, 2004). Results showed that the PDEC towers met most of the cooling requirements and that they contributed significantly in eliminating the use of conventional cooling. In the summer of 2017, the maximum external air temperature in Zion was recorded as around 42°C, while the internal temperature did not exceed 27°C (Ford et al, 2010).

2.2. PDEC case study with misting nozzles

The Torrent Research Centre (TRC) in Ahmadabad, India was the first large scale application of misting nozzles spraying into the top of the tower inlet. TRC has six laboratory buildings and some administrative spaces. In each building, the PDEC system is positioned above a central atrium that separates the offices from the laboratories. On the major axis of each building, shafts are built to maximise air circulation and exhaust the warm air out of the building. When the outside temperature reaches its maximum, the PDEC drops the interior temperature by between 10 and 15°C. The system has achieved 64% energy savings in cooling demand when compared to a conventional air conditioning system (Ford et al., 1998).

3. Case study of Dar Al-Rahmaniah library: Location and Climate

The PDEC building chosen in this study was the Dar Al-Rahmaniah library, which has two PDEC towers. The PDEC towers use the wetted pads approach to cooling. The library is situated in Alghat city, latitude 26.03°N, in the central region of Saudi Arabia. The city is in the north-western part of Riyadh province. Its climate is characterised as hot and arid, with external dry bulb temperatures (DBT) in summer reaching 45°C. The annual average DBT and wet bulb temperatures (WBT) are 36.5°C and 18.8°C, respectively. The library was monitored for over 70 days during the summer of 2018. The daytime relative humidity was typically below 20% during the same period, and the prevailing wind directions during the summer season are north and north-west. Figure 1 shows the library and its two PDEC towers.

Figure 1: The main entrance of Dar Al-Rahmaniah library and the two PDEC towers

4. Building Information

It is apparent that the designer of the Library tried to reflect the surrounding environment in the building. The use of construction elements from the same environment, such as straw bale walls covered with earthen plaster and wooden roof structure, gives a clear expression of how the building belongs to its land. The high thermal mass of the used material could provide a cooler internal temperature of the occupied spaces. The main entrance is located on the north-west side of the building between two PDEC towers, with the left-hand tower designated as Tower A in this study and B on the right side of the entrance (Figure 1). It is apparent from the location of the Tower that the design concept is to capture the prevailing summer winds and direct them into the building. The two towers are approximately 10m high with four openings on the top. At the bottom of each Tower, there is one large opening to deliver the cool air to the occupied space. The library is mainly a large open room cooled by the two PDEC towers. Clerestories are placed in the centre of the roof facing north-eastern and south-western side. The leeward clerestory openings in the roof were designed to assure the circulation of the air inside the building. Tables 1 and 2 show the architectural details and construction specifications for the building and the Towers.

Table 1: Construction specifications for the building

	Construction Specifications
Space height	4.4m
Library floor area	443 m^2
External walls	112cm total thickness: earthen plaster finish + straw bales (average size: 95 x 48 x 30cm) + earthen plaster finish
Roof	10cm light clay straw plaster + 7cm heavy clay plaster + 2cm lime plaster finish
column	Cast in place concrete column

Table 2: PDEC Tower specifications and details for Tower A (B similar)

	PDEC tower specifications
Tower Height	10m
Tower cross-section Dimensions	3.7m x 3.4m (become narrower at the top)
Wind Catcher	Four sides openings at the top (1.5m height x 2m width each)
Supply openings	One supply opening at the bottom of each tower (2m width x 1.8m height)
walls	46cm total thickness (20cm concrete masonry + 20cm stone block)

5. Work schedule

Data loggers were installed in the library for more than 70 days from 21st June to the 30th Aug 2018. The recordings were set for 24 hours continuous logging each day with a logging interval of 10 minutes. The library working time is divided into two shifts from Sunday to Thursday. The first shift starts from 09:00 to 12:00 while the second shift is from 16:00 to 20:00. The PDEC Towers were set to work for 24 hours each day.

6. Monitoring Equipment

Four different data logging equipment were used for the monitoring of the building. The recorded parameters included external and internal dry-bulb and wet-bulb temperature, external and interior relative humidity, external wind speed and wind direction, and internal air velocity. The data logger types used in the monitoring process are explained as follows:

6.1. Kestrel 5500

The Kestrel 5500 is a weather meter that can read and record a wide range of parameters. These parameters include wind speed, wind direction, dry-bulb temperature, RH and wet-bulb temperature. The meter is easy to set up and install. This mini weather station was installed above the library roof to record different weather parameters.

6.2. Kestrel 5200

The Kestrel 5200 is like the Kestrel 5500. The most apparent difference is that the 5200 meter does not contain a compass, so it cannot read and record wind direction. However, it can record extra parameters such as evaporation rate and moisture content. The Kestrel 5200 could be used to measure internal or external weather parameters. Two Kestrel 5200 were installed at the Tower supply openings to collect the supply air conditions.

6.3. EXTECH SDL350 Thermo-Anemometer

The EXTECH SDL350 consist of two parts - the meter and a probe that contains the sensors. The meter is featured by its sensitive sensors, which can record temperature and air velocity readings at low values. The EXTECH SDL350 was chosen to record air velocity readings from within the PDEC Tower.

6.4. Rotronic HL-1D

The Rotronic HL-1D is a compact and easy to install data logger. It can record air temperature and relative humidity for a long period. Seven data loggers of this type were installed within the PDEC Tower B and the occupied spaces.

7. Accuracy

The specifications of the sensors are summarized in Table 3. All the loggers were new and unused, and so the factory calibrations were valid. However, to check consistency between the loggers they were all, before installation in the library, run in a closed room environment for 24 hours. Note that the minimum starting speed for the Kestrel loggers is 0.6m/s. This means that external wind speeds below 0.6m/s will be recorded as zero.

Table 3: Data loggers and sensors specifications

	Measurement range	Accuracy	Reporting interval
Kestrel 5500	Temp: -29 to 70°C RH: 10 to 90%, WS: 0.6 to 40m/s	Temp: ±0.5°C RH: ±2% WS: ±3%, compass: ±5°	10 minutes
Kestrel 5200	Temp: -29 to 70°C RH: 10 to 90% V: 0.6 to 40m/s	Temp: ±0.5°C RH: ±2% V: ±3%	10 minutes
EXTECH SDL350 Thermo-Anenometer	Temp: 0 to 50°C V: 0.2 to 25m/s	Temp: ±0.8°C V: ±5%	10 minutes
Rotronic HL-1D	Temp: -20 to 70°C RH: 0 to 100%	Temp: ±0.3°C RH: ±3.0%	10 minutes

8. Installation

The data loggers mentioned above were installed in different locations in the library and the PDEC towers (Figure 2, 3 and 5). All the data loggers were labelled and numbered to simplify and organise the process of installation. The schematic drawings show the position of the sensors. The mini weather station (Kestrel 5500) was installed centrally above the roof of the library. The meter was raised above the roof by approximately 1.2m. Besides, the meter was shaded as recommended by the manufacturer (Figure 4). Two Kestrel 5200 were installed at the supply openings of Tower A and B at a roughly 1.4m height from the floor. Four temperature and humidity data loggers (H1-1D) were nailed on walls in different locations within the library. These locations include near supply opening of Tower A (computer zone), near supply opening of Tower B (administration zone), the middle of the Library, and the back of the library. The height of the sensors was 1.6m, which provides an ideal position within the occupied spaces. One more H1-1D meter was installed on near the supply opening of an AC unit to collect data of the working hours of the mechanical cooling units. Two H1-1D meters were also installed within Tower B. one was at the top, 2.3m below pads, while the other was at the bottom at a 1.6m height from the floor. The anemometer was installed inside Tower B. The probe sensors were positioned centrally inside the Tower at 2.9m above the floor.

