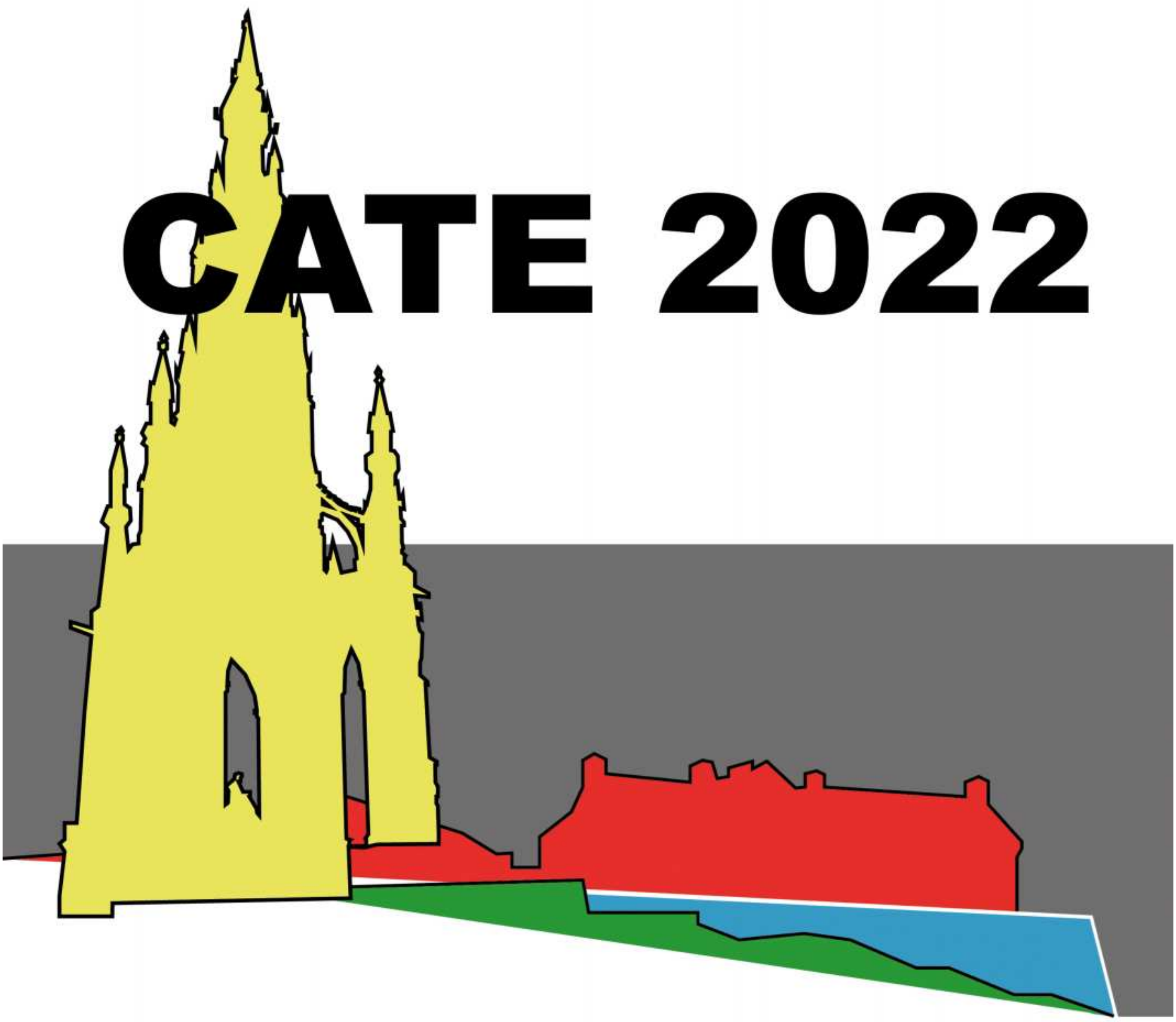
COMFORT AT THE EXTREMES:

*COVID, CLIMATE CHANGE AND VENTILATION*

**Royal College of Physicians of Edinburgh**
**Edinburgh, 5-6th September 2022**




# PROCEEDINGS OF THE 3rd INTERNATIONAL CONFERENCE ON COMFORT AT THE EXTREMES: COVID, CLIMATE CHANGE AND VENTILATION

Edited by Susan Roaf and Will Finlayson

Proceedings of the 3rd International Conference on:

**Comfort at the Extremes: Covid, Climate Change and Ventilation**

5th – 6th September 2022

**Royal College of Physicians of Edinburgh, Scotland**



**ISBN**: 978-1-9161876-4-1

Published by the Ecohouse Initative Ltd.

# INTRODUCTION TO THE PROCEEDINGS

Since 2020, both the COVID-19 pandemic and the ever more extreme climate events we experience have begun to fundamentally alter the way we think about how buildings must be designed and operated for our heating, and pandemic-riven world.

Radical progress is now essential to create buildings that are ahead of the curve to lead such thinking. Emerging and innovative research and design developments were brought to the 3rd International Conference on Comfort At The Extremes in Edinburgh by a range of different stakeholders from academia, the professionals, politics and industry.

The issue of affordability was also a factor in much new thinking on keeping people thermally safe in buildings, particularly for the vulnerable old, young and sick. In the 20th Century comfort was increasingly seen as a problem to be solved by an engineer with a machine. Today, the provision of comfort has become the remit of those involved in physics, medicine, behavioural psychology, physiology, sociology, architecture, planning, urban design and development and behavioural sciences. They were all represented at CATE 22.

Contributions from many different disciplines are included in the following papers that we hope will provide inspiration for significant steps forward in our efforts to create and run buildings that can keep people affordably, and acceptably comfortable and healthier, even in the more extreme climates and conditions we will all have to occupy in the future.

## Conference Chairs

Susan Roaf

Emeritus Professor of Architectural Engineering,
Heriot Watt University, Edinburgh

Rajat Gupta

Professor of Sustainable Architecture and Climate Change and
Director of the Oxford Institute for Sustainable Development,
Oxford Brookes University

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# Humans and buildings in times of climate change – a perspective on resilience

**Hannah Pallubinsky[1, 2], Wouter D. van Marken Lichtenbelt[1] and Rick P. Kramer[3]**

[1] Dept. of Nutrition and Human Movement Sciences, NUTRIM School of Nutrition and Translational Research on Metabolism, Maastricht University, the Netherlands, h.pallubinsky@gmail.com;
[2] Research and teaching area Healthy Living Spaces, Institute for Occupational, Social and Environmental Medicine, Faculty of Medicine, University Hospital RWTH Aachen, Germany;
[3] Department of the Built Environment, Eindhoven University of Technology, the Netherlands

**Abstract:** As comfort seekers, we avoid being exposed to temperatures outside of our comfort zone. However, in the light of climate change and the need to drastically reduce our carbon footprint, we need to rethink many of our habits. Enhancing our own human resilience, by training our bodies' thermoregulatory system, presents an opportunity to reduce energy use, while at the same time, improving our health. Allowing for more thermal variation in the indoor environment has the potential to enhance human thermal resilience, while also saving energy and decreasing CO2 emissions.

**Keywords:** Resilience, dynamic indoor climate, natural variation, human health, healthy buildings

## A perspective on resilience of humans and buildings

As we are confronted with climate change, it is more important than ever to assess strategies of adaptation towards, and future prevention of, the fast-paced progressing of global warming. In 2021 alone, we witnessed a variety of severe weather phenomena (such as the Western North American heat wave, the European floods, and wildfires across the globe) caused by or contributed to by climate change (Schiermeier, 2021, Kreienkramp et al., 2021). Much scientific and political interest lies in preparing our cities and living spaces for these challenges, by implementing new technologies as well as physical reinforcements, and by adopting innovation in urban planning. Within this context, the built environment needs to become more sustainable and resilient to limit its own negative impact on climate change. At the same time, it should provide pleasant and healthy living and working environments, but also protect people from weather extremes. Over time, particularly in western and industrialised countries, buildings have evolved to not just provide comfort and necessary protection, but rather shield its occupants more or less completely from what is happening in the outdoor environment. Concurrently, spending the vast majority of time in buildings, us humans have gotten so used to a constant, comfortable indoor environment that we are no longer able to cope with natural thermal fluctuations. However, we should consider that not
just our physical environment, but also our human bodies have the potential to become more resilient to withstand thermal challenges like heat waves and cold spells.

The time has come to shift perspective, as this overprotective character and provision of omnipresent comfort are neither feasible nor desirable any longer, considering the enormous amount of energy and resources spent to provide tightly controlled thermal environments (often with the same target temperature all year round). On top of all that, research has shown that being in a constant state of comfort can actually have negative impacts on health and deteriorate our human capability to deal with thermal challenges. Importantly, research at our lab and elsewhere has shown that humans are very well able to cope with both cooler as well as warmer temperatures than are usually present in the indoor environment (van der Lans et al., 2013, Pallubinsky et al., 2017, Pallubinsky et al., 2020, Taylor, 2014). Being regularly exposed to thermal stimuli outside the comfort zone is known to enhance our thermoregulatory capacities, while also improving certain health-related aspects such as metabolic and cardiovascular function (Brunt et al., 2016a, Brunt et al., 2016b, Pallubinsky et al., 2020, Hoekstra et al., 2018).

The adaptive comfort model has made an important first step towards endorsing seasonal changes in indoor temperature, at least in naturally ventilated buildings. We advocate for taking even larger and bolder steps in adapting our thermal indoor environment, to keep pace with the fast progression of climate change. This conference contribution will raise awareness for novel and alternative avenues to deal with future climate challenges, both with respect to the built environment and humans. Allowing more thermal variation and dynamics indoors, and thus stimulating physiological and psychological adaptation in humans, has the potential to 1) save precious resources, 2) decrease the negative impact of building CO2 footprints and 3) provide building occupants with the opportunity to become more resilient and healthier at the same time. Importantly, this does not ignore that we must protect ourselves, and especially vulnerable individuals, from the hazardous effects of thermal extremes: general recommendations to cope with heat waves and other weather events, e.g. avoiding direct sun radiation and ensuring sufficient hydration, are indispensable (Public Health England and NHS, 2014).

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# Hospital ward air cleaning and COVID-19: the need for a rigorous scientific approach

Clive B Beggs[1], Matthew J Butler[2], Christine Peters[3], Andrew Conway Morris[4,5,6], Victoria L Keevil[2,4]

1. Carnegie School of Sport, Leeds Beckett University, UK
2. Department of Medicine for the Elderly, Cambridge University Hospitals, UK
3. Department of Microbiology, NHS Greater Glasgow and Clyde, UK
4. Department of Medicine, University of Cambridge, UK
5. John V Farman Intensive Care Unit, Cambridge University Hospitals, UK
6. Division of Immunology, Department of Pathology, University of Cambridge, UK

## Abstract

The knowledge base associated with the use of supplementary air filtration in hospitals is weak, with little known about how filtration devices should be deployed or the likely health benefits that might be accrued. Nevertheless, there is good reason for thinking that room air filtration might help to mitigate the nosocomial transmission of COVID-19 and also reduce aerial dissemination of pathogens around the clinical environment. In response to this the Addenbrookes Air Disinfection Study (AAirDS) was initiated, aimed at evaluating the impact of room air filtration on the nosocomial transmission of SARS-CoV-2 and other HCAIs in medicine for older people inpatient setting. This 12-month before-and-after, controlled, quasi-experimental study that involved the installation of 12 room air filtration units, containing HEPA filters and UV-C lamps, on two medicine for older people wards. This was accompanied by the installation of 18 sensors throughout the control and intervention wards to continuously monitor PM and $CO_2$ levels as well as the ambient temperature and humidity. This United Kingdom Health Security Agency (UKHSA) funded study aims to start addressing many of the short-comings in the knowledge base associated with room air filtration.

## Funding and acknowledgments

The Addenbrookes Air Disinfection Study (AAirDS) is funded by the UK Health Security Agency and was approved by the NHS Health Research Authority and Health and Care Research Wales (HCRW) (IRAS ID 299336) and the Central Bristol Research Ethics Committee (REC reference: 22/SW/0010). AAirDS is also supported by the NIHR Cambridge Biomedical Research Centre (BRC-1215-20014). The views expressed are those of the authors and not necessarily those of the NIHR or the Department of Health and Social Care.

Dr Victoria L Keevil is funded by a MRC/NIHR Clinical Academic Research Partnership Grant (CARP; grant code: MR/T023902/1). Dr Andrew Conway Morris is supported by a Clinician Scientist Fellowship from the Medical Research Council (MR/V006118/1).

Dr Conway Morris sits on the scientific advisory board of Cambridge Infection Diagnostics.

## 1.0 Introduction

The COVID-19 pandemic has advanced understanding of how respiratory viral infections spread within buildings. It is now known that small aerosol particles play a dominant role in the transmission of SARS-CoV-2 [1-7]. These are formed when exhaled respiratory droplets, <100 µm in diameter, evaporate to become aerosol particles [8, 9] approximately 20–34% of their original size [10]. Particles of this size can remain suspended in the air for many minutes [11] and can be readily inhaled, with those in the size range 2.5 - 20 µm thought to account for 90% of the viral transmission at the nasopharynx [10]. As such, transmission of SARS-CoV-2 is thought to primarily occur when infectious aerosol particles in this size range come into contact with angiotensin-converting enzyme 2 (ACE2) receptors in the nasopharynx [12] and further down the respiratory tract [13].

Infectious respiratory aerosols can be liberated in large quantities when talking, singing, or simply breathing [14-16] and may build up to high concentrations in room air, if the space is not adequately ventilated [11]. Even where background ventilation appears adequate, air flow direction also appears to be a key determinant of infection carriage and risk for transmission [7]. Consequently, poorly ventilated spaces that may contain infectious individuals, such as hospital wards, can pose a considerable threat to patients and healthcare workers alike, with numerous nosocomial COVID-19 outbreaks reported in the literature [17-25]. The problem can be particularly acute in wards containing older and/or immunocompromised patients who are vulnerable to developing severe disease following viral infection and who importantly are usually already unwell and admitted for non-COVID-19 illnesses. Furthermore, in open-plan wards with multi-bedded bays, pressure gradients may exist due to room mechanical ventilation or wind pressure, with the result that respiratory aerosol particles can migrate considerable distances [26]. As such, vulnerable patients who are at some distance (>2 m) from an infector can become exposed. Realisation of this issue has led to growing interest in non-pharmaceutical interventions such as room air filtration [27] and air disinfection [28, 29], and also utilising carbon dioxide ($CO_2$) monitoring [30, 31] to optimise ventilation [32]. Collectively, these aim to mitigate the transmission of SARS-CoV-2 within the clinical setting.

Portable free-standing air filtration devices that contain high efficiency particulate air (HEPA) filters have been shown to be effective at removing pathogens and allergens from room air in schools [33] and also on hospital wards [34]. As such, there is good reason to believe that appropriate deployment of this technology might help to mitigate transmission of SARS-CoV-2 on hospital wards. However, much of the evidence supporting the use of air cleaning technologies is based on laboratory and modelling studies, with very little epidemiological work having been undertaken. Consequently, little is known about how these air cleaning technologies should be deployed to best effect, or indeed, as to which context they are most suited. So in short, many questions remain unanswered regarding supplementary room air cleaning and its deployment in the clinical setting.

## 2.0 Weak evidence base

Understanding of how respiratory viral infections are transmitted has changed radically during the COVID-19 pandemic. Early in the pandemic it was thought that COVID-19 was primarily spread by direct contact and via large respiratory droplets >100 µm in diameter that behave ballistically. However, it is now known that smaller aerosol particles that become airborne play an important role in transmission of the SARS-CoV-2 virus [1-4, 7]. As such, the airborne route of transmission, which was largely ignored prior to the pandemic, has suddenly been elevated in importance. Unfortunately, because this issue was overlooked for many years prior to the pandemic, the evidence base regarding the airborne transmission and aerial dissemination of nosocomial pathogens in hospitals is weak, with most of the work undertaken in this area and technical guidance focusing on operating theatres [35], with much less attention devoted to the ventilation of hospital wards and outpatient areas, despite most nosocomial outbreaks of COVID-19 occurring in these spaces [17-25]. Furthermore, because airborne transmission has historically not been perceived as a problem, few guidelines exist for the deployment of room air filtration devices in hospitals, or indeed in other contexts.

The lack of any guidelines regarding room air filtration reflects the poor evidence base that exists regarding the efficacy of the technology. While recent studies have shown that filtration devices can reduce the airborne microbial bioburden [34] and particulate matter (PM) [26] in ward air, high quality epidemiological evidence demonstrating that HEPA filters can actually reduce nosocomial COVID-19 infections is sadly lacking. Consequently, little is known about: (i) where room air filtration devices should be employed to best effect; (ii) how many filtration devices should be employed in any given context; (iii) the size of the devices that should be deployed; (iv) the locations in which the devices should be installed; and (v) the likely impact of the devices on the transmission of SARS-CoV-2 and other nosocomial infections. Given also that the performance of room air cleaners is greatly influenced by the number of people present in a room space, the activities undertaken, and the background ventilation rate, this means that much remains unknown about where and how room air filtration should be employed for optimum effect.

Validation is another issue that has received little attention. Over the course of the pandemic manufacturers of air cleaning technologies have flooded the market with devices claiming to make buildings 'COVID safe', yet few appear concerned with demonstrating that their devices actually have a beneficial health effect. All too often manufacturers make claims about their products that are unsubstantiated, with little supporting microbiological/epidemiological evidence presented. As such, the end-user has little idea as to whether or not the air filtration devices are actually having an effect in any given context. Indeed, without employing PM sensors and undertaking validation experiments it is difficult to assess the performance of room air filters in any given context. Yet to date relatively little work has been done on validating and monitoring the performance of room air filters [26]. Consequently, much work is still required to better understand how best to monitor and validate the performance of supplementary room air filtration in the clinical context.

## 3.0 Air filtration on hospital wards

One application which appears particularly well suited to room air filtration is on hospital wards that often contain immunocompromised patients who are vulnerable to healthcare-associated infections (HCAIs). Such patients are frequently immobile and spend long periods in an environment where bacterial, viral and fungal pathogens may be present. As such, these patients are at higher risk of contracting a nosocomial infection during a hospital stay. The situation is made worse by the selective pressures experienced in healthcare facilities, which mean that the bacterial species found in hospitals often exhibit drug resistance [36-38], which can lead to increased morbidity and mortality [38]. Indeed, in 2016/2017 there were an estimated 653,000 HCAIs among adult inpatients in NHS general and teaching hospitals in England alone, of which 22,800 patients died as a result of their infection [39]. In addition, numerous nosocomial outbreaks of COVID-19 have occurred in hospitals throughout the pandemic [17-25]. Collectively, this represents a substantial financial burden on healthcare systems, with for example the cost to the NHS in England for 2016/2017 estimated to be about £2.7 billion [39].

Although the role of the airborne transmission of COVID-19 is now well recognised [1-7], the role that aerial dissemination plays in the transmission of other HCAIs has been largely overlooked [40]. This is primarily because of the ridged classification system that has traditionally been used to describe routes of transmission (i.e. direct contact transmission, fomites transmission, airborne transmission, oral transmission, etc.), does not allow for composite pathways that involve multiple routes of transmission. Yet, bacterial species in particular can be liberated into the air in large quantities by activities such as: bed making

[41, 42]; curtain drawing [43]; and the use of non-invasive ventilators [44]. Bacteria released into the air by such means can either be flushed from the room space by the ventilation system (as evidenced by the large amounts dust and debris that accumulates in ventilation ductwork systems in hospitals [40]), or, more likely, settle out due to gravitational deposition onto fomites and other horizontal surfaces within the room space [45-47]. Electrostatic deposition onto plastic surfaces and polymer fabrics (e.g. bed curtains, PPE aprons, etc.) can also occur [48]. As such, aerial dissemination of bacteria arising from activities such as bed making can make a major contribution to bacterial contamination of room surfaces and by inference fomite transmission (i.e. transmission involving inanimate objects that become contaminated, which then come in contact with susceptible individuals). Given that humans shed between $2 \times 10^8$ and $10 \times 10^8$ skin squamae per day [49, 50] and that each squamae can carry >100 bacteria [51], it has been estimated that 51–257 bacteria per second will be deposited on a $1m^2$ surface in a typical four-bedded ward bay [40] – something that appears to be supported by the findings of numerous studies involving the dispersal of *S. aureus* [52, 53] and *C. difficile* [54-56]. Furthermore, recent work has shown that airborne PM can be widely disseminated throughout hospital wards [26], confirming the findings of earlier studies that demonstrated that bed making is associated with raised PM counts in ward bays [42] and the dispersal of microorganisms from patient rooms into nearby hallways [41]. Therefore, it is likely that the aerial dissemination of nosocomial pathogens contributes significantly to microbial contamination of the clinical environment, and that this in turn might play a role in fomite transmission. Consequently, there is reason to believe that the utilisation of portable HEPA filters on hospital wards might assist in reducing the overall environmental bioburden, thus helping to reduce HCAIs [57-59].

### 4.0 The Addenbrookes Air Disinfection Study (AAirDS)

In response to the COVID-19 pandemic a team at Addenbrookes Hospital, Cambridge, initiated the Addenbrookes Air Disinfection Study (AAirDS), aimed at evaluating the impact of room air filtration on the nosocomial transmission of SARS-CoV-2 and other HCAIs in medicine for older people inpatient setting. This United Kingdom Health Security Agency (UKHSA) funded study aims to start addressing many of the short-comings in the room air filtration knowledge base described above.

The AAirDS is a 12-month before-and-after, controlled, quasi-experimental study that commenced in 2022 and involves the installation of 12 room air filtration units (AFUs; 8 x AeroTitan2000s & 4 x Aerotitan3000s, Air Purity UK Ltd, Cambridge, England), containing HEPA filters and UV-C lamps, on two medicine for older people wards; 6 units on each ward. This was accompanied by the installation of 18 sensors (AeroSentinelV2s, Air Purity UK Ltd, Cambridge, England) throughout the control and intervention wards; 6 on each in both the corridors and the bays, to continuously monitor PM and $CO_2$ levels as well as the ambient temperature and humidity.

Importantly, the AAirDS will not only evaluate the environmental conditions in the various wards, but also the microbiological burden in the air and on surfaces, together with epidemiological work retrieving the number and type of HCAIs acquired during the study period, through an electronic health record. It is anticipated that the AAirDS will yield important information about the extent to which AFUs can: (i) reduce the microbial bioburden in the clinical space; and (ii) mitigate the spread of HCAIs, including those caused by SARS-CoV-2, although the latter will be impacted by the small sample size studying the effect of AFUs on only 2 wards (power calculation in progress). It is also hoped that by recording PM and $CO_2$ levels at multiple locations in the wards and coordinating this with epidemiological data, that important insights will be gained into the role that aerosols play in mediating the spread of HCAI.

### 4.1 Initial results

Preliminary work [26] undertaken during the commissioning period has demonstrated that the action of a single AFU, located in a corridor, can greatly reduced airborne particulate levels of all sizes throughout the ward space ($p<0.001$). This work also revealed that aerosol particle counts tended to rise and fall simultaneously throughout the ward space when the AFU was not in operation, with PM signals from multiple locations being highly correlated (e.g. $r = 0.343 – 0.868$ (all $p<0.001$) for PM1). Collectively, this indicates that aerosols were freely migrating between the various sub-compartments of the ward, suggesting that social distancing measures alone cannot prevent nosocomial transmission of SARS-CoV-2. However, when air filtration was introduced the PM levels greatly reduced throughout the ward space, suggesting that filtration has the potential to mitigate the nosocomial transmission of COVID-19 and reduce aerial dissemination of other harmful pathogens.

In addition to the findings above, one thing that the AAirDS preliminary work also highlighted was the need for in situ commissioning work to demonstrate the efficacy of the filtration devices. All too often, air filtration devices are placed in rooms without any consideration given to either their performance or range. It is therefore important to commission air filtration devices using PM sensors before they are utilised in order to demonstrate that they are effective at reducing PM levels throughout entire ward spaces.

## 5.0 Conclusions

The knowledge base associated with the use of supplementary air filtration in hospitals is weak, with little known about how filtration devices should be deployed and the likely health benefits that will be accrued. Nevertheless, there is good reason for thinking that the installation of room air filtration will help to mitigate the nosocomial transmission of COVID-19 and also reduce aerial dissemination of pathogens around the clinical environment. The AAirDS aims to assess the extent to which air filtration can help reduce the microbial bioburden in the clinical space, and mitigate the spread of HCAIs, including those caused by SARS-CoV-2. It should also shed light on the role that aerosols play in mediating the spread of HCAI in hospital wards.

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# Indoor environmental quality evaluation of lecture room environments: changes due to infectious disease risk management

**Adam O Donovan[1,2], Fergus Delaney[1] and Paul O'Sullivan[1,2]**

[1] MeSSO Research Group, Department of Process, Energy and Transport Engineering, Munster Technological University, Rossa Avenue, Bishopstown, Cork, Ireland. (corresponding author: adam.odonovan@mtu.ie)

[2] MaREI Centre For Energy, Climate and Marine, Ireland.

**Abstract:** The global COVID pandemic has seen a significant change in ventilation practices, where the need to ventilate buildings has been put centre stage. Longer-term ventilation approaches are likely to incorporate hybrid ventilation strategies to deal with the multi-objective challenge of enhanced comfort resilience in the face of a warming climate but may also need to rely on heat recovery technologies to ensure energy efficient ventilation in wintertime. There are also several buildings which are not likely to undergo energy efficient upgrades for some time and risk management strategies are being implemented in these buildings. Improvements in indoor air quality in existing educational buildings more generally are likely to improve the students learning performance, attendance and could lead to a safer internal environment. Despite this need, a recent review of the literature cites limited examples of evaluations of air quality in university settings. This paper will present an indoor environmental quality evaluation of ten university lecture rooms both before and after changes in ventilation behaviour and systems, that were accelerated due to the COVID-19 pandemic. Preliminary results indicate substantial reductions in indoor carbon dioxide concentrations in all lecture rooms in the post pandemic environment, with mixed changes in indoor temperatures. Mean reductions in carbon dioxide concentrations of between 28% and 53%, and maximum reductions in carbon dioxide concentrations of between 31% and 84% were observed due to behavioural and system changes. These reductions demonstrate the impact these changes have had on these indoor environments and by extension on the infectious disease risk at lecture room level which could lead to an improvement in student learning performance also.

**Keywords:** evaluation, monitoring, education, ventilation, performance

## 1. Introduction

The global COVID pandemic has seen a significant change in ventilation practices, where the need to ventilate buildings has been put centre stage. Recent research has shown us that many buildings and existing practices were not well positioned to cope with unforeseeable and extreme events such as a global pandemic and that buildings and how they are designed and used are crucial to controlling infectious disease risk (Awada *et al.*, 2021). The focus of many building societies and federations has been to improve or increase ventilation rates and/or increase the filtration of air to limit infection risk in indoor spaces (ASHRAE, 2021; Kurnitski, Boerstra and Franchimon, 2021). There are many studies that have emerged recently that focus on educational settings and the changes in indoor air quality (IAQ) or indoor environmental quality (IEQ) due to the recent pandemic (Aguilar *et al.*, 2021; Alonso *et al.*, 2021; Meiss, Jimeno-merino, *et al.*, 2021; Predescu and Dunea, 2021; Schibuola and Tambani, 2021; Zivelonghi and Lai, 2021). Reviews in this area have highlighted that it is likely that mixed-mode or hybrid ventilation (HV) systems will be required to ensure the best year-round performance and that more studies are needed to investigate the heating period and university buildings, as most studies thus far have looked at primary and secondary schools only (Jia *et al.*, 2021). Existing research in teaching environments have mainly measured parameters such as temperature, humidity and carbon dioxide ($CO_2$) to determine IAQ , thermal comfort and learning performance (Wargocki *et al.*, 2020; Aguilar *et al.*, 2021; Alonso *et al.*, 2021; Meiss, Jimeno-Merino, *et al.*, 2021; Paschoalin Filho *et al.*, 2022). These studies show that schools can decrease $CO_2$ levels through the effective management of ventilation rates both naturally and mechanically (Aguilar *et al.*, 2021; Alonso *et al.*, 2021), with $CO_2$ levels being well below recommended levels in one naturally ventilated case (Aguilar *et al.*, 2021). However, many have highlighted the consequences for focusing entirely on $CO_2$ levels, with some suggesting negative effects to comfort performance (Alonso *et al.*, 2021) and others highlighting that good $CO_2$ levels may hide poor air quality in other areas (Zivelonghi and Lai, 2021; McLeod *et al.*, 2022). The benefit of $CO_2$ is that it has been correlated to student performance (Wargocki *et al.*, 2020) and that it can be used to assess ventilation performance (Aguilar *et al.*, 2021). While many studies have highlighted the need to provide dedicated ventilation systems in educational environments (Pan *et al.*, 2021; Schibuola and Tambani, 2021; Zivelonghi and Lai, 2021) the reality is that given existing retrofit rates being below current targets, there are also many buildings which are not likely to undergo energy efficient upgrades for some time (BPIE, 2021). It is therefore critical to understand the capacity of existing systems to ventilate spaces adequately (and mitigate infectious disease spread) as well as maintain thermally comfortable conditions. The capacity of human behaviour has been seen to be very effective at increasing the comfort dead band and reduce the need for cooling, the same could be argued as to the capacity of humans to adjust their behaviour to ventilate spaces in the face of pandemic conditions and unpreceded restrictions and health guidelines. In this paper we present an IEQ evaluation of multiple lecture room environments before and after the COVID-19 pandemic. The aims of this study were to:

1. Determine and evaluate what differences occurred in IEQ related parameters due to changes in behaviour in NV lecture rooms.
2. To determine the effect of installing mechanical ventilation (MV) systems in rooms that were originally naturally ventilated, and,
3. To determine what likely changes in student performance have occurred due to structural and behaviour related changes.

## 2. Materials and Methods

To address the above aims, data was gathered from ten lecture room indoor environments from a pre-COVID monitoring period and a post-COVID monitoring period. Pre-COVID data was gathered in 2013/2014 as part of an IAQ monitoring campaign undertaken in the case study university. The post-COVID data was gathered using a new campus wide IAQ monitoring system which was installed in 2021 to determine if any lecture rooms were under-ventilated and to aid in assisting with the return of college students and staff in a safe manner. In addition to this, an onsite ventilation assessment was carried out on all ten of the rooms investigated in this study. Based on this assessment, five of the ten rooms underwent a ventilation system upgrade prior to the 2021/2022 academic year. Table 1 describes the ventilation principles used in the rooms as of March 2022.

**Table 1:** Summary of ventilation principles in each lecture room studied

| Room Name | NV principle | NV Component | MV system installed? |
|---|---|---|---|
| LR1 | | | Yes |
| LR2 | Stack | Stack duct in ceiling | No |
| LR3 | | | Yes |
| LR4 | Single Sided | Top-hung outward opening | No |
| LR5 | Single Sided | Top-hung outward opening | No |
| LR6 | Single Sided (Cross Flow Effect) | Louvres and door (two sides) | No |
| LR7 | Single Sided (Cross Flow Effect) | Top-hung outward opening (two sides) | No |
| LR8 | Single Sided | Top-hung outward opening | Yes |
| LR9 | Single Sided | Top-hung outward opening | Yes |
| LR10 | Single Sided | Top-hung outward opening | Yes |

Specific upgrades were made to LR3 and LR8 which already had a supply ventilation system, to include a new extract ventilation system in these rooms. New supply and extract ventilation systems were installed in LR9 and LR10 also. This led to several rooms which had hybrid ventilation systems namely LR8, LR9 and LR10. No information was given as to the operation of MV systems used in the pre-COVID dataset, however, there was a practice of energy reductions to improve campus energy efficiency which may have led to some systems being off during this period. **Figure 1** indicates the general methodology adopted in this study.

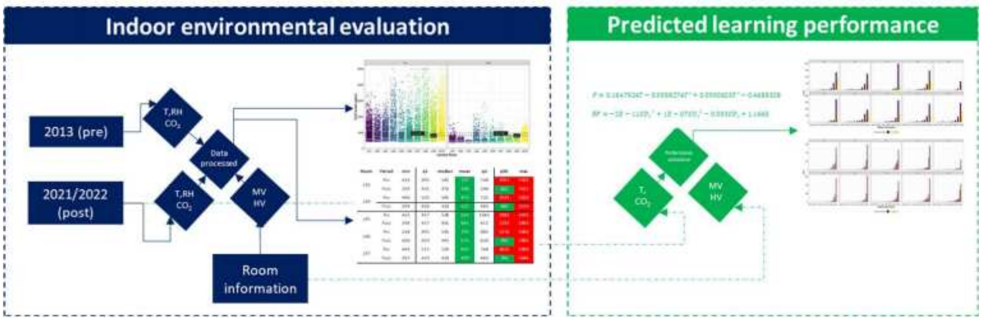


**Figure 1:** General methodology applied to data gathered.

Initially, the data gathered in pre and post-COVID environments was scrubbed using RStudio (RStudio, 2021) to down sample data to hourly intervals. Each dataset was then combined into one global database containing temperature, relative humidity, and $CO_2$ concentration data. The data selected for this analysis was during the months typical of the winter season (October to March), which would represent the most challenging time to use NV systems in mild to cold climates due to draught issues. The dataset was refined further to only consider hours between 8am and 10pm, which was the maximum allowable occupancy period for lecture rooms considered. Table 2 indicates the instrument specifications of instruments used to gather this data in both pre and post-COVID data gathering periods. To categorise this data the limit for category I of EN 16798-1 (CEN, 2019) was used for $CO_2$ data (which was 950 ppm assuming an outside concentration of 400ppm) and was also contextualised using the limit proposed by the Well standard (indicated as 800ppm by (McLeod *et al.*, 2022). Temperature and was categorised according to the lower limit of 16°C as well as Category II from EN 16798-

1 (20°C lower limit), where lower temperatures were of interest due to the winter season months considered. Humidity data was categorised according to the wider limits of between 30% and 70% which is the maximum in EN 16798-1. It should be noted that the focus of this study was on temperature and $CO_2$ data predominately, as relative humidity (RH) levels were seen as being generally acceptable.

**Table 2:** Instrument specifications for pre and post COVID data gathering systems.

| Manufacturer (Model) | Dataset | Parameter | Accuracy | Range |
|---|---|---|---|---|
| Hanwell (Climabox 3, RL5406) | Pre | Temperature | ±0.1°C | -10 to 60°C |
| | | Relative Humidity | ±2% | 0-100% |
| | | $CO_2$ | ±50ppm | 0 to 5000ppm |
| AirThings (CO2) | Post | Temperature | ±0.1°C | 4 to 60°C |
| | | Relative Humidity | ±2% | 0-85% |
| | | $CO_2$ | ±30ppm | 400 to 5000ppm |

Following this evaluation stage, the same data and some additional room information was used to model the likely change in student learning performance using a temperature based model (Seppänen, Fisk and Lei, 2006) and a $CO_2$ based model (Wargocki *et al.*, 2020). These are shown in Equations 1 and 2, for temperature (T) and $CO_2$ models respectively, where $P$ is the productivity relative to maximum and $\boldsymbol{RP}$ is the relative productivity.

$$\boldsymbol{P = 0.1647524T - 0.0058274T^2 + 0.0000623T^3 - 0.4685328} \quad (1)$$

$$\boldsymbol{RP = -2E - 11CO_2{}^3 + 1E - 07CO_2{}^2 - 0.003CO_2 + 1.1665} \quad (2)$$

Despite the considerable amount of literature on temperature-based models and relative performance, only a few consider the range of temperatures in the internal environment (Wargocki, Porras-Salazar and Contreras-Espinoza, 2019). Therefore, the model used for office work was used in this incidence. A model developed for school children was used to consider performance and $CO_2$ levels. In the absence of a combined model that was applicable to university-aged students or staff these models were used as approximations of likely performance.

## 3. Results and discussion

### 3.1. Evaluation of IEQ in all spaces

Figure 2, Figure 3 and Figure 4 indicate the changes in internal parameters between pre (2013) and post (2021/2022) pandemic datasets. Average reductions of between 28% and 53%, with maximum reductions of between 31% and 84% in $CO_2$ concentrations in different classrooms for similar seasons are observed. Differences in temperature are smaller overall, with some zones being less than 5% to 15% lower on average, but others are 7 to 14% higher on average. Overall, global minimum values have increased except for two out of three lecture rooms which decreased by 10% to 41% in minimum terms.

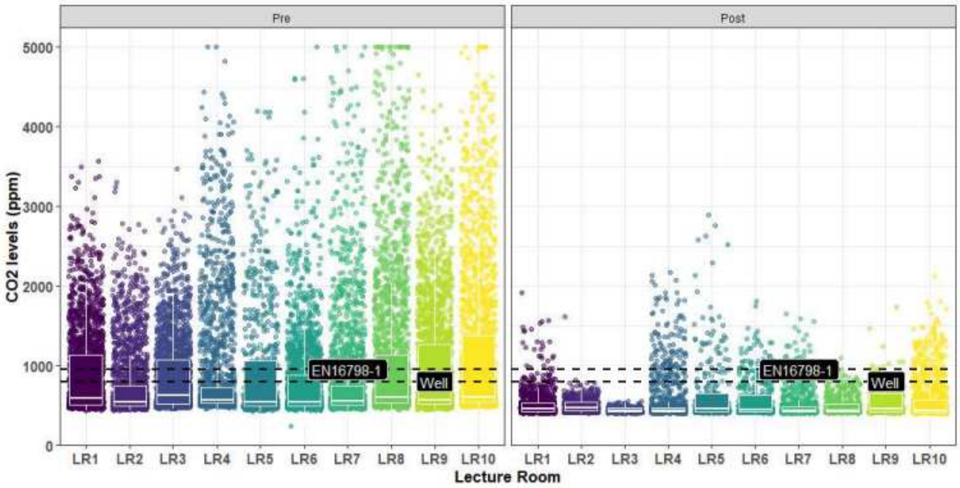


**Figure 2:** Jitter and boxplots of $CO_2$ concentration data for different lecture room environments. (Dashed indicates upper limits for Category I of EN16798-1 and the Well Standard)

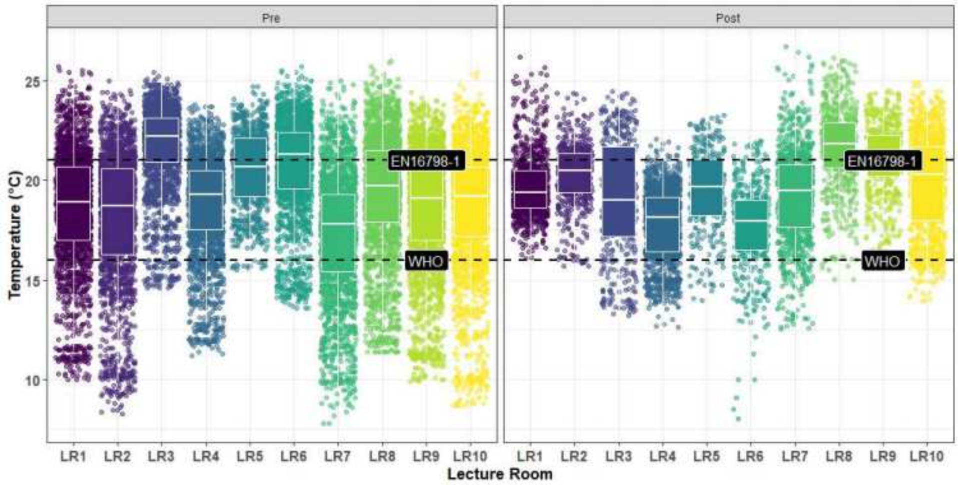


**Figure 3:** Boxplot and jitter plot of internal temperatures in different lecture room environments. (Dashed lines indicate minimum threshold values for the WHO and Irish regulations and Category I EN16798-1 respectively)

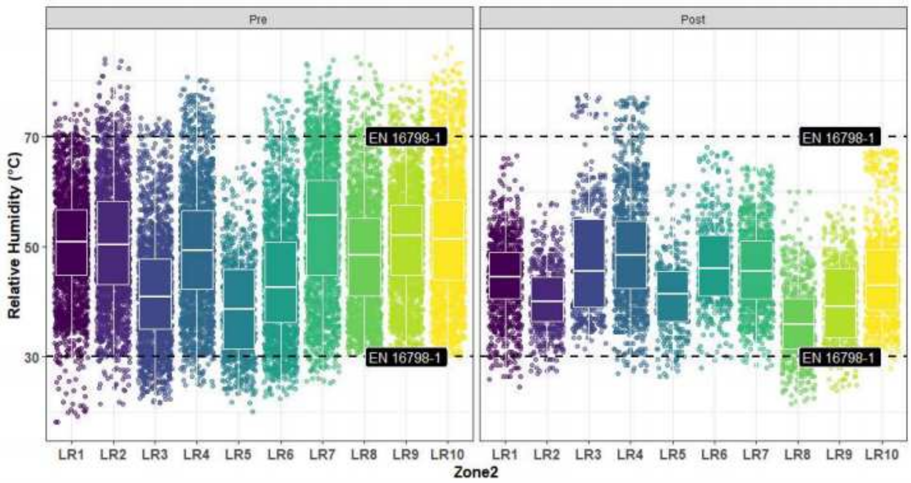


**Figure 4:** Boxplot and jitter plot of internal RH in different lecture room environments. (Dashed lines indicate minimum threshold values according to EN16798-1)

For most lecture rooms global minimum values increased by 13% to 89%, depending on the room. When it comes to RH overall, there is a reduction in humidity levels using post-COVID ventilation strategies this leads to a reduction of between 12% and 26% in some zones, but others increase by 0% to 13%. Maximum reductions of between 5% and 31% were observed.

### 3.2. IEQ in NV only space

**Table 3** indicates the change in $CO_2$ levels for all naturally ventilated rooms based behavioural changes only. Overall, NV rooms only saw average $CO_2$ concentration reductions of between 28% and 40%, with reductions in maximum $CO_2$ concentrations of between 45% and 67% depending on the room studied.

**Table 3**: Summary statistics of $CO_2$ concentration in different lecture rooms before and after ventilation behaviour changes in NV rooms only (Shaded mean and 90$^{th}$ percentile and maximum values indicate performance according to EN16798-1)

| Room | Period | min | q1 | median | mean | q3 | q90 | max |
|---|---|---|---|---|---|---|---|---|
| LR2 | Pre | 433 | 495 | 545 | 737 | 748 | 1367 | 3303 |
| | Post | 399 | 431 | 472 | 500 | 546 | 622 | 1612 |
| LR4 | Pre | 460 | 535 | 565 | 875 | 725 | 1934 | 5000 |
| | Post | 394 | 416 | 433 | 527 | 469 | 840 | 2170 |
| LR5 | Pre | 425 | 497 | 538 | 921 | 1065 | 2082 | 4195 |
| | Post | 398 | 417 | 455 | 641 | 651 | 1203 | 2890 |
| LR6 | Pre | 238 | 495 | 545 | 791 | 885 | 1378 | 5000 |
| | Post | 400 | 419 | 441 | 571 | 630 | 944 | 1809 |
| LR7 | Pre | 443 | 511 | 550 | 827 | 748 | 1615 | 5000 |
| | Post | 397 | 419 | 433 | 499 | 483 | 700 | 1646 |

**Table 4:** Summary statistics of temperature in different lecture rooms before and after ventilation behaviour changes in NV rooms only (Shaded mean, 1$^{st}$ quartile and minimum values indicate performance according to EN16798-1 (less than 20°C) and Irish regulations (less than 16°C)

| Room | Period | min | q1 | median | mean | q3 | q90 | max |
|---|---|---|---|---|---|---|---|---|
| LR2 | Pre | 8.3 | 16.3 | 18.7 | 18.1 | 20.6 | 21.8 | 25.0 |
| | Post | 15.7 | 19.4 | 20.5 | 20.3 | 21.3 | 21.9 | 24.4 |
| LR4 | Pre | 11.2 | 17.5 | 19.3 | 18.8 | 20.5 | 21.4 | 23.8 |
| | Post | 12.6 | 16.4 | 18.1 | 17.8 | 19.1 | 19.8 | 22.1 |
| LR5 | Pre | 15.5 | 19.2 | 20.7 | 20.5 | 22.1 | 22.9 | 24.7 |
| | Post | 14.0 | 18.2 | 19.7 | 19.5 | 21.1 | 22.2 | 23.3 |
| LR6 | Pre | 13.6 | 19.6 | 21.3 | 20.7 | 22.4 | 23.4 | 25.7 |
| | Post | 8.1 | 16.5 | 18.0 | 17.6 | 19.0 | 20.2 | 22.0 |
| LR7 | Pre | 7.8 | 15.4 | 17.8 | 17.3 | 19.3 | 21.0 | 25.0 |
| | Post | 12.6 | 17.7 | 19.5 | 19.2 | 20.8 | 21.8 | 26.7 |

Categorically speaking behavioural changes could reduce $CO_2$ concentrations to within acceptable levels for EN16798-1 for 90% of the internal values measured and for four of the five lecture spaces studied. In absolute terms, behavioural changes could reduce $CO_2$ concentrations by between 220ppm and 348ppm on average, with maximum reductions of between 1305ppm and 3354ppm depending on each lecture room. Table 4 indicates the changes in internal temperatures due to behavioural changes. These current minimum values in each room indicate a cold thermal environment from a comfort perspective. It is also evident that there are no substantial differences between pre and post COVID environments, with two out of five of the rooms studied having warmer temperatures internally (by 11-12%) and three out of five of the rooms studied having a colder indoor environment (by 5-15%) on average.

### 3.3. IEQ in HV or MV rooms

Table 4 indicates the $CO_2$ levels for all rooms that were NV pre-COVID and had upgrades to be MV or HV post-COVID. Overall, HV and MV rooms saw a reduction in average $CO_2$ concentrations of between 41% and 53%, with maximum reductions of between 46% and 78% between pre and post environments depending on the lecture room.

**Table 5:** Summary statistics of $CO_2$ concentration in different lecture rooms before and after ventilation behaviour changes in rooms that were NV in pre-COVID and HV or MV post-COVID (Shaded mean and 90th percentile and maximum values indicate performance according to EN16798-1)

| Period | Room | min | q1 | median | mean | q3 | q90 | max |
|---|---|---|---|---|---|---|---|---|
| Pre | LR1 | 430 | 508 | 585 | 876 | 1128 | 1671 | 3573 |
| Post | | 398 | 420 | 455 | 517 | 534 | 702 | 1919 |
| Pre | LR3 | 460 | 515 | 620 | 853 | 1075 | 1566 | 3475 |
| Post | | 395 | 415 | 428 | 439 | 463 | 479 | 551 |
| Pre | LR8 | 443 | 530 | 603 | 1038 | 1134 | 2210 | 5000 |
| Post | | 398 | 417 | 434 | 489 | 515 | 667 | 1096 |
| Pre | LR9 | 440 | 515 | 570 | 965 | 1260 | 2018 | 4655 |
| Post | | 398 | 415 | 457 | 543 | 650 | 777 | 1735 |
| Pre | LR10 | 475 | 543 | 605 | 1106 | 1377 | 2485 | 5000 |
| Post | | 398 | 412 | 434 | 562 | 569 | 958 | 2123 |

**Table 6:** Summary statistics of temperature in different lecture rooms before and after ventilation behaviour changes in rooms that were NV in pre-COVID and HV or MV post-COVID (Shaded mean, 1st quartile and minimum values indicate performance according to EN16798-1 (less than 20°C) and Irish regulations (less than 16°C)

| Period | Room | min | q1 | median | mean | q3 | q90 | max |
|---|---|---|---|---|---|---|---|---|
| Pre | LR1 | 10.0 | 17.0 | 18.9 | 18.6 | 20.7 | 21.9 | 25.7 |
| Post | | 16.1 | 18.6 | 19.4 | 19.7 | 20.5 | 21.7 | 26.2 |
| Pre | LR3 | 14.6 | 20.9 | 22.2 | 21.7 | 23.1 | 23.8 | 25.4 |
| Post | | 13.2 | 17.2 | 19.0 | 19.0 | 21.7 | 23.0 | 24.5 |
| Pre | LR8 | 11.4 | 17.9 | 19.7 | 19.4 | 21.5 | 22.8 | 26.0 |
| Post | | 15.0 | 20.6 | 21.8 | 21.6 | 22.9 | 24.1 | 26.1 |
| Pre | LR9 | 9.9 | 17.0 | 19.1 | 18.5 | 20.8 | 21.8 | 24.4 |
| Post | | 15.9 | 20.2 | 21.2 | 21.1 | 22.2 | 23.3 | 24.5 |
| Pre | LR10 | 8.7 | 17.2 | 19.2 | 18.6 | 20.7 | 21.9 | 25.4 |
| Post | | 13.9 | 18.0 | 20.3 | 19.9 | 21.7 | 22.7 | 24.9 |

Categorically speaking behavioural changes could reduce $CO_2$ concentrations to within acceptable levels for EN16798-1 for 90% of the internal values measured for all HV and MV lecture spaces studied. In absolute terms, the combined effect of behavioural changes and the use of MV systems could reduce $CO_2$ concentrations by between 359ppm and 548ppm on average, with maximum reductions of between 1654ppm and 3904ppm depending on each lecture room. Table 5 indicates the changes in internal temperatures due to behavioural changes and increased ventilation rates that include MV systems. Like the measurements in NV spaces there would appear to be unacceptable minimums, however, not to the same extent. In these rooms in four out of five HV or MV rooms the post-COVID environment is warmer, with an increase in of 1.7°C in these four rooms, and an increase of 4°C to 6°C decrease on the minimum temperatures observed.

### 3.4. Predicted learning performance

Figure 5 and Figure 6 indicates the changes in predicted student performance levels according to two different models one for temperature and one for $CO_2$ levels. When temperature-based performance predictions are examined, both positive and negative changes in relative learning performance results are observed. For four out of the ten lecture rooms an average reduction in performance is seen of between 1% to 3% is observed compared to the pre-COVID environment. For these four rooms (i.e. LR3, LR4, LR5, LR6) minimum performance values reduced further by 5% to 34%, when compared to the pre-COVID results. The worst-case being in LR6, where a reduction in performance was likely due to overcooling with the NV system. For six out of the ten lecture rooms studied, average performance increases of 2% to 5% and increases in the worst-case performance of between 8% and 39%, were observed when compared to pre-COVID equivalents.

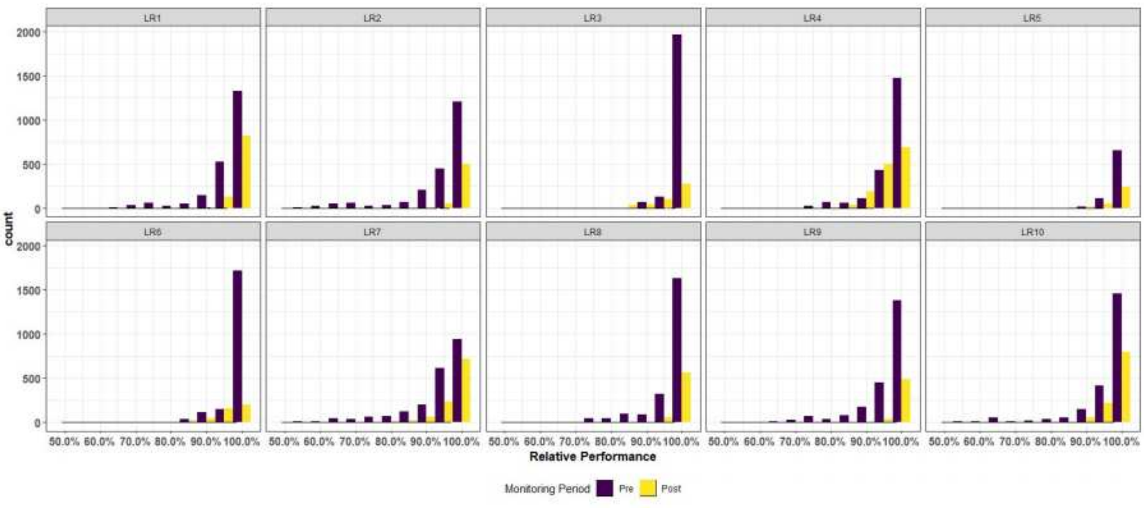


**Figure 5:** Histograms of relative performance for each room using a temperature based-model (Seppänen, Fisk and Lei, 2006) in pre and post-COVID environments (Colour indicates pre and post-COVID datasets)

When the $CO_2$-based performance predictions are examined, a considerable change in performance is observed between pre and post-COVID environments. All ten lecture rooms had increases in mean predicted relative performance of between 4% and 10% compared with the pre-COVID environment. Substantial changes in the minimum performance levels were also observed with increases of 31% to 126% when compared to the pre-COVID environment. The best improvement was seen in LR8 which was a HV room that underwent a ventilation upgrade in 2021.

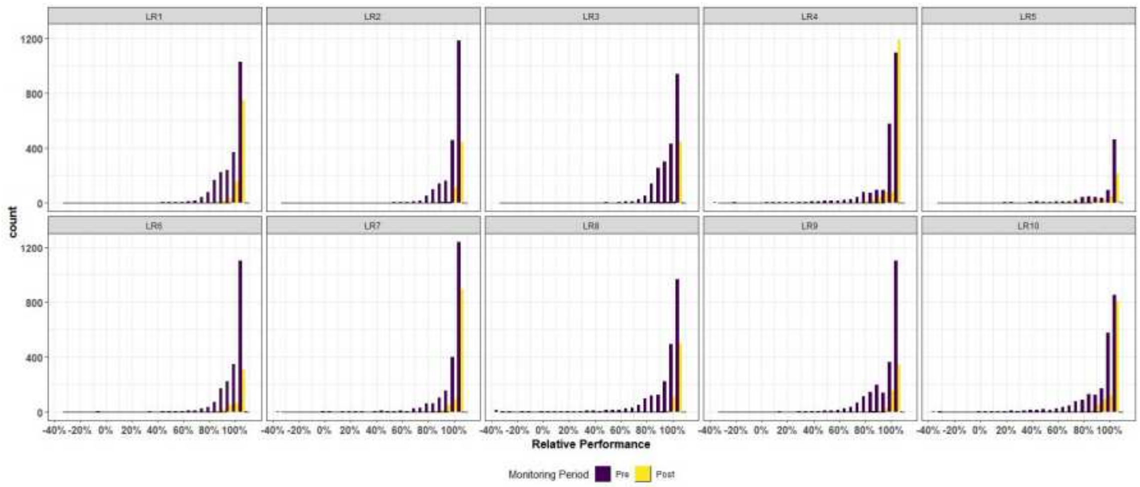


**Figure 6:** Histograms of relative performance for each room using a $CO_2$ based model (Wargocki *et al.*, 2020) in pre and post-COVID environments (Colour indicates pre and post-COVID datasets)

Overall, these performance results indicate a likely improvement in relative performance for the students in these lecture rooms. The mixed results in temperature results highlight the need to consider improving the fabric and supply systems in winter months to reduce likely overcooling specific rooms. However, considerable improvements in performance based on reduced $CO_2$ levels are observed in all rooms.

## 4. Conclusions and future work

Based on the above data it is evident that changes in ventilation behaviour and system upgrades which were brought about because of the COVID-19 pandemic have had a considerable effect on $CO_2$ levels in all lecture rooms. The best and most reliable solutions would appear to be MV and HV systems which led to the greatest reductions in $CO_2$ levels. Predictions of relative performance also highlight the likely substantial improvements in performance between pre and post-COVID internal environments when $CO_2$-based models are used, while some mixed results are indicated when using a temperature-based model. The main limitation of the work presented (which could be addressed by future work) is that the work does not consider the subjective opinions of the occupants in each room and does not consider draught risks or measured learning performance. Given the lack of a combined IAQ or IEQ model with respect to the academic performance of university-aged students, future work should consider the learning performance of these groups in more detail. In addition to this, more work is needed in isolating the air change rates for NV, MV and HV rooms to determine which in-situ systems lead to the most reliable results. This work did not consider the effect that opening types would have on comfort, IAQ and performance, however, more work is also needed in identifying lower cost options outside of retrofitting MV such as the use of more efficient and higher performing openings. In addition to this, while HV systems would appear to be the best and most obvious solution to maintaining low $CO_2$ levels in all seasons, there is also a need to consider how to overcome the limitations that

NV systems have such as security, pollution, and draught risks to name a few. Future work should consider overcoming the limitations and constraints that are presented for NV systems as MV systems may be too costly for all universities or educational buildings. Finally, given the review of existing literature more work is needed to determine what differences existing in other IEQ or IAQ related variables which may affect performance including particulates.

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## Acknowledgements

The authors would like to kindly acknowledge to support of the buildings and estates team in the university involved, as well as the support of the indoor environmental company for providing access to data.

# Covid Risk$^{airborne}$, a tool to test the risk of aerosol transmission of SARS-CoV-2 under different scenarios: a pre-school classroom case study

**Miguel Ángel Campano[1]*, Jesica Fernández-Agüera[1], Samuel Domínguez- Amarillo[1], Ignacio Acosta[1] and Juan José Sendra[1]**

[1] Instituto Universitario de Arquitectura y Ciencias de la Construcción, Escuela Técnica Superior de Arquitectura, Universidad de Sevilla, 41012 Seville, Spain.
* Correspondence: mcampano@us.es (M.A.C.); Tel.: +34 954559517

**Abstract:** The COVID-19 emergency has shown that airborne transmission of SARS-CoV-2 is especially relevant in poorly bad ventilated spaces with high occupancy density, like non-university classrooms, a widespread space typology with very sensitive occupants. Of these, pre-school classrooms stand out, due to the vulnerability of children. Thus, this study has estimated the existing transmission risk of SARS-CoV-2 in a pre-school classroom, due to the especial vulnerability of the children, regarding to different indoor $CO_2$ excess levels. This statistical evaluation has been performed through 68 calculation hypotheses, grouped into 4 cases, according to who is the primary infected occupant (one of the children or the teacher) and depending on whether the teacher wears a mask or not. It can be concluded that, to have acceptable risk conditions for airborne disease transmission (with one infected occupant) in pre-school classrooms, it is necessary to maintain sufficient ventilation conditions to reach a maximum average excess $CO_2$ level exhaled of 150 ppm, while teachers should wear well-fitting N95 respirators. In this way, infection risk is much higher when the primary infected occupant is the teacher and is wearing no mask or a surgical one —5 or 6 times more.

**Keywords:** $CO_2$ concentration; School buildings; SARS-CoV-2; Airborne transmission; COVID-19 infection risk

## 1. Introduction

The airborne transmission of SARS-CoV-2 (Severe Acute Respiratory Syndrome Coronavirus 2) is widely proven by scientific community (Morawska and Cao, 2020; Greenhalgh *et al.*, 2021; Miller *et al.*, 2021; Tang *et al.*, 2021; Wang *et al.*, 2021; World Health Organization, 2021; Burgos-Ramos, Urbieta and Rodríguez, 2022), with the main COVID-19 outbreaks occurring indoors (Qian *et al.*, 2021; Randall *et al.*, 2021; Wang *et al.*, 2022). In this way, medium and long-range transmission —beyond 1.5 m— is especially relevant in poorly bad ventilated spaces (Li, 2021; Peng *et al.*, 2022).

In this way, one of the most widespread space typologies are non-university classrooms, in which children —considered as sensitive and vulnerable population— spend an average of 5-6 hours a day, from Monday to Friday during nine months a year, focused on winter and mid-seasons. In this way, classrooms are high occupancy density spaces with usually poor ventilation conditions, as several studies have pointed out in southern Spain (Fernández-Agüera *et al.*, 2019; Villanueva *et al.*, 2021), France (Annesi-Maesano *et al.*, 2012), Italy (De Giuli, Da Pos and De Carli, 2012; Annesi-Maesano *et al.*, 2013; De Giuli *et al.*, 2014) and Portugal (Almeida *et al.*, 2011; Campano *et al.*, 2017), among others, due a lack of ventilation. Given that there have also been several documented COVID-19 outbreaks in educational buildings (Fontanet *et al.*, 2021; Lorthe *et al.*, 2022), it is necessary to promote healthy classrooms through self-protection practices and adequate indoor air quality (IAQ). Thus, the removal of the virus-containing aerosols from indoor air —by ventilation, air filtration or UV radiation— is an essential part of the prevention strategy.

One of the main ways to assess the degradation of the IAQ in occupied spaces —with no other significant sources or sinks of indoor carbon dioxide ($CO_2$) — is monitoring the indoor $CO_2$ level, which can be a good proxy to evaluate and control the aforementioned ventilation rates, especially in spaces with high occupancy density such as non-university classrooms (Persily and de Jonge, 2017; American National Standards Institute and American Society of Heating Refrigerating and Air-Conditioning Engineers, 2019; Zhu *et al.*, 2020; Pavilonis *et al.*, 2021; Peng and Jimenez, 2021; Peng *et al.*, 2022). As it was mentioned already, the measurement of the excess $CO_2$ level exhaled ($\Delta CO_2$) can also be used to estimate the airborne transmission risk of respiratory diseases such SARS-CoV-2, tuberculosis, or measles, given that virus-containing aerosols are emitted during the respiratory process as $CO_2$ does. Thus, the infection risk of SARS-CoV-2 can be estimated using the indoor $CO_2$ excess as a proxy through adaptations (Jiménez Palacios and Peng, 2021; Peng and Jimenez, 2021; Peng *et al.*, 2022; Rowe *et al.*, 2022) of the Wells-Riley model (Rudnick and Milton, 2003).

In this way, it is possible to estimate the COVID-19 infection risk indoors —strictly via aerosols— is to use the online tool COVID Risk $^{airborne}$ (https://www.covidairbornerisk.com/), non-profit developed by Campano et al. (Campano-Laborda et al., 2021) and based on the adaptation of the Wells-Riley model performed by Peng and Jiménez (Jiménez Palacios and Peng, 2021; Peng and Jimenez, 2021).

The main aim of this work is to estimate and analyse the existing transmission risk of SARS-CoV-2 in a pre-school classroom, due to the especial vulnerability of the children and the lack of proper use of masks due to their age, regarding to different indoor $CO_2$ excess levels. With the results of this theoretical study, it is possible to optimize the ventilation and self-protection strategies of the occupants.

## 2. Materials and Methods

The following phases have been established to develop this study:

- Sample
- Boundary conditions
- Hypotheses under study
- Infection risk indicators

### 2.1. Sample

An Andalusian pre-school classroom was chosen as the study case. Its shape, dimensions, HVAC systems, furniture and theoretical occupation are standardized according to the design standards established for non-university educational institutions (Junta de Andalucía, 2003). The premise is 50 m² and 3 meters high, designed for a maximum capacity of 24 children (Campano, 2015). It has its own bathroom, with a direct access from inside the classroom, as well as an associated schoolyard, accessible from a door on the façade of the premise (Figure 1).

The classroom has no suspended ceiling or perforations in the inner partitions with the adjacent classroom nor the corridor. The external vertical wall is composed by a half-brick wall with rendering, an air chamber, projected polyurethane as thermal insulation and a plasterboard. The internal partitions are composed of two layers of plasterboard with mineral wool between them.

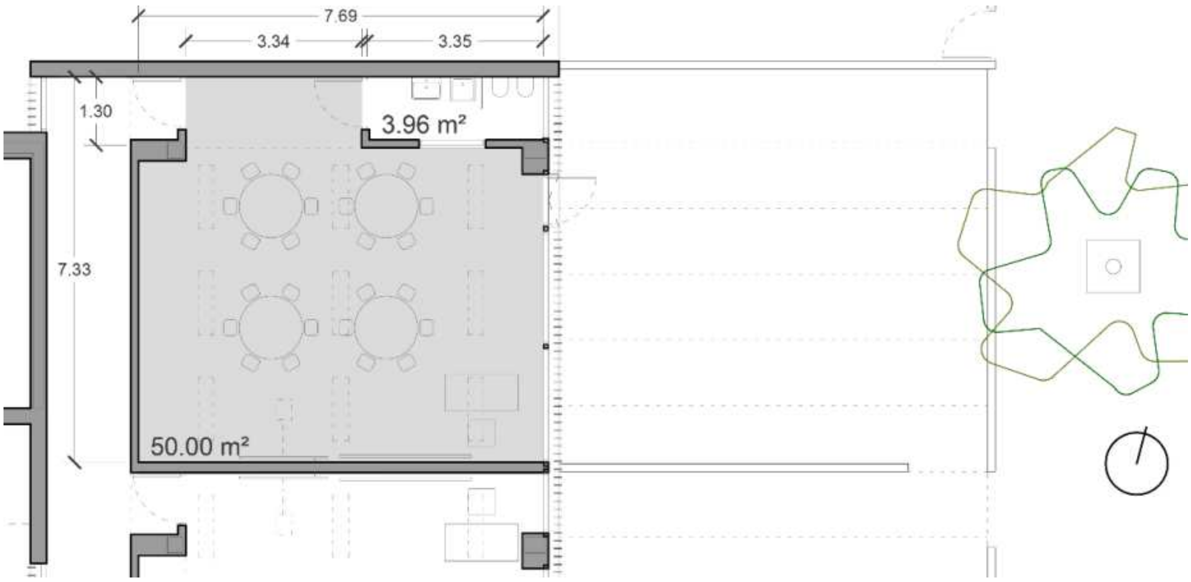


Figure 1. Ground plan of the pre-school classroom under study, following design standards for regional educational institutions.

Heating system is composed by hot water (HW) radiators, with no provision for cooling systems (Campano, Sendra and Domínguez, 2011; Campano *et al.*, 2019).

Ventilation is traditionally relied by windows operation and uncontrolled infiltrations, despite the Spanish Standard on thermal installations in Buildings (RITE) (Ministerio de la Presidencia del Gobierno de España, 2021) establishes the controlled mechanical ventilation as the only option for non-residential buildings. In winter conditions, the lower limit for operative temperature set by Spanish RITE is 21 ºC, while the maximum operative temperature in summer conditions is 25 ºC.

The school day in pre-school and primary public schools of Andalusia is 5 hours, usually from 9:00 a.m. to 2:00 p.m., with a half-hour break in between. Each centre can establish the starting point of said break, although it is usually in the middle of the school day (from 11:15 to 11:45).

**2.2. Boundary conditions**

The calculation conditions required to estimate the existing infection in the pre-school classroom under study are listed in Table 1 (Campano-Laborda *et al.*, 2020).

The exposure time (event duration) is established in 135 minutes, given that it can be considered the average period between the lunch break and the start/end of the school day. The pre-school classroom under study is also considered to be in winter environmental conditions, with the existing HW radiator system operating to achieve compliance with the hygrothermal conditions of the RITE ($T_a$ 21ºC and *HR* 40%).

It has been estimated that there is always an infected occupant with a high viral load in the classroom, as a realistic hypothesis for the airborne transmission risk simulations.

Table 1. Boundary conditions of the case of study for the statistical study of infection risk

| **Dimensions** | | | |
|---|---|---|---|
| Area (m²) | 50.0 | Heigh (m) | 3.0 |
| **Environmental conditions (winter season)** | | | |
| Indoor air temperature (ºC) | 21.0 | Relative indoor air humidity (%) | 40 |
| Atmospheric pressure (atm) | 1.0 | Indoor atmosphere | Still air |
| **Variant of SARS-CoV-2** | | | |
| Variant of SARS-CoV-2 | Omicron BA.2 | Percentile of viral exhalation rate (%) | 85 |
| **Occupancy parameters and type of activity** | | | |
| No. of infectious occupants | 1 | No. of people present | 25 |
| Mean age of occupants (years) | 5 | Event duration (min) | 135 |
| Intensity of activity of the children | Sitting – Oral respiration | Intensity of activity of the teacher | Standing – Speaking |

### 2.3. Hypotheses under study

Four scenarios were considered for this study, using the average excess $CO_2$ level exhaled ($\Delta CO_2$) during 135 minutes of a regular educational day (exposure period) as a proxy to calculate how many 'quanta' inhaled each occupant (a 'quanta' can be considered as the minimum infectious dose of the aerosol pathogen whose inhalation leads to infection in 63% of vulnerable people). They are grouped in two categories, according to the occupant who was initially infected (child or teacher).