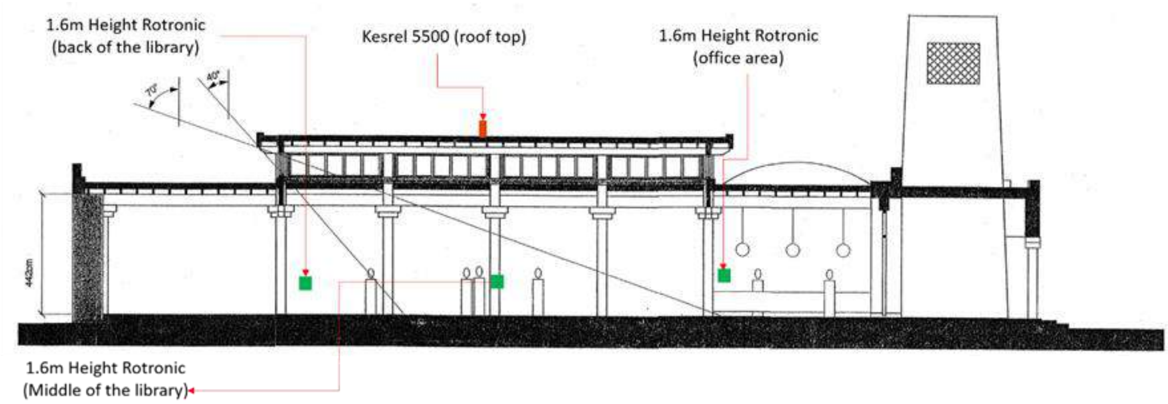

Figure 2: Section A-A

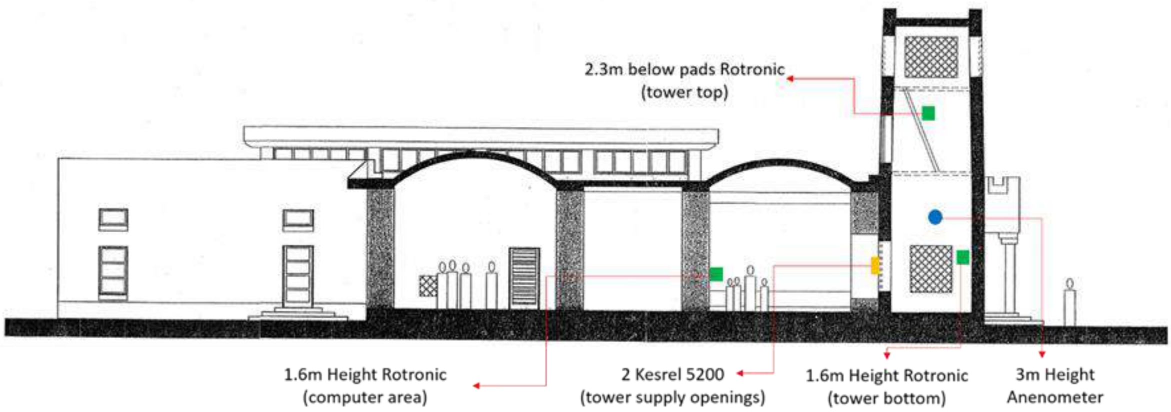

Figure 3: Section B-B

Figure 4: Pictures taken during the installation of the data loggers

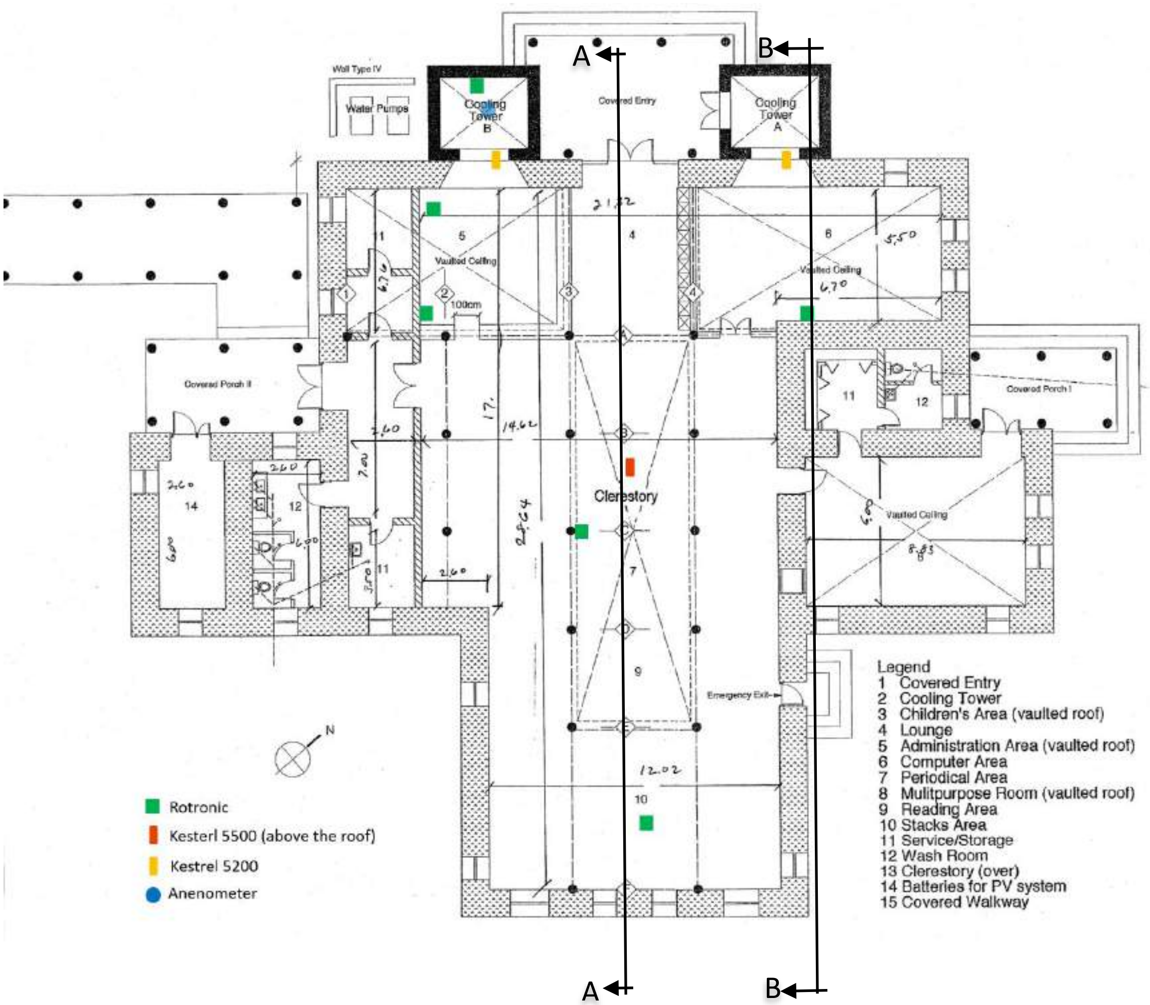

Figure 5: Library floor plan showing the location of the data loggers installed

9. Results and Analyses

For the hot, dry climate of Saudi Arabia, the monitored performance demonstrated the ability of the PDEC system to cool the incoming air. The temperature difference between the external air and that delivered at the bottom of the PDEC towers ranged from 6°C in the early morning to 16°C during the hottest parts of the days (~3.00pm). Despite the PDEC towers providing cooling for most of the time, there was still a need for mechanical cooling as the PDEC towers could not provide enough cooling all the time. It was noted that under certain weather conditions the performance was less effective. The wind speed and wind direction played significant roles in the overall performance of the PDEC.

9.1. Wind Speed

It was apparent from the logged data that the wind speed had a direct influence on the performance of the PDEC towers. Figures 6, 7 and 8 show that the lower the wind speed then the higher the humidity levels and the greater the temperature reductions achieved. On 8th and 9th August, and during a time when the wind speed went above 4m/s, the performance of the two PDEC towers became unstable, leading to fluctuations in the supply air temperature, higher internal air temperatures, and lower humidity levels. As a result, the loss of PDEC cooling had to be offset by mechanical air conditioning, which was running during work hours. This scenario happened frequently during the 26th/27th July and 7th August. A possible explanation for this is that turbulence increased around the tower inlet opening at the top due to the higher wind speeds, as discussed by Kang and Strand (2016). This situation can be seen in the supply air velocity, which decreased during the periods of higher external wind speeds. On the other hand, during calm wind conditions, the towers performed better, leading to lower supply air temperatures.

9.2. Wind Direction

Although the PDEC towers produced cooled air for most of the time, specific wind directions reduced the size of the cooling of one or both PDEC towers. One finding was that the south and south-west winds had a negative influence on cooling for Tower A. It was observed that the temperature at the tower at the supply opening went up while humidity levels dropped when winds came from south and south-west directions. This suggests that the south-western clerestory openings in the roof were allowing a positive pressure to be generated in the room that acted against the ingress of cool air from Tower A.

In Figures 9, 10 and 11, Tower B can be seen to have performed better than Tower A at specific times during the 23rd and 24th of June. The supply temperature increased, and humidity levels decreased below 50% for Tower A while Tower B was performing better, with supply temperatures going down to below 20°C at some times. This situation occurred during similar weather conditions where the wind direction bearing was approximately between 140° to 270° (SW). The same situation occurred for several days during the monitoring. These days include 11th, 12th, 13th, 17th, 21st, 22nd, and 24th July, and 2nd, 7th, 9th, 22nd August.

During calm weather, and when winds become north or north-north-west (i.e. directly on to Tower A), Tower A performed better. For these ambient conditions, Tower B's performance dropped compared to Tower A, and the temperature at the zone near the supply opening of Tower A (computer zone) became lower than the temperature at the Tower B supply opening. Possibly, Tower B could be acting as an exhaust shaft at some points. This scenario happened during weekends or after work hours, which suggests that clerestory openings might have been closed at these times. This situation occurred on the 27th July and 8th August.

9.3 Overall Performance

The overall capacity of the PDEC towers to provide useful levels of cooling performance in the hot, arid climate of Saudi Arabia was demonstrated. Although both towers performed well most of the time, it was apparent that Tower B was more effective than Tower A (Figure 12). This finding could be linked to a couple of reasons. First, the W and SW wind direction has played a role as it was explained previously. Secondly, the layout of the Library could be a reason for that. It can be seen in the floor plan layout that the supply opening of Tower A is facing a wall that creates the computer zone within the Library main space. These obstructions could minimise the airflow from Tower A, which would lead to less performance under certain circumstances. On the other side, Tower B has a direct connection with the library open space with no obstructions.

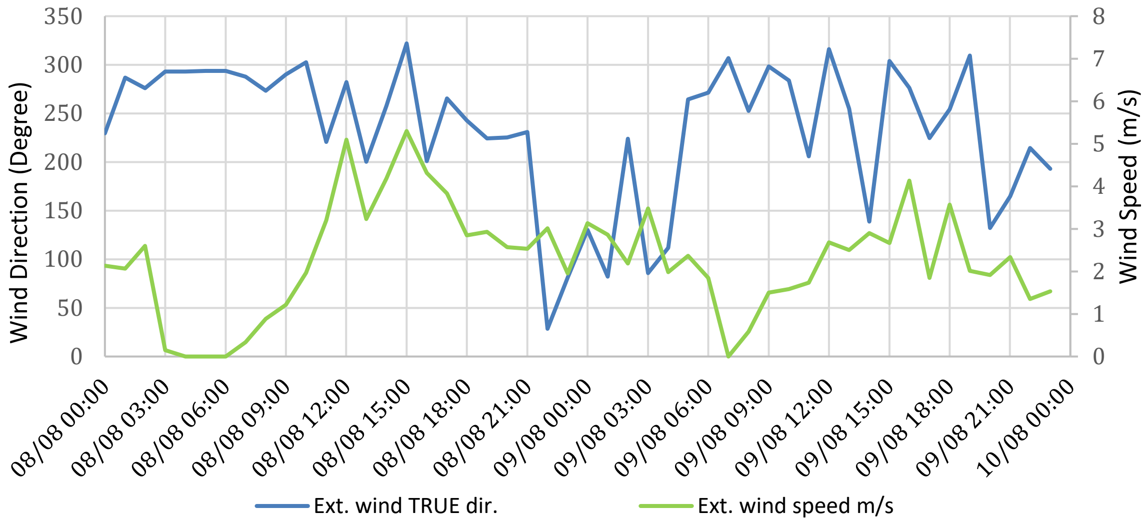

Figure 6: Wind speed and wind direction for the 8th and 9th August.