- CASE 1: One infected child by SARS-CoV-2 (sitting – oral respiration) and no one wearing a mask in the classroom.
- CASE 2a: Teacher infected (standing – speaking) and no one wearing a mask in the classroom.
- CASE 2b: Teacher infected (standing – speaking), wearing a surgical mask (non-fitted) and the rest of occupants with no masks.
- CASE 2c: Teacher infected (standing – speaking), wearing a well-fitting N95 respirator and the rest of occupants with no masks.

The risk calculations defined above were performed considering increases in the average indoor-outdoor $CO_2$ differential of 100 ppm, with an excess range of 100 to 1600 ppm, as previously measured in this type of premises (Fernández-Agüera *et al.*, 2019).

This procedure also allows to consider the following thresholds:

- The Spanish RITE $CO_2$ limit value for classrooms (indoor air quality of IDA 2), which can be expressed as an increase of 500 ppm of $CO_2$ above the outside level for spaces with high occupancy density (Ministerio de la Presidencia del Gobierno de España, 2021).
- The recommendations developed for schools during the COVID-19 emergency situation, which establishes a $CO_2$ threshold of 300 ppm above the outside level (Jones et al., 2020; Minguillón et al., 2020; Plataforma Aireamos, 2021). This limit is close to the IDA 1 $CO_2$ threshold of the Spanish RITE (350 ppm), applicable to hospitals, nurseries and nursing homes.
- The recommendation developed for indoor educational spaces, both for classrooms with vulnerable occupants or with no masks, and for corridors (spillway spaces), which

establishes a $CO_2$ threshold of 150 ppm above the outside level (Plataforma Aireamos, 2021).

### 2.4. Infection Risk Indicators

This statistical study is developed through two risk indicators, adapted to airborne disease transmission (Peng and Jimenez, 2021; Peng *et al.*, 2022):

- Attack rate (*AR*): The proportion of occupants in the event who could have inhaled the necessary infectious dose of the aerosol pathogen whose inhalation leads to infection in 63% of vulnerable people ('quanta').
- Relative risk of infection ($H_r$): Number of 'quanta' emitted by a single infected person which are inhaled by a single person for a given exposure time and premises of the volume specified.

The main point of both indicators is that they are not referred to the number of vulnerable occupants (those who are liable to contract the disease), so they can be used regardless of the number of people vaccinated or the effectiveness of the different vaccines.

There are three categories of risk (low, medium, and high) for these indicators, according to previous studies of different indoor scenarios and existing documented outbreaks, as it can be seen in Table 2 (Peng and Jimenez, 2021; Peng *et al.*, 2022).

For the Wild-type SARS-CoV-2, it can be considered that there are no documented outbreaks when *AR* was under 0.5% (Peng et al., 2022), which can be correlated with a value of *Hr*<0.001.

Table 2. Limits for relative risk (*Hr*) and attack rate (*AR*) indicators (Peng and Jimenez, 2021) corrected for SARS-CoV-2 Omicron variant BA.2 sublineage.

| | **Low** | **Medium** | **High** |
|---|---|---|---|
| *AR* (%) | < 0.5 | < 5.0 | ≥ 5.0 |
| $H_r$ ($h^2/m^3$) for wild-type SARS-CoV-2 | < 0.00100 | < 0.01000 | ≥ 0.01000 |
| Corrected $H_r$ ($h^2/m^3$) for Omicron variant BA.2 | < 0.00035 | < 0.00294 | ≥ 0.00294 |

### 2.5. Calculation tool

The simulation software used to evaluate the aforementioned infection risk indicators (*AR* and $H_r$) is COVID Risk$^{airborne}$ (https://www.covidairbornerisk.com/), developed by Campano et al. (Campano-Laborda et al., 2021). This tool (Figure 2) estimates the SARS-CoV-2 propagation —strictly via medium and long-range aerosols— using the adaptation (Jiménez Palacios and Peng, 2021; Peng and Jimenez, 2021; Peng *et al.*, 2022) of the Wells-Riley model for simulating disease propagation (Rudnick and Milton, 2003).


Figure 2. Landing page of Covid Risk$^{airborne}$ tool.

This methodology has been validated by comparison with existing COVID-19 outbreaks (Peng *et al.*, 2022), as it can be seen in Figure 3.

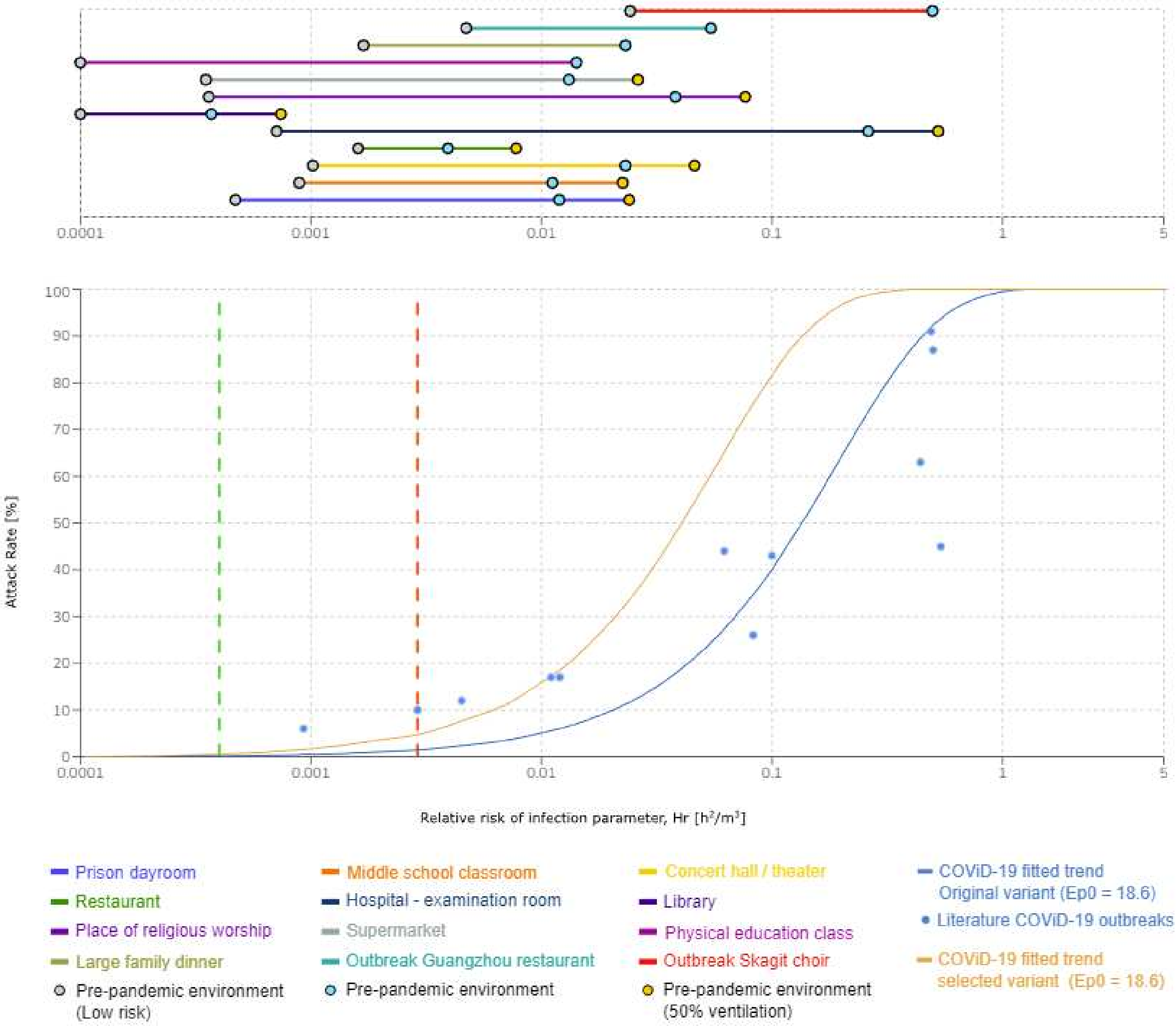


Figure 3. Graphic analysis of the Attack Rate (AR) versus the Relative risk of infection ($H_r$), calculated via COVID Risk$^{ariborne}$ using the methodology of Peng *et al.* (Peng *et al.*, 2022).

Among the various considerations made by this tool, it should be noted that:

- The increased transmissibility of the SARS-CoV-2 variants is obtained from the reports of the European and North American Centres for Disease Control and Prevention (Campbell *et al.*, 2021; Centers for Disease Control and Prevention, 2022).
- The estimation of the airborne viral emission is performed through the expiratory activity, which depends on the metabolic and vocalization activities (Morawska *et al.*, 2009; Buonanno, Stabile and Morawska, 2020).
- The evaluation of the average ventilation rate and the recommended short-term exposure values for inhalation, in m³/h per occupant, are calculated through the metabolic rate, which depends on activity, age and gender (Wang *et al.*, 2011; Peng *et al.*, 2022), as well as the $CO_2$ emission (Persily and de Jonge, 2017).
- The decay rate of the virus infectivity in aerosols depends on the Air Temperature ($T_a$), Relative Humidity of the air (*HR*), the UV index and the deposition of virus-containing aerosols to surfaces (Schuit *et al.*, 2020; Smither *et al.*, 2020; van Doremalen *et al.*, 2020).
- The theoretical aerosol retention efficiency of masks, respirators and face shields (Davies *et al.*, 2013; Milton *et al.*, 2013; Melikov, 2015) is considered as:
  - Surgical mask (non-fitted): 32.5%
  - Well-fitting N95 respirator: 90.0%

## 3. Results and discussion

### 3.1. Results

The graphical evolution of $H_r$ with respect to *AR* can be seen in Figure 4.

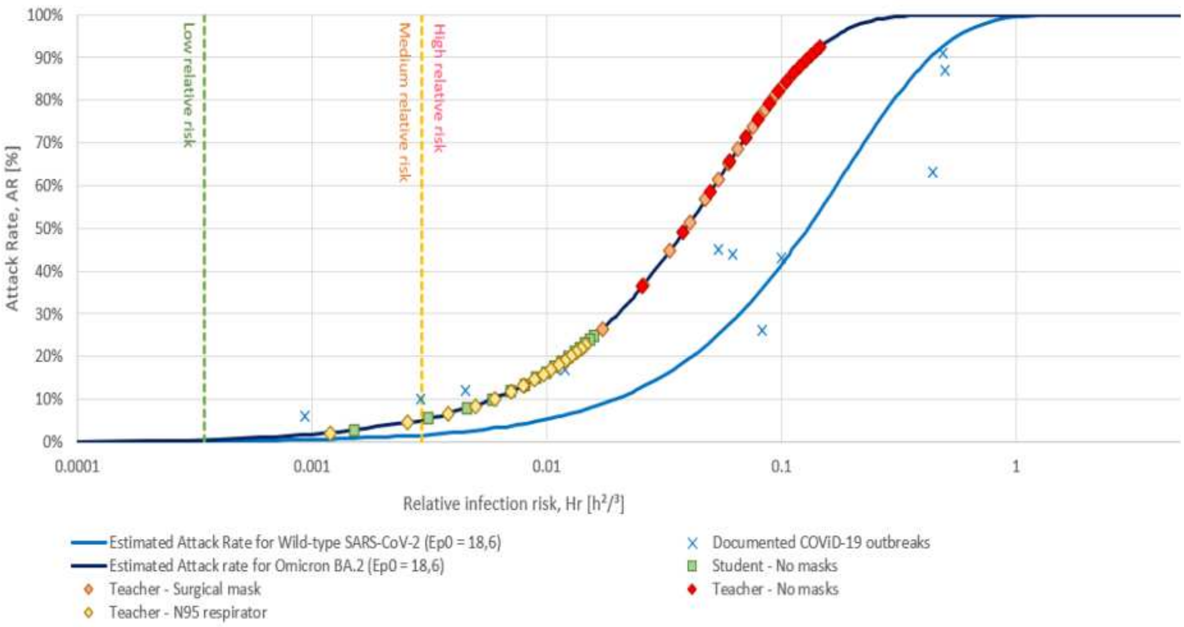


Figure 4. Graphical analysis of the Attack Rate (AR) with respect to the Relative risk of infection ($H_r$) for the 4 case studies of the pre-school classroom. Exposure time of 135 minutes.

The mean values of $H_r$ and *AR* parameters are listed in Table 3 for the four cases under analysis, with respect to $\Delta CO_2$.

Table 3. Mean values of Attack Rate (*AR*) and Relative Risk of infection (*Hr*) of SARS-CoV-2 (Omicron BA.2) per case, based on indoor boundary conditions

| | Case 1 | | Case 2a | | Case 2b | | Case 2c | |
|---|---|---|---|---|---|---|---|---|
| **Average $CO_2$ value** | **Child - no masks** | | **Teacher - no masks** | | **Teacher - surgical mask** | | **Teacher – well-fitting N95 respirator** | |
| | **Oral breathing** | | **Talking** | | **Speaking** | | **Speaking** | |
| ***$\Delta CO_2$* (ppm)** | ***AR* (%)** | ***$H_r$* ($h^2/m^3$)** | ***AR* (%)** | ***$H_r$* ($h^2/m^3$)** | ***AR* (%)** | ***$H_r$* ($h^2/m^3$)** | ***AR* (%)** | ***$H_r$* ($h^2/m^3$)** |
| 1600 | 24.7 | 0.0160 | 92.5 | 0.1463 | 82.6 | 0.0988 | 22.8 | 0.0146 |
| 1500 | 23.8 | 0.0153 | 91.6 | 0.1399 | 81.2 | 0.0945 | 21.9 | 0.0140 |
| 1400 | 22.8 | 0.0147 | 90.5 | 0.1334 | 79.6 | 0.0900 | 21.0 | 0.0133 |
| 1300 | 21.8 | 0.0139 | 89.3 | 0.1266 | 77.9 | 0.0855 | 20.1 | 0.0127 |
| 1200 | 20.8 | 0.0132 | 87.9 | 0.1196 | 76.0 | 0.0807 | 19.1 | 0.0120 |
| 1100 | 19.8 | 0.0124 | 86.3 | 0.1123 | 73.8 | 0.0758 | 18.0 | 0.0112 |
| 1000 | 18.6 | 0.0117 | 84.3 | 0.1047 | 71.3 | 0.0707 | 16.9 | 0.0105 |
| 900 | 17.4 | 0.0108 | 82.0 | 0.0969 | 68.5 | 0.0654 | 15.7 | 0.0097 |
| 800 | 16.2 | 0.0100 | 79.1 | 0.0885 | 65.2 | 0.0598 | 14.5 | 0.0089 |
| 700 | 14.8 | 0.0091 | 75.6 | 0.0797 | 61.4 | 0.0538 | 13.1 | 0.0080 |
| 600 | 13.3 | 0.0081 | 71.2 | 0.0704 | 56.8 | 0.0475 | 11.7 | 0.0070 |
| **500 (IDA 2)** | **11.7** | **0.0070** | **65.7** | **0.0605** | **51.4** | **0.0408** | **10.1** | **0.0060** |
| 400 | 9.9 | 0.0059 | 58.5 | 0.0497 | 44.8 | 0.0336 | 8.4 | 0.0050 |
| **300** | **7.8** | **0.0046** | **49.1** | **0.0382** | **36.6** | **0.0258** | **6.5** | **0.0038** |
| 200 | 5.4 | 0.0032 | 36.4 | 0.0256 | 26.4 | 0.0173 | 4.4 | 0.0026 |
| **150** | **4.1** | **0.0024** | **28.5** | **0.0190** | **20.2** | **0.0128** | **3.3** | **0.0019** |
| 100 | 2.6 | 0.0015 | 19.1 | 0.0120 | 13.3 | 0.0081 | 2.1 | 0.0012 |

As can be seen both in Table 3 and in Figure 4, the relative infection risk ($H_r$) of almost all the situations studied is high. There are no situations with low risk, existing two categories:

- High risk (<25%): The primary infected occupant is a child, or is the teacher, who is wearing a well-fitting N95 respirator.
- Very high risk (>25%): The primary infected occupant is the teacher, who is wearing no mask or a surgical one (non-fitted).

The graphical evolution of $\Delta CO_2$ with respect to *AR* can be seen in Figure 5.

On the one hand, the hypotheses studied which have *AR* under 5% (threshold for high risk of outbreaks) are:

- One of the children is the infectious occupant —which is sedentary, silent, and breathing orally— and there is a low interior $CO_2$ excess ($\Delta CO_2$ ≤150 ppm).
- The teacher is infectious occupant —which is standing and speaking, being the only one wearing a well-fitting N95 respirator— and there is a low interior $CO_2$ excess ($\Delta CO_2$ ≤200 ppm).

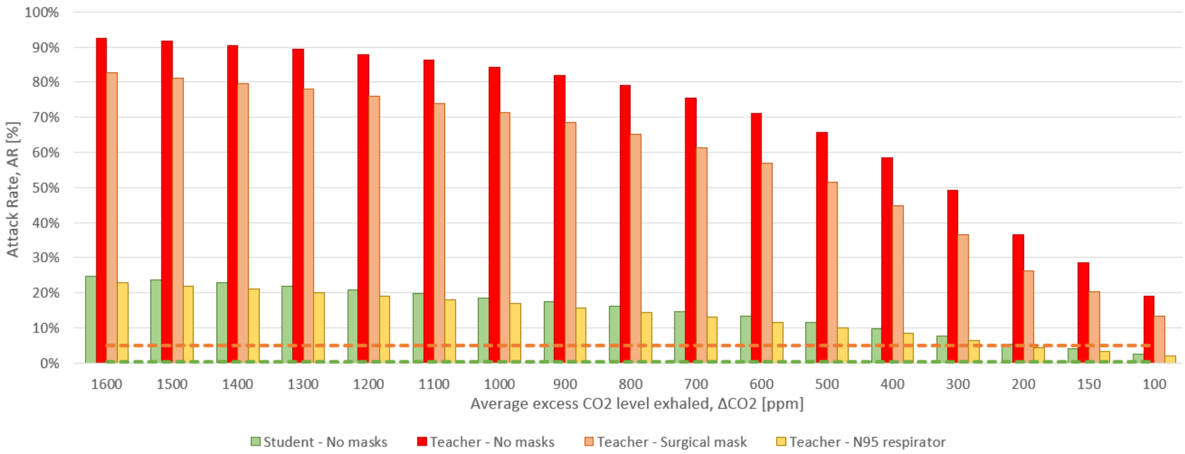


Figure 5. Graphical analysis of the Attack Rate (AR) with respect to the average excess $CO_2$ level exhaled ($\Delta CO_2$) for the 4 case studies of the pre-school classroom. Exposure time of 135 minutes.

This $\Delta CO_2$ value of 150 ppm agrees with the recommendations developed by Aireamos for indoor spaces with vulnerable occupants or with no masks.

On the other hand, the proportion of occupants who can inhale a sufficient viral dose (*AR*) rises much more markedly with respect to $\Delta CO_2$ when the primary infected occupant is the teacher. This is due to a higher to a greater emission of potentially virus-laden aerosols, both their increased vocalization activity and their increased metabolic rate (because of their age and weight). In this way, when the teacher was the primary infected occupant and was not wearing a well-fitting N95 respirator, there was no situation with AR under 20% but with $\Delta CO_2$ ≤100 ppm.

When AR is analysed according to RITE threshold ($\Delta CO_2$ of 500 ppm), it can be seen that:

– If the infectious occupant is either one of the children, or the teacher (wearing a well-fitting N95 respirator): *AR* is 10-11%, doubling the admissible threshold.
– The teacher is infectious occupant, who either is wearing no mask or a non-fitted surgical one: AR is over 50-65%, 10-12 times the admissible threshold.

### 3.2. Study limitations

The present study has the following limitations:

– It was developed through a set of simulations, despite the method was previously validated by comparison with existing COVID-19 outbreaks.
    – Whilst it is not an epidemiological model, it can be used as a component of such approaches to estimate variations in aerosol propagation across a range of inputs.
    – The model excludes droplet and contact/fomite transmission and assumes that 2 m (6 ft) social distancing is honoured. Otherwise, the infection rates calculated would be higher.
    – Several parameters used in the model are uncertain, as they were estimated based on current knowledge.
– These simulations, of a statistical nature, simplify the existing problem by considering that the atmosphere in the classroom is uniformly distributed, so the results may differ slightly from real cases.
– The hypotheses proposed are conservative, since they are based on a maximum occupancy of the enclosure, in which there is also an infected person with a high viral

load (85% percentile of viral exhalation rate). Thus, transmissibility may be lower in many carriers.

### 3.3. Future lines of research

Given these limitations, future studies are suggested. They can be focused on increasing the types of classes under study to have a broader characterization of the risk of transmission in educational centres, as well as on expanding occupancy level, schedules, and prevention measures —like HEPA filters, UV radiation or HVAC systems with filters. In addition, more types of premises in another building typologies can be analysed.

## 4. Conclusions

A study has been performed to estimate the existing transmission risk of SARS-CoV-2 in a pre-school classroom, due to the especial vulnerability of the children and the lack of proper use of masks due to their age, regarding to different indoor $CO_2$ excess levels. The statistical evaluation of the infection risk has been performed through 68 calculation hypotheses, grouped into 4 cases, according to who is the primary infected occupant (one of the children or the teacher) and depending on whether the teacher wears a mask or not.

It can be concluded that, to have acceptable risk conditions for airborne disease transmission (with one infected occupant) in pre-school classrooms, it is necessary to maintain sufficient ventilation conditions to reach at least an average excess $CO_2$ level exhaled of 150 ppm, as well as teachers should wear well-fitting N95 respirators. In this way, infection risk is much higher when the primary infected occupant is the teacher and is wearing no mask or a surgical one —5 or 6 times more.

Thus, the use of a $CO_2$-controlled mechanical ventilation system is necessary in pre-schools classrooms to ensure adequate indoor air quality, especially during emergency situations due to high risk of airborne disease transmission.

## 5. Acknowledgements

The authors wish to express their gratitude to Juan Diego Velarde Rodríguez and professor José Luis Jiménez Palacios, as well as the platforms Aireamos (https://www.aireamos.org/) and VentilANDo (http://www.ventilando.org/), which were very supportive in developing this study, as well as to Blas-Lezo for the encouragement of this article. The authors wish to express their thanks for all the technical and financial support provided, including the research project Metr$CO_2$ (Ref 4190/1113), funded by Metro Sevilla, a Regional Government of Andalusia franchisee, as well as to the funds provided by the Agencia Estatal de Investigación (AEI), the Ministerio de Ciencia e Innovación (MCIN) of the Government of Spain, and the Junta de Andalucía.

## 6. Funding

The results presented were funded by MCIN/ AEI /10.13039/501100011033 through the research project CHRONOLIGHT (Ref PID2020-117563RB-I00), as well as by the Programa Operativo FEDER 2014-2020 of the Consejería de Economía, Conocimiento, Empresas y Universidad de la Junta de Andalucía through the research project UNCOVER (Ref US-1381053). This contribution was partially funded by VII PPIT de la Universidad de Sevilla, as well as to the Contrato de Acceso of the VI PPIT de la Universidad de Sevilla.

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# On Higher Ventilation Rates and Energy Efficiency in Post-COVID-19 Buildings: A New Thermal Comfort Model based on Indoor $CO_2$ Levels and Temperature

**Sarah Crosby[1] and Adam Rysanek[1, 2]**

[1] Department of Mechanical Engineering, University of British Columbia, Vancouver, Canada, sarah.crosby@mech.ubc.ca;

[2] School of Architecture and Landscape Architecture, University of British Columbia, Canada

**Abstract:** In recent work, a Bayesian model was developed to predict occupants' thermal comfort as a function of thermal indoor environmental conditions and indoor $CO_2$ concentrations. The model was trained on two large IEQ field datasets of physical and subjective measurements collected from over 900 workstations in 14 buildings across Canada and the US. Posterior results revealed that including measurements of $CO_2$ credibly increases the prediction accuracy of thermal comfort. In this paper, the new predictive thermal comfort model is integrated into a building energy model that simulates an open-concept mechanically-ventilated office located in Vancouver. Several occupancy profiles are investigated to reflect and compare post-COVID-19 occupancy schedules. This paper proposes a solution for building managers, who are under pressure to increase current ventilation rates during the COVID-19 pandemic, to make changes to the building's control system so that fresh air is increased with minimal energy increase and with no effect on thermal comfort. For instance, simulation results suggest that $CO_2$ levels can be lowered from 800 to 500 ppm while maintaining the current levels of thermal satisfaction if the heating setpoints are lowered from 24 to 21°C. The heating energy demand will only be increased by 32% compared to an increase of 81% if the indoor air temperature were kept at 24°C.

**Keywords:** Occupant Thermal Satisfaction, Indoor Air Quality, Building Energy Modelling; COVID-19 Air-changes-per-hour, Hierarchical Bayesian Modelling

## 1. Introduction

In the effort to reduce the performance gap between model-predicted thermal comfort and actual perceptions of thermal satisfaction, emerging studies have found evidence in support of the multi-domain and multi-contextual nature of thermal comfort (Huang et al., 2012; Jamrozik et al., 2018; Jokl & Kabele, 2006; Rupp et al., 2015; Schweiker et al., 2020). Prior studies have found that the judgment of thermal satisfaction is a cognitive process where the perception of thermal comfort is affected by the psychological effect of many IEQ physical conditions that occupants encounter in the built environment, not only thermal conditions (Djongyang et al., 2010; Huang et al., 2012; Lin & Deng, 2008; Pellerin et al., 2004). Research has shown that the performance gap between standard model-predicted thermal comfort and thermal comfort observations, which affect building operations and controls, could be filled by including new parameters in thermal comfort models, such as measurements of $CO_2$ concentrations (Gauthier et al., 2015).

(Crosby & Rysanek, 2021) investigated the independent correlations between occupants' thermal satisfaction and thermal and non-thermal parameters of IEQ, such as $CO_2$ concentrations, light levels, and noise levels. Bayesian regression was applied to the COPE dataset, a field dataset of objective and subjective IEQ measurements collected from about 800 occupants of open-plan offices in nine buildings across Canada and the United States(Veitch et al., 2007). They have found significant evidence to suggest that occupants' perceived thermal satisfaction is correlated with indoor $CO_2$ levels. For instance, under the same psychrometric conditions, a modest increase in indoor $CO_2$ levels from 500 ppm to 900 ppm is found to be correlated with a decrease in thermal satisfaction by 30± 8% (Crosby & Rysanek, 2021). Furthermore, they found strong evidence to suggest that adding measurements of indoor $CO_2$ concentrations to thermal comfort models provides better predictive accuracy than models that would not include these parameters.

These findings have been further updated using a new field IEQ database conducted at the University of British Columbia (UBC). The UBC dataset consists of instantaneous physical and subjective measurements of IEQ collected from 150 workstations in four buildings between 2019 and 2020 from open-plan offices (Crosby & Rysanek, 2022). An updated hierarchical Bayesian logistic regression model was developed to determine whether the evidence base for the prior findings is strengthened upon the addition of new data. It was found that including indoor $CO_2$ concentrations as an independent variable when predicting occupant thermal satisfaction credibly improved the prediction accuracy of occupant perceived thermal satisfaction, reinforcing the prior findings.

In this paper, the new predictive thermal comfort model, derived from the hierarchical Bayesian regression of the combined COPE and UBE datasets is adapted and integrated into a building energy model (BEM). It aims to investigate the potential energy costs resulting from pumping higher amounts of fresh air indoors while lowering the heating setpoint and maintaining the same levels of thermal comfort. A 241.5 $m^2$ open-plan mechanically-ventilated office space located in Vancouver is simulated in TRNSYS for the month of January. The control system is set so that the indoor air temperature and the indoor $CO_2$ levels are maintained fixed. Different configurations of both the heating setpoint and the indoor $CO_2$ setpoint are examined. The corresponding heating demand and thermal satisfaction are calculated for each examined scenario in order to examine possible energy-savings scenarios to increase the air change rates while not compromising the occupant's thermal comfort.

In the wake of the COVID-19 pandemic, the office work setup has greatly changed with more workplaces moving towards hybrid working models, where office occupants are no more working 100% of their full-time capacity at the office. Different hybrid working approaches have been recently implemented in workplaces and the current, post-COVID-19, occupancy schedules need to be reflected in building energy models. This is especially of importance when the heating energy demand of office spaces is studied. In this paper, different occupancy profiles have been examined to reflect and compare the current occupancy schedules in office spaces after the COVID-19 pandemic. Heating energy demands for each of the investigated occupancy profiles and for a combination of indoor air temperature and indoor $CO_2$ levels setpoints are investigated.

Another key change in office buildings after the COVID-19 pandemic is the need to increase the amount of fresh air requirements to mitigate the risk of airborne virus transmission. Various researchers and organizations, including the WHO (World Health Organization, 2021) , recommended increasing the percentage of indoor fresh air and the current values of air change per hour (ACH) to help reduce the spread of COVID-19 in indoor environments, which means that the indoor $CO_2$ levels setpoint needs to be lowered (Allen et al., 2021; Joseph R. Biden, Jr., 2021; Peters et al., 2022). It has been recommended to increase current ventilation rates to 4 to 6 air changes per hour (Allen & Ibrahim, 2021). The added cost of moving more air as well as heating a larger volume of air poses a considerable challenge to building managers and operators (Allen & Ibrahim, 2021). This paper then aims to investigate whether buildings' control systems can be changed so that current ventilation rates can be increased with minimal energy increase and without sacrificing occupants' thermal comfort, an important challenge to building modellers in a post-COVID-19 world.

## 2. Methodology

The predictive thermal comfort model, developed by Crosby & Rysanek (2022), is integrated into a TRNSYS framework to examine the potential energy savings that can be achieved by using the model to control both the heating setpoint and the required ventilation rates without compromising the occupant's thermal comfort. The model predicts the probability of occupants' thermal satisfaction, $p(S)$ as a function of indoor air temperature, $T$, and indoor $CO_2$ concentrations, $C$, $p(S \mid T, C)$ as follows:

$$p(S \mid T, C) = \frac{1}{e^{-\lambda}}, \lambda = \left[(\beta_T . T) + (\beta_{T^2} . T^2) + (\beta_C . C) + \beta_o\right] \quad (1)$$

Where T = indoor air temperature (°C), C = indoor $CO_2$ levels (ppm), $\beta_C$, $\beta_T$, and $\beta_{T^2}$ are the model parameters for C, T, and $T^2$ respectively, and $\beta_o$ is the constant coefficient. The maximum a posteriori estimates (MAPE) and the 95% Credible Intervals (CrI) of each model parameter ($\beta$) are summarized in Table 1.

Table 1. Model parameters' maximum a posteriori estimates (MAPE) with 95% credible intervals

| Model Parameter ($\beta$) | Maximum a posteriori estimates (MAPE) | 95% CrI |
|---|---|---|
| $\beta_o$ | 0.15 | CrI [-0.22, 0.5] |
| $\beta_T$ | 1.3 | CrI [0.093, 2.2] |
| $\beta_{T^2}$ | -0.25 | CrI [-1.8, 1] |
| $\beta_C$ | -0.74 | CrI [-1.4, -0.099] |

An open-plan office in the Centre for Interactive Research on Sustainability (CIRS), a four-storey building on the campus of the University of British Columbia (UBC), is selected as a case study for this work. The office, illustrated in Figure 1, is modelled as a single-zone with a floor area of 241.5 $m^2$ and a floor-to-ceiling height of 3.7 m. The model has two exterior walls exposed to the outside and two walls with adiabatic zone boundary conditions (i.e. no heat transfer between the zone and its surrounding is assumed). The office is located on the third floor and has two large windows on the north and south sides of the building, as shown in Figure 1. The fenestration area is 50 $m^2$ per side, which is equivalent to a 0.58 window-to-wall ratio (WWR). The windows have a U-value of 1.1 $W/m^2.k$ and a G-value of 0.62. The external walls' construction has a thickness of 0.377 m and a U-value of 0.25 $W/m^2.k$. The floor and ceiling constructions of the zone are modelled as adiabatic boundary conditions with the outside.

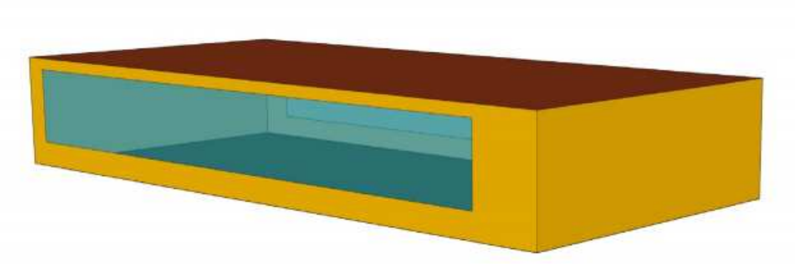

Figure 1. The simulated open-plan office geometry

Four daily schedules are developed to reflect and compare possible occupancy profiles for post-COVID-19 back to work settings. Schedule 0 is designed to simulate a 100% full-time occupancy capacity for all of the 5 working days and is used as the baseline to reflect the pre-pandemic occupancy profiles. Schedules 1, 2, and 3 are possible occupancy profiles for post-COVID-19 work settings that involve hybrid working models where the office is never occupied with either the 100% occupancy capacity or the entire 5 weekdays. Table 2 and Figure 2 summarise the examined occupancy profiles. The weekend occupancy profiles are assumed to have no occupancy for the entire 2 days.

Table 2. Daily occupancy schedules used to scale the internal heat gain and indoor $CO_2$ production rates

| **Schedule 0 (Pre-COVID-19)** | **Schedule 1 (Post-COVID-19)** | **Schedule 2 (Post-COVID-19)** | **Schedule 3 (Post-COVID-19)** |
|---|---|---|---|
| 5 days,100% full capacity | 3 days,100% full capacity | 5 days, 50% full capacity | 5 days, 60% full capacity |

The office lighting control system is configured so that the lights are turned on if the occupancy is greater than zero, and turned off otherwise. The radiative heat gain from lighting is assumed equal to 25.2 KJ /hr /$m^2$. The heat gain produced by the electrical equipment heat gain is assumed 43.2 KJ / hr / $m^2$, and is scaled using the occupancy schedules in Figure 2. The internal heat gains generated by the office occupants are modelled in TRNBuild by specifying a maximum thermal gain generated and scaling this internal gain throughout the day using the predetermined office occupancy schedules.