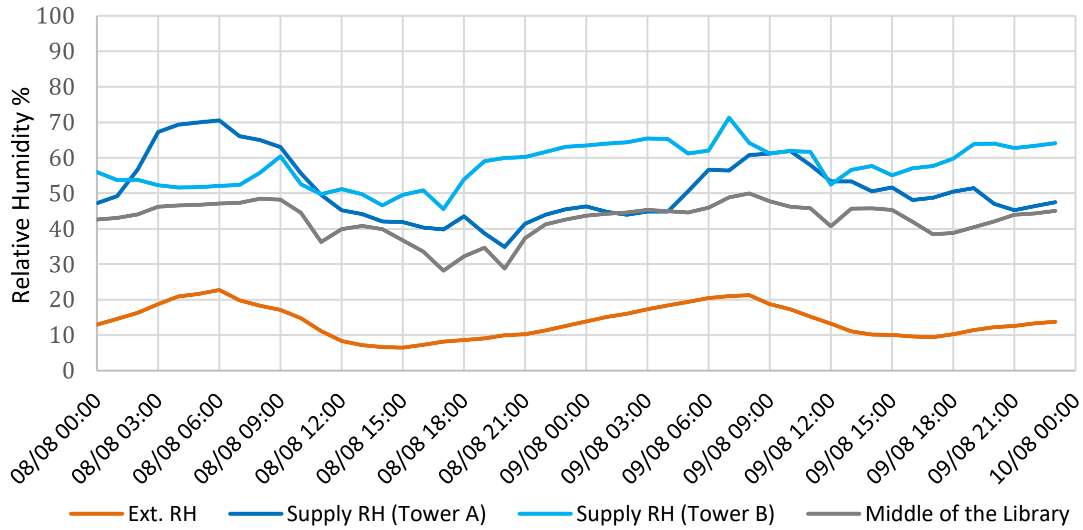

Figure 7: External and Internal Relative Humidity during the 8th and 9th August

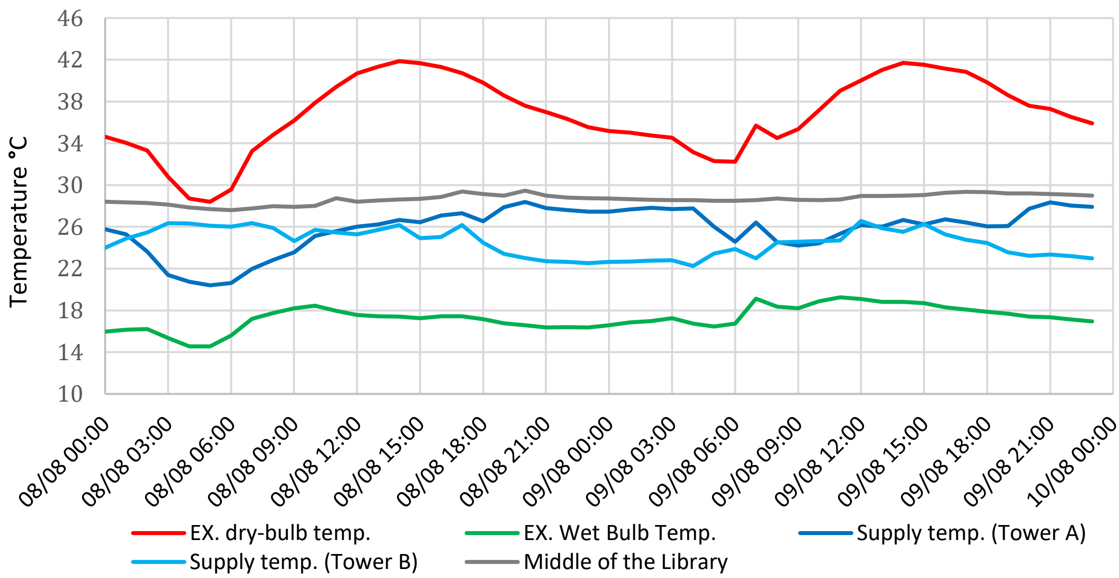

Figure 8: External DBT, WBT, and internal temperatures for the 8th and 9th August

Figure 9: Wind speed and wind direction for the 22nd - 24th June

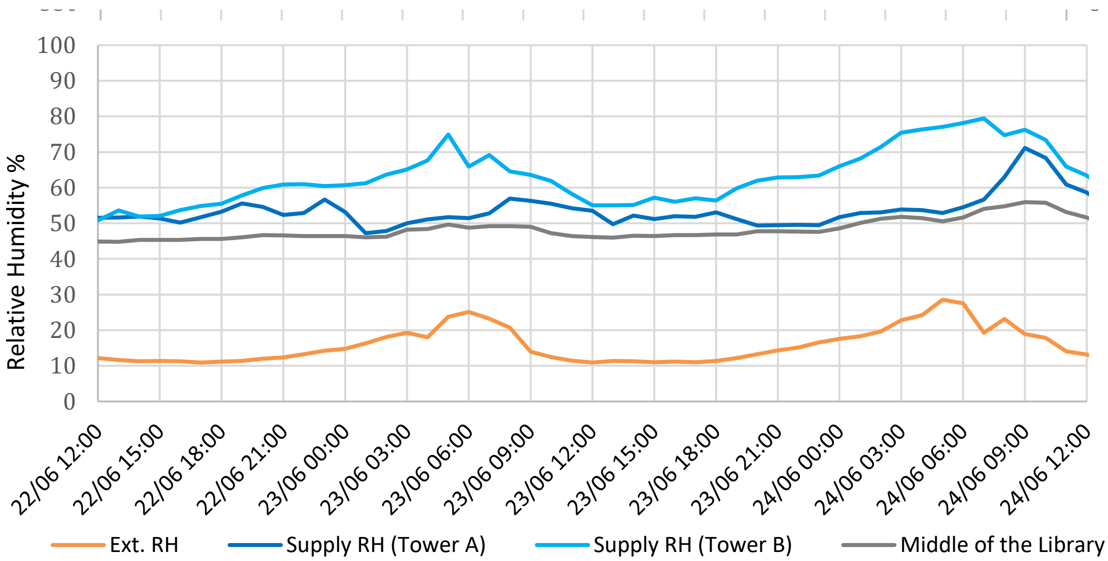

Figure 10: External and Internal Relative Humidity for the 22nd – 24th June

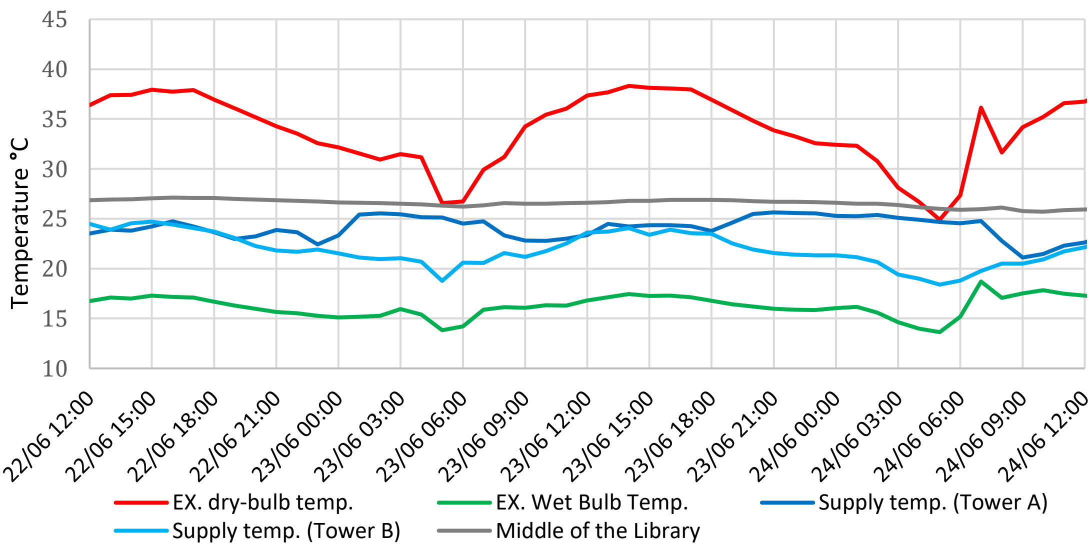

Figure 11: External DBT, WBT, and internal temperatures for the 22nd – 24 June

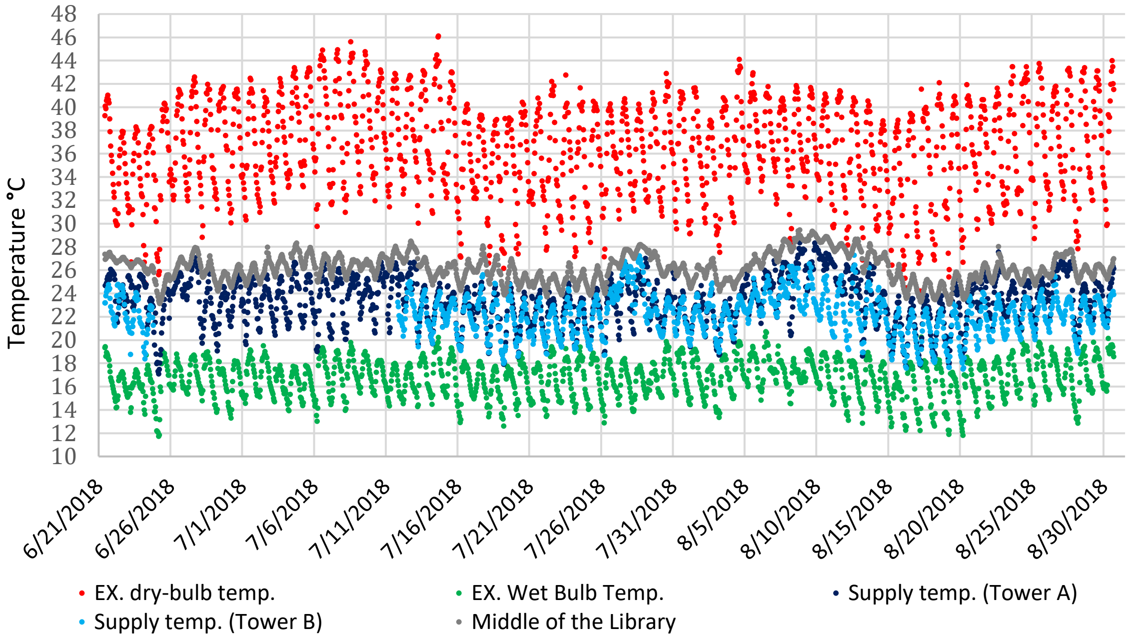

Figure 12: External DBT & WBT, and internal temperatures at Tower A and Tower B supply openings and the middle of the library during the whole monitoring period (70 days)

10. Conclusion

This paper has presented the analysis and results of the performance of an existing PDEC building – the Dar Al-Rahmaniah Library in Saudi Arabia. The primary objective of this case study was to quantify the actual level of cooling performance of real PDEC towers. The case study provided detailed information about the applicability of the PDEC Tower in the climate of Saudi Arabia. The findings showed that the two PDEC towers provided cooling to the building, although the degree of cooling was affected by prevailing wind speeds and directions. Limitations of the current study include the one season (summer) nature of the measurements (meaning that most winds blew from a narrow range of directions) and the fact that very low wind speeds could not be measured as the weather logger only recorded speeds above 0.6 m/s. Future work will include computer modelling of the Library and the validating of the model against the measured data. If that is successful, then detailed parametric analyses of the case study will be undertaken to provide a better understanding of PDEC performance and contribute to the future design and development of PDEC towers.

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Field test of the performance of a double skinned ORV8 Tent Envelope

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Abstract:

More and more people globally are living in temporary structures as a result of catastrophic or systemic displacement of populations, as a result of climate change, wars and economic pressures. The need for more research on the cost and performance efficiency of tent materials and structures is clear but hindered the lack of precedents in the field. Little systematic research has been put into optimising tent designs for different climates and many new materials that may potentially be very effective in tents are not tested in relation to their performance as building materials. This paper describes first steps taken towards the development of an experiment evaluation of an innovative fabric, ORV8, in relation to its potential use in constructing a yurt like tent to be erected in the extremely cold and windy climate of Antarctica. The manufacturers of the specialised fabric (ORV8) encouraged testing in advance to check it would perform adequately thermally and structurally on site. This would also help justify larger scale manufacture of the material. To explore and test its performance, an experimental proto-tent was fabricated and then tested in a meat storage facility in Hull that is run continuously at around -20^{0}C. This paper reports on how the tent performed thermally during these exploratory tests and concludes with the lessons learn during the process.