The maximum internal heat gain generated by the occupants is 75 W convective gain and 75 W radiative gain. The occupancy schedules, displayed in Figure 2, are used to scale these internal heat gains. An occupancy density of 10 $m^2$/person is assumed, which is equivalent to an occupancy of 25 people.

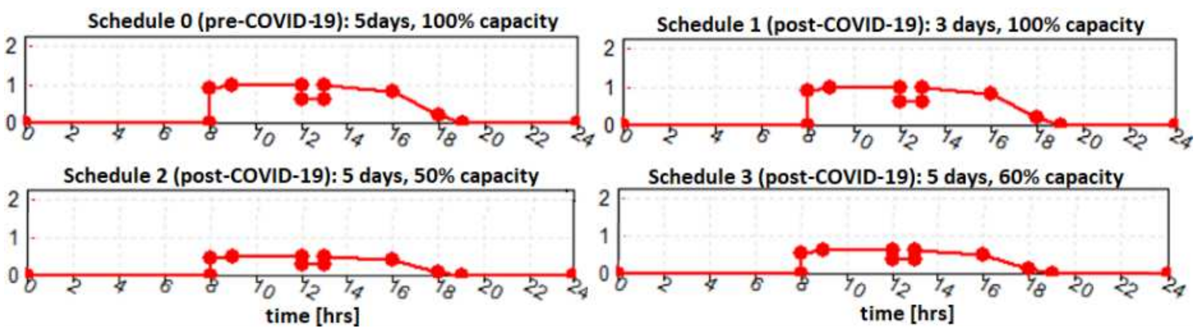


Figure 2. Weekdays schedules used to scale the internal heat gain and indoor CO2 production rates

A total of 144 simulations, 36 simulations for each of the four investigated schedules, are undertaken. Each simulation corresponds with a unique indoor air temperature setpoint and indoor $CO_2$ setpoint. The range of setpoints covered spans an air temperature setpoint of between 21 and 25 °C and $CO_2$ levels of between 500 ppm and 1000 ppm. This broadly covers the range of observed indoor temperatures and $CO_2$ levels in the prior UBC and COPE datasets. Under each simulation, a setback air temperature setpoint of 15 °C is assigned and the ventilation system is deactivated during unoccupied periods.

The heating energy demand for the month of January, the coldest month in the year in Canada, is calculated for each scenario and for each of the developed occupancy schedules using TRNSYS. Thermal satisfaction predictions are evaluated for each combination of indoor air temperature and $CO_2$ concentration level using the Bayesian predictive thermal satisfaction model in Eq.1.

## 3. Results and Discussion

144 simulations were completed where 36 simulations for each of the four occupancy profiles have been undertaken. Each simulation is associated with a particular indoor $CO_2$ setpoint and indoor air temperature setpoint simulating the open-plan office space for the month of January. A simulation time-step size of 10 min was selected for the 144 simulations. For each of the simulations, the heating energy [KWh/m$^2$], air changes per hour, indoor $CO_2$ concentrations, and ventilation rates [L/s] were calculated for each day in the month of January.

Monthly values of heating energy demand in [KWh/m$^2$] for each scenario of indoor air temperature and indoor $CO_2$ setpoints were evaluated for each of the investigated occupancy schedules. Table 3 summarizes the raw data resulting from the 36 simulations performed for each different scenario of schedule 1 (post-COVID-19).

Table 3. Monthly heating energy demand [KWh/m$^2$] for 36 scenarios of indoor air temperature setpoint and indoor $CO_2$ setpoint for schedule 1 'post-COVID-19', (3 days, 100% full capacity)

| C / T | 20 °C | 21 °C | 22 °C | 23 °C | 24 °C | 25 °C |
|---|---|---|---|---|---|---|
| **500 ppm** | 8.355506 | 9.471294 | 10.5032 | 11.46159 | 12.44644 | 13.45435 |
| **600 ppm** | 7.251001 | 8.025247 | 8.935622 | 9.822631 | 10.72242 | 11.64701 |
| **700 ppm** | 5.56417 | 5.815475 | 6.452946 | 7.193784 | 7.95787 | 8.746684 |
| **800 ppm** | 4.831999 | 4.729806 | 5.289289 | 5.959954 | 6.659504 | 7.384382 |
| **900 ppm** | 4.40411 | 4.062286 | 4.649039 | 5.27416 | 5.933471 | 6.621838 |
| **1000 ppm** | 4.400005 | 3.732644 | 4.272521 | 4.870145 | 5.50467 | 6.168761 |

Figure 3 presents the aggregate simulation results for schedule 0 (pre-COVID-19) in the form of a contour plot generated via MATLAB. The plot correlates monthly heating energy demand with indoor air temperature setpoint, indoor $CO_2$ setpoint and occupants' thermal satisfaction. Thermal satisfaction predictions, inferred from the prior Bayesian model (Crosby & Rysanek, 2022), are visualized as a heatmap where dark red colours represent higher likelihoods of perceived thermal dissatisfaction and green colours represent a higher likelihood of thermal satisfaction. Values of heating energy demand [KWh/m$^2$], evaluated for different configurations of indoor air temperature and $CO_2$ levels, are displayed as solid black contours.

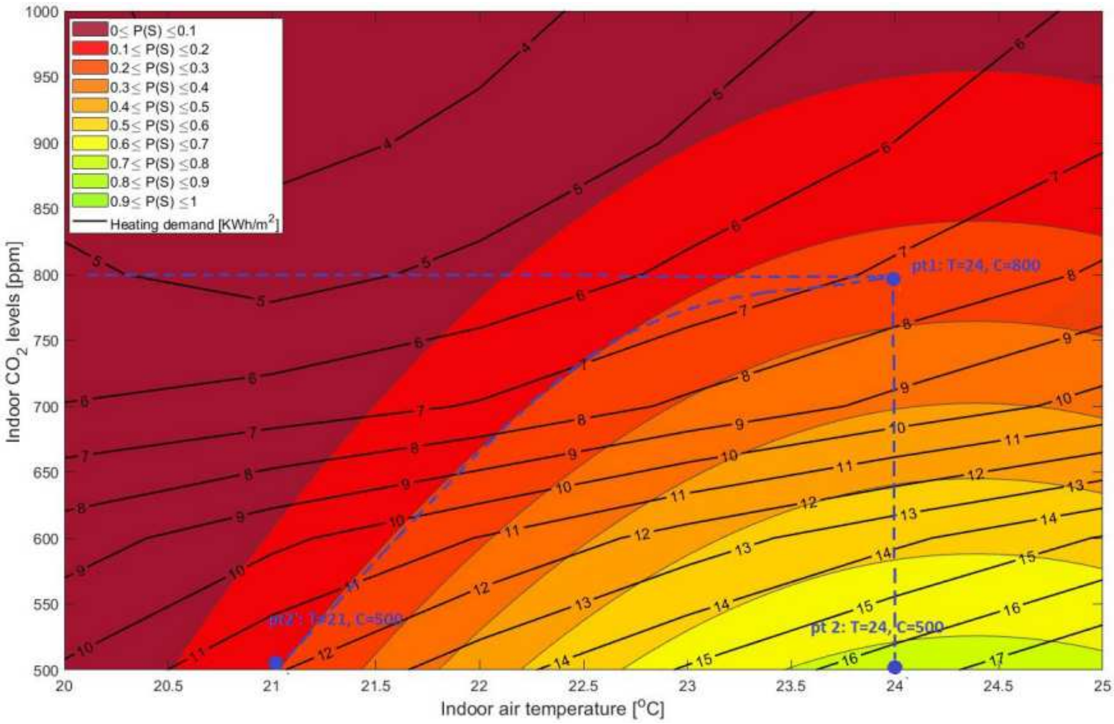


Figure 3. Heating energy demand in [KWh/m$^2$] as a function of indoor air temperature and indoor $CO_2$ levels (denoted as black solid contours) for pre-COVID-19 occupancy schedule. Predictions of thermal satisfaction, p(S), represented as a heat map: dark red represents higher thermal dissatisfaction and green colour represents higher thermal satisfaction levels.

The simulation results, shown in Figure 3, suggest that there are multiple pathways for increasing building ventilation rates indoors, which affect heating energy demand and thermal comfort differently. For instance, for building managers and operators that are under pressure to increase the current air change rates, if the conditioned space is currently maintained at an indoor air temperature of 24 $^oC$ and a $CO_2$ level of 800 ppm (point 1), one solution may be to increase ventilation rate such that the indoor air temperature is kept at 24 $^oC$ and the $CO_2$ level is lowered to 500 ppm (point 2). In that case, the total energy demand for heating and ventilation would be increased by 131 % but perceived thermal satisfaction would increase as well.

However, if one would seek to only maintain current levels of perceived thermal satisfaction, building managers could choose to decrease indoor heating setpoints to 21 $^oC$ while lowering the indoor $CO_2$ concentrations to 500 ppm (point 2'). In this case, the increase in energy demand might only be increased by about 66%. Such multi-contextual thermal comfort models may then be used by building managers to make changes to the building's control system so that fresh air rates can be increased with minimal energy demand increase and no effect on occupant thermal comfort.

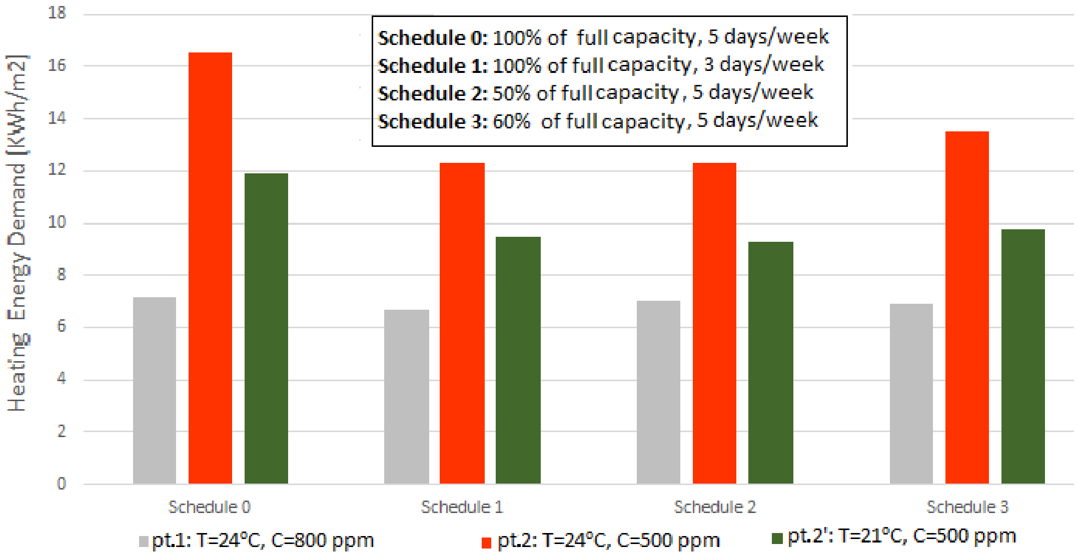


Figure 4. Monthly heating energy demands of the investigated occupancy schedules for pt. 1, 2, and 2'.

In order to compare the four occupancy schedules (shown in Figure 2), the monthly heating energy demands for the three scenarios displayed in Figure 3, are calculated and displayed in Figure 4. It is revealed from the results, shown in Figure 4, that it is possible to increase the fresh air amounts while maintaining the same level of occupants' thermal comfort by lowering the heating setpoint and increasing the air change rates. This is applicable to the pre-COVID-19 schedule as well as all the investigated post-COVID-19 occupancy schedules, as shown in Figure 4.

Comparing schedules 1 and 3, both schedules correspond to 60% of the pre-COVID-19 working schedule. Schedule 1 represents 100% of the full occupancy capacity with occupants coming only 3 days per week, while in schedule 3, the office workers occupy the office during the five working days but only 60% of the full capacity are present at a time. It is also noteworthy that schedule 1 saves slightly more heating energy than schedule three.

Table 4. Comparison between the percentage increase in monthly heating energy demand for both scenarios of increasing the ventilation rates for the four investigated occupancy schedules

| **Schedule** | **% Increase in heating energy (pt.1 to pt2.)** | **% Increase in heating energy (pt.1 to pt2'.)** |
|---|---|---|
| Schedule 0 (5 days, 100%) | 130.96% | 65.95 % |
| Schedule 1 (3 days, 100%) | 86.897 % | 42.22% |
| Schedule 2 (5 days, 50%) | 81.3556% | 31.842% |
| Schedule 3 (5 days, 60%) | 95.063 % | 41.22% |

Table 4 summarizes the percentage increase in the monthly heating energy demand if one can adopt scenario 1-2 vs. scenario 1-2' for increasing the ventilation rates indoors, calculated for the four investigated occupancy profiles. It is revealed from the results that, using the Bayesian predictive model of thermal comfort (in Eq.1) to increase the amount of fresh air while lowering the heating setpoint and maintaining the same thermal comfort levels, saves more energy than maintaining the indoor temperature setpoints for all the investigated schedules.

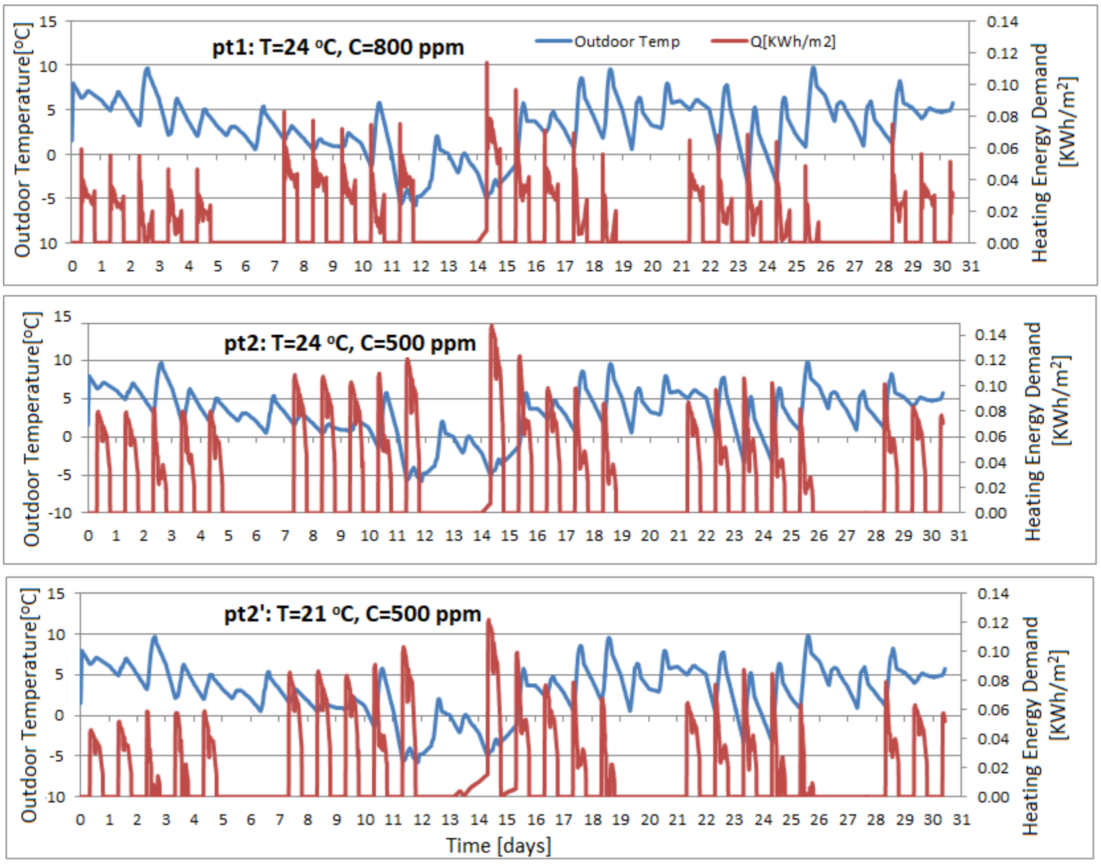


Figure 5. Daily heating energy demand [KWh/m2] and outdoor temperature [°C] for the month of January, schedule 0 (pre-COVID-19) for the three investigated points (T=24 °C, C=800 ppm; T=24 °C, C=500 ppm, T=21 °C, C=500 ppm)

The daily values of heating energy demand in [KWh/m$^2$] for the three investigated scenarios (pt.1, pt.2, and pt.2') for the entire month of January are evaluated and displayed along with the outdoor temperature in Figure 5. It is noted that the heating energy consumption increases as the outdoor temperature decreases, as seen in Figure 5. As the amount of fresh air increases from point 1 to point 2, the heating energy demand increases as well. In scenario 2', however, the heating energy demand is lower than that for point 2 since both points have the same $CO_2$ concentration setpoint, but point 2' has a lower heating setpoint than point 2, which contributed to reducing the heating energy demand.

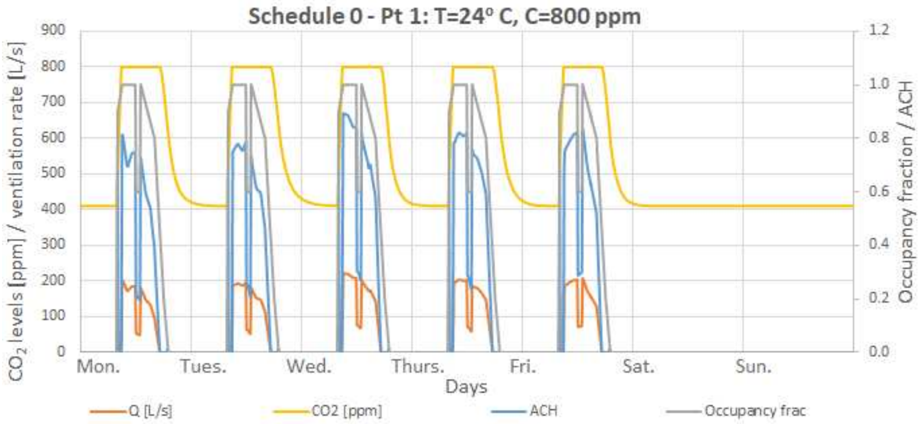


Figure 6. Schedule 0 ( 5 days/week, 100% full-time ) $CO_2$ levels [ppm], ventilation rate [L/s], Occupancy fraction, and Air change rate for point 1 (T=24°C, C=800 ppm).

Figures 6, 7, and 8 display the values of daily $CO_2$ concentrations levels [ppm], ventilation rates [L/s], occupancy fraction, and values of air changes per hour for one week of January for the pre-COVID-19 schedule (schedule 0) for pt.1, p.t2, and p.t2' respectively. It is noted from the figures that the air changes per hour, the indoor $CO_2$ levels, and the ventilation flowrates increase as the occupancy fraction increases.

It is also shown in Figures 6, 7, and 8 that the air changes per hour and the ventilation rates increase when the indoor $CO_2$ setpoint is lowered (from point 1 to point 2 and from point 1 to point 2'). The value of ventilation rate and air changes per hour is zero at the weekends and on the days where the occupancy is set to zero.

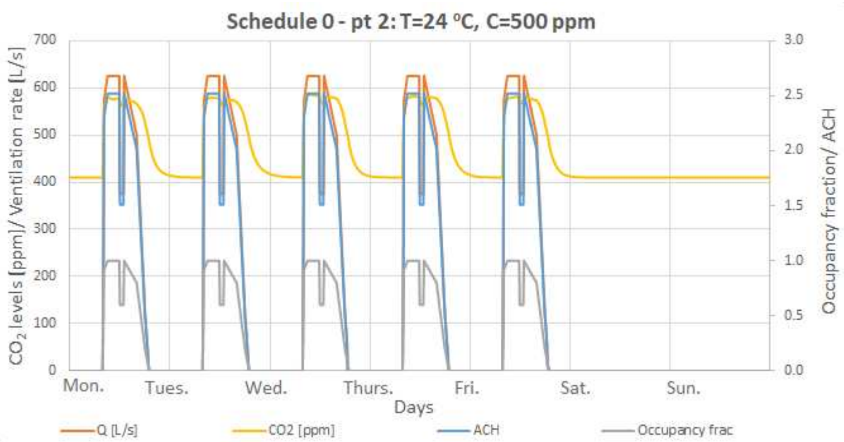


Figure 7. Schedule 0 ( 5 days/week, 100% full-time ) $CO_2$ levels [ppm], ventilation rate [L/s], Occupancy fraction, and Air change rate for point 2 (T=24°C, C=500 ppm).

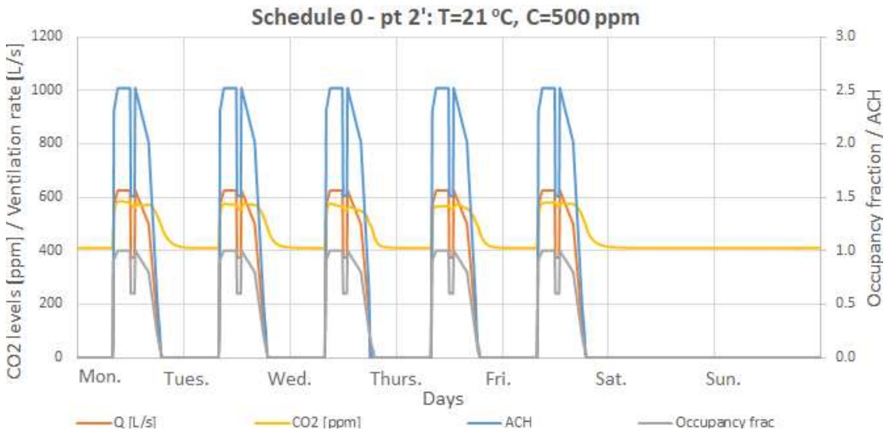


Figure 8. Schedule 0 ( 5 days/week, 100% full-time ) $CO_2$ levels [ppm], ventilation rate [L/s], Occupancy fraction, and Air change rate for point 2' (T=21$^{o}$C, C=500 ppm).

## 4. Conclusions

This paper made use of a data-driven predictive model of thermal comfort that predicts occupants' thermal satisfaction as a function of indoor air temperature and $CO_2$ levels. The model was integrated into a building energy model framework and a single-zone mechanically-ventilated open-plan office, located in Vancouver, was simulated for the month of January, the coldest month of the year. The control system was set up so that the indoor air temperature and $CO_2$ levels are maintained fixed.

In this work, different configurations of indoor air temperature setpoints and indoor $CO_2$ levels were examined. The setpoints covered strange between 21 and 25 $^{o}$C for air temperature and between 500 ppm and 1000 ppm for $CO_2$ levels. The corresponding heating demand and thermal satisfaction were calculated for each examined scenario in order to investigate potential energy savings associated with pumping more fresh air while lowering the heating setpoint and while not compromising the occupant's thermal comfort. Four daily occupancy schedules were developed to reflect and compare different occupancy profiles for post-COVID-19 back-to-work hybrid working models. A total of 144 simulations, 36 simulations for each of the four investigated schedules, were undertaken.

The simulation results showed that, by using the predictive thermal satisfaction model, it is possible to increase the ventilation rates with minimal building energy demand increase while not compromising occupants' thermal comfort. For all the studied post-COVID-19 occupancy profiles, the increase in heating energy, resulting from pumping higher amounts of fresh air, was always lower when the Bayesian predictive thermal comfort model was used so that the heating setpoint is lowered while maintaining fixed thermal comfort levels. This paper presented a solution for building managers and operators who have been under pressure to increase the current amounts of fresh air to lower the risk of spreading the COVID-19 virus indoors.

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# Designing Health Structure in Emergency Contexts. Natural Ventilation as Response to COVID-19 Pandemic.

**Marianna Nigra[1], Marco Simonetti[2] , Luca Galleano[3], Vincenzo Gentile[4]**

[1] Politecnico di Torino, Italy, DIST – Interuniversity Department of Regional and Urban Studies and Planning, FULL: Future Urban Legacy Lab, mgnigra@gmail.com
[2] Politecnico di Torino, Italy, DENERG – Department of Energy, marco.simonetti@polito.it
[3] Politecnico di Torino, Italy, DENERG – Department of Energy, luca.galleano@polito.it
[2] Politecnico di Torino, Italy, DENERG – Department of Energy, vincenzo.gentile@polito.it

**Abstract:** The importance of ventilation as response to pandemic emergency is a concept that trace its roots back in the history of human pandemic and it remains valid up to the current covid-19 emergency. Yet, extreme climates, scarcity of resources, and poverty might impinge heavily on the ability of designing a built environment fit for the purpose of guarantee environmental conditions appropriate to respond to pandemic. Often, in contexts of scarcity and hot climates, safety parameters of ventilation in buildings are achieved *as ersatz*, rather than by design, due to the difficulties of managing economic resources, thermal characteristic, and ventilation requirements. Keep buildings cool and well ventilated seems to be still a challenge.

This work presents a study carried out to design health structures - both permanent and temporary - in response to covid-19, in the Global South. Specifically, the study focused on: 1) the design of a Severe Acute Respiratory Infection (SARI) Treatment Center (hospital for airborne diseases) in the city of Dori in Burkina Faso, and 2) the design and test of High Performance Tents.

Natural ventilation is studied by mean of transient dynamic simulations, using Energy+ software, and the probability of contagion are evaluated applying the Gammaitoni-Nucci model, based on the original Wells and Riley approach. The yearly dynamic simulations are supported by specific 3D airflows analysis by mean of CFD (Computational Fluid Dynamic), with the intent to underline the effects of different internal partitions configuration. CFD is also used to evaluate pressure coefficient at the openings. Through this ventilation study and morphological design proposal, this work provides compositional, technological and environmental solutions to overcome limits due to the need of coexistence of ventilation and thermal control, and socio-economic limitations. The significance of this work is the ability to show the importance of the balance between passive ventilation, architectural design and behavioral organization by design. Such approach can play a critical factor to achieve healthy and resilient environment, and offer a feasible solution to the need for health buildings in hot climates and poor contexts.

**Keywords:** Natural Ventilation, COVID-19, Architecture, Passive Design, Global South

## 1. Natural Ventilation and Health

The role of natural ventilation to ensure healthy space is well known since the work of *Hippocrates* was translated and taken into account in the design of the Renaissance cities (Rahm 2021; Allard 1998), or since the construction of the ancient cities in Iran with the wind chimney architypes (Grosso 2017). Yet, today we are facing the need to re-underlying and further explore the crucial role of natural ventilation as a way to reduce the spread of contaminant in the context of airborne diseases, such as COVID-19. This might be particularly true for the context in which resources are scarce therefore passive design solution to design buildings might be the solely alternative.

## 2. The Design Challenges

The work presented in this paper is the ventilation study to support the design process carried out in conjunction with two different International humanitarian organization for the design and testing of both temporary and permanent health structure, such as high performance emergency tents, and a Severe Acute Respiratory Infection (SARI) treatment centre. These two projects were characterised by different challenges.

The SARI treatment centre was project was located in Dori, Burkina Faso, where the climate is characterised by an oppressive wet season, mostly cloudy and sweltering all the year. Temperature varies from 15°C to 40°C and is rarely below 12°C or above 43°C. Moreover, the months of December and January are characterized by important sandstorms. In such context, an existing design required a review based on the use of natural ventilation due to the lack of energy supply on site. The main challenge was therefore to propose a natural ventilated building layout based on strict requirement of airflow rate for critical patient at 160l/s as established by the World Health Organization (WHO 2009), in order to limit, control and prevent the spread of COVID-19. Moreover, other specific design challenges were: to design different circulation paths for health care workers (HCW) and patients, with independent ventilation systems; optimise microclimatic characteristics over the year; ensure thermal control during the hottest months; and ensure the respect and dignity of the local population, by offering the possibility of closing window at night.

The High Performance Emergency Tents had to certain extent similar challenges. The main challenge was to test the ability of the tents to ensure the airflow rate of 160 l/s. To do so, it was crucial to undertake a study that could analyse together, the tents layout (single module, or multiple modules layout), and the local climatic conditions of the possible sites where the tents could be located. To further test the possibility to eliminate contaminant in the air within the tents, a number of design solutions have been explored in order to assess the role of different internal partitions inside the tents.

## 3. The Methodological Approach

The methodological approach selected for the two case studies set its premises into the domain of ventilation studies, about which an overview is presented in the following section. Moreover, specific methodological approaches and methods are defined for the simulations and design of the two proposed case studies.

### 3.1 A brief overview of the state of art

Quantitative modelling and theories are largely used in different fields to quantify risks and probabilities of hazardous events. Epidemic modelling has struck back again in these days due to the COVID19 emergency. Quantitative models describe the probability for an individual, or for a group of people, to be infected in specific conditions (type of environment, time of exposure, source characteristics, etc.). There are mainly two types of approaches: Wells-Riley (WR) model and the Dose–Response Model (Guo, et.al. 2021; Hobday et. al. 2013, Li et. al. 2007).

The WR theory was developed during ’70s and ‘80s and constitutes the scaffold for the airborne transmission of multiple epidemics such as tuberculosis, measles and influenza (Wells 1934; Riley 1978). The theory describes the responsibility of airborne transmission to very small particles called “droplet nuclei”, a conglomerate of organic matter, containing micro- pathogens and emitted through the respiratory activity. Being extremely lightweight, droplet nuclei are scarcely influenced by the gravity field and follow mainly the typical Brownian motion (To, et. al. 2020). This characteristic makes concrete the possibility of having particles floating in the air from several minutes to hours starting from their original emission. The presence of droplet nuclei floating in the air influences drastically the infection path, not anymore related only to direct/indirect contacts between people and fomites, but also to the interaction with 'the air you breathe and the environment you live'. Droplet nuclei, generally identified as particles with aerodynamic diameter lower than 5 µm (Morawska, Johnson, Ristovski 2009), may be generated following two different paths: directly emitted by infective subjects through talking, sneezing, breathing, or because of evaporation of bigger droplets after the emission. The diameter distribution of emitted droplets covers a wide range, with a large component of particles bigger than 20µm (Morawska, Johnson, Ristovski 2009). After the emission, the fall of droplets is mainly driven by the gravity field and disturbed by the local air convection but, if the evaporation of water through this phase is sufficiently fast, once the diameter is smaller than 5µm the initial droplet becomes a droplet nucleus. Given this physical condition, the possibility to get the infection after the interaction with a droplet nucleus is a stochastic event strongly connected to the residence time of a susceptible person in a closed volume (V) containing dispersed droplet nuclei. The WR model quantifies the probability of this event. The formulation exploits a Poisson probability distribution and the concept of quanta (q): a statistical entity, specific for a type of disease, defining the needed number of infective particles leading to number of infected person equal to the 63.2% of the susceptible sample. The WR model is based on different hypothesis and limitation:

1. The selected volume must contain at least one infectious subject.

2. The minimum viral load, called "quantum" must be known and must be constant.

3. The susceptible person is considered infected by breathing one quantum.

4. The quanta distribution in the volume is considered homogeneous as well as a perfectly mixed air.

5. The viral load is removed at a constant rate by the fresh air stream.

6. Steady-state conditions with initial quanta concentration equal to 0.

The WR model is suitable in case of quick evaluation, due to the minimum set of data requested. The assumption of perfectly mixed indoor air, that implies a homogenous concentration of pathogen, allows a simple relation between probability of contagion and air change/ventilation flow rate to be leveraged. Nevertheless, it is reasonable to think that the pathogen concentration is higher closer to the infectious subject and it will be affected by the airflow topology in the indoor volume. This is particularly true where there is not mechanical ventilation or indoor fans that ensures a forced mixing of the air.

Various modifications to this model were proposed to consider filtration, air disinfection, respiratory protection, etc. For instance, the Gammaitoni – Nucci model (GN) allowed to overcome the limitation represented by steady-state conditions through the adoption of differential equations. Using the GN model (Gammaitoni and Nucci 1997) it is possible to consider an initial quanta concentration in the room different from 0. This fact for instance is necessary to simulate the passage of an infectious subject over dynamic evolution of the model. Nevertheless, the assumption of air perfect mixing remains a required condition for the GN model. Nonetheless, it is known that a perfect mixing is far from being achieved and local effects in the volume can play a role in pollutant distribution, depending on the air system configuration features, like air supply and exhaust positions, supply air velocity, supply air temperature and turbulence characteristic of the supply jet. Moreover, different particles can interact in different ways with the air flows in an indoor environment, depending on their size and on the local air flow turbulence conditions. In the case of naturally ventilated buildings, the perfect mixing hypothesis is not always verified due to primary air streams that cause different volume distribution of fresh and exhaust air. Nevertheless, the hypothesis of perfect mixing is closer to the reality when large fresh air flow rates are involved even in the case of natural ventilation. Indeed, the larger the Air Change Rate the bigger the contaminant dilution effect and thus the influence of internal gradients of concentration.

### 3.2 The Severe Acute Respiratory Infection Treatment Centre natural ventilation simulation and design

Context characteristics, requirements, and challenges

The existing design for the SARI Treatment Centre in Dori, Burkina Faso was organized in three identical blocks placed perpendicularly among them and containing ten patient rooms each (Figure 1). Each room was divided into three environments: 1) a bedroom hosting the patient, 2) a private bathroom, and 3) a small room filtering the access from/to the corridor. The design requirement was to guarantee a minimum of 160 l/s/patients air flow-rate in the room (Atkinson, Chartier, Pessoa-Silva 2009). This threshold corresponds to an Air Change Rate (ACR) equal to 4-6 volumes per hour. This requirement is quite strict considering that a typical building ranges among 0.3 and 0.8 volumes per hour. The design of the natural ventilation strategy presented the following challenges:

1. It was not possible to exploit the orientation of the building according to primary wind directions. The three main blocks were designed perpendicular to each other, which meant optimizing one orientation would disadvantage another block.

2. It was necessary to place an insect screen in front of every opening reducing the effective opening area of 50% (according to the characteristics of the net).

3. Natural ventilation is strongly influenced by stochastic processes that can modify the boundary conditions affecting the effective ventilation rate. In particular, two processes were individuated as much critical: the variation of wind intensity and direction and occupant behaviour. On one hand, weather conditions can be simulated using the Typical Metheorological Year (TMY) of the selected location, i.e. Dori in Burkina Faso. On the other hand, the occupant beahviour can be forecasted considering the worst condition that is represented by a manual closing of openings during night time (10:00pm to 7:00am) and during dust storm (occurring when wind velocity > 5 m/s).