Keywords:

1. Introduction

When looking at a range of innovative materials for use in an experimental tents to be erected in Antarctica in January 2019 it was thought that perhaps a space-blanket like material may work really well, with its very good thermal performance and lightness. With advice from contacts in Dupont and Camvac a 'wish list' of the properties for the tent materials were developed and material identified that might provide for them: Light. Strong, thermally excellent and fire-resistant. Based on the advice the manufacturer of suitable materials Orvec, based at Hull were approached (http://www.orvec.com). With them, the pre-selection of a fabric for experimental testing was undertaken and Orvec+insul8 (ORV8) was chosen. However, the manufacturers were unwilling to supply the large quantities of the material needed for an experimental tent without further testing being done to provide confidence in its suitability for the project.

ORV8 is a four layered material and there were no experimental results available and the understanding of its performance was based largely on empirical evidence and field trial experiences of the manufacturers and two groups of users. No thermal modelling was undertaken, or calculations of the balance of heat produced and lost during its hypothetical use of the tent were made. Stainton Reid, director of Sheerspeed Shelters Ltd. (https://www.sheerspeed.com) and a master tent maker, had already used ORV8 on ice fishing tents supported on a collapsible structure with an Orvec+insul8 (ORV8) external envelope and had found it to stand up very well on an exposed outdoor site over twelve months. ORV8 is also used successfully in Finland as the container material for emergency evacuation, hypothermic, carriers by the Finnish army at temperatures down to -25^{0}C. It was thus decided to test the ice fishing tent with the additional inner suspended lining to provide the confidence needed in its thermal performance to construct the full tent to be pitched in Antarctica in February 2019 for the Extreme Lodge project (www.extremelodge.org).

The aim of the field test undertaken in August 2018 was to practically evaluate the thermal performance of a Sheerspeed Ice fishing tent with a ORV8 external envelope and an additional inner envelope of Orve-wrap (http://www.orvecare.com/orvewrap/) with fleece on one side and Mylar on the other side of the material sandwich. This was tested in a very low temperature facility (-20^{0}C) in the meat and fish storage warehouse of AJK Ltd. cold storage in Hull. This was done in two stages:

1. The thermal performance was evaluated first with the outer envelope only then with the inner suspended lining, looking at heat transfer through the tent cloth(s) and structure.
2. Look at the details of the thermal performance of the construction of the fabric envelopes to assess where flaws in the design exist or could be improved upon.

2. People involved in the field tests

The test rig for the experimental envelope was been developed by two main players. The Material supplied by Tony Codd / Orvec (www.orvec.com/) and the production manager David Arksey for the ORV8, a four layer material including a waterproof external material with a reflective low emissivity Mylar core and fleece internal layer. The tent envelope was detailed and manufactured Stainton Reid of Sheerspeed (www.sheerspeed.com). The final tent will have an external rain-proof and super-strong Dyneema fabric envelope reused from racing yacht sails made by Northsails (https://www.northsails.com/) but during the field trials the external 'raincoat' was not tested. The fixings of the envelopes to the structure are largely of Velcro. The testing was done inside the facilities of AJK Ltd., cold storage specialists in Hull since 1881 (http://www.ajkltd.co.uk).

The testing team includes Professor Adrian Pitts of the School of Architecture at the University of Huddersfield, Tony Codd of Orvec and Susan Roaf of Heriot Watt University.

3. Testing Programme

In field and climate chamber testing of fabrics for clothing, sleeping bags and tents the most relevant measurement parameters are considered to be the insulation and vapour resistance properties of a material, followed by its wind and waterproofness and moisture absorption properties (Havenith, 2009). For this experiment vapour permeability and wind and waterproofness are not being investigated. In experiments relating to tent materials here the key measurements are considered to be for:

- heat resistance (convection/radiation)
- air permeability (affecting heat resistance in wind)
- wicking
- perforations in the construction

The five-stage approach advocated for such testing by Goldman and Umbach (1974) and used widely in the clothing research community and is shown in the schema presented in Table 1 to which we have added stage zero.

Level 7	Test tested over a year in Antarctica
Level 6	Final tent fabricated
Level 5	Test deign modified
Level 4	Analysis
Level 3	Prototype tested in Cold Store
Level 2	Prototype test tent assembled
Level 1	Materials selected
Level 0	Tasks developed

Table 1. Experimental Levels of the Project (after Goldman and Umbach (1974)

The structure being experimented with consists of a pop out tent structure 1.5 x 1.5 m x 2m high with two envelopes of ORV8, one stretched over the structure and attached internally by Velcro to it and a second suspended from it by Velcro, internal to the structure.

Figure 1 a) Four ORV8 layers include an external silicon coated polyester layer that offers wind and water-proofing with a metalised PET (Polyethylene terephthalate) or MPET and a PET bonded using a glue to ensure that it is non-conductive. A needle punched a polyester fleece is added, needled and carded to a level that cost efficiently optimises its thermal properties and provides a wipeable inner surface, b) Tent erected in warehouse.

In order to establish the rates of heat gain and loss under different heat charging conditions the tent performance was interrogated within the cold store in the following testing order:

- Tent erected with the outer skin of ORV8
- Left for 1 hour with door open to allow the structure to reach equilibrium in the facility.
- Heat source (small gas camping stove on low) placed in the tent and the door shut to see the thermos-dynamic impact of the internal heat source. Left for 30 minutess only as the camping stove went out. Surface measurements and thermal images taken.
- Structure opened, heater removed, inner lining fitted and door left open to get temperatures back down to equilibrium – close up leave for an hour.
- Introduce heat source for five minutes.
- Person occupies tent for 15 minutes

4. Testing Equipment

- 3 Central HOBO loggers (type UX 100-023) thermometers suspended by string centrally from clips attached to each of the internal surfaces of the tent linings at c. 30cm (sleeping height), 100cm (sitting height) and 1.40 (standing height) above the ground and externally at c. 750 above the ground.
- An external air temperature logger was placed externally c. 1 foot from tent corner.
- 2 internal HOBO loggers (type U12-012) were suspended in the centre of the right and left hand sides of the tent some 10 cms below the roof / wall junction.
- A CEM DT-615 digital thermometer for general readings in support of the tests and to which a thermocouple surface temperature probe was also attached and used only for spot checks. This showed the external surface temperature to be consistent with the cold room environment. In the absence of significant radiative variations it is doubtful that these would be important for the cold room. It was not possible to measure other surfaces without interfering with the experiment.
- Seek thermal RevealXR thermal imaging camera.

Figure 2. a) ORV8 outer skin b) ORV8 with hung data loggers c) Tent with inner

5. The testing schedule:

09.00 – Health and Safety induction with Stuart from AJK Ltd.
09.30 - Half hour to assemble and put tent in cold store.
10.00 - Test 1 begins – leave equipment to get to equilibrium
10.00 - Test 1 ends, thermal images and surface temperatures taken and tent extracted and reassembled
10.30 - Test 2 begins – close tent down and leave for an hour.
11.30 - Test 2 ends, thermal images and surface temperatures taken.
12.30 - Test 3 begins – put cooker in and leave for c. half an hour.
13.00 - Test 3 ends, thermal images and surface temperatures taken and inner lining tent attached and left to reach equilibrium.
14.00 - Test 4 begins – cooker put in tent for c. 15 mins. and SR stays in tent for 15 mins.
14.30 - Test 4 ends, thermal images and surface temperatures taken
15.00 – Test rigs and equipment removed and data taken home for analysis

6. Cold store facility test results

Of the measurements it may be deduced that anything before 11.00am readings is transport and set up/stabilization time so is not irrelevant to the questions posed in the experiment, although helpful for calibration. Anything after about 14.00 is also not relevant to the main experiment but shows how all sensors returned to relatively stable and close values showing the internal and external climates are virtually similar.

Figure 3. Data logger and fixings

Figure 4. tent open showing central loggers

Of the reading results, the top right position and top left position are those sensors were put up close to the tent fabric and are likely to have different readings because of the proximity and impact of the tent surface itself but they are indicative that there are some variations. Their data can be used to infer very little about the actual surface temperature, likewise readings from the sensors in the small black balls gave one or two strange values which is why they were discounted as it seems likely the cold/damp affected the connecting cable. Three very valuable lessons were learnt form the thermal images**:**

- The single envelope did not perform that well as it did in this tent construction result in very clear cold bridging. Any heat source internally was captured and visibly transported through the Orve-Insulate skin, as shown in the figures below.
- The single skin tent did not provide a very high level of insulation as evidenced by the clear thermal stratification visible through the tent envelope with the light gas stove.
- The tent was extremely well sewn together as there were no cracks or splits where the internal heat was visible through the external envelope along the seams or zips.

Figures 2b) and 4) show top, middle and bottom HOBOs suspended in the centre of the tent and the outside temperature. The fact that the outside temperature is slightly warmer at times may be because the logger was in the corner close to the floor.

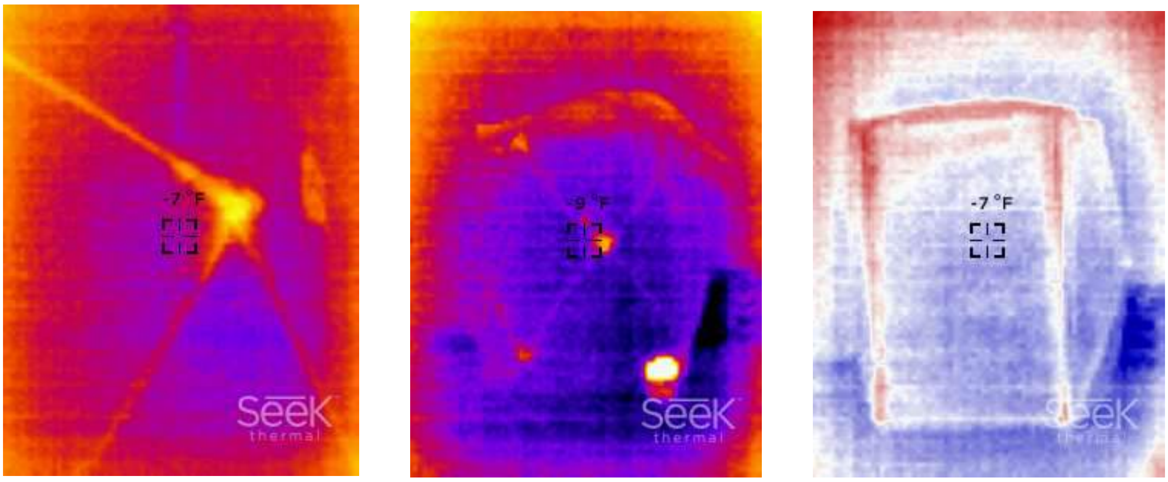


Figure 5. a) Cold bridging visible With ORV8 only

b) Thermal stratification clearly visible with single skin

c) Structural cold was clear with 1 skin

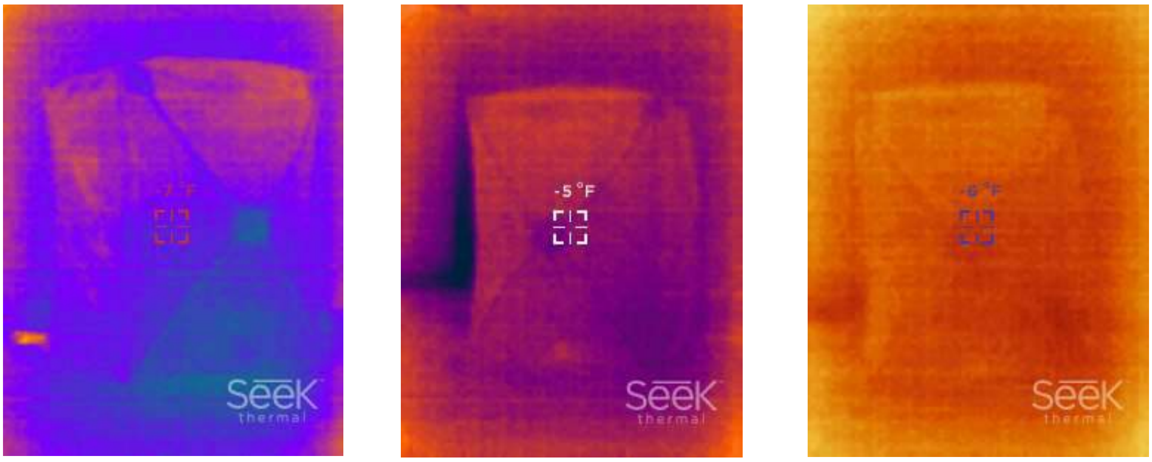
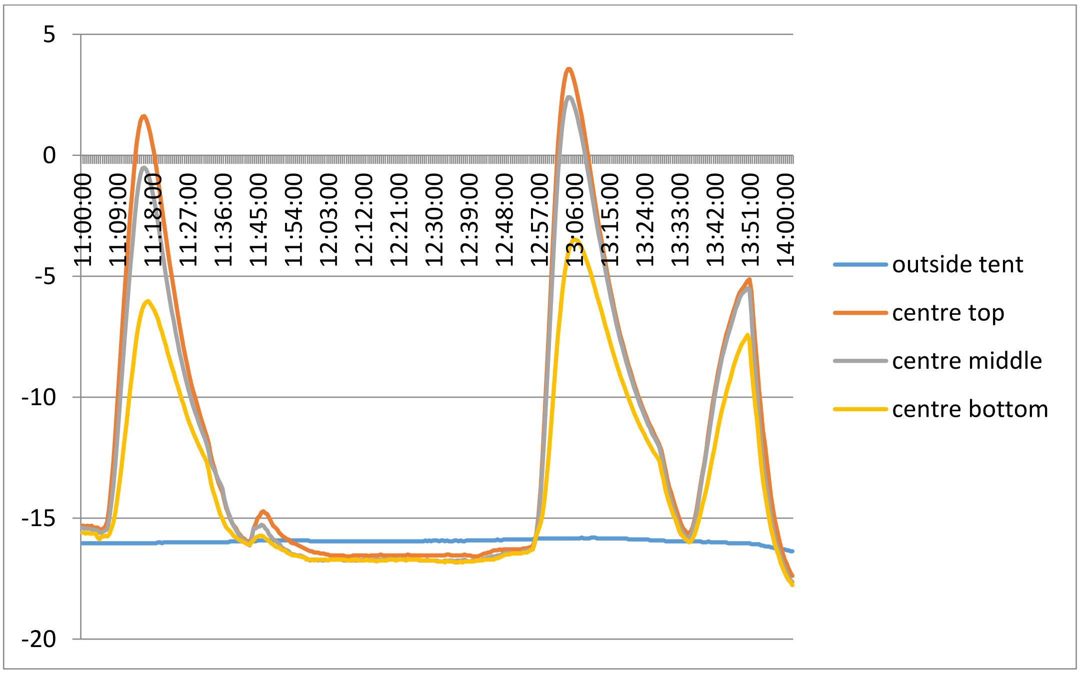


Figure 6 a) Some Stratification with the stove on

b) Cold bridging nearly gone with double skin

c) Very good thermal performance with two skins



Graph 1. Readings from the three HOBOs hung vertically in the centre of the tent.

The thermal measurements and the thermal images show a number of clear lessons:

- The thermal stratification within the closed tent during different test phases of the experiment shows that the upper reaches of the space are warmest, followed by the central area then the lower level closer to the uninsulated floor. The temperature increase in the basic tent with the heater on was significant before it was stopped. The temperature at head height rose over approximately 10 minutes from -15.4C to +1.6C with a maximum rate of increase of about 2.2C/minute
- It also clearly shows that over the very short period that that the gas stove was alight during the two test phases (first and second peaks) each test phase that the internal tent temperature rose higher in the tent with the internal lining fitted (second peak) than in the tent with only the external tent enveloped in place and sealed up (first peak). The temperature increase in the tent with the additional layer of fabric with the heater on was also significant before it was stopped. The temperature at head height rose over approximately 10 minutes from -16.2C to +3.6C with a maximum rate of increase of about 3.4C/minute - ie a better performance.
- It was also clear that when Susan Roaf occupied the tent with no other heat source (peak three) that she caused the internal temperature within the tent to rise fairly steeply, then plateauing off slightly until the temperature fell when the tent flap was opened. The temperature at head height rose over approximately 15 minutes from -15.6C to -5.1C with a maximum rate of increase of about 1.1C/minute - ie some benefit even if only occupied by one person as a heat source.
- The comparative calibration between all the sensors shows only modest variations with a maximum average variation of between 0.1 and 0.2 C, a not significant finding in the circumstances but with more time some small adjustments to accuracy of those readings might be made.

The CEM DT-615 digital thermometer was used for general readings in support of the tests and to which a thermocouple surface temperature probe was attached for spot checks. These showed the external surface temperature to be consistent with the cold room environment. In the absence of significant radiative variations, it is doubtful that this would be important for the cold room. We could not measure other surfaces without interfering with other tests.

7. Second Polar Lodge Envelope Testing Experiments 8th August 2018

A second experiment was undertaken in Hull in August 2018 looking at the impact of using the highly reflective side of an Orve+wrap lining with one side reflective and one side on the inside or the outside of the inner lining envelope of the tent. The experiment was carried out by Tony Codd and the team at ORVEC International Ltd and proved useful in interrogating that question. The shelter was tested in an outside area with initially dry sunny conditions. As the test progressed it clouded over so direct sunlight was intermittent.

Fig 7a). Car park erection b) ORV8 external skin on c) ORV8 + Orve+wrap inner lining

Three temperature probes were positioned as follows:

1- 40cm from the top of the shelter
2- 100cm from the top of the shelter
3- Outside and in the shade of the shelter

Test 1: Standard ORV8 envelope, closed shelter for a one hour duration
Test 2: Orve+wrap lining in place with fleece innermost, shelter closed for one hour
Test 3: Person stood in closed shelter for 15 minutes - Shelter left open for around one hour
Test 4: Orve+wrap reversed, green reflective side innermost, shelter closed for one hour
Test 5: Person in closed shelter for 15 minutes

8. Second Polar Lodge test results (see Graph 2)

- Readings confirm the significance of the stratification of temperatures within the tent.
- Test 1 shows the external envelope performs worse than with a double envelope when the conditions outside were warm.
- Shows that when the fleece is on the inside of the material the internal temperatures are lower internally than when the shiny reflective lining is to the inside.

When the green reflective lining, with its very high emissivity, is facing inwards the internal temperature peaks are demonstrably higher than with the fleece lining. This is because more of the heat is being let through from the outside. With the fleece internally and the high emissivity to the outside of the inner lining the heat is not penetrating from the outside because that reflective surface is not allowing heat flow through it. It is clear here that the addition of a second Orve+wrap inner lining to the outer ORV8 skin significantly reduces the heat ingress through the envelop. This is less so when the low emissivity fleece lining is located internally than when the high emissivity reflective green surface in placed inside.

9 Conclusions

The lessons from fairly rudimental field tests such as those outlined above can be influential in persuading investors to fund the use of innovative materials for experimental projects. The learning from such tests can also be useful in helping shape the design decisions of those developing new ideas and forms that in turn may yield good results in more advanced tests. Empirical learning that results from such tests can be important in shaping new design ideas.

Graph 2. Graph of temperature readings from 2nd Hull tent experiment. Key: Blue- 40cm from top of shelter; Green- 100cm from top of shelter; Black- outside and in the shade of the shelter

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Assessment of thermal overheating in free-running buildings in Cairo

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Abstract: Assessing human health under climate change in hot climates is of particular importance in the Middle East. Cairo is one of those cities that have an estimated 2018 population as high as 13 million, with a metropolitan population of 21 million, which makes it the largest city in Africa and the Middle East. In and around Cairo, many of the summer seasonal deaths are blamed on human discomfort due to anthropogenic climate change. High urban population density, urban heat island effect, cramped living conditions including housing, schools and prisons are all reasons to the increase of heat-related health problems in Cairo. Therefore, this initial study investigates and maps overheating in free-running residential buildings in Cairo. The study follows a combined, monitoring and observational assessment of the 2015 heat wave (19-day event) in Egypt. Using surface urban heat island maps, representative urban areas were determined and field measurements were carried out to assess indoor air temperatures and relative humidity. This was followed by observational field visits and interaction with local citizens to document the impacts and adaptation measures corresponding to overheating. The paper provides insights on indoor human discomfort with a focus on physical and non-physical heat stress reasons during climate extremes. The study provides initial insights on thermal comfort that can prompt local professionals and governments to address overheating and thermal stress in free-running residential buildings.

Keywords: city climate, heat wave, thermal comfort, heat stress, behavioural adaptation

1. Introduction

Overheating in buildings is expected to increase as global warming continues. Meanwhile, there has been an increasing amount of attention paid to the massive human health risk posed by overheating in free-running buildings. Carbon Brief's analysis conducted by Pidcock and Pearce in 2017 indicate that 85% of 48% heat waves studied worldwide were found to have been made more likely to occur or more severe as a result of climate change. More importantly, scientists found that human-caused climate change has altered the likelihood or severity of an extreme weather event in 68% of cases studied (Pidcock and Pearce in 2017). Human-caused climate change in the city is directly related to the urban heat island effects. In fact, climate change and the urban heat island (UHI) effect interact in two ways. First, the warming climate will increase already higher temperatures in UHI areas. Second, the increased heat islands effects can magnify the presence of climate change by intensifying heat waves (EPA 2019).

Therefore, the impact of climate change on the internal summertime temperatures in Egypt's buildings is likely to increase with the increase in the occurrence of extreme heat waves. Elevated temperatures in urban households are of particular concern and this may be exacerbated with the poor building construction quality (Attia et al. 2012). We believe that this leads to heat-related problems ranging from thermal-discomfort and productivity-reduction to illness as well as death. High indoor temperature impairs the ability to recover from heat stress (Kovats et al. 2008) and increased sleep fragmentation (Buysee et al. 2010). Heat-related mortality is most pronounced among the elderly (Åström et al. 2011). In August 2015, as per Ministry of health, Egypt temperatures soared to 47°C (116F) and at least 105 people died in three days. Sixty died due to heatstroke only.