4. Windows at night were required to be closed, as the local population believe that at night bad spirits could enter the building from opened window.

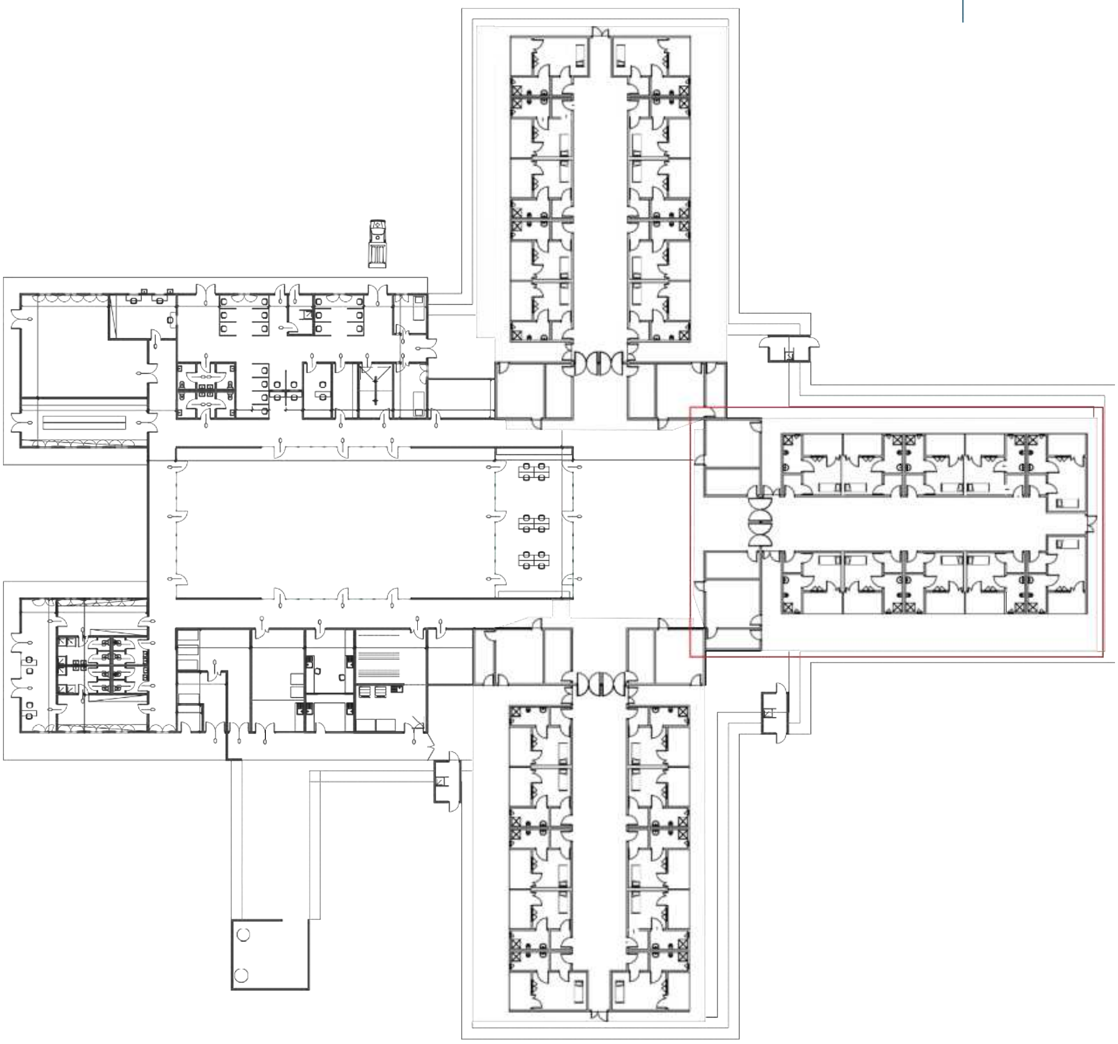

Figure 1: Overall layout for the SARI Treatment Centre of Dori, Burkina Faso

## Strategy

A building adopting a mixed-mode natural ventilation strategy was designed (Figure 2). It relied on some mechanical fans to ensure the satisfaction of the strict performance limits and to reduce the risk of contaminants infection from the room to the corridor. Each of the room environment uses a different ventilation strategy:

1. The bedroom environment was designed to use a cross-ventilation strategy with large openings oriented outdoor and a window over the upper part of the internal wall. The opening over the internal wall did not communicate with the corridor but with the unconditioned space under the roof. The different window heights allow the stack effect to be exploited.

2. The bathroom was ventilated by a one-sided ventilation strategy, i.e. a unique window over the external wall. The ventilation of this environment was considered not crucial since the time spent by patients and operators within this environment is limited.

3. The room filtering the access from/to the corridor used mechanical ventilation. In detail, a fan is placed in the ceiling to extract exhaust air directly to the outdoor. This solution allowed

the environment to have a negative pressure compared to the corridor and avoiding the dispersion of contaminants from the room to the corridor.

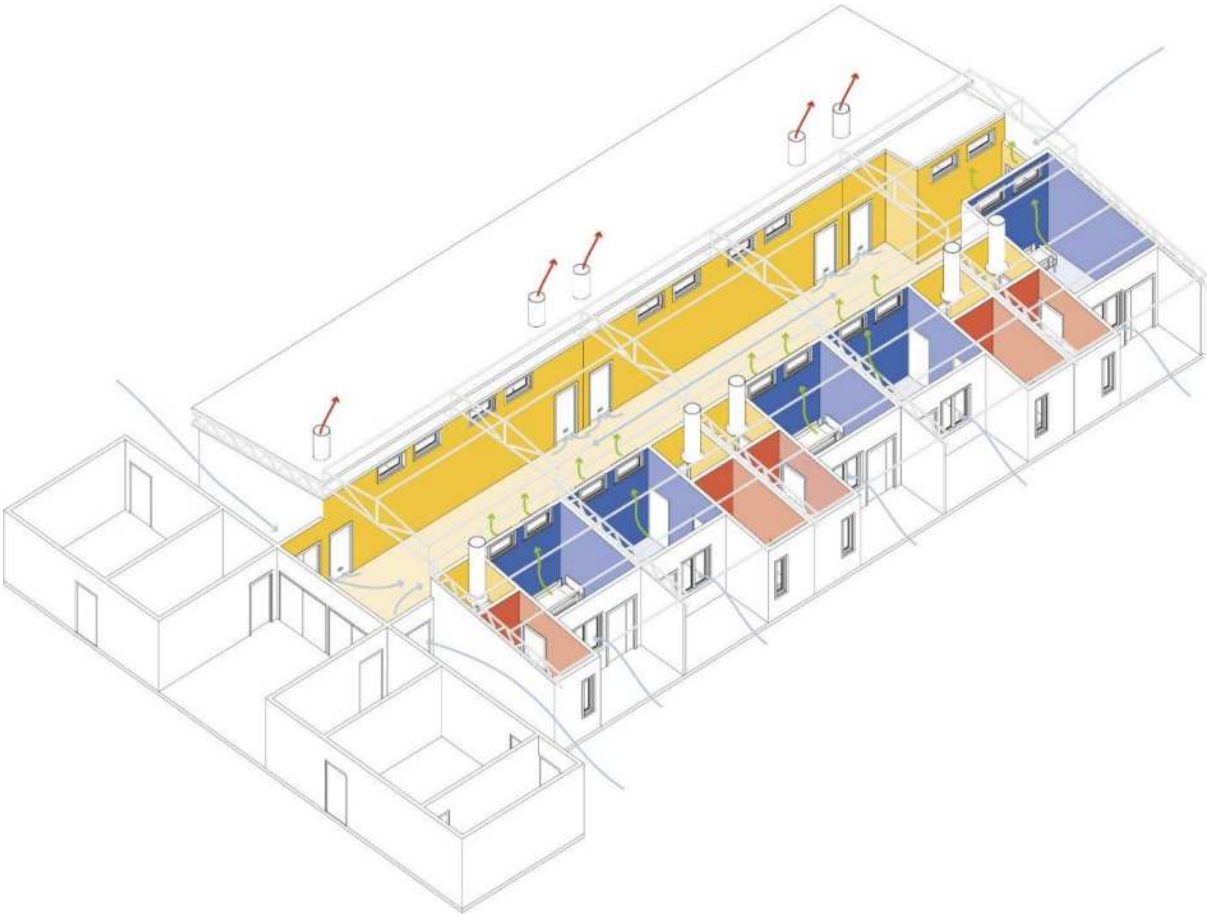

Figure 2: Overall ventilation scheme for the SARI Treatment Centre of Dori, Burkina Faso

## Methodology and methods

The assessment of the performance of the building simulations weas undertaken through Energy Plus - Design Builder. This software allowed the ACR (Air Change Rate) of every single environment of the healthcare structure to be calculated on an hourly basis. The Typical Metheorological Year (TMY) of Dori airport weather station was used as reference to simulate the climatic boundary conditions. Each room was listed as a single zone (e.g. room 1, room 2...), plus the corridor and the unconditioned environment under the roof were considered as standalone zones. Rooms were further segmented into bedroom, bathroom and divider filtering the access to/from the corridor. Each bedroom was considered occupied by a single patient 7/7 days and 24/24 hours. Simulations were performed for the entire building.

Additionally, it was necessary to estimate the trend of airborne infection diffusion to further assess the effectiveness of the ventilation strategy. The formula used (Buonanno, Stabile, Morawska 2020) to calculate the concentration of virus quanta in the room is the following:

$$N_t = \frac{q \cdot I}{n} + \left(N_0 - \frac{q \cdot I}{n}\right) e^{-n \cdot t}$$

Where Nt is the quanta concentration at time t, q is the quanta/hour emitted by an infected person - for our simulations a value of 100 quanta/hour was considered as emission rates that can be reach by an asymptomatic infectious SARS-CoV-2 subject performing vocalization during light activities (Buonanno, Stabile, Morawska 2020). 1 is the number of infected people in the room (in this case 1 patient per bedroom), n is the ACR hourly profile resulting from the simulations of Design Builder, N0 is the initial concentration of airborne infection in the room and t is the time in hour. This formula is applied recursively updating the time-varying terms.

Once the quanta of infection in the room is known it is possible to estimate the risk of contagion of a person accessing the room. In this case the formula utilised (Buonanno, Stabile, Morawska 2020) is:

$$Risk = 1 - e\left(-\frac{p \cdot q \cdot I}{V} \cdot \frac{N_t \cdot t + e^{-N_t \cdot t} - 1 - \left(\frac{N_t \cdot n}{q \cdot I}\right) e^{-N_t \cdot t} + \left(\frac{N_t \cdot n}{q \cdot I}\right)}{N^2}\right)$$

Where Risk is an indicator ranging between 0 (minimum risk) and 1 (maximum risk), p is the infected person respiration rate (0.6 m3/h is a typical value for sedentary activity), V is the volume in m3 and Nt is the concentration of airborne infection calculated with the formula above mentioned.

The risk increases according to the time spent with an infected subject. In the healthcare facility the major risk involves sanitary personnel taking care of the patient. It is reasonable that the time spent by the sanitary staff into the room is always less or equal than 1 hour. Thus, periods of 1 hour were considered as the most dangerous case. Therefore, the calculation is repeated recursively by varying the boundary condition and setting t = 1 hour.

### 3.3 High Performance Tents natural ventilation simulation and design

A 5-step methodology and methods was elaborated to analyze and design the optimal configuration in terms of natural ventilation of the High Performance Tents (Figure 3).

1. Define families of application and parameters: To assess the performance of the tent, simulations were undertaken through Energy Plus - Design Builder. This software allowed the ACR of every single environment of the field hospital to be calculated on an hourly basis. The TMY of the different locations airport weather stations were used as reference to simulate the climatic boundary conditions. Each tent (48 sqm) was listed as a single zone and was considered occupied by with the maximum capacity (8 patients) 7/7 days and 24/24 hours. Simulations were performed for the entire tent and hospital camp. However, we focused on the only the tents that are the most critical environment of the entire facility, in particular the ones on the two opposite sides (NE and SW) of the camp.

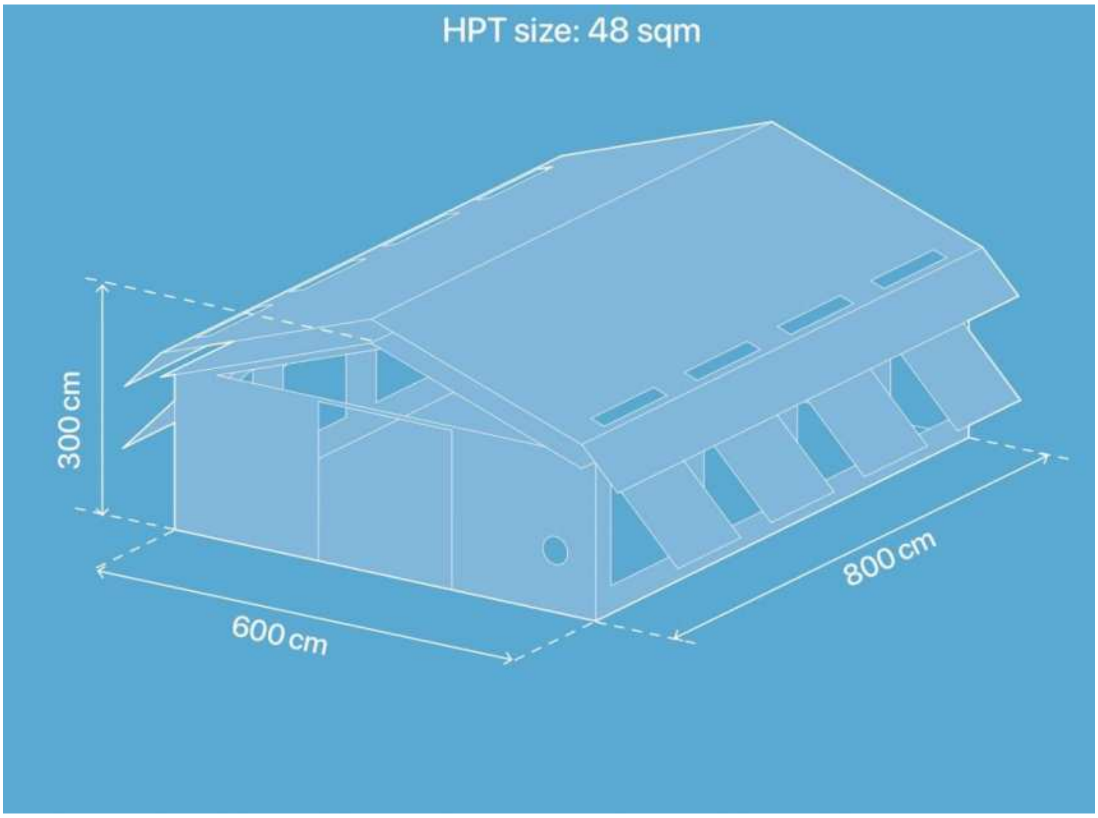


Figure 3: High Performance Tent Dimension

2. Simulate the performance with 1D dynamic tool (Energy+/Design Builder): Simulations have been run on 12 different locations ( 3 for each climate zone, and each one for a different wind speed threshold + 3 specific locations (Figure 4). The locations were the following:

| | Tropical | Temperate | Polar |
|---|---|---|---|
| Low (<2 m/s) | Bangui<br>Central African Republic | Van<br>Turkey | Mayo<br>Canada |
| Moderate (2-4 m/s) | Macapa<br>Brasil | Port Elizabeth<br>South Africa | Tiksi<br>Russia |
| High (>4 m/s) | Subic Bay<br>Philippines | Hutag<br>Mongolia | Ukivik<br>Greenland |

| Tropical | | |
|---|---|---|
| Bafata<br>Guinea Bissau | Al-Damazin<br>Blue Nile | Agadez<br>Niger |

Figure 4: Locations and characteristics considered for the High Tents simulations

3. Simulate local effect with 3D CFD, including indoor add-on (like separation elements): to better evaluate the wind behaviour on the tents we used CFD simulations. Although CFD 3D is a powerful tool, the computational activity is highly demanding, and cannot be used to make simulation of hourly values for 1 year. We therefore used CFD 3D to check specific conditions, in particular: - Indoor airflow paths and ventilation

efficiencies in the volume, considering the effects of add-ons, like individual cabins, panels, additional layers and screens - Outdoor aerodynamics in case of multiple tents, deriving the actual wind intensity available for a tent under the influence of other structures in a complex site - Pressure coefficients at the windows of any tents in a complex site, that are used as input to the 1D dynamic simulations to produce refined set of hourly values for yearlong simulations.

4. Feedback 1D simulations with local effects: To make more reliable energy simulations we extracted the pressure coefficient for each surface (and for each wind direction with 45° incremental) from the CFD simulation. Furthermore, we set different operational strategies to deal with low temperature in temperate and polar climates, as showed in figure 5:

| | Temperate | Polar |
|---|---|---|
| Summer | •Window always open | •Window always open |
| Winter | •Windows open if interior T air>15<br>•Heating on (interior T air=18°) during night | •Daytime: Windows open if interior T air>15; night: windows closed<br>•Heating always on (interior T air=18°) |

Figure 5: Characteristics in temperate and polar climates

5. Complete a full set of simulations covering all the parameters combinations.

## 4. Results

### 4.1 The SARI Treatment Centre Results

There were two main issues to be faced in this site: as already mentioned, the first is a climate issue. December and January are characterised by sandstorms, meaning that windows have to be closed. We set a wind speed treshold at 5 m/s during these months to simulate this climatic phenomenon, when the wind speed exceed this value, the windows are closed. The second issue is a cultural one. People close windows to protect themselves from spirits. In this case we evaluated the performance of natural ventilation with all the winows closed.

We solved these issues:

1. By introducing an always open ventilation grid (as showed in Figure 6).

Figure 6: Ventilation system of single room

2. By evaluating the infection risk and set operational rules

In the night window closure mode the limit of 160 l/s was not respected for the very majority of time, especially in the leeward room. To overcome this limitation and improve the performance of the building a ventilation vent was introduced. This vent remains always open even during night time with the exception of the insect screen. Several dimensions of the vent were studied. Outcomes are reported for the minimum (circular 20 cm diameter) and the maximum (rectangular 45*120 cm) case. The latter is a vent with the same width of the outdoor window and the height necessary to ensure minimum ventilation requirement for a significant majority of time. The simulations show that even the minimum vent allowed the fresh air flow-rate to be increased in the more critical moments, i.e. nights with no wind and windows closed. However, the strict threshold of 160 l/s is overtaken very seldom during night time, especially in the leeward bedroom. This fact is a clear consequence of the stochastic variable affecting natural ventilation design (e.g. human behavior closing windows and weather conditions causing low wind speed). On the contrary the wider vent solution ensures the respect of the threshold for the very majority of time. Nevertheless, a big opening vent on the outdoor wall may cause dissatisfaction of the patient's expectation (e.g. patient might not appreciate sleeping with low sense of security due to a large opening in the wall).

Some considerations must be taken into account at this point. The night time was outlined as the more critical moment for ACR. Notwithstanding, night time is also a moment when the room is occupied by the patient only, not representing a source of risk for the healthcare personnel. For this reason, the trend of contaminant in the environment was simulated to understand the variation of the airborne infection quanta in the room. The calculation was repeated on an hourly basis for the day of the year having the median value of ACR (in TMY occurred on 13-14 September) and the day of the year having the minimum value of ACR (in TMY occurred on 03-04 July). Since the night time is the most challenging period the simulation started at 10:00pm when the windows are closed.

The different simulation studies prove that natural ventilation results to be efficient for SARI treatment centers in combination with mechanical systems, but design and operational precautions have to be taken. As previously mentioned, the ward presented in the preliminary project was based on a typical mechanical served facility, and modifications at the plan could be introduced to improve natural airflow by detaching the ward with a filter space.

Furthermore, using a symmetric double-shell sloped roof (Figure 7) enhances the thermal behavior of the hospital by preventing excessive indoor heat gain and improving the collection of more fresh air for both the rooms and corridor thanks to the stack effect.

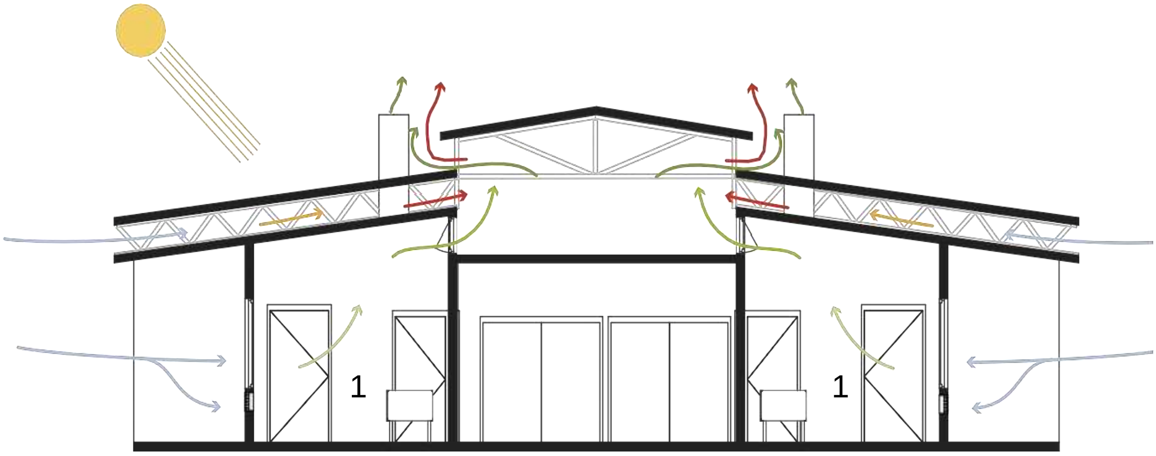


Figure 7: Double roof system

Using double top windows instead of a singular one can facilitate operations and leave a higher degree of airflow control while introducing a grid for night ventilation when the windows are closed can reduce the concentration of viruses in the air. In this case, operational precautions must be taken to prevent the risk of potential staff members infections. Indeed, we suggest that staff should enter the room in the morning for opening the windows only within a limited time span, and then exit before entering again 10 minutes later for visiting the patients.

Further developments could focus on the thermal performance of the building, with the aim of enhancing the environmental quality and temperature under the aegis of natural ventilation, rather than relying on AC/Mechanical Systems. Two possible development strategies are envisioned: A first approach is to further study and design the building envelope and materials, trying to mitigate the high-temperature of Dori, by relying on local low passive technologies, such as adobe blocks isolated with natural fibres such as either kenaf (*Hibiscus altissima*), earth blocks and cow-dung, or fonio (*Digitaria exilis*) straw (Bamogo. Et. al 2020; Ouedraogo, et. al. 2017). A second strategy could be the development of experimental methods for passive cooling of the building, by ustilising the project as a test bed for ongoing technological research and development.

### 4.2 The High Performance Tents Results

The High Performance Tents analysed with open plan demonstrated to be easy to ventilate and to ensure the removal of the contaminant within short time frame.

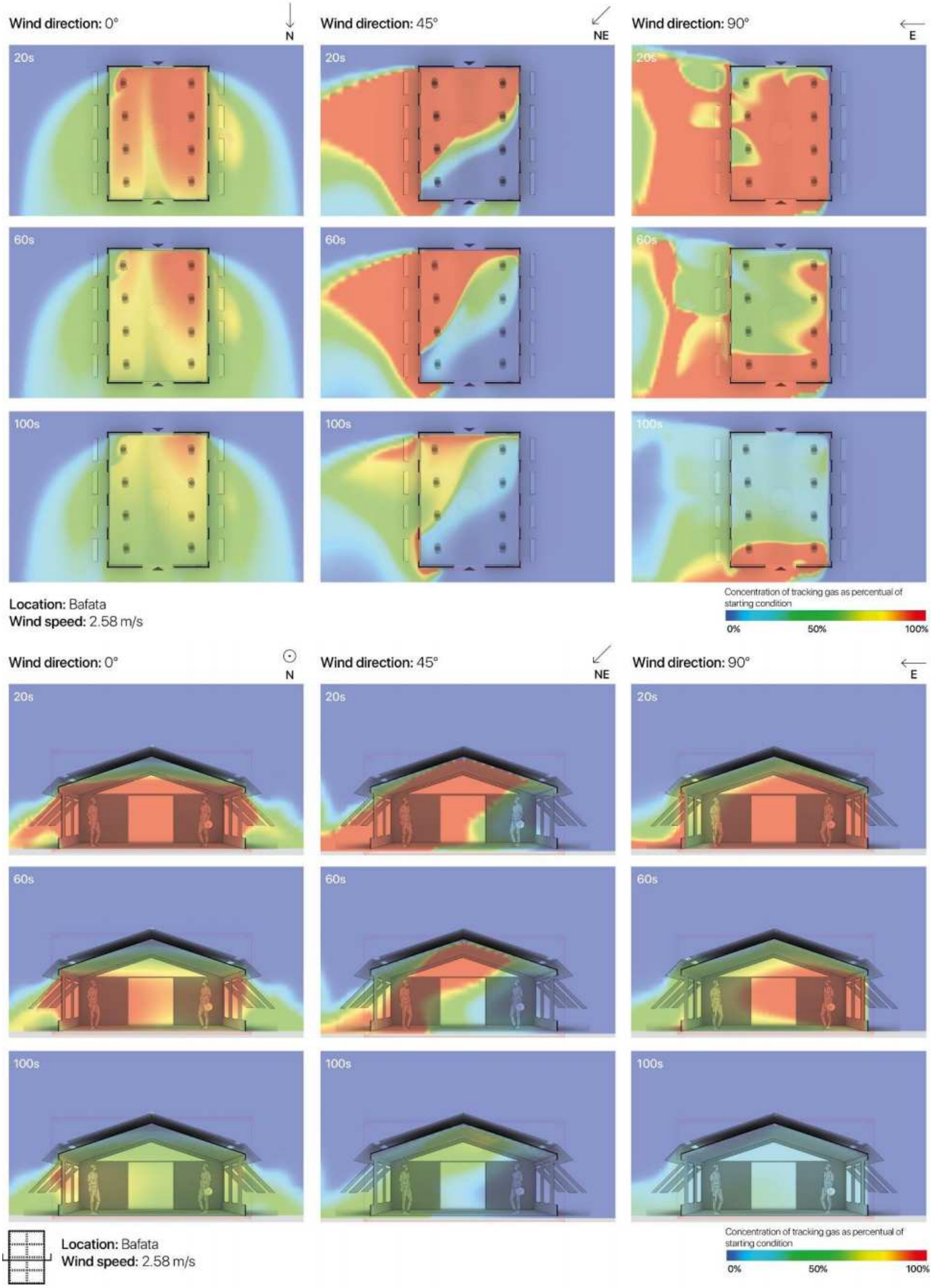


Figure 8: High Performance Tents results of simulation to see how contaminant is removed by natural ventilation in an open space tent

Yet, the thermal comfort is a very critical factor that might impinge on the correct use and ventilation process of the tents in context of extreme cold climate. Thermal control therefore become crucial in the possibility of undertaking natural ventilation with the High Performance Tents. The position of the tents in relation to the microclimatic conditions of the context also is a very critical factor to ensure that sufficient airflow rate is ensured, therefore it is essential to exploit the main wind prevalence direction when possible.

The simulation of the of internal partitions in the tents also demonstrated that such options is not necessarily game changer in terms of performance of the natural ventilation process to eliminate contaminant from the indoor space. Yet, they could reduce to a certain degree the possibility of contamination between different areas within the tent. This might be useful in the case the tent would be use as space to accommodate patient that still have to be gone under *triage* procedure.

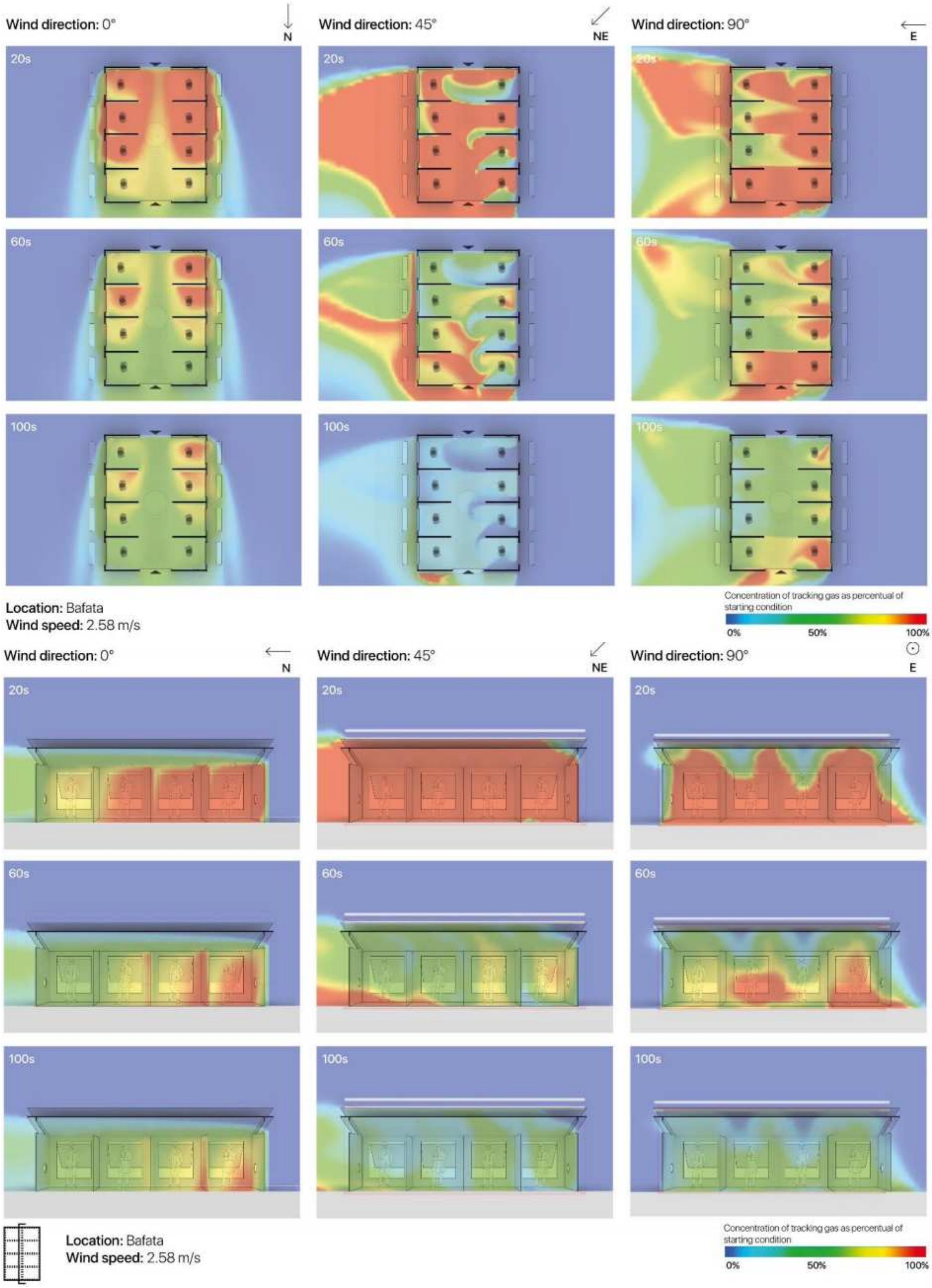


*Figure 9: High Performance Tents results of simulation to see how contaminant is removed by natural ventilation in a tent with internal partitions*

## 5. Discussion

The simulation and design undertaken for two case studies presented showed and confirmed the re-known importance of natural ventilation is supporting the control of contaminant in indoor spaces. Yet, by looking at two different types of health structures, such as temporary and permanent it is important to teas out two main lessons learned: 1) the need for thermal control, and 2) the important of the relation with the microclimatic characteristics.

In the case of the SARI Treatment Centre, required parameters of natural ventilation and thermal control could be designed and achieved by implementing hybrid ventilation methods and technological solutions that could respond to the microclimatic conditions of the context. In the case of the tents, being those products that are not customisable in terms of climatic response – or just to a certain level – it becomes critical understanding the optimal configuration of the context to which they will be shipped to ensure that minimum comfort characteristics could be ensured.

It is therefore important to recognise that if natural ventilation plays a significant role in supporting and controlling the possibility of containing the spread of airborne diseases, the possibility of designing facilities that can be climatic-responsive and also socially adaptable to the context is very important to ensure that the right comfort and safety are achieved, but also that the local population would accept and rely on such facilities without stigmas. The role of low/tech passive design could facilitate such objectives. Yet, it remains complicate to adapt temporary structure that are normally considered as solutions viable for all the contexts, and therefore – unless new products will be developed – the airflow rate and the indoor comfort would be subjected to a negotiation process in relation to the microclimatic context characteristics, as well as energy supply and availability.

This work has some limitations. In the SARI Treatment Centre in Dori, Burkina Faso further investigations needs to be undertaken in relation to thermal control of the building, as well as some of the technical solutions suggested like the vent needs to be tested to understand their performance at night.

## 6. Conclusion

Although the importance of natural ventilation for the health of buildings is not a new concept, the covid-19 pandemic has pushed many sectors to review the importance of air quality and natural ventilation in the built environment. The work presented demonstrated that natural ventilation could represent a viable medium to control, limit and manage the spread of contaminant in indoor spaces, if carefully designed. This might be a crucial step in designing and delivering safe indoor space for areas in the in which energy resource are scarce and passive design approach is the only possible one. Methodological approaches to design should be need flexible and ad-hoc, striving for exploiting and giving value to the relation with the microclimatic context characteristics, as well as with the social one, when possible. Further studies should focus on the possibility of implementing climate responsive emergency temporary structure that could rely at their best on natural ventilation and passive approach to thermal control.