There are very few studies in Egypt that addressed thermal comfort in residential buildings, this include the work of Gado et al. (2009), Fahmy et al. (2009), Sheta et al. (2012) and Sedki et al. (2013). Gado et al. (2009) evaluated the effectiveness of natural ventilation strategies in relation to thermal comfort. However, their study was focused on social housing located in the New Al-Minya city of the Egyptian desert climatic region (hot and dry). Only three walk-up housing blocks were monitored for five days and simulated using ECOTECT. The study relied on Szokolay's static comfort model and finally focused on investigating the effectiveness of passive cooling measures without a specific focus on comfort. Then, Fahmy et al. (2009b) investigated the outdoor-indoor thermal comfort in a multifamily residential building (only one room) during summer in Cairo. The study was theoretical, without field measurements, applied Fangers' static model, and focused mainly on the outdoor comfort improvement measures using ENVI-met. Moreover, the work of Sheta et al. (2012) claimed to investigate the thermal behaviour of new construction in the New Cairo community in compliance with Egyptian regulations. The study was based on real weather data and investigated the influence of several energy conservation measures on comfort during the hottest week of the year using EnergyPlus. However, the study did not apply the Egyptian energy code (HBRC 2016), which defines static thermal comfort limits ranging between 21.8˚C to 30˚C. However, the authors relied on another static threshold (23˚C and 29˚C) based on the work of Robaa (2003). Unfortunately, the work of Robaa (2003) on human thermal comfort in Egypt was theoretical and did not involve indoor field measurements or surveys. The work of Sedki et al. (2013), investigated the effect of orientation on thermal comfort in a residential building block in October 6th city in Greater Cairo. Based on monitored data of three apartments during a winter week the authors created a simulation model using IES-VE and assessed the comfort using ASHRAE 55 adaptive comfort model (2004). The study proofed that the three apartment's occupant are discomfort able during 43-50% of the winter week (hours). Despite the importance of thermal comfort being acknowledged in literature, so far, only limited attention has been paid to thermal comfort research in free-running buildings in Egypt. Considering the overview of literature, it is clear that there no structured or large scale investigation on comfort conditions.

Therefore, this study assesses the thermal comfort conditions and overheating in free-running residential apartments across Greater Cairo. The paper aims at assessing the appropriateness of current adaptive and non-adaptive thermal comfort models during overheating conditions in dwellings. The study presents results and observations on the impacts of overheating on occupants as well as occupants behavioural adaptation characteristics. The work is an incremental contribution to a slowly advancing knowledge in the area with extreme climate.

2. Methodology

As a follow up of our literature review we developed research methodology (quantitative and qualitative) following a four stage approach. Firstly, we determined the measurement locations based mapping the areas with the highest urban heat island effect potential in Cairo. Secondly, we installed a weather station in the city centre and distributed 32 data loggers to record the indoor air temperature and relative humidity in 32 randomly selected apartments. Thirdly, field observations and interviews took place with the selected apartment occupants to investigate the overheating impact and behavioural adaption measures. Fourthly, the measurement data were archived and cleaned to create thermal indoor assessments and calculate the overheating hours. The following sections provide further details on the research endeavour.

2.1. Geographical Mapping

In order to assess the thermal overheating at the city scale, we had to find representative residential apartments located in Cairo. Greater Cairo, the capital of Egypt is located in the south part of the Nile delta consisting of three main governorates Cairo, Giza, and Qalyubia with a total population as high as 13 million, with a metropolitan population of 21 million. The city was founded in 2,000 BC and since then evolved formally and informally resulting in a complex and historically layered city. According to a Ministry of Housing source 40% of all Greater Cairo residents live in informal housing, (Hafez 2014). The city climate intensifies segregation and inequalities between the various social classes, resulting in the intensification of low-income groups in the city centre and the immigration of middle and higher income groups to the peripheries (Roesler 2017). The climate of Cairo (Latitude: 30 08N, Longitude: 031 24E, Altitude 23m) is classified as tropical and subtropical desert climate (Bwh Köppen climate classification) and summers are hot (Köppen et al. 1930).

The selected apartments are located in different districts and governorates of Greater Cairo. Because Greater Cairo's administration is divided between three governorates and more than 65 major districts, it was decided to select the apartments for measurements based on indicators found in literature (Fahmy et al. 2009ab and Shashua-Bar 2010). As shown in Table 1, we selected four major indicators associated with the UHI effects in cities. Using those criteria limited vast search scope to identify the streets with the highest UHI effects potential. Searched street canyons with extreme microclimate conditions allowed locating apartments in buildings situated in those street canyons.

Table 1. The four used indicators to identify the urban street with highest UHI effect potential

Indicator	Urban Density [person/km2]	Traffic [car/hour] at 17:00	Aspect ratio [coefficient]	Tree Coverage [%]
Threshold	**> 15.000**	**> 800**	**> 0.8**	**≤ 30**

Most street canyons have been extracted from Egyptian geographic information system data (GIS) and cadastral data (CAD). CAD is a vector data made available by the Egyptian General Survey Authority. GIS and CAD data provide information about urban densities and streets aspects ratio. With the help of the study of Taheri Shahraiyni et al. (2016), who calculated the surface urban heat island effect and the land surface temperature, we identified representative urban street canyons in Greater Cairo with the highest UHI effect potential. This was followed by field visit and field measurements for selected streets as described in the following section.

2.2. Field Measurements

Upon identification of representative street canyons with a high UHI affect potential, 40 streets were visited to validate the thresholds for the 4 selection indicators and complete any missing information such as tree coverage or traffic density. Then, we launched a request through social media for volunteering individuals who reside in building apartments situated in the selected street canyons. Apartments should be operating in a free running mode without any air conditioning system. Finally, we located 32 volunteering individuals who are willing to host our data loggers and observational team.

Officially the 2015 summer heat wave took place from the first to nineteenth of August (19-day event) in Egypt (Mitchel 2016). However, the measurements were conducted in 32 different apartment buildings in Cairo from the 20th of July to the 20th of August 2015 (30 days) to cover a larger range of measurements and compare the thermal comfort before and after the heat wave.

In each apartment, air temperature and relative humidity data loggers were installed in living rooms. The measurements taken in main living space of apartments are considered representative for each apartment, similarly to the work of Colton et al. (2014) and Lai et al. (2009). The instrumentation was placed in order to have recordings taken at living rooms directly oriented on the street canyon. The loggers were typically installed on walls and measurements were taken by the loggers every 30 minutes. The temperature and humidity were monitored by using HOBO U12-012 data logger. For outdoor temperature and humidity were monitored in a weather proof box on rooftops of buildings. Table 2 provides more details about the monitoring instrument.

During the apartment's visits, portable equipment was also used to take temperature, relative humidity and point-in-time measurements at the street level. Moreover, one of the 32 apartments hosted a testo-480 measurement kit to measure temperature, humidity, air flow meter, pressure, degree of turbulence, heat radiation, CO_2, illumination intensity, PMV/PPD and WBGT. On the roof of the same apartment buildings, a HOBO U30 Weather Station was installed to create an external weather file.

Table 2. Details of instrument used for measurements

Parameter	Instrument	Make	Range	Accuracy
Temperature	HOBO U12-012	Onset USA	-20 ºC to 70 ºC	± 0.35 °C (0-50 °C)
Humidity	HOBO U12-012	Onset USA	0 to 95% RH	± 2.5% (10-90%)
Climate measurement	Testo 480	Testo Germany	-200 to +1370 °C	±(0.3 °C + 0.1 % of mv)

2.3. Observational studies

Field measurements were followed by observational field visits and interviews conducted with local citizens that document the impacts and adaptation due overheating. Observational studies were conducted to investigate the heat wave event and collect data to determine probable impacts and adaptation measures. We could not find reliable epidemiological information on the mortality rates during the heat wave. Therefore, we created a team of 16 investigators who were paid to observe and interview occupants and their built environment. The 16 investigators are post-graduates from the Faculty of Social Works. They were grouped into teams of 2 and each team visited 4 apartments between the 1st and 18th of August 2015. They were briefed on the study purpose and asked to characterise the street canyons, visited apartments and more importantly observe what happens in real life situations with a focus on physical and non-physical heat stress reasons. The observation log books were collected and analysed to provide an understanding of how occupants behave during the heat wave. The experiment was conducted in accordance with the ethical standards in the Declaration of Helsinki.

2.4. Comfort assessment

The measurement results were collected to test them against several comfort models. We tested the impact of applying Fanger's model (ISO 2005), Givoni's model (with and without fans), ASHRAE 55 adaptive comfort model (2017) and EN 16798 (formerly 15251) adaptive comfort model (CEN 2015) on comfort, similar to the work of Attia et al. (2015 and 2019).

3. Results:

The results of the study are presented in this section following the 4 staged approach of the methodology.

3.1. Geographical Mapping

Figure 1a shows the urban density map of Greater Cairo and the district with an urban density above 15.000/km[2]. The distribution of districts with high UHI effect potential can be found as well (Figure 1b). Figure 1 indicates that the highest urban density is found is informal planned districts along and closes to the Nile River in the centre. Accordingly, our selected street canyons are listed in Table 2. The range of street coverage values of all streets was 3% to a maximum of 28%. The aspect ratio of the 15 street canyons varied from 0.8 up to 1.8 and street traffic between 17:00 and 18:00 hours during working days was between 615 up to 1555 car/hour.

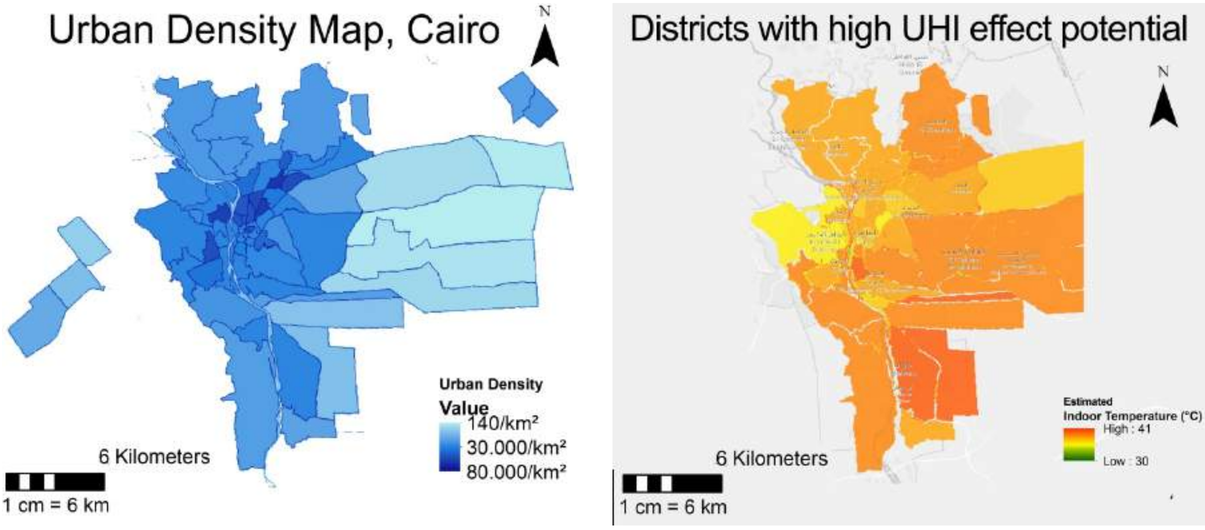

Figure 1a. the urban density map, b. estimated districts with high UHI effect potential based on Taheri Shahraiyni et al. (2016)