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# Post-Occupancy Assessment and the Integrated Design Process: the Architectural Requalification of a Family Health Strategy (FHS) on the João Domingos Netto settlement, in Presidente Prudente/SP, Brazil

**Luísa Faria de Mello Quelho[1] and Luiza Sobhie Muñoz[2]**

[1] Toledo Prudente University Center, Brazil; luisa.fmq@hotmail.com
[2] Toledo Prudente University Center, Brazil; luiza.smunoz@gmail.com

**Abstract:** The adequate architecture must consider the project's location and its local climatic characteristics. However, it's common the standardization of some Brazilian's small health spaces, as it shows at the study object - the Family Health Strategy (FHS) on the João Domingos Netto settlement in Presidente Prudente/SP, Brazil. This case is different since the neighbourhood's planning covered two health units in opposite sides. Nevertheless, during the first construction, due to unforeseen events a small part was added to the already existing structure. Thermally uncomfortable, undersized internal spaces, unqualified outdoor spaces and a lack of enough natural ventilation internally are problems applied to the FHS. In the pandemic context, became even more urgent to fix these problems. Thus, this work aims to develop a requalification proposal for the study object, so, post-occupancy assessment methods were used to evaluate whether the design was meeting the users' needs. Having known that, simulations and calculus were made in both current situation and proposal. This approach showed the importance of technology and integrated design process as a tool for decision making; in addition, the proposed design showed sensible reductions on incident radiation, consequently, heat gain, and an important increase on natural ventilation internal flow.

**Keywords:** thermal comfort; natural ventilation; post-occupancy assessment; integrated design process; health spaces.

## 1. Introduction

### 1.1 Brazilian public health system

The Constitution of the Federative Republic of Brazil states that "health is everyone's right and the State's duty" (Brazil, 1988). In this context, the national health system (SUS) was created to improve the Brazilian population's quality of life by preventing diseases and treating people free of charge (Brazil, 2021). To do so, the health system's structure is divided into different levels, one of which is focused on small health care environments. This type of institution spreads throughout the urban fabric, based on the scale of the neighbourhood and, according to Brazil (2021), it is separated into three types: (I) Family Health Strategy (FHS), which focuses on low priority cases and offers the possibility for scheduling, follow-up appointments, and access to medical specialists; (II) Basic Health Unit (BHU), also focuses on low priority cases and offers the possibility for scheduling, however, with lower chances of follow-up appointments and less access to specialists; and (III) Emergency Care Unit (ECU), that focuses on emergency cases with no possibility of scheduling and operates all day long.

### 1.2 The environmental comfort in public health units: challenges and the pandemic scenario

These types of health care environments are intended to support basic health necessities of the population and are the foundation of the public health chain in Brazil. In order to reach the goals outlined in the Constitution, not only the system's structure is needed, but also the assurance of environmental quality. These buildings must be comfortable and inviting, so to achieve this, the design phase is crucial. Bittencourt (2002) discusses a Brazilian nomenclature issue stating that, until 1994, the Ministry of Public Health called everything that was related to this theme as "hospital architecture", and after the decree N° 1884 (Brazil, 1994) the title was altered to "health care environment architecture", finally contemplating all its importance.

Beyond the nomenclature problem, it's important to highlight that most of the smaller health care buildings, such as FHSs, BHUs and ECUs, are standardized. In general, these buildings are designed and built without considering local characteristics, such as climate conditions, physical properties, and local context. In fact, these buildings are replicated across the city.

The case of the FHS located at the João Domingos Netto settlement not only has all the unfavourable characteristics that have been discussed up until now but is also worse. The plan was to have one FHS and one BHU on opposite sides of the neighbourhood, so the whole population could be contemplated. However, while the first building was being built, the city hall declared the financial resources were insufficient for both health units. The neighbourhood has eight thousand inhabitants, and each of these units would support approximately 4 thousand people, the new plan was to add a small part of the BHU into the already existing FHS (Presidente Prudente, 2016).

The original area was designed to take 180m², approved by the city hall in 2014, and 80m² was the addition needed to change one FHS into two (I and II), so each of them could take care of four thousand people, enough for the population demand. On the other hand, that generated a few problems, such as a lack of internal space efficiency, shortage of natural ventilation, and accessibility issues as some people live closer to other neighbourhoods' health environments than their own. It's important to emphasize that Presidente Prudente, a medium-sized city located in the Western region of São Paulo state and distant roughly 560 km from the capital of the state, has 231,953 inhabitants (IBGE, 2021). This city has a total of 37 health units, being 24 of those FHSs (Presidente Prudente, 2016), and two of them are in João Domingos Netto settlement.

All these problems cited above, became even more urgent in the pandemic context, when declared by World Health Organization (WHO) (2020) that every health environment should take all the safety measurements recommended, such as wearing masks, face shields and using hand sanitizers. While those measures were restricted to individuals' actions, it was essential that the building was also prepared to tackle this situation. All closed spaces were required to have natural ventilation and discourage people gathering more than necessary.

Regarding that, Bittencourt (2020) stablished four safety measurements for health care environments: people flow, ventilation, climatization and coatings. Together, they make an efficient, safe, and comfortable space, especially in pandemic times when the focus is to stop the transmission of the virus. Russel (2021) expresses a general concern when he exemplifies how unprepared the world is for biohazard threats, saying that families were having to say goodbye to loved ones via iPad and refrigerated trucks were full of bodies because funeral homes were at their maximum capacity. All that is a motivating fuel to change, people had to adapt to remote technology, bring health professionals closer to the population and for architecture it's no different, since the spaces must be capable to handle the required demand, as well as comfortable and biologically safe.

Having a massive number of legislations is no excuse to make the health care environment uncomfortable (Bittencourt, 2002). Bittencourt (2016) presents a relation between the human behaviour in the city – a work from Jan Gehl (2010), Cities for People –

and health spaces, where it happens in a smaller scale. As an example, where Gehl starts with protection from accidents, Bittencourt finishes with "uncomfortable sensorial experiences". Still, they both discuss "comfort", considering actions such as walking, sitting, seeing, hearing, etc.; the common element is how the user interacts with its surroundings, the city, or a health care environment, concentrating on having a positive sensorial experience.

In the context of comfort in health environments, it is imperative to highlight the importance of green spaces, how positively it influences human psychology and social wellbeing (Scherer and Fedrizzi, 2016), which means that vegetation benefits the environment in different circumstances, as it helps on creating better moods, promotes sociability and improves comfortability, essential in pandemic times. Walking or standing under trees' crowns is way more comfortable than in unshaded spaces, and the former situation is a key element to improve the use and quality of open spaces. This is due, especially, to the evapotranspiration effect and reduction of land surface temperature promoted by the trees (Coutts and Tapper, 2017).

Such improvement of open spaces' quality is essential to ensure its occupation, which is important in the pandemic context, once in these ventilated and open areas the COVID-19 transmission is lower. In addition, it's important to emphasize that implementing vegetation in the built environment means generating social, economic, and environmental benefits. In health environments it's the same, Boyd (2003) states "hope that my garden gives pleasure and peace to all those who use it" referring to a garden she designed for Frank Gehry's building at Dundee, a Maggie's Cancer Care Centre.

Health care environments' comfortability must be carefully considered. As expressed by Teixeira et al. (2013) "the bond with the health services users amplifies health action's effectiveness and favours user's participation during service provision […]" while Bittencourt (2002) complements the idea mentioning ten factors that need to be considered at the design conception, which are: accessibility, acoustics, biosecurity, climate, visual communication, colours, ergonomics, natural and artificial illumination, chemical substances, and vibrations.

**1.3 The post-occupancy assessment process**

An important method to evaluate the users' needs is the post-occupancy assessment (POA). This method is based on the concept that the design process is not linear, but circular. Until recently, it was assumed that the design process ended when the building was finished but this belief was dismissed when, through research and analysis, the design cycle became a fact. This means that the interaction user vs. building is very important, and a diagnosis can be generated based on several evaluations to improve the building's efficiency (Villa et al., 2018).

The post-occupancy assessment method requires four phases: (I) gather building information; (II) develop the diagnosis; (III) create recommendations for the study-space; (IV) share results for future designs (Ornstein and Romero, 1992). Each step has its own number of procedures that should be adjusted according to demand. Some of them must be mentioned (Villa et al, 2018) such as Walkthrough, in which technical observation alongside the user is carried out, problems are found, hypothesis are thought, and information is acquired; Specific Interview, focused on a "key-person", who talks about problems experienced by the users (related to the physical environment or to emotional matters); and Behavioural Map, a drawing in which the observer registers the users' routes and behaviour, which can determine the layout efficiency, people flow, and space use pattern. For all these procedures and for the POA in general, the team must be prepared and organized, so the process can be done in the best way possible, and it will all result in recommendations that can be separated in short-, medium- and long-term.

In this context, the integrated design process is essential to ensure that all design possibilities and its consequences can be assessed. Thus, computer simulations are very strategic tools, allowing the possibility of generating numerical data and predicting risks if the recommendations are not followed. According to Gonçalves (2015), computer simulations are not only tools for architecture performance assessment, but also for integration between architecture and engineering. In this paper, computer simulations were done in order to verify the decision-making efficiency during the design process.

To bring these concepts to the study object, this paper aims to develop an architectural requalification project for the Family Strategic Health, located at João Domingos Netto settlement. For this, a POA process was developed for the entire building – its indoor and outdoor areas – as well as computer simulations to ensure the users' needs were met.

## 2. Methods

This work was divided in five steps in order to achieve its objectives. First, a theoretical study was complete about the themes involved: design for health buildings, thermal comfort, and post-occupancy assessment. Second, a post-occupancy assessment was carried out for the FHS, which involved a Specific Interview, Technical Observations, Walkthrough, and a Behavioural Map.

The third step involved bioclimatic simulations and air changes per hour (ACH) calculations for the current situation. A diagnosis for the sunlight hours and radiation incidence parameters, both in winter and summer periods, were developed in support of the bioclimatic simulations. These simulations were carried out in the Ladybug Legacy®, a plug-in on Grasshopper®, which is a plug-in of Rhinoceros 3D®. To run these simulations, an Energy Plus Weather (EPW) file was used as an input for climate characterization for the study object (Figure 1). To do so, a model made in SketchUp®, based on an AutoCAD® file provided by the City Hall, was exported to Rhino3D®, where the simulations took place.

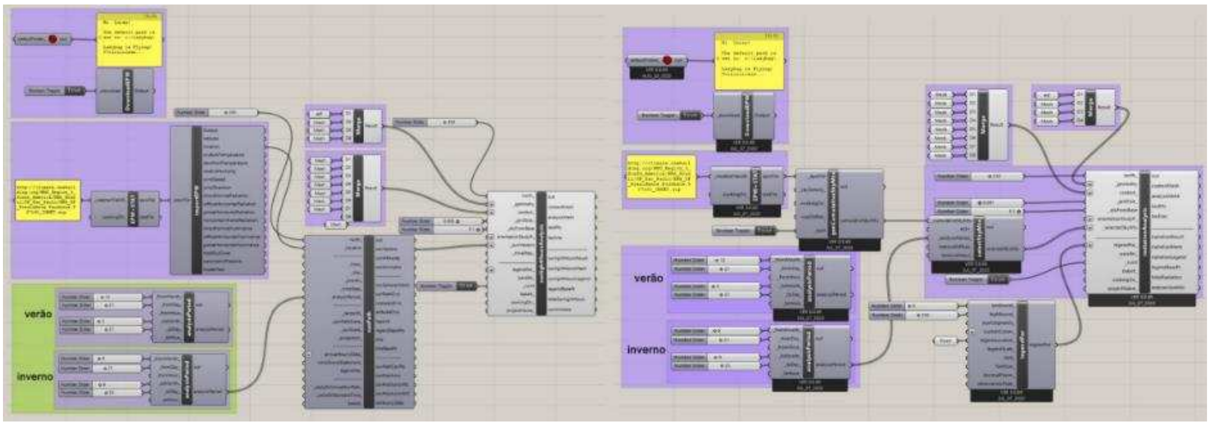


Figure 1. Sunlight hours and Radiation Analysis setup used.

Still on the third step, Climate Consultant® was used to find out the wind average speed with an EPW file. The air changes per hour calculus was developed based on ASHRAE (1985) standards using the Excel® software, and the calculation was done according to the parameters made available on Lamberts et al (1997) (Table 1). The calculus was realized for two situations: Case I, when the rooms presented only one opening; Case II, when the rooms presented more than one opening.

Table 1. ACH calculus parameters.

| ACH CALCULUS | | | |
|---|---|---|---|
| Case I | Vref = Vavg x K x $Z^a$ | Q = 0,025 x Aeq x Vref | ACH = (Q x 3600) / Va |
| Case II | Vref = Vavg x K x $Z^a$ | Q = 0,6 x (ΣAeq) x Vref x (√0,35) | ACH = (Q x 3600) / Va |

Source: Prepared by the author (2021), according to Lamberts et al (1997).

Where: Vref = wind reference velocity (m/s);
Vavg = wind average velocity;
K = parameter for the building location (urban environment = 0,35);
Z = window height (0,1 for doors) (meters);
a = parameter for building location (urban environment = 0,25);
Q = air flux for each opening (m/s);
Aeq = opening equivalent area ($m^2$);
ACH = air changes per hour;
Va = room volume ($m^3$).

In the fourth step, the requalification design was developed. To do so, the software AutoCAD®, SketchUp® and V-Ray® were used. In sequence, the fifth step, new computer simulations were carried out, now for the proposed situation. These simulations followed the same method: carried out in the Ladybug Legacy®, a plug-in on Grasshopper®, which is a plug-in of Rhinoceros 3D®. To run these simulations, the same Energy Plus Weather (EPW) file was used as an input for climate characterization.

## 3. Results and Discussion

The development of the requalification design required previous processes supported by POA methods and strategies, those being the Specific interview, Walkthrough, Technical Observations, Behavioural Map, and Simulations, to support the decision-making. Through these procedures, it was possible to develop the design guidelines and, consequently, the requalification design. All involved results and the final design are presented in the following topics.

### 4.1 The Post-occupancy assessment and the design guidelines

To begin the process, a Specific Interview was conducted with Flávio Colaço, former community health agent, on August $27^{th}$, 2020, at the Family Health Strategy. He explained how the neighbourhood plan was supposed to be and what was done instead once the original proposal fell through, meaning the creation of the two FHS to substitute the BHU that could not be built. An important point Colaço brought to light was the amount of people working there. The staff counts with six community health agents, two doctors, two assistants, and one nurse in each FHS, besides a dentist who works in both units.

At the interview, some problems were mentioned, such as lack of space in one of the reception rooms while the other is underused, insufficient storage room (Figure 2a), deficiency of natural ventilation, patients having to wait outside due to COVID-19 (Figures 2b and 2c), dry environment, and thermal discomfort.

Figure 2a.

Figure 2b.

Figure 2c

Figure 2a. Chairs kept in the corridors.
Figure 2b. Undersized reception room and undersized openings.
Figure 2c. Patients waiting outside.
Source: personal collection (2020).

A consequence of the standardization is the necessity of utilizing artificial climatization (Figure 3a), due to the inadequate natural ventilation, and blinds, because of the glare effect caused by solar incidence on that environment (Figure 3b). For the same reasons, windows remain closed at all times. It is important to highlight those dirty blinds and curtains are convenient elements for air transmitted diseases.

Figure 3a.


Figure 3b.

Figure 3a. Air conditioning machines above every window.
Figure 3b. Intense glare, blinds always closed.
Source: personal collection (2020).

On the same day, it was possible to carry out a Walkthrough process and Technical Observations. Results are available on the synthesis map (Figure 4a) and table (Figure 4b) below. It is clear that the study object displays a lot of problems, especially related to the deficiency of space available for users, for stocking and reception, undersized dimensions in some environments, a failure in meeting the regulations and standards, such as ASHRAE, and thermal discomfort due to exposure to solar radiation.


Figure 4a. Walkthrough synthesis map.
Source: Graphic base provided by the City Hall and walkthrough results prepared by the author (2020).

| COLOURS | ENVIRONMENTS | OBSERVATIONS |
|---|---|---|
| (blue) | STORAGE 1 AND 2 | LACK OF SPACE, CHAIRS PILED UP IN THE CORRIDOR |
| (magenta) | NURSE'S ROOM 1<br>PRE CONSULT 1<br>DOCTOR'S ROOM 1<br>KITCHEN<br>HEALTH COMMUNITY AGENTS ROOM<br>DOCTOR'S ROOM 2<br>NURSE'S ROOM 2<br>PRE CONSULT 2 | ENVIRONMENTS THAT DOESN'T MEET THE ASHRAE (1985) NATURAL VENTILATION REGULATION ABOUT AIR CHANGES PER HOUR |
| (blue)<br>(magenta) | RECEPTION ROOM I | DOESN'T MEET THE REGULATION (ASHRAE, 1985) AND UNDERUSED SPACE |
| (magenta)<br>(green) | VACCINE<br>DENTIST'S ROOM<br>PROCEDURE'S ROOM | DOESN'T MEET THE REGULATION (ASHRAE, 1985) AND AT THE VISIT IN THE MORNING PERIOD, WAS NOTED INTENSE INSOLATION |
| | PHARMACY<br>RESTROOMS | NON ANALYZED ENVIRONMENTS OR NO OBSERVATIONS |
| (blue)<br>(green) | OUTSIDE AREA<br>RECEPTION ROOM II | UNDERDIMENSIONED RECEPTION ROOM, DOES NOT SUPPORT THE PATIENT DEMAND, AND OUTSIDE AREA BEING USED AS RECEPTION ROOM, NO SUN PROTECTION AND NOT WELCOMING BUILDING |

Figure 4b. Synthesis map legend.
Source: prepared by the author (2020).

A Behavioural Map (Figure 5) was also developed. Using a printed blueprint of the building, the study took place at the most used reception room, although in this case, it was assembled on the outside due to the pandemic. Each coloured line shows the path taken by a user that day.

Reviewing the studies, it is noticeable that besides the thermal discomfort, the lack of waiting areas was evident, resulting in a few patients in the available seats and multiple others having to stand, as did the nurse who was measuring the temperatures and handing out sanitizer to those approaching the front desk. Regarding the need of staying outside, it is important to emphasize that the outdoor space does not have structure and physical conditions to shelter these users.


Figure 5. Behavioural map.
Source: Graphic base provided by the City Hall and behavioural map prepared by the author (2020).

After those processes carried out in-loco, the bioclimatic simulation assessment was done for the current situation. This simulation aimed to investigate sunlight hours and radiation incidence on the building's facades. The simulations show the facades during both periods, summer (Figures 6b and 6d) and winter (Figures 6a and 6c). The colour legend indicates how much radiation the building receives, varying between 0 to 220 kWh/m² as represented on Figures 7, (Figures 7b and 7d on summer, 7a and 7c on winter). Due to the lack of vegetation or any shading element in the outdoor area, the whole building receives a massive quantity of sunlight hours. This is directly related to the radiation analysis, which shows higher values for the facades, but especially for southwest and northwest.

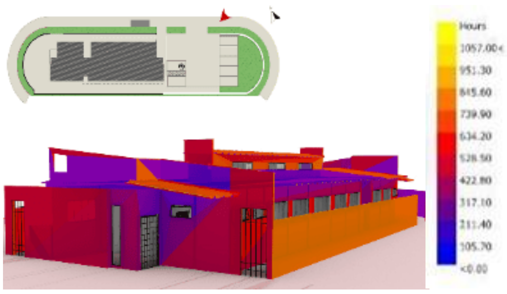


Figure 6a.

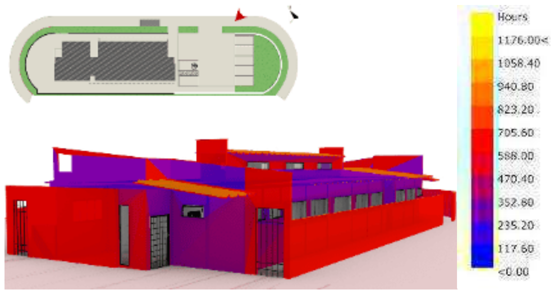



Figure 6b.

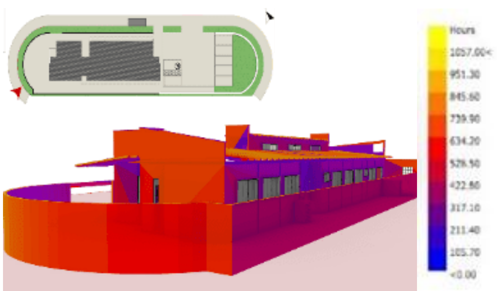


Figure 6c.

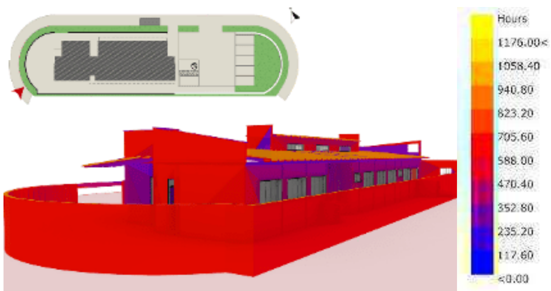



Figure 6d.

Figure 6a. Southeast/northeast facade with colour legend - winter.
Figure 6b. Southeast/northeast facade with colour legend - summer.
Figure 6c. Southwest/northwest facade with colour legend - winter
Figure 6d. Southwest/northwest facade with colour legend - summer.
Source: Simulations prepared by the author (2021) through EPW files.

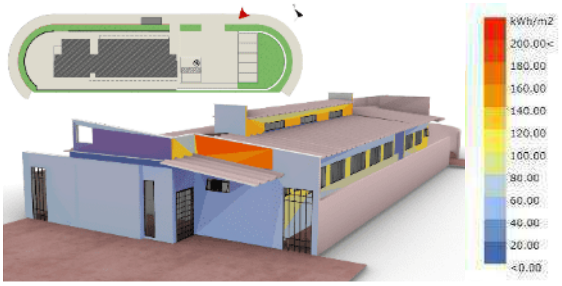



Figure 7a.

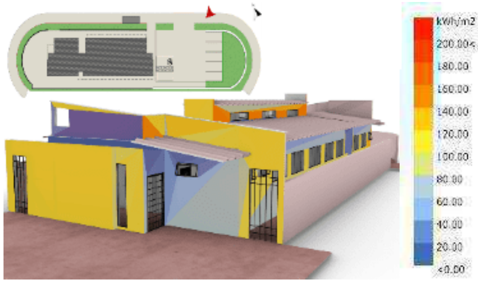



Figure 7b.

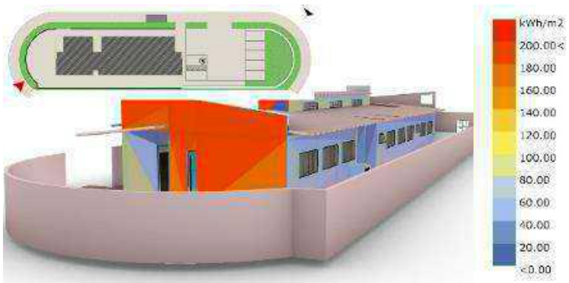



Figure 7c.

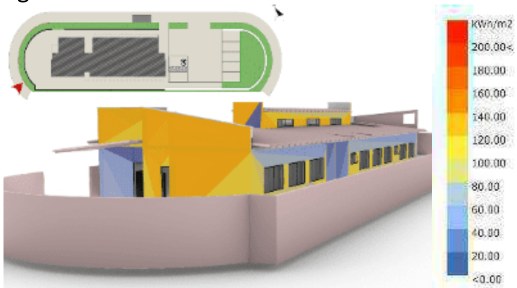



Figure 7d.

Figure 7a. Southeast/northeast facade with colour legend - winter.
Figure 7b. Southeast/northeast facade with colour legend - summer.
Figure 7c. Southwest/northwest facade with colour legend - winter.
Figure 7d. Southwest/northwest facade with colour legend - summer.
Source: Simulations prepared by the author (2021) through EPW files.

However, it's important to observe that the southeast/northeast facades, where people wait for their appointment outdoors, are also completely exposed to solar radiation. This leads to complete thermal discomfort in those areas and is an important guideline for the requalification design process.

After sunlight hours and radiation analysis, the last factor studied was the interaction of the ventilation within the building. For such, the air changes per hour (ACH) were calculated and compared to the ASHRAE (1985) standards; therefore, it was essential to prepare an opening frame table, as shown in Figure 8b – according to the openings displayed on Figure 8a.

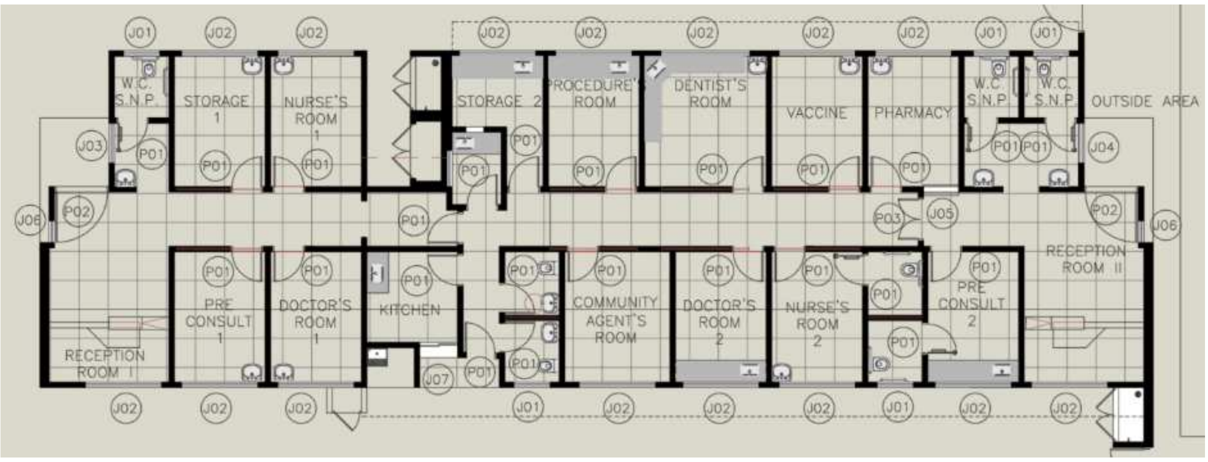



Figure 8a. Blueprint with numbered opening frames.
Source: Graphic base provided by the City Hall, edited by the author (2021).

| current framing table | | | | | | | |
|---|---|---|---|---|---|---|---|
| frame type | name | width [m] | height [m] | sill [m] | Z [m] | % of opening | A [m²] |
| window | j01 | 1 | 0,6 | 1,5 | 1,5 | 100 | 0,6 |
| window | j02 | 2,1 | 1 | 1,5 | 1,5 | 50 | 1,05 |
| window | j03 | 1,1 | 2,4 | 0,1 | 0,1 | 40 | 1,056 |
| window | j04 | 1,1 | 0,6 | 1,5 | 1,5 | 100 | 0,66 |
| window | j05 | 0.95 | 1 | 1,1 | 1,1 | 100 | 0,95 |
| window | j06 | 0,6 | 2,4 | 0,1 | 0,1 | 40 | 0,576 |
| window | j07 | 1,05 | 1 | 1,1 | 1,1 | 50 | 0,525 |
| door | p01 | 0,9 | 2,1 | 0 | 0,1 | 100 | 1,89 |
| door | p02 | 1,5 | 2,1 | 0 | 0,1 | 100 | 3,15 |
| door | p03 | 1,2 | 2,1 | 0 | 0,1 | 100 | 2,52 |

Figure 8b. Opening frames table.
Source: prepared by the author (2021).

Having collected these numbers, the air changes per hour calculus (Figure 9) was put together and checked according to the regulation, to find out whether the environment was adequate and meeting the standards.

ACH CALCULUS - CURRENT SITUATION

| *case I → one opening | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| environment | Vref = Vm • K • Z^a | | | | | Q = 0,025 • A • Vref | | ACH = (Q • 3600)/Va | | conclusion |
| | Vaverage | K | Z | a | Vref | A | Q | Va | ACH | |
| storage I | 2,25 | 0,35 | 1,50 | 0,25 | 0,87 | 1,05 | 0,02 | 28,35 | 2,91 | meet |
| pre consult I | 2,00 | 0,35 | 1,50 | 0,25 | 0,77 | 1,05 | 0,02 | 28,35 | 2,58 | doesn't meet |
| nurse's room I | 2,25 | 0,35 | 1,50 | 0,25 | 0,87 | 1,05 | 0,02 | 28,35 | 2,91 | doesn't meet |
| doctor's room I | 2,00 | 0,35 | 1,50 | 0,25 | 0,77 | 1,05 | 0,02 | 28,35 | 2,58 | doesn't meet |
| kitchen | 2,25 | 0,35 | 1,10 | 0,25 | 0,81 | 0,52 | 0,01 | 19,68 | 1,92 | doesn't meet |
| storage II | 2,25 | 0,35 | 1,50 | 0,25 | 0,87 | 1,05 | 0,02 | 20,47 | 4,02 | meet |
| procedure's room | 2,25 | 0,35 | 1,50 | 0,25 | 0,87 | 1,05 | 0,02 | 28,35 | 2,91 | doesn't meet |
| community agent's room | 2,00 | 0,35 | 1,50 | 0,25 | 0,77 | 1,05 | 0,02 | 32,91 | 2,22 | doesn't meet |
| dentist's room | 2,25 | 0,35 | 1,50 | 0,25 | 0,87 | 1,05 | 0,02 | 37,95 | 2,17 | doesn't meet |
| doctor's room II | 2,00 | 0,35 | 1,50 | 0,25 | 0,77 | 1,05 | 0,02 | 28,35 | 2,58 | doesn't meet |
| vaccine | 2,00 | 0,35 | 1,50 | 0,25 | 0,77 | 1,05 | 0,02 | 28,35 | 2,58 | doesn't meet |
| nurse's room II | 2,25 | 0,35 | 1,50 | 0,25 | 0,87 | 1,05 | 0,02 | 28,35 | 2,91 | doesn't meet |
| pre consult II | 2,25 | 0,35 | 1,50 | 0,25 | 0,87 | 1,05 | 0,02 | 28,35 | 2,91 | doesn't meet |

| *case II → more than one opening | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| environment | Vref = Vm • K • Z^a | | | | | Q = 0,6• A • Vref • √0,35 | | ACH = (Q • 3600)/Va | | conclusion |
| | Vaverage | K | Z | a | Vref | A | Q | Va | ACH | |
| reception room I | 2,25 | 0,35 | 1,50 | 0,25 | 0,87 | 1,01 | 0,31 | 66,90 | 16,81 | doesn't meet |
| reception room II | 2,25 | 0,35 | 1,50 | 0,25 | 0,87 | 1,01 | 0,31 | 53,86 | 20,88 | meet |
| pharmacy | 2,25 | 0,35 | 1,10 | 0,25 | 0,81 | 0,70 | 0,20 | 28,35 | 25,59 | meet |

Figure 9. Air changes per hour calculus.
Source: Prepared by the author (2021).

The environments on Case I are spaces where there's only one window and the door access are through internal circulation, and its calculus and equations are explicit in Table 2. While the environments on Case II have more than one opening: the pharmacy has two windows, and the receptions have one window and a door that goes to the outside area, calculus and equations are demonstrated in Table 3. Each calculus parameter was presented in the Methods topic.

Table 2. Air changes per hour case I calculus.

| | | | |
|---|---|---|---|
| Case I | $Vref = Vavg \times K \times Z^a$ | $Q = 0{,}025 \times Aeq \times Vref$ | $ACH = (Q \times 3600) / Va$ |

Source: Prepared by the author (2021), according to Lamberts et al (1997).

Table 3. Air changes per hour case II calculus.

| | | | |
|---|---|---|---|
| Case II | $Vref = Vavg \times K \times Z^a$ | $Q = 0{,}6 \times (\Sigma Aeq) \times Vref \times (\sqrt{0{,}35})$ | $ACH = (Q \times 3600) / Va$ |

Source: Prepared by the author (2021), according to Lamberts et al (1997).

Following the assessment, 12 out of 16 environments do not meet the ASHRAE (1985) standards for air changes per hour, where the rooms must achieve, at the least:

- Kitchen = 10 - 30 ACH;

- Storage = 2 - 15 ACH;
- Procedure room = 6 - 12 ACH;
- Reception room = 18 - 25 ACH;
- Consults rooms = 8 - 15 ACH.

It is valuable to underline that Consults rooms include pre-consults, nurses' rooms, community health agents' room and dentist's room, Procedure room include procedure room and vaccine, and Storage includes both storages and pharmacy. With the ventilation calculus and the pandemic necessities, the air quality improvement became another guideline. Gathering the POA methods results, the simulations and the calculus, it was possible to prepare a diagnosis and recommendations chart (Table 4).

Table 4. Diagnosis and recommendations chart.

| ENVIRONMENTS | OBSERVATIONS | PRIORITY | RECOMENDATIONS |
|---|---|---|---|
| STORAGE 1 AND 2 | Lack of space. | Medium. | Join storage 1 with the reception room's restroom. |
| NURSE'S/DOCTOR'S ROOM, PRE-CONSULTS, CHA'S ROOM AND KITCHEN | Doesn't meet ASHRAE (1985) standards. | Medium. | Adequate to the standards by creating openings to induce crossed ventilation. |
| RECEPTION ROOM 1 | Doesn't meet the ASHRAE (1985) regulation and underused space. | Low. | Demolish. |
| VACCINE, DENTIST'S AND PROCEDURE'S ROOM | Doesn't meet the ASHRAE (1985) regulation and too much insolation in the mornings. | High. | Create openings for crossed ventilation and elaborate a strategy for thermal relief. |
| RECEPTION ROOM 2 | Space doesn't support the patient's demand. | High. | Extend the area using part of the parking lot. |
| OUTSIDE AREA | Used as reception room, too much sun exposure, no quality space. | High. | Elaborate quality outside area, demolish outer walls so people feel more welcomed by the FHS. |

Source: Prepared by the author (2021).

Acknowledging all these problems and difficulties reported by the users and bioclimatic simulations, the design's guidelines are:

- Reconcile the design to the local climatic conditions;
- Make the building safer regarding the transmissibility of respiratory diseases, through bioclimatic strategies;
- Adjust the spaces where people flow is more intense;
- Enrich the outdoor area, inserting landscape elements and bioclimatic strategies to ensure the space quality;
- Requalify the open spaces, creating welcoming areas;
- Readjust the environments according to their air changes per hour stablished by the ASHRAE (1985) standards.

With the goal to unify both Family Health Strategies in one unit, the rooms were reorganized to improve people flow, as can be seen on Figure 10. The blue hatch represents a simple exchange between them, the red hatch means structure changes and the “x” stands for the space’s subtraction.


Figure 10. Blueprint with changes plan.
Source: Prepared by the author (2021).

### 4.2 The requalification and the integrated design process

The results of the changes in the rooms locations can be seen in Figure 11. With no reception room 2, a bigger reception room 1, and a quality area on the outside, the patients can choose where to wait. In the days where temperatures are higher than usual, the outside waiting space will keep the thermal sensation lower due to the shading area provided by a checkered trellis and a reflecting pool – acting as an evaporative cooling system. This pool was purposely positioned in function of the main wind direction, which is oriented from east to west, and thus providing the evaporative cooling effect for the reception.

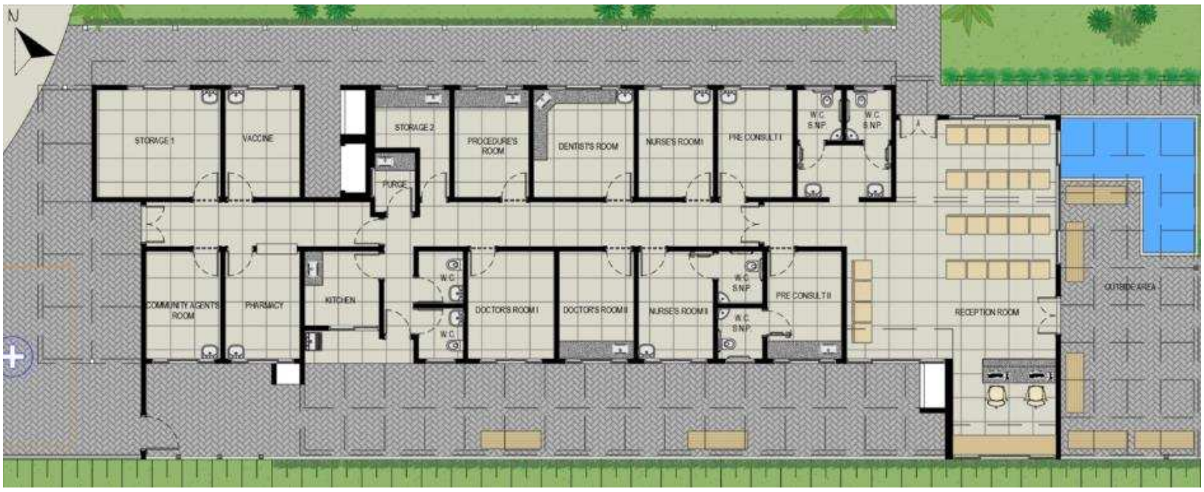



Figure 11. Proposed blueprint.
Source: Prepared by the author (2021).

When planning the reorganization of the spaces, it was noted the best locations to install solar protections, which are outside of the new reception room (Figure 12), where patients can wait; on the service/emergency access; and on the southwest side of the building since the proposal suggests replacing the outer wall with a fence, so it still limits people access, and yet it is covered in vegetation allowing visual permeability.

The vegetation coverage was implemented across the entire area, in order to expand these shading spaces, reducing the land surface temperature and, hence, improving environmental quality to this area.

Figure 12. Solar protections and reflection pool.
Source: Prepared by the author (2021).

Another change was the parking lot. With the expansion of the reception room, it got smaller, although with enough space for three parking spots, one of them intended for people with special needs. On the other side of the building, there is another parking spot created for ambulances and its access is through a carriage porch, as it can be observed on Figures 13 and 14.

Figure 13. Proposal site plan.
Source: Prepared by the author (2021).

Figure 14a.

Figure 14b.

Figure 14a. Northeast facade.
Figure 14b. East/Northeast facade.
Source: Prepared by the author (2021).

It is also critical to draw attention to the southwest facade, where the sun is more intense, as represented by Figure 15 (15a for morning and 15b for afternoon). The vegetation on the fence helps protecting the building from solar radiation. Concerning the openings on that orientation in the reception room, light shelves were inserted to reduce the excess radiation and avoid sun glare, as it's exposed on Figure 16 (16a for morning and 16b for afternoon).

Figure 15a. Figure 15b.

Figure 15a. Southwest facade in the morning.
Figure 15b. Southwest facade in the afternoon.
Source: Prepared by the author (2021).

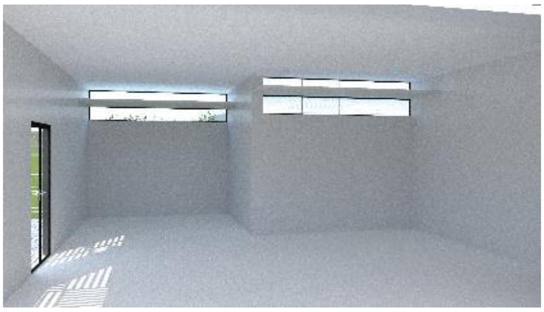
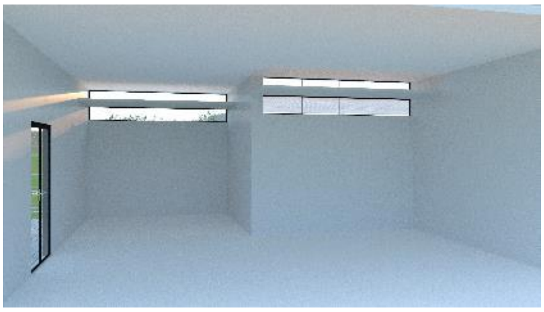
 

Figure 16a. Figure 16b.

Figure 16a. Reception room in the morning.
Figure 16b. Reception room in the afternoon.
Source: Prepared by the author (2021).

Lastly, sheds were opened internally, above the doors, so cross-ventilation could be stimulated in all the rooms, as Figure 17 reveals. Only the kitchen kept its air circulation apart from the other spaces for health reasons, however just as the other environments, its ACH is now meeting the regulations.

Figure 17. Windows on the internal circulation.
Source: Prepared by the author (2021).

The methods used to put the spaces in accordance with the regulations were represented in the blueprint in Figure 18. A new framing table was made, so the calculus for air changes per hour could be redone, as shown in Figures 19 and 20. It is essential for a health environment to keep the ACH according to the ASHRAE (1985) regulations, ensuring safety regarding the transmissibility of respiratory diseases, necessity made more evident through the COVID-19 pandemic.


Figure 18. Proposed blueprint with numbered opening frames.
Source: Prepared by the author (2021).

| proposed framing table | | | | | | | |
|---|---|---|---|---|---|---|---|
| frame type | name | width [m] | height [m] | sill [m] | Z [m] | % of opening | A [m²] |
| window | j01 | 2,1 | 1 | 1,5 | 1,5 | 50 | 1,05 |
| window | j02 | 2,45 | 1 | 1,5 | 1,5 | 50 | 1,225 |
| window | j03 | 1 | 0,5 | 1,6 | 1,6 | 100 | 0,5 |
| window | j04 | 3,2 | 1,5 | 0,6 | 0,6 | 50 | 2,4 |
| window | j05 | 4,5 | 1,5 | 0,6 | 0,6 | 50 | 3,375 |
| window | j06 | 2,35 | 0,6 | 2,25 | 2,25 | 50 | 0,705 |
| window | j07 | 1,35 | 1 | 1,1 | 1,1 | 100 | 1,35 |
| window | j08 | 0,75 | 0,6 | 2,25 | 2,25 | 100 | 0,45 |
| window | j09 | 2,75 | 0,6 | 2,25 | 2,25 | 50 | 0,825 |
| window | j10 | 3,3 | 0,75 | 2,4 | 2,4 | 100 | 2,475 |
| window | j11 | 3,45 | 0,75 | 2,1 | 2,4 | 100 | 2,5875 |
| door | p01 | 0,9 | 2,1 | 0 | 0,1 | 100 | 1,89 |
| door | p02 | 1,3 | 2,1 | 0 | 0,1 | 100 | 2,73 |
| door | p03 | 1,7 | 2,8 | 0 | 0,1 | 100 | 4,76 |
| door | p04 | 1,2 | 2,1 | 0 | 0,1 | 100 | 2,52 |

Figure 19. Framing table for proposed design.
Source: Prepared by the author (2021).

| ACH CALCULATION - PROPOSED SITUATION | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| *case I → one opening | | | | | | | | | | |
| environment | Vref = Vm • K • Z^a | | | | | Q = 0,025 • A • Vref | | ACH = (Q • 3600)/Va | | conclusion |
| | Vaverage | K | Z | a | Vref | A | Q | Va | ACH | |
| kitchen | 2,00 | 0,35 | 1,50 | 0,25 | 0,77 | 4,76 | 0,09 | 19,68 | 16,86 | meet |
| storage II | 2,25 | 0,35 | 1,50 | 0,25 | 0,87 | 1,05 | 0,02 | 20,47 | 4,02 | meet |

| *case II → more than one opening | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| environment | Vref = Vm • K • Z^a | | | | | Q = 0,6• A • Vref • v0,35 | | ACH = (Q • 3600)/Va | | conclusion |
| | Vaverage | K | Z | a | Vref | A | Q | Va | ACH | |
| reception room | 2,25 | 0,35 | 2,40 | 0,25 | 0,98 | 4,47 | 1,56 | 189,12 | 29,60 | meet |
| pre consult II | 2,25 | 0,35 | 1,5 | 0,25 | 0,87 | 0,58 | 0,18 | 28,35 | 22,78 | meet |
| pre consult I | 2,25 | 0,35 | 2,25 | 0,25 | 0,96 | 0,82 | 0,28 | 28,35 | 35,65 | meet |
| nurse's room I | 2,25 | 0,35 | 2,25 | 0,25 | 0,96 | 0,58 | 0,20 | 28,35 | 25,21 | meet |
| nurse's room II | 2,00 | 0,35 | 1,50 | 0,25 | 0,77 | 0,58 | 0,16 | 28,35 | 20,25 | meet |
| doctor's room II | 2,25 | 0,35 | 1,5 | 0,25 | 0,87 | 0,58 | 0,18 | 28,38 | 22,76 | meet |
| dentist's room | 2,25 | 0,35 | 2,25 | 0,25 | 0,96 | 0,61 | 0,21 | 37,98 | 19,83 | meet |
| doctor's room I | 2,25 | 0,35 | 1,5 | 0,25 | 0,87 | 0,64 | 0,20 | 32,88 | 21,68 | meet |
| procedure's room | 2,25 | 0,35 | 2,25 | 0,25 | 0,96 | 0,58 | 0,20 | 28,35 | 25,21 | meet |
| pharmacy | 2,25 | 0,35 | 1,5 | 0,25 | 0,87 | 0,413 | 0,13 | 28,35 | 16,22 | meet |
| vaccine | 2,25 | 0,35 | 2,25 | 0,25 | 0,96 | 0,58 | 0,20 | 28,35 | 25,21 | meet |
| storage I | 2,25 | 0,35 | 2,25 | 0,25 | 0,96 | 0,58 | 0,20 | 47,06 | 15,19 | meet |
| community agent's room | 2,25 | 0,35 | 1,50 | 0,25 | 0,87 | 0,58 | 0,18 | 28,35 | 22,78 | meet |

Table 20. ACH table for proposed design.
Source: Prepared by the author (2021).

Having completed the design proposal and ventilation calculus, according to the already presented equations, it was time to redo the computer simulations to verify in the bioclimatic field whether the changes were successful for all environments. The first one was the sunlight hours, and the procedure was the same, modelling made in SketchUp®, imported to

Rhino3D®, and simulated on Grasshopper® and Ladybug Legacy®. For comparison purpose, the Figures 20 and 21 show the FHS's current situation and proposed design.

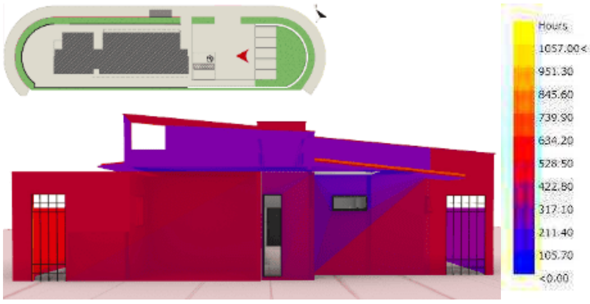



Figure 20a.


Figure 20b.

Figure 20a. Southeast facade - winter – current situation.
Figure 20b. Southeast facade - winter – proposed design.
Source: Prepared by the author (2021) through EPW files.

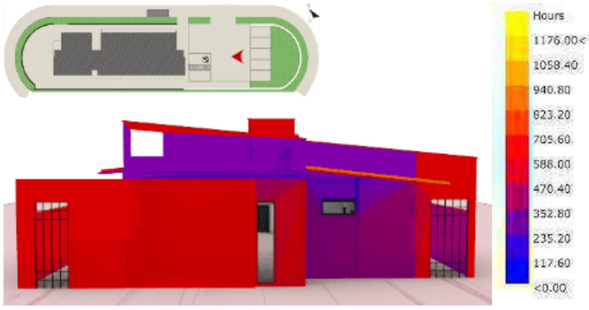



Figure 21a.


Figure 21b.

Figure 21a. Southeast facade - summer – current situation.
Figure 21b. Southeast facade - summer – proposed design.
Source: Prepared by the author (2021) through EPW files.

In the first figure it is already possible to notice a colour change, the sunlight hours on winter have a reduction of 50% on the southeast facade. That is the space where the patients have been waiting for their appointments nowadays, thus the importance of such reduction. The Figures 22 and 23 make evident that even when the outer wall is removed, it's still possible to have solar protection through landscape elements which, in fact, not only allow the ventilation influx through the building, but also makes the environment more welcoming due to the biophilic design and its psychological impact. This facade (Figures 24 and 25) on the southwest is the one with most solar protections, the checkered trellis and vegetation. It's noticeable how the colours changed to represent fewer sunlight hours affecting the building.

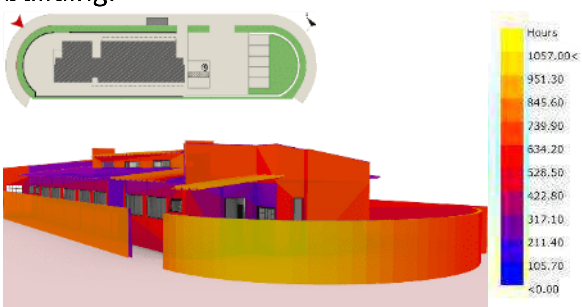



Figure 22a.

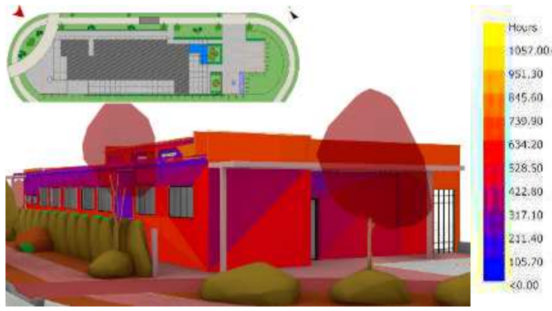



Figure 22b.

Figure 22a. East/Northwest facade - winter – current situation.
Figure 22b. East/Northwest facade - winter – proposed design.

Source: Prepared by the author (2021) through EPW files.

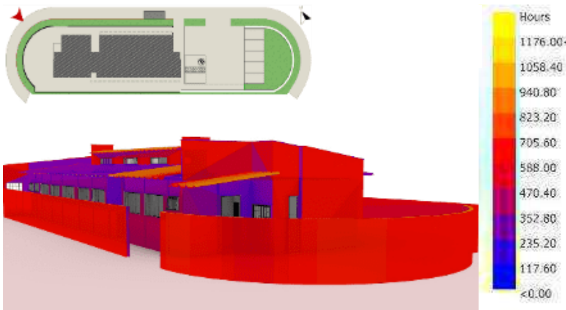
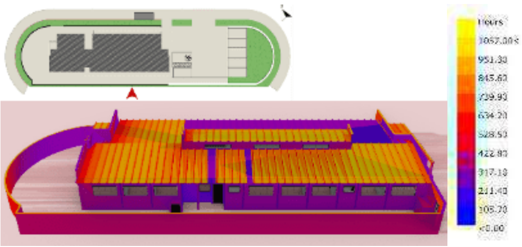




Figure 23a. Figure 23b.

Figure 23a. East/Northwest facade - summer – current situation.
Figure 23b. East/Northwest facade - summer – proposed design.
Source: Prepared by the author (2021) through EPW files.



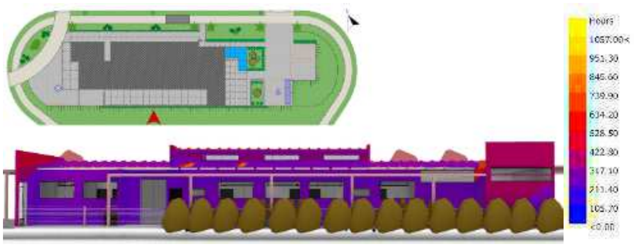
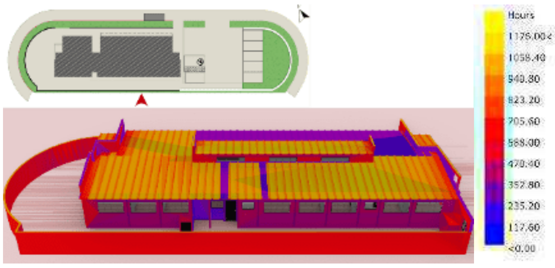




Figure 24a. Figure 24b.

Figure 24a. Southwest facade - winter – current situation.
Figure 24b. Southwest facade - winter – proposed design.
Source: Prepared by the author (2021) through EPW files.



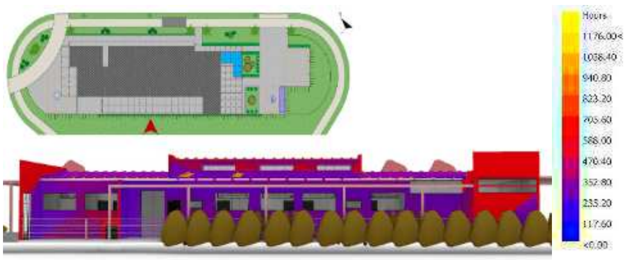




Figure 25a. Figure 25b.

Figure 25a. Southwest facade - summer – current situation.
Figure 25b. Southwest facade - summer – proposed design.
Source: Prepared by the author (2021) through EPW files.

The second simulation – radiation analysis – verifies the results pointed by the Figures 26 to 31 showing significant colour changes indicating the effectiveness of the sun protections. It is more evident in Figures 26 and 27 how the radiation affects the building in different periods of the year on the current situation, however, on the proposed design, the radiation levels remain low all year round because of the checkered trellis and the vegetation. Another crucial betterment of this space being used by patients waiting for appointments during the pandemic.

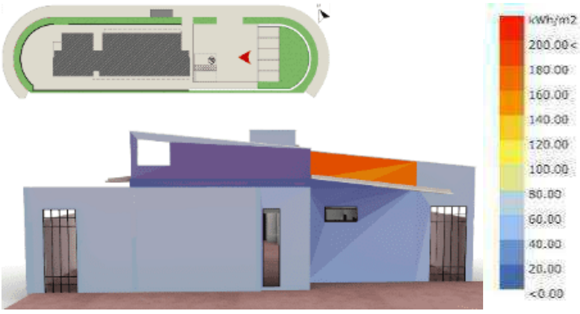



Figure 26a.


Figure 26b.

Figure 26a. Southeast facade - winter – current situation.
Figure 26b. Southeast facade - winter – proposed design.
Source: Prepared by the author (2021) through EPW files.

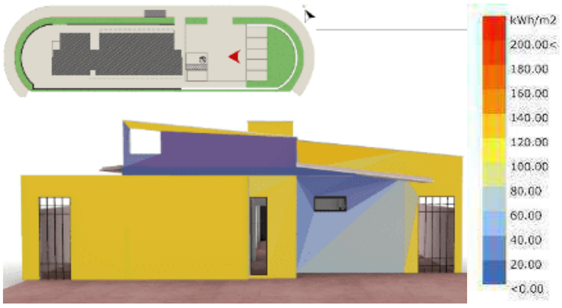



Figure 27a.


Figure 27b.

Figure 27a. Southeast facade - summer – current situation.
Figure 27b. Southeast facade - summer – proposed design.
Source: Prepared by the author (2021) through EPW files.

Even though this area has its access restricted to workers only (Figures 28 and 29) it still needs to be protected against the radiation, so the building does not absorb that much direct radiation, keeping it comfortable on the inside. The outer wall protection in the current situation does not help the radiation which is still high (Figures 30a and 31a), especially in summer, and despite the new design proposing to take it down, with the trellis and vegetation the radiation is blocked enough to keep the inside on comfortable temperatures (Figures 30b and 31b).

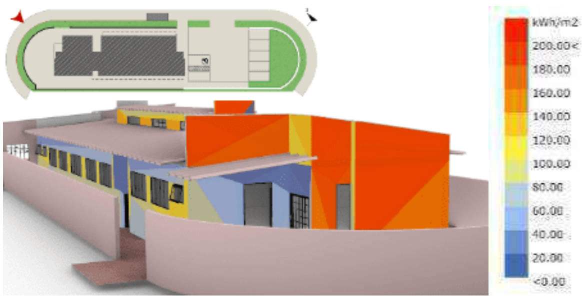



Figure 28a.

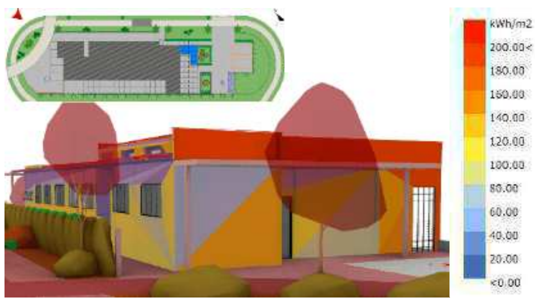



Figure 28b.

Figure 28a. East/Northwest facade - winter – current situation.
Figure 28b. East/Northwest facade - winter – proposed design.
Source: Prepared by the author (2021) through EPW files.

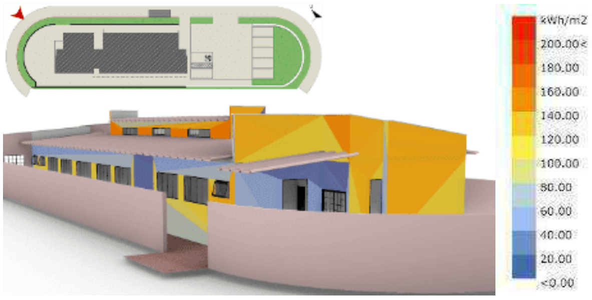



Figure 29a.


Figure 29b.

Figure 29a. East/Northwest facade - summer – current situation.
Figure 29b. East/Northwest facade - summer – proposed design.
Source: Prepared by the author (2021) through EPW files.

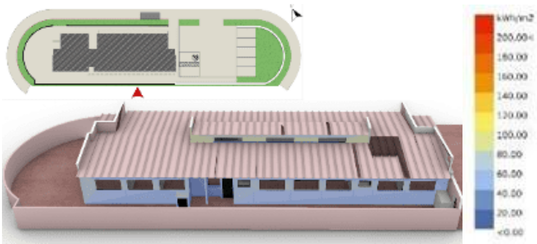


Figure 30a.

Figure 30b.

Figure 30a. Southwest facade - winter – current situation.
Figure 30b. Southwest facade - winter – proposed design.
Source: Prepared by the author (2021) through EPW files.

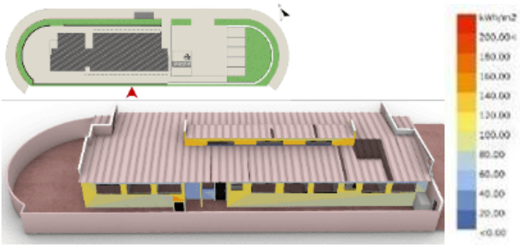


Figure 31a.

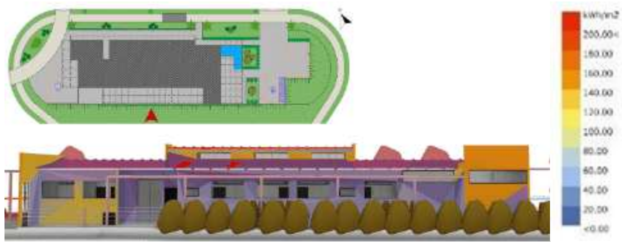


Figure 31b.

Figure 31a. Southwest facade - summer – current situation.
Figure 31b. Southwest facade - summer – proposed design.
Source: Prepared by the author (2021) through EPW files.

## 4. Conclusions

Recognizing the standardization of health institutional spaces and its lack of consideration of local climatic characteristics the Family Health Strategy in its current situation cannot be defined as comfortable and for that, the proposed design's goal is to improve it for the users and in all comfort extents.

Examining the Post-Occupancy Assessment results, it was possible to elaborate the guidelines based on the users' needs. Consequently, the design brought adequate spaces that meet the regulations, standards, and comfort principles, resulting in a safe space – against air transmissible diseases, including COVID-19 – and convenience to all the patients waiting for their appointments, being inside or outside the building. With design changes that do not demand great costs, the benefit is significant for all the users, counting with improvements on the energetic efficiency field.

This intervention is necessary so it can bring benefits to the neighbourhood (such as increase of environment quality), besides participating on the adaptive transitory moment of medicine in the pandemic, bringing patients and FHS workers closer, causing a positive impact on life quality and population health, and contributing to the creation of future architecture and engineering studies related to health environments.

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# Field measurement of human thermal comfort in winter across China

**Xiaowen Su[1,2,3], Bjarne W. Olesen [2], Zhaojun Wang[1, 3], Ongun Berk Kazanci[2]**

[1] School of Architecture, Harbin Institute of Technology, Harbin, China, 18b934034@stu.hit.edu.cn;

[2] International Centre for Indoor Environment and Energy – ICIEE, Department of Civil Environmental and Resource Engineering, Technical University of Denmark, Lyngby, Denmark;

[3] Key Laboratory of Cold Region Urban and Rural Human Settlement Environment Science and Technology, Ministry of Industry and Information Technology, Harbin, China.

**Abstract:** Energy use in building for heating depends on the thermal comfort requirements of the occupants. Personal thermal comfort and clothing behaviours in buildings during winter were studied. The Chinese Thermal Comfort Database contains 41977 sets of data which are from five climatic zones: Severe cold, Cold, Hot Summer and Cold Winter, Hot Summer and Warm Winter and Temperate zones. The database includes indoor and outdoor thermal environmental parameters and thermal responses of the occupants. 14646 sets of data from winter conditions in buildings were screened for analysis. Clothing insulation in Hot Summers and Cold Winter region was classified into seven levels for further studies. Logistic regression was adopted to estimate the change of thermal sensation in the response to indoor operative temperatures. The results indicated that the neutral temperature ranges for occupants in 1.0-clo garments were [17.0 - 24.1 °C] in Severe cold zone, [15.4 - 24.0 °C] in Cold zone and [15.0 - 23.1 °C] in Hot Summer and Cold Winter zone. Adding clothing insulation improves occupants' thermal comfort in winter, but the limitation is maximum clothing insulation of 1.9 clo. The study provides a reference for the creation of comfortable thermal environments with a low energy use.

**Keywords:** Thermal comfort, clothing level, climatic zones, field study, neutral temperature range.

## 1. Introduction

With the development of modern technology, mechanical means are used to provide a desired comfortable temperature for occupants, which led to increased energy use in the building stock (IPCC, 2007). Reducing the energy use in buildings is an urgent goal worldwide. China, as a developing country, is also playing a significant role in the global promotion of a sustainable development. It is reported that the northern urban heating (NUH) in China the energy use for heating in 2016 (BERC, 2018) accounted for 21% of the total energy use in commercial buildings. Owing to the significant improvement in the efficiencies of heating systems and equipment, the energy use in NUH part for an entire heating system primarily depends on the thermal comfort requirements of the occupants. Therefore, an insight into personal thermal comfort during winter is important for predicting the needed heating and increasing building energy performance.

Thermal comfort is defined as a status of mind which expresses satisfaction with the thermal environment (ISO 7730, 2005). It is complicated to predict the range of temperatures for thermal comfort conditions, as the required conditions are affected by multiply factors (Taleghani et al., 2013), e.g., cultural influences, environmental and personal factors. Due to the variability of climatic characteristics, indoor environments and the thermal comfort of occupants have been studied in different climate regions (Yan et al., 2017; Toe and Kubota, 2013). The individuals' thermal adaptability varied according to the climate region they lived in (de Dear, 2020). The requirements of comfortable thermal environments were found to be separate in different regions, which mainly related to the environment they usually were exposed to (Humphreys et al., 2013). China is a vast geographical country with a large south-north span, where regional distinction exists in outdoor climates and indoor environments. The comfort temperature was nearly equal to the indoor mean air temperature in the severe cold zone of Harbin, where indoor heating systems were adopted (Wang, 2006). An obvious difference between the comfort temperature and the indoor temperature was found in other climate zones of China (Yan et al., 2017). Therefore, the thermal comfort of occupants in different climate zones was studied.

Clothing insulation ($I_{clo}$) is an important factor when predicting or evaluating the indoor thermal environment and the adjustment of clothing insulation is a powerful behavioural response to changeable climatic conditions (de Dear and Brager, 1998). Allowing a greater clothing adaption and a wider range of indoor climatic conditions could save a significant amount of energy without sacrificing thermal comfort (Schiavon and Melikov, 2008). The choice of clothing is easily affected by external and indoor climatic conditions. Clothing resistance was more likely to rely on the outdoor air temperature early in the morning while indoor air temperature seems to influence the change of clothes during the day (Carli et al., 2007). In existing standards, clothing is specified at a constant value for cooling mode (0.5 clo) and heating mode (1.0 clo). People might change their clothes according to indoor environments. In this study, the preference of indoor temperatures for occupants at different clothing levels was studied.

The measurement of thermal sensation is usually done by the ASHRAE seven-point scale, which builds a correlation between a linguistic expression and a numeric voting, such as the explanation of "Neutral" when TSV (Thermal sensation vote) equals "0". However, the actual thermal sensation felt by human subjects might not always be the point on the ASHRAE scale (Humphreys and Hancock, 2007), especially for the interval scale. Thermal neutrality was usually regarded as the optimal thermal comfort condition. "TSV = 0" was widely used to describe thermal neutrality (Hwang, 2007). It is found that people had confusion on deciding the appropriate vote of their thermal status when they were close to the thermal neutrality (Xie et al., 2019). A comfort range of temperature is recommended to represent the neutral status (ASHRAE 55, 2017). In the present study, a neutral range of operative temperature was estimated for the different climatic zones.

Based on a national-wide field survey in China, the following objectives are used in the present study.

1) To study thermal environments and thermal comfort of occupants from different climatic zones.

2) To investigate the influence of clothing insulation on individual thermal comfort.

3) To give the neutral temperature ranges when occupants wear 1.0-clo garments.

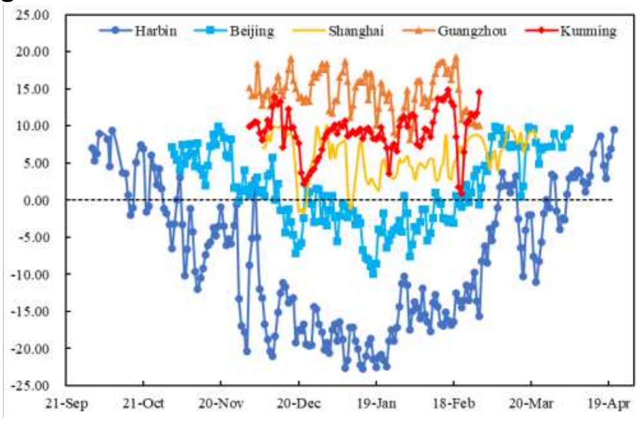
## 2. Research methods

### 2.1 Background

There are five different climatic zones across China: severe cold (SC), Cold, Hot Summer and Cold Winter (HSCW), Hot Summer and Warm Winter (HSWW) and Temperate zones (Temp) (GB 50176-2016). The classification is based on average outdoor air temperatures of the coldest month and of the hottest month. The geographical location of the five Climatic zones is shown in Figure 1. The regional variation impacts the difference in indoor climate and thermal preference of occupants (Su et al., 2022). The outdoor weather in winter is freezing in the north part of China, while the weather in the south part of China is warmer.


Figure 1. Climatic zones in China

Figure 2 displays the daily mean outdoor air temperature in typical cities of the five climatic zones, which were collected by meteorological information centre of China Meteorological Administration. The outdoor mean air temperature is below 0 °C in the coldest month and low temperatures last longer in Harbin and Beijing, which are located in the northern parts of China. However, the mean outdoor air temperature exceeds 0 °C during the whole winter in Guangzhou and Kunming. The heating system is operated differently in the north and south regions, separated based on the Qinling Mountain-Huai River line. There is a huge demand of heating in winter in the northern China.




Note: Harbin represents "Severe cold region", Beijing represents "Cold region", Shanghai represents "Hot summer and cold winter region", Guangzhou represents "Hot summer and warm winter region", and Kunming represents "Temperate region".

Figure 2. Daily mean outdoor temperate of five Climatic zones in winter

## 2.2 Data source

The Chinese Thermal Comfort Database was established in 2018 based on "the 13th Five-Year" National Science and Technology Major Project of China - Fundamental Parameters on Building Energy Efficiency in China. It contains 41977 sets of data which are from widely distributed sites, covering 24 provinces and 50 cities in 5 climatic zones of China. The contents in the database include indoor and outdoor thermal environmental parameters and thermal responses of the occupants for local and whole-body comfort, which were obtained through strict requirements of the Chinese industry standard (MOHURD, 2014).