Table 2. the selected streets canyons with the highest UHI effect potential ()

	District	Street Name	Apts.	Traffic [cars/hour]	Aspect Ratio [coefficient]	Trees Coverage [%]
1	Rowd al Faraj	Shobra	2	885	1.2	3
2	As Sabtiyyah	Bolak al Gadida	1	725	1.1	21
3	Hadaiq al Qubbah	Masr we al Sudan	2	1235	1.1	10
4	Al Abasiya	Al Wayli / Al Gaysh	1	1405	1-1.2	20
5	Nasr city	Abbas El-Akkad	3	1175	0.8-1	28
6	Shubra Al Khaymah	Al Teraa Al Bolakia	2	1065	1.1	3

7	Imbaba	Al Aqsur	2	765	1.3	22
8	Ard El Lwaa	Ali Ibn Abi Taleb/ Teraat Al Magnoona	3	615	1.5	5
9	Bulaq Ad Dakrur	Zenein Canal	3	635	1.8	17
10	Al Duqqi	Mohi Al Din Abiy al Ezz	2	725	1.0	25
11	Al Gizaa	King Faisal Street	2	1165	1.0	10
12	Al Gizaa	Al Haram	3	1555	0.8-1	25
13*	Basateen*	Ahmed Zaki*	3	865	1-1.1	18
14	Dar as Salam	Al Fayoumy	2	695	1.1	14
15	Al Qasr al Ayni	Al Qasr al Ayni	1	750	0.8	28

* The weather station location

In this study, the residences were built ranged from 1965 to 2013. The basic building construction for all apartments is a reinforced-concrete post and beam structure with 0.15m thick brick infill walls without insulation. Windows are single glazed, transparent and have a 0.003m thick glass pane. The apartment's characteristics are almost identical with similar physical properties as indicated in the previous study by Attia et al. (2012).

3.2. Field Measurements

The results of the field measurement can be found in Figure 2. The heat wave period is highlighted in red in Figure 2b. The indoor air temperature reached its maximum of 41.4 °C at 19:30 by August the 7th. Relative humidity was not the primary reason of the overheating. Figure 2c indicates that humidity levels reach 100% on some instances. Around half of the heat wave days had humidity levels exceeding 60%.

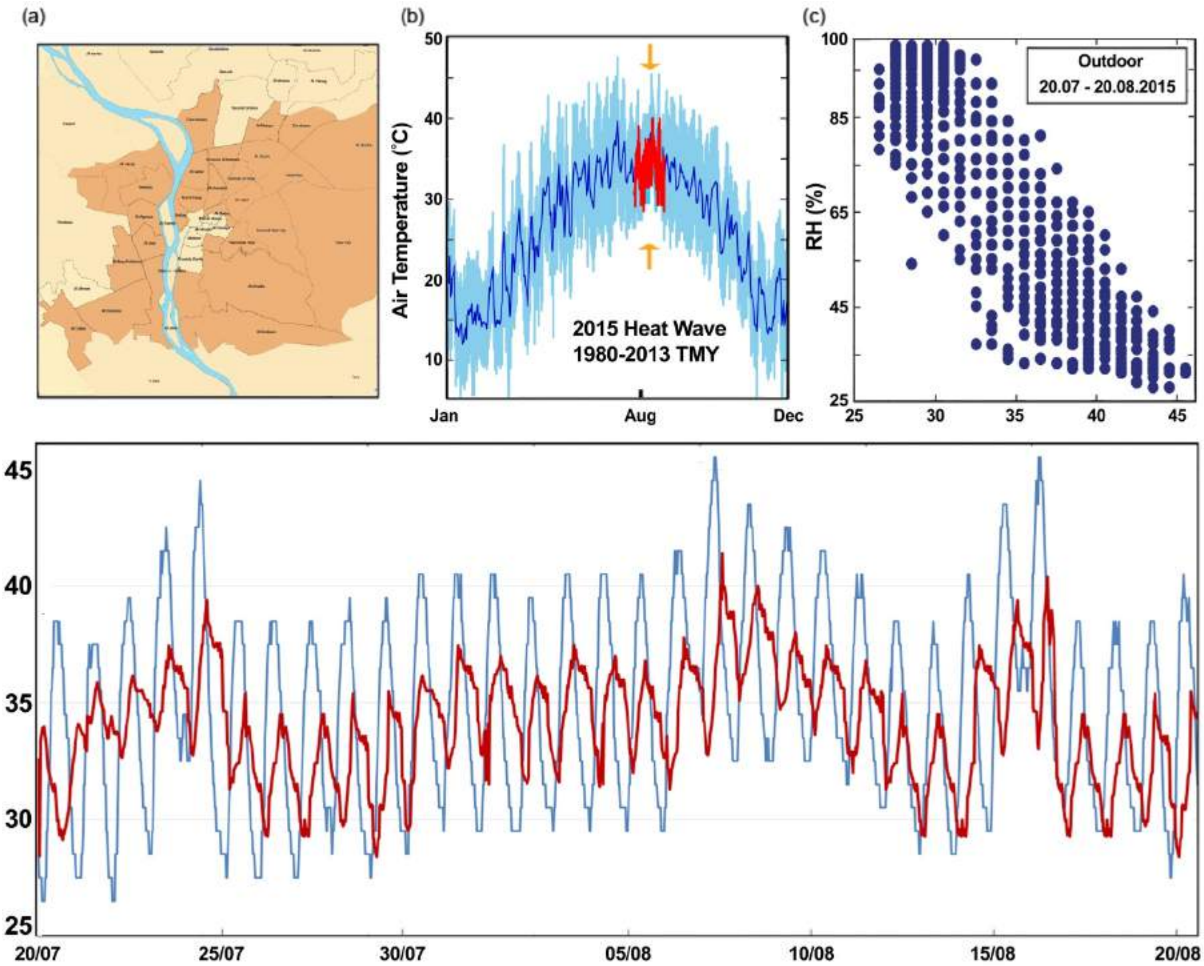

Figure 2. (a) District location over Cairo where the 15 street canyons were identified. (b) The measured outdoor air temperature in Cairo through 20 Jul to 20 Aug. The red line shows the 2015 heat wave; the light blue region is the outdoor air temperature covering 1980-2013 based on TMY file; and the dark blue line is the outdoor mean daily temperature. (c) A scatter plot of the indoors measured daily air temperature against relative humidity levels for all days over the20 Jul to 20 Aug period. (d) Average measured outdoor air temperature (blue) and (red) and indoor air temperature of the 32 apartments.

3.3. Observational studies

Of the 32 visited apartments, at least 55 study participants were observed using at least three adaptive behaviours throughout the study period. All apartments were occupied by single-family residences with an average of 4 to 6 occupants. All apartment occupants identified economic factors; ranging from lack of resources to buy air conditioners or pay for related electricity costs. A total of 12 apartments had at least 2 fans each and 20 had three fans or more. Twenty five apartments had shading protection in the form of external curtain or draperies, venetian blinds, drop-arms awnings, or folding-arm awning. At least, six of heat-adaptive behaviours, listed in Table, 3 were used by occupants. The most frequently used behaviours over the entire study period were 'opening windows or doors', turning fans "ON" and sleeping late i.e. 2:00 am in the morning.

Table 3. Heat-adaptive behaviours reported by the investigators in the log books during the heat wave

Behaviour	Description
Drinking	Drinking plenty of cold water, iced water and lemon juice; drinking cold instant drinks (flavoured powder); drinking excessive quantities of black tea.
Sleeping	Shifting the day rhythm and shifting daily activities to the night; shopping and eating outdoor after sunset; sleeping late and waiting for fresh breezes after midnight; waking up midday during weekends; sleeping with open windows, turn "ON" fans and sleep in light clothing; sleeping in the balcony or move the mattress to the coolest space in the apartment. Switching the life style to the nigh mode.
Eating	Eating fruits and vegetables such as figs, peach, grapes and watermelons; eating salty meals, avoiding cooking and specially avoid the use of the oven; eating ready-made or homemade fast meals (burger and sandwiches); using frozen vegetables to avoid withered vegetable; eating sweet deserts and ice cream. Overall occupants reported eating less during the heat wave.
Taking a shower	Taking showers frequently: after work, after waking-up and before going to sleep.
Changing clothes	Choosing clothes made of breathable materials like cotton; choosing loose-fitting clothing such as Jelllabiyas; wearing clothes once a day; avoiding clothes with collars; wearing slippers and sandals; changing the veil style to Spanish style for females; cutting long hair for females; shortening; turning the washing machine more frequently.
Opening windows	Opening windows or doors during night; leaving blinds in the semi-closed position during day. Closing aluminium windows during day to avoid the scorching weather.
Turning fans "ON"	Turning fans "ON" day and night; using table fans, floor fans, ceiling fans, and standing fans; using a fan in living and sleeping rooms; turning fans "ON" in the kitchens.
Interior furniture	Taking out carpets and rugs and store to maximize the thermal mass effect.
Leaving the apartment	Leaving the house after 8:00 pm and hanging around public spaces and coffee shops until morning. With the increasing outdoor temperature above 32 °C, almost all males were leaving the apartments.
Medications	Increasing the use of gastrointestinal medication, disinfectant and anti-bacterial pills and increasing the use of hypertension medications for low blood pressure.

Regarding the impacts of the heat wave, Table 4 summarizes the key observed impacts associated with the heat wave.

Table 4. Heat-related impacts reported by the investigators in the log books during the heat wave

Impact	Description
Sweating	Increasing sweat rate and water depletion. A relative humidity of 60% or more hampers sweat evaporation, which hinders the body's ability to cool itself.
Sleeping	Increase in difficulty to get adequate sleep; affecting the ability to fall asleep, stay asleep and feel refreshed from sleep. Increase stress.
Mobility	Avoiding outdoor activities and reducing mobility.
Cognitive performance	Reducing cognitive function (working memory and selective attention/processing speed,), concentration and the ability to take decisions during the heat wave; Increasing the use of black tea and coffee to wake up in the morning and concentrate during the day. Students reported impossibility to study during the heat-wave.
Heat-related illness	heat exhaustion, fatigue, dehydration, heat oedema, heat syncope, exfoliation and heat rash, diarrhoea (dairy products and fruits), hypertension (low blood pressure)
Physical environment	Magnification of UHI effect resulting in higher night-time temperatures; stagnant atmospheric conditions and poor air quality; increase of flies.

3.4. Comfort assessment

The measurement results were collected to test them against several comfort models. We tested the impact of applying Fanger's model (1970), Givoni's model (1998), ASHRAE 55 adaptive comfort model and EN 16798 adaptive comfort model on comfort, similar to the work of Attia et al. (2015). As shown in Figure 3 and 4, most of the hours (79%) of the heat wave period remained above the most adaptive comfort model's (ASHRAE 55) thresholds. The result proves a very high overheating in a free-running residential building. Overheating is seen to occur in the 32 investigated apartments stretching all over Cairo.

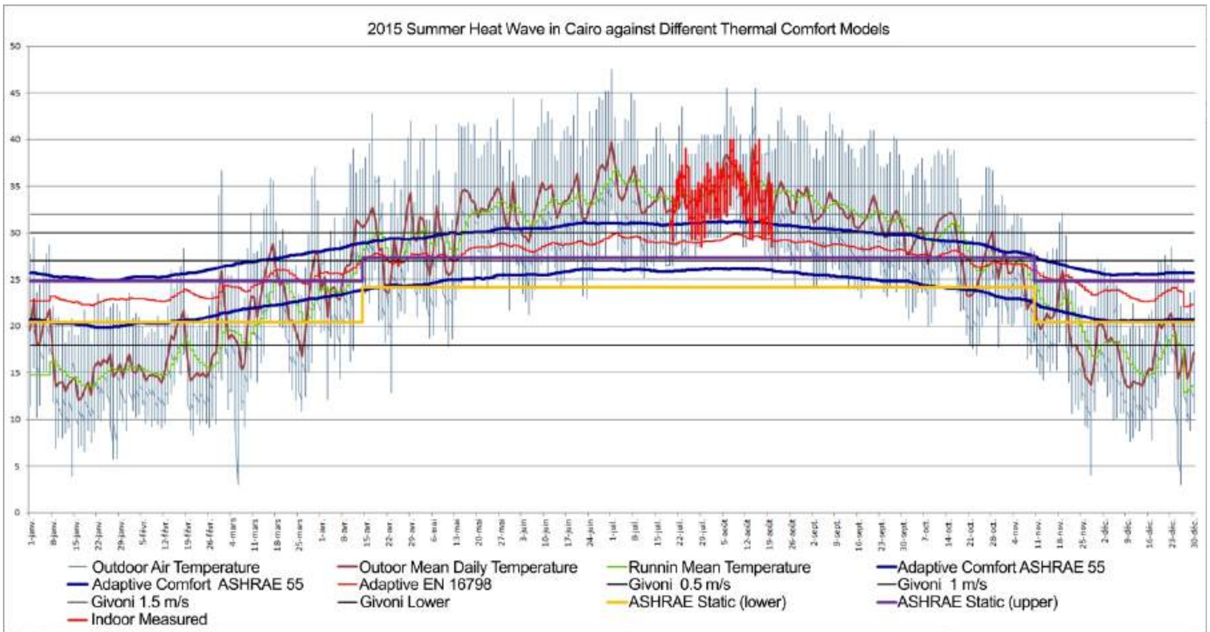

Figure 3. Plot of the measured indoor temperatures in Cairo against four different thermal comfort models.

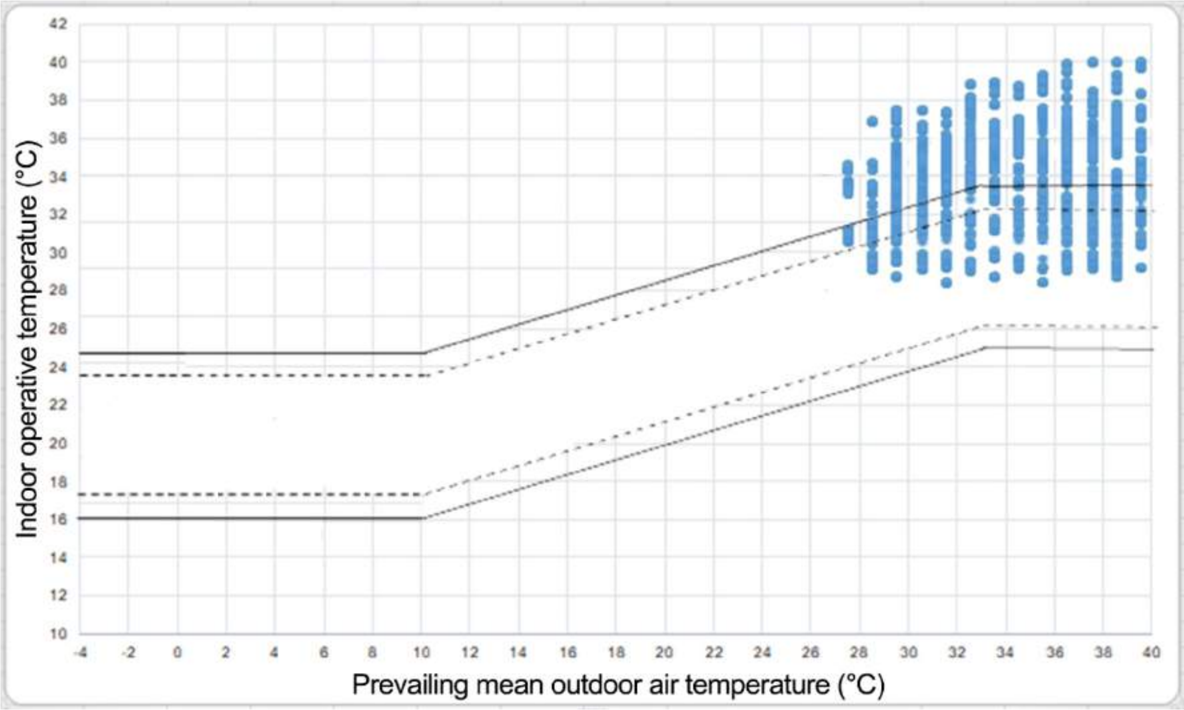

Figure 4. Operative temperate values distributions from the four-week recording periods in the heat wave of 2015, in Cairo through 20 Jul to 20 Aug, against the ASHRAE 55 adaptive comfort model. Only 21% of hours fall within the comfort range.

4. Discussion:

In this study, an analysis of thermal comfort was undertaken during the 2015 Egyptian heat wave. The aim of this study was to assess the thermal comfort in free-running conditions during extreme climate conditions in Cairo. The followings sections summarize and discuss the study findings:

- 32 free-running apartments were studied in 15 different representative streets in Cairo. All external walls are constructed of concrete post and column structure and fired redbrick (0.125 cm thickness) with conductivity (U-Value) of 2.5 W/m^2 K.
- In August 2015, the indoor temperature reached 41°C and indoor relative humidity reached 92% indoors in Cairo's free running residential buildings. During the heat wave the average indoor air temperature was 34 °C and around half of the days had humidity levels exceeding 60%. Thus, apartments in Cairo have the tendency to overheat in summer making night-ventilation less effective.
- Measurements prove that during 19 consecutive days of a heat wave; occupants suffered from heat stress and heat associated ailments. For example, occupants tend to suffer from physical impairments. Observation study documents and lists the heat wave impact on occupant's behaviour and daily life routine.
- Current adaptive comfort models are obsolete during extreme climates conditions in Cairo.
- Present study created an inventory of behavioural adaptation measures undertaken by occupants during the heat wave. One of the most common heat-adaptive

behaviours of occupants is shifting their day to day activities to the night and to delay the sleeping timings. Using fans has a great role in mitigating overheating discomfort.

High temperature and high humidity are the principal drivers of human discomfort. Although the findings are not new, we believe that this work is important because it recognizes overheating and provides solid evidence that indoor temperatures exceeded all current upper-limits of adaptive comfort models. Furthermore, we built a unique methodology that combines GIS, measurements and field observations, which resulted in presenting hard evidence on comfort conditions in Cairene households during extreme summers. For this study, we selected the ASHRAE 55 adaptive comfort model (2017) because we consider it the best model that can tolerate high humidity limits of up to 80% or more (Attia et al. 2019). Future research should test other thermal comfort models including the compliance with the Egyptian energy efficiency code (HBRC 2016).

The overheating in Cairene households is critical to the human body and has a significant impact on occupant's well-being, productivity, and satisfaction. Heat waves can impact human health causing increases in morbidity and mortality (Lomas et al. 2017). Although there is strong evidence linking extreme heat with excesses in mortality, there is less literature describing the impact on morbidity, including the impacts on specific age groups in free-running residential buildings during heat waves. This study also tried to focus on quantifying the physical heat stress and the social aspects by observing and documenting the heat wave related adaptive behaviours during extreme climatic conditions. However, we failed to provide an epidemiological analysis. Despite the significant increase of mortality rate in Cairo in 2015 (9.6 per 1,000 individuals) compared to 2014 and 2016 (9.0 per 1,000 individuals), it was difficult to get access to monthly mortality rates for Greater Cairo's districts. In fact, we agree with Mitchel (2016) that a full epidemiological analysis is needed.

Observation logbooks indicate that the heat wave was physically uncomfortable and also psychologically stressful for most occupants. Occupants were struggling to buy air-conditioning or pay their electricity bills to escape the scorching heat. Almost all residents wished to have an air conditioning but pointed to their financial constraint. Already the 32 investigated households spent more than 8-14 % of their income on utilities, (natural gas for cooling and electricity for lighting and appliances), and indicated that utilities bills are a burden. Since energy poverty (or fuel poverty) is commonly defined as 10 % of total household income (Nussbaumer et al. 2012), this study findings indicates that most households suffer from energy poverty. In Egypt, this term is not well-known but most participants pointed to this without articulating is explicit as a source of mental stress during extreme days.

Finally, this study represents a step in the understanding of health impacts of thermal overheating in a hot climate city. We hope that this study will prompt debate about current thermal comfort standards and their appropriateness for assessing overheating of free-running buildings during climate extremes. Proposed methodology, which combines GIS, measurements and field observations, should be useful for assessing overheating risks in other buildings types. On the long term, the influence of anthropogenic climate change needs to be investigated similar to the work of Mahdy et al. (2015) and Lomas et al. (2012). On the short term, it is anticipated that the Egyptian government on the national and local level will react to these findings and seek to improve the quality of life and well-being of occupants in residential households. Currently, regulators fail to apply much pressure with regard to bioclimatic design or efficiency standards (Attia et al. 2009 and 2012). Consequently, developers and house builders should receive incentives or abide by the regulatory requirement to provide passive measures for heat protection. Otherwise, economic improvements of the investigated households incomes will be associated with the proliferation of low-efficiency air conditioning units that threatens our ability to tackle climate change magnify the UHI effects in Cairene streets.

5. Conclusion:

Measurements in 15 different representative streets and 32 free-running apartments were performed to represent the indoor and outdoor climate in Cairo. The study provides a snapshot of thermal comfort during the 2015 Egyptian heat wave. The study is the first comprehensive study in Egypt that provides insights on the physical and non-physical observation regarding heat stress and heat associated complaints. For example, occupants tend to suffer from physical impairments. Observation study documents and lists the heat wave impact on occupant's behaviour and daily life routine. The study proves that current adaptive comfort models are obsolete during extreme climates conditions in Cairo and there is a serious need for mitigating overheating discomfort. The study documents the heat wave consequences and provides an evidence based understanding of the severity of climate in Cairo.

6. Acknowledgement

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