The objective measured parameters indoor air temperature, relative humidity, and air velocity, etc. The information from individuals includes their clothing insulation, activity level and subjective evaluations of the indoor climate. Questions of thermal sensation applied ASHRAE seven-point scale (−3 cold, −2 cool, −1 slightly cool, 0 neutral, +1 slightly warm, +2 warm, +3 hot); Thermal comfort applied a five-point scale (1 comfortable, 2 slightly uncomfortable, 3 uncomfortable, 4 very uncomfortable, 5 unbearable); In most cases, the sensation and comfort votes were discrete. Thermal acceptability vote (-1 unacceptable, -0.1 slightly unacceptable, 0.1 slightly acceptable, 1 very acceptable) used the continuous scale with the breakpoint at "0" (-1 unacceptable, -0.1 slightly unacceptable, 0.1 slightly acceptable, 1 very acceptable). The metabolic rate of the subject was determined according to the reference value of ASHRAE Standard 55 and ISO 7730. In this study, the data was collected from the five climatic zones in winter. The data were all from surveys in field buildings. The underlying assumption of the field survey is that people were able to control their environment in such a way that they tried to reach comfort. A total of 14646 valid questionnaires were gathered for further analysis.

### 2.3 Data processing

The normality test shows that the operative temperature and clothing insulation follow the normal distribution. Since the probability of the majority of the data falling between average ± 3SD (standard deviation) is 99%, the value out of this range was regarded as outliers and was screened out.

One way ANOVA method was adopted for the variance analysis when there are at least 3 categories. The data when occupants vote "0" for the thermal sensation were particularly selected and marked as "thermally neutral state". Variation analysis of operative temperatures between a neutral state and all conditions was conducted by the independent sample t test.

Since a clothing insulation difference of 0.15 clo was the minimum value that should not be averaged to represent multiple occupants (ASHRAE 55, 2017), the continuous variable of clo-value was translated into categorical variables by Bin method at an interval of 0.3 clo, as shown in Table 1. It is inconvenient and uncomfortable for occupants to wear too thick clothes. Therefore, clothing insulation within the moderate range from 0.25 clo (underwear, T-shirt, shorts, socks, shoes) to 2.35 clo (underwear, long-sleeve shirt (thin), long-sleeve shirt (thick), long-sleeve sweater (thick), down jacket, thermos-trousers, jeans, stocking (thick), boots) was selected to study the influence on individuals' subjective perceptions. Moreover, a broad range of clothing insulation was seen in the Hot summer and cold winter (HSCW) region since there are no district heating systems and people adjust their clothing to obtain thermal comfort. Clothing data in this region was classified for understanding the influence of clothing on respondents' thermal comfort.

Table 1. Transferring clothing insulation into categorical variables

| Level | Range | Mean value | Amount |
|---|---|---|---|
| 1 | 0.25 - 0.55 clo | 0.4 clo | 271 |
| 2 | 0.55 - 0.85 clo | 0.7 clo | 277 |
| 3 | 0.85 - 1.15 clo | 1.0 clo | 578 |
| 4 | 1.15 - 1.45 clo | 1.3 clo | 743 |
| 5 | 1.45 - 1.75 clo | 1.6 clo | 820 |
| 6 | 1.75 - 2.05 clo | 1.9 clo | 384 |
| 7 | 2.05 - 2.35 clo | 2.2 clo | 383 |

Logistic regression was used to establish the relationship between the indoor operative temperature ($t_o$) and thermal sensation of occupants. Logistic regression was developed based on the logit transformation (Lancaster and Cox, 1971) as shown in equation (1) and the linear relationship between the independent variables and dependent variables is shown in equation (2). Moreover, the logit transformation deals with the odds ratio (OR) which quantifies the strength of the association.

$$\text{logit}\ (p) = ln\frac{p}{1-p} \tag{1}$$

$$\text{logit}\ (p) = \beta_0 + \beta_1 x_1 + \cdots + \beta_n x_n \tag{2}$$

The occurrence probability (p) represents the positive response in the logistic regression part. The points where the probability equalled 50% were considered as the threshold for transformation. For example, when $x_i$ reached the threshold of stimulating 50% in the y-axis, it was termed entering the occurrence zone.

As the logistic regression aimed at dealing with a binary response, the thermal sensation from the survey was divided into two categories. The seven-point thermal sensation votes (TSV from "-3" to "+3") were arranged in "Cooler and neutral" (TSV ≤ 0) and "Cooler than neutral" (TSV < 0) respectively, as shown in Table 2. When $t_o$ reached the threshold of stimulating 50% probability of the "neutral and cooler" transition curve, it was termed as entering the neutral zone; and when $t_o$ decline to that of the "cooler than neutral" curve, leaving the neutral zone. The neutral range of operative temperature was between the two thresholds. Since it was hard to decide the difference when the voting was around thermally neutral status, or the status might last for a certain range of thermal stimulus in the environment, the concept of the thermally neutral range (Nikolopoulou and Lykoudis, 2006) could be alternative and used in the present study.

Table 2. Arrangements of thermal sensation vote

| Description | Abbreviation |
|---|---|
| Cooler than neutral | TSV < 0 (TSV = -1, -2, -3) |
| Cool and neutral | TSV ≤ 0 (TSV = 0, -1, -2, -3) |

## 3. Results

### 3.1 Distribution of indoor environments

The database contains the environmental parameters including indoor air temperature ($t_a$), relative humidity (RH) and air velocity ($v_a$), which are directly measured in the field studies. It also includes mean radiant temperature ($t_{mrt}$), which is measured either by globe thermometer and then calculated through the equation combining $t_a$, $v_a$ and globe temperature or by the definition equation combining angle factor weighted average of surface temperatures. The results showed a significant difference between $t_a$ and $t_{mrt}$ in the non-uniform environments: $t_{mrt}$ in SC and cold areas was about 1 °C lower than $t_a$, due to the influence of the cold weather and corresponding cold indoor surfaces (windows, walls). On the contrary, $t_{mrt}$ in HSCW zone was higher than that of $t_a$, which resulted from the solar radiation during the day. Therefore, operative temperature ($t_o$) (Winslow et al, 1937) as a comprehensive thermal index of the environment is used in the subsequent analysis. $t_o$ is defined as a uniform temperature of a radiantly black enclosure in which an occupant would exchange the same amount of heat by radiation and convection as in the actual non-uniform environment. It is the weighted mean of the air temperature and the mean radiation temperature by the heat transfer coefficient of convection and radiation, respectively. When the air velocity is less than 0.2m/s, the value is the arithmetic mean of the two types of temperature. The operative temperature distribution is shown in Figure 3. The neutral operative temperature when occupants vote "0" was also illustrated for comparison. Although the outdoor air temperature (Figure 2) in severe cold (SC) and cold regions is low in winter, $t_o$ is significantly higher than that in hot summer and cold winter (HSCW) regions and temperate regions when considering all votes of subjects (right part in Figure 3). The difference of neutral operative temperature between climatic zones became smaller (left part), indicating the neutral temperature tends to be consistent. The mean value of $t_o$ for neutral state in HSCW (17.8 °C) and Temp (15.8 °C) areas were significantly higher than that for all votes merged (HSCW: 16.7 °C, Temp: 13.6 °C). This indicates an essence of increasing the indoor air temperature for pursuing the neutral thermal state. Since the data collected in hot summer and warm winter zone (HSWW) were only from rooms with centralized heating, the $t_o$ in this region was concentrated at a higher value of 23.8 °C in all conditions. The mean value of $t_o$ was almost the same in the neutral state and all conditions in SC and Cold zones, which attributes to the central heating system adopted in both zones.

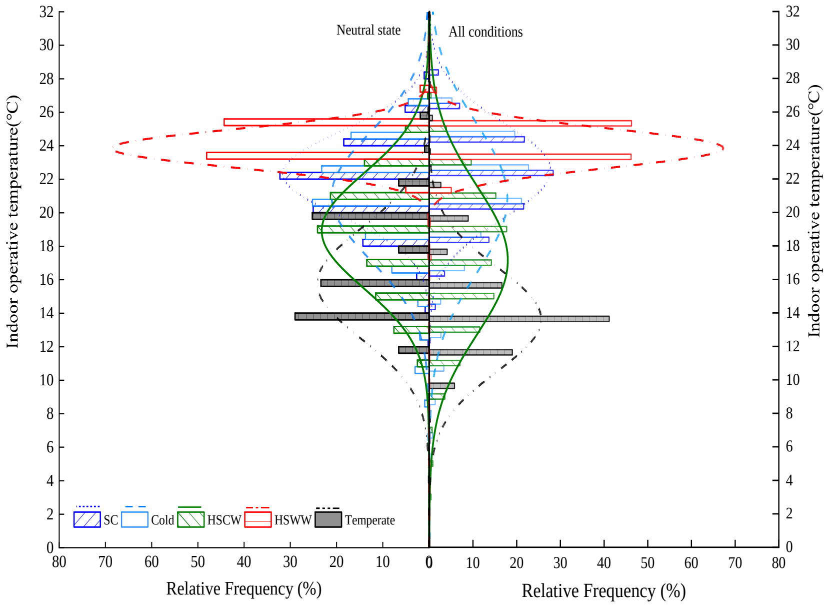



Figure 3. Indoor operative temperature among five climatic zones

Table 3 summarizes the measurements of relative humidity (RH) and air velocity ($v_a$) in the investigated buildings in five climatic zones.

Table 3. Measurements of relative humidity (RH) and air velocity ($v_a$)

| Zones | SC | Cold | HSCW | HSWW | Temperate |
|---|---|---|---|---|---|
| RH (%) | 33± 11[a] | 34± 19 | 52 ± 13 | 53 ± 10 | 17 ± 14 |
| $v_a$ (m/s) | 0.06 ± 0.04 | 0.01 ± 0.00 | 0.03 ± 0.02 | 0.10 ± 0.00 | 0.32 ± 0.14 |

a - Mean ± Standard deviation

It is clear that the relative humidity (around 33%) in severe cold (SC) region and Cold area is significantly lower than that of buildings in hot summer and cold winter (HSCW) area (52%), since high temperatures correspond to a higher partial pressure of saturated vapour and result in the low relative humidity. The indoor air velocity is within a reasonable range (< 0.2 m/s) in a majority of regions, except for the temperate region where an adverse indoor environment exists with low relative humidity and high air velocity. Since interviewees were recommended to stay in the room for at least 15 min before they filled in the survey questionnaire, light physical activity (metabolic rate around 1.1 met) was recorded for the majority of occupants.

### 3.2 Distribution of clothing insulation

Figure 4 illustrates the distribution of clothing insulation in all climatic zones. The mean clo-value concentrated around 1.0 clo in the majority of climatic zones and that (around 1.06 clo) in cold zone was slightly higher. A wide distribution of clothing insulation was found in HSCW zone and the mean clo-value is 1.36 clo, due to the slightly cold indoor climates. A comparison of clo-value was conducted between the neutral state and all conditions. As shown in Figure 4, there is a similar distribution of clothing data in the neutral state. However, a significant difference was found between the two distributions in most climatic zones, except for HSWW zone. This indicates that clothing insulation plays an important role in the judgment of thermal neutrality. The majority of the interviews were carried out in air-conditioned rooms in hot summer and warm winter (HSWW) zone where the thermal environments were in a narrow range and occupants seldom changed clothes.

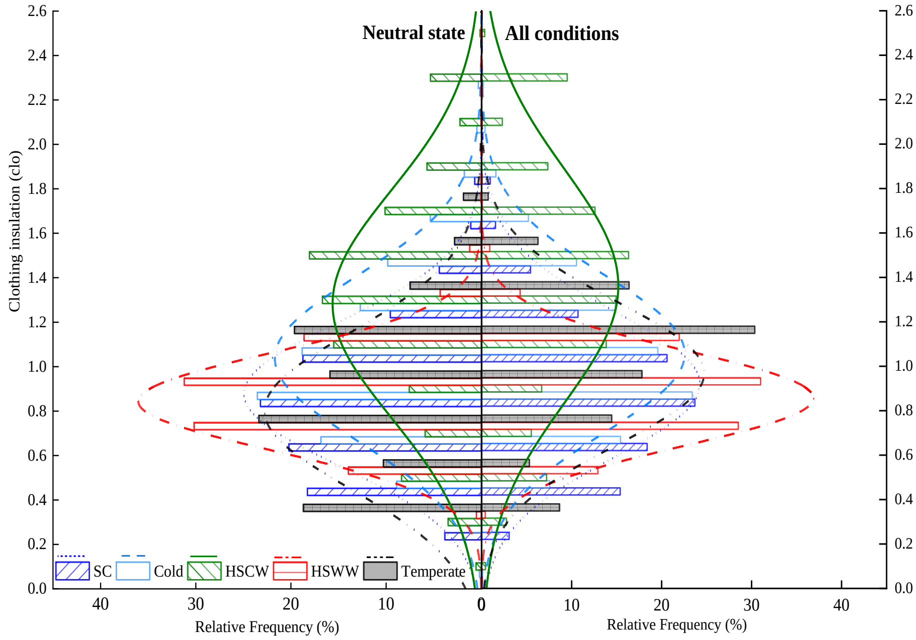



Figure 4. Distribution of clothing insulation between neutral state and all conditions

### 3.3 The influence of clothing insulation on thermal comfort

Clothing data in HSCW area were further selected to study the influence of clothing insulation on occupants' thermal comfort. Figure 5 shows the variation of mean thermal sensation (MTS) with operative temperatures at different clothing levels and Table 4 gives the regression details. The range of $t_o$ varied at different clothing level. As shown in Table 4, $I_{clo}$ at 0.4-clo level corresponds with higher operative temperatures while $I_{clo}$ at 2.2-clo level is related with lower operative temperatures. The regressions are only applicable within the limited range of operative temperature.

At both ends of clothing level (0.4-clo and 2.2-clo levels), the mean thermal sensation (MTS) of occupants was sensitive to the change of operative temperature with the high slope of 0.118 and 0.140, respectively. The slopes of other linear regressions were in the range between 0.008 and 0.009, indicating a slight decrease of the sensation sensitivity to the variation of $t_o$.

Neutral temperature ($t_n$) was regarded as the temperature when people votes "0". There was a similar $t_n$ among a wide range of clothing (0.4 - 1.9 clo), as the regression lines of the six clothing levels intersected with the reference line "MTS = 0" at the range from 20 °C to 22 °C. However, $t_n$ for 2.2 - clo level (the calculated value is 25.4 °C) is unreasonable since the regression is built on the condition of to less than 22 °C. The correlation between MTS and $t_o$ will change at a higher temperature when occupants wear such thick clothes.

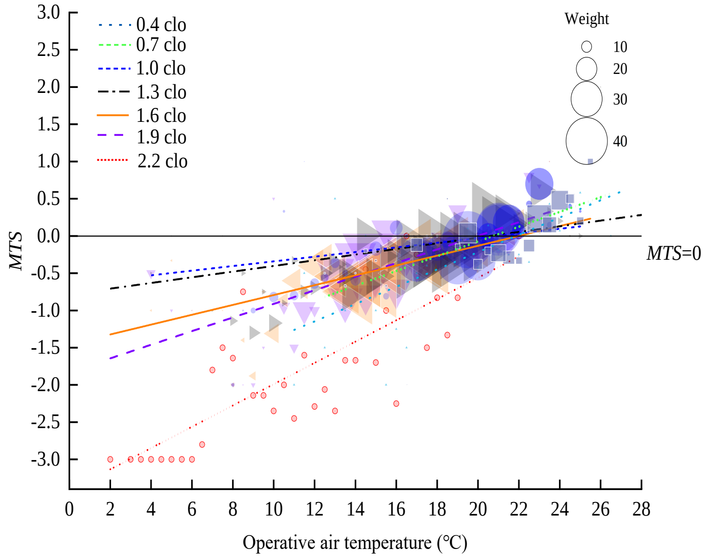



Figure 5. Mean thermal sensation (MTS) along with operative air temperature in different clothing insulation

Table 4. Weighted linear regression in different clothing insulation

| $I_{clo}$ | $t_o$ (°C) | Coef. [a] | Int. [b] | $R^2$ | $t_n$ (°C) | Sig. [c] |
|---|---|---|---|---|---|---|
| 0.4 | [11.0-27.0] | 0.12 | -2.62 | 0.55 | 22.2 | ** |
| 0.7 | [12.5-26.5] | 0.09 | -1.82 | 0.49 | 20.9 | ** |
| 1.0 | [8.0-25.0] | 0.09 | -1.70 | 0.62 | 20.0 | ** |
| 1.3 | [4.0-31.5] | 0.08 | -1.66 | 0.69 | 20.0 | ** |
| 1.6 | [4.0-25.5] | 0.08 | -1.73 | 0.64 | 21.1 | ** |
| 1.9 | [4.0-23.5] | 0.09 | -1.83 | 0.49 | 20.1 | ** |
| 2.2 | [2.0-22.0] | 0.14 | -3.559 | 0.51 | - | ** |

a. Coefficients of the weighted linear regression.
b. Intercept of the regression.
c. Significance of the model. ** means "$p \leqslant 0.01$".

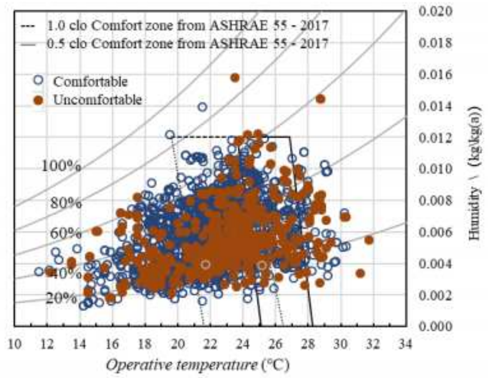
### 3.4 Thermal preference in different climatic zones

There are many uncertainties that differentiate thermal comfort from thermal sensation, such as cultural and psychological factors. In such a case, there may be a discrepancy of thermal environment required by thermal sensation vote and thermal comfort vote. A comparison between the required environments was conducted to study the influence of non-thermal factors.

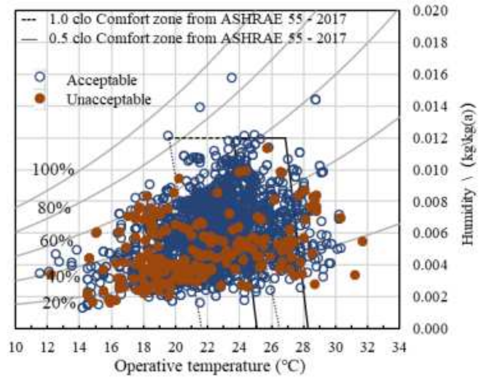
It is suggested that comfort shall be evaluated using votes on the thermal sensation (TSV) and/or acceptability (TAV) scales in ASHRAE-55 standard. Moreover, thermal sensation votes on seven-point scale between -1.5 and +1.5, inclusive, shall be regarded as "comfortable" observed during the survey period. Acceptability votes between 0.1 (slightly acceptable) and 1 (very acceptable), inclusive, shall be labelled as "acceptable". Under the division principle, the maps of "comfortable" and "acceptable" points were drawn in the graphic 0.5/1.0-clo comfort zone of ASHRAE-55 standard. The result of the severe cold (SC) zone was taken as an example due to the limited space, as shown in Figure 5. Except for the points out of the 0.5/1.0-clo comfort zone, there are still plenty of "uncomfortable" points located in the comfort zone. However, there were less amounts of "unacceptable" scatters and they mainly concentrated in the region below the comfort zone. From the opposite view, it can be indicated that people accept a wide range of thermal environments than that required by thermal sensation. That is, even though people vote "warm" which is out of the comfort range, they may accept the current environment. This again shows a high tolerance to the environment in the field situation, for people have adjustable methods when they feel "cool" or "warm".

It can be also seen that there are a large number of "comfortable" scatters that stayed in the "0.5-clo comfort zone" (solid line frame) with relatively high operative temperatures. It is an energy waste to sustain the winter thermal environment in the summer comfort zone, since more heating supply was required. Accordingly, it is recommended to lower the temperature for heating in winter in SC zone to maintain the points at 1.0-clo comfort zone.

The scatter map illustrates a considerable overlap of points between "comfortable/acceptable" and "uncomfortable/unacceptable" status, indicating that people vote differently when they are exposed to the same thermal environment. To eliminate the interferences of individual characteristics, thermal environments should be evaluated through a certain voting proportion by a group of people rather than an individual vote.




(1) Thermal sensation




(2) Thermal acceptability

Figure 6. Operative temperature distinguished by (1) Thermal sensation, (2) Thermal acceptability in SC zone

## 4. Discussion

### 4.1 Neutral thermal environments in different climatic zones

As shown before, there were significant discrepancies in both indoor and outdoor thermal environments as well as the daily clothing of people between climatic zones. The various external surroundings cause different physiological and psychological responses inside the human body. The preferred thermal environments were different for occupants in different climatic zones.

To obtain the thermally neutral range of operative temperature, transition curves with "neutral and cooler" and "neutral than cooler" were drawn based on the logistic regression. Since the clothing level may influence the preference of indoor air temperature, the regression was only established within 1.0-clo garment. Figure 7 presents the transition curves delineating the neutrality zone of operative temperature ($t_o$) in national zones and individual zone respectively. The samples in the Hot summer and warm winter (HSWW) region and temperate region were small, where indoor air temperatures of the investigated rooms varied in a narrow range. The neutral temperature ranges of the two climatic regions were not presented.

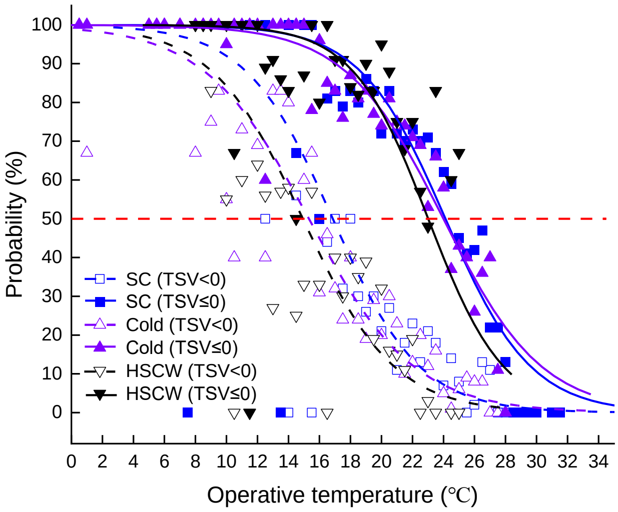



Figure 7. Transitional curves for neutral range of operative temperature in 1.0-clo garment in three climatic zones

As shown in Figure 7, the distance between the "cooler than neutral" curve (TSV < 0) and the "neutral and cooler" curve (TSV ≤ 0) at the probability of 50% was considered as the neutral temperature range. The width of a neutral range could be conceived as an indication of the extent of tolerance, which may vary between the various climatic regions. It is noticeable that there are considerable data from rural areas of the cold region, where individual private heating was adopted and indoor air temperature varied greatly. Thus the neutral scope of $t_o$ (15.4 - 24.0 °C) was also expanded. The upper limit of the neutral range (23.1 °C) in HSCW zone was a bit lower than that of the other climatic zones. The temperature difference of 1 °C indicates the occupants' adaptability to coldness when there is no indoor central heating system. The "cooler than neutral" curves of Cold and HSCW zones were almost identical and the threshold of the transaction from "cooler than neutral" to "neutral and warmer" was around 15 °C in both climatic zones. The lower threshold (17°C) for SC zone was slightly higher as occupants are living in heated rooms. In this perspective, it is reasonable for the heating design temperature of 18 °C when people were in 1.0-clo garments. However, the value was below the comfort region in ASHRAE-55 standard. In the surveyed buildings, occupants could take measures to adjust themselves to the thermal environment, e.g., drinking hot water, doing warming exercises, etc. They accept a relatively cool environment. It is suggested for building designers to provide chances for residents' self-adaptability to the environments, e.g., set the value of $t_a$ at the lower limit of the thermal comfort zone to actuate occupants to actively adapt to the environment. It was found (Ning et al., 2016) that 8% of heating energy would be saved in winter, if the indoor air temperature was modified from 24.3 °C to 20.7 °C. Therefore, a lower heating design temperature could not only improve human adaptability, but could also help reduce carbon dioxide emission.

### 4.2 Thermal preference in different clothing insulation

As mentioned before, occupants adjusted their clothing to maintain comfort states and they may have different preferences of thermal environments in different clothing levels. Variance analysis was conducted on the operative temperature between a thermally neutral state and all conditions. As shown in Table 5, there is no significant difference of operative temperature between the low clothing level of "1" and "2". This suggests that the operative temperature played a little role in the neutral thermal sensation at this state. However, when people were dressed in higher clothes (levels of "3-7"), operative temperature for neutral states was significantly higher than that in all conditions, indicating that increasing operative temperature contributes to the thermal neutrality. A significant decrease of $t_n$ was found at clothing level "7" (2.2 clo), with the mean value of 13.4 °C. When the $t_n$ of all clothing level was reordered, the median value was 18.6 °C. The number of $t_n$ exceeding 18.6 °C declined sharply with the increase of clothing. People can achieve the thermal neutrality in the cold environment by wearing thick clothes. This indicates a behaviour adjustment and psychological adaption in the field environments.

Table 5. Difference of operative temperature between thermally neutral state and all conditions

| Clothing level | 1<br>0.4 clo | 2<br>0.7clo | 3<br>1.0 clo | 4<br>1.3 clo | 5<br>1.6 clo | 6<br>1.9 clo | 7<br>2.2 clo |
|---|---|---|---|---|---|---|---|
| Δ $t_o$ (°C) | 0.0 | 0.2 | 0.5 | 0.6 | 0.9 | 1.0 | 1.4 |
| Significance | - | - | * | ** | ** | ** | ** |

In addition, a comparison of TSV and TAV was made between different clothing levels. The results were shown in Figure 8.

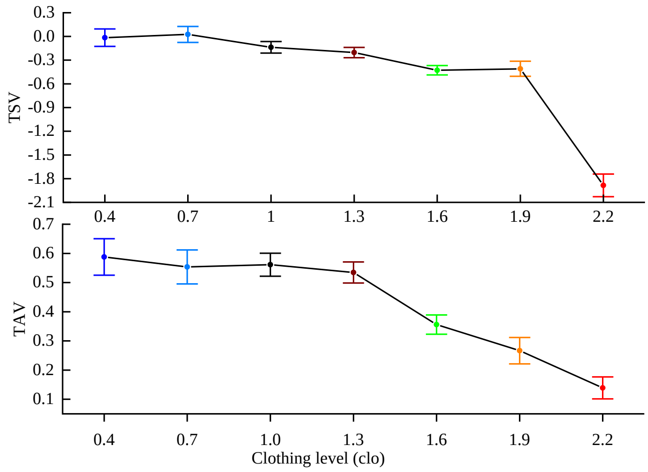



Figure 8. Comparison of TSV/TAV in different clothing

Although a significant decline of the thermal sensation was merely found in clothing level of "2.2 clo", the thermal acceptability decreased significantly when the clothing level exceeded the level "4" (1.3 clo). This indicates that adding clothing insulation compensates for the decrease of indoor temperature, but the thermal acceptability still decreases. The compensation is limited when clothing insulation exceeds 1.3 clo. It is inconvenient for occupants to do indoor tasks in thick clothes, which causes the discomfort. However, the mean votes in all clothing levels were more than 0.1 (slightly acceptable), indicating an acceptability of the environments as a whole. Based on the analysis above, a maximum clothing insulation of 1.9 clo is suggested for winter conditions.

## 5. Applications

For engineering purposes, the “comfort” sensation should be converted to and expressed in measurable, physical quantities. This is facilitated using the acceptable limit of operative temperature. Neutral temperature ranges at 1.0 - clo garments were shown in the three climatic zones. This provides recommendations for indoor environment design in heating seasons. The acclimation of human beings to the environments should be considered and lower temperature for heating supply is encouraged. People actively adapt to the environment. Though adding clothes is effective for occupants to protect themselves from cold, the effect is missing when clothing insulation exceeds 1.9 clo. Allowing the adjustable range of clothing can not only improve occupants’’ thermal states, but also contribute to building energy efficiency.

## 6. Conclusions

This study discussed the thermal environment, thermal comfort and clothing behaviours of occupants based on the Chinese thermal comfort database in the five zones: Severe cold (SC), Cold, Hot summer and cold winter (HSCW), Hot summer and warm winter (HSWW) and Temperate areas. Conclusions can be drawn as follows.

(1) Indoor operative temperatures (to) in Severe cold area and Cold area were much higher than that in Hot summer and cold winter zone (HSCW) and Temperate zone in winter, while the difference of neutral operative temperature between climatic zones became smaller. The neutral operative temperature in HSCW (17.8 °C) zone and Temperate (15.8 °C) area were significantly higher than the mean operative temperature for all conditions (HSCW: 16.7 °C, Temp: 13.6 °C).

(2) The mean clo-value concentrated around 1.0 clo in most climatic zones. The distribution of clothing insulation was widest in Hot summer and cold winter (HSCW) zone, with the mean value of 1.36 clo. The clothing insulation in this region was studied and it was found that the neutral temperatures at the clothing level of 0.4 – 1.9 clo were all converged in the range from 20 °C and 22 °C.

(3) From the map of operative temperature distinguished by thermal sensation and thermal acceptability in severe cold (SC) zone, it is indicated that people accept a wide range of thermal environments than that based on thermal sensation. It is recommended to lower the temperature for heating in winter to maintain the thermal environments at the winter comfort zone. Since people may vote differently when they are exposed to the same thermal environment, thermal environments should be evaluated through a certain voting proportion by a group of people rather than an individual vote.

(4) The neutral temperature ranges for occupants in 1.0-clo garments were [17.0 - 24.1 °C] in Severe cold zone, [15.4 - 24.0 °C] in Cold zone and [15.0 - 23.1 °C] in Hot summer and cold winter zone. Adding clothing insulation of Hot summer and cold winter zone compensates for the decrease of indoor temperature, but the effect is missing when clothing insulation exceeds 1.9 clo. It is suggested to allow the adjustable range of clothing when designing indoor thermal environments, which can not only achieve thermal comfort of occupants, but also contribute to building energy efficiency.

## 7. Acknowledgments

This work was supported by "the 13th Five-Year" National Key R&D Program of China (Grant No. 2018YFC0704502). The authors would like to express their gratitude to the China Scholarship Council (CSC) for supporting the first author's 12-month stay at the Technical University of Denmark.

## 8. Appendices

Table A. Regression results of the transition curves with and "neutral than cooler" (TSV<0) and "neutral and cooler" (TSV≤0)

| Zones | Formula[a] |
|---|---|
| Severe cold | $P(TSV < 0) = \frac{100\exp(6.02 - 0.35t_{op})}{1+\exp(6.02 - 0.35t_{op})}$ |
| | $P(TSV \leq 0) = \frac{100\exp(8.80 - 0.36t_{op})}{1+\exp(8.80 - 0.36t_{op})}$ |
| Cold | $P(TSV < 0) = \frac{100\exp(4.54 - 0.30t_{op})}{1+\exp(4.54 - 0.30t_{op})}$ |
| | $P(TSV \leq 0) = \frac{100\ \exp(7.59 - 0.32t_{op})}{1+\exp(7.59 - 0.32t_{op})}$ |
| Hot summer and cold winter | $P(TSV < 0) = \frac{100\ \exp(5.08 - 0.34t_{op})}{1+\exp(5.08 - 0.34t_{op})}$ |
| | $P(TSV \leq 0) = \frac{100\ \exp(9.48 - 0.41t_{op})}{1+\exp(9.48 - 0.41t_{op})}$ |

Note: a - All regressions were fitted well with the R-square of more than 0.90. Moreover, coefficients of the regression models were statistically significant.

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# Thermal indices and comfort in low- and middle-income residences during dry seasons: A case study of Dutse Alhaji and Lugbe in Abuja, Nigeria.

**Michael U. Adaji[1] and Timothy O. Adekunle[2]**

[1] Department of Maths, Engineering and Construction, Newham Sixth Form College, Prince Regent Lane, London, E13 8SG, UK. Email: michael.adaji@newvic.ac.uk

[2] School of Architecture, College of Architecture + Planning, University of Utah, Salt Lake City, UT 84112, USA

**Abstract:**

This research examines thermal indices and comfort in low- and middle-income residences during dry season in Abuja, a hot and humid climate. The study assesses selected residences in Dutse Alhaji and Lugbe within the Federal Capital Territory (FCT) in Abuja. The principal focus of the study is to evaluate thermal indices and comfort in various seasons. To accomplish the research goals, the study considered environmental monitoring of variables, comfort surveys, and mathematical models to compute the thermal indices in different buildings in the study locations. The analysis showed that the thermal indices exceed the applicable thresholds for heat stress and overheating. The mean thermal sensations across the case studies in the dry season showed either "slightly warm" or "warm". In Lugbe, the neutral and preferred temperatures varied from 28.8°C-29.5°C during the dry seasons. While in Dutse Alhaji, the temperatures varied from 28.0°C-30.1° dry season. The temperatures were not within the acceptable bands of ASHRAE-55, CIBSE TM52, and EN16798-1 thermal comfort models. The study suggests residents are vulnerable to heat stress in different periods of the day. The research recommends the integration of passive design interventions that are more affordable, accessible, and user-friendly.

**Keywords:** Thermal indices and comfort, dry seasons, hot and humid climate, low- and middle-income residences

## 1. Introduction

The paper examines thermal indices and comfort in low- and middle-income residences during dry seasons in Abuja. The study intends to assess the monitored and simulated results using the existing thermal comfort standards and compare the variables with the applicable stress indices. It aims to understand if occupants are prone to extreme warm dry season temperatures and heat stress in the buildings.

Existing research in the field noted that humans are highly sensitive to environmental heat and being exposed to high-temperature situations which may have disastrous consequences (Erickson et al., 2019). Heat stroke, for example, may result in sudden death or damage to the body's major organs and physiological functions (NIEHS, 2022; US DHHS, 2022). Since 1950, several studies have examined human thermal comfort in both indoor and outdoor environments, yielding a variety of numerical and diagram-based comparisons (Abdel-Ghany et al., 2013). A recent study by Adaji et al. (2019) conducted on residential buildings in Abuja, Nigeria for a hot-humid climate showed that a wide range of weather variations can occur within a geographical site across the world. In the study (Adaji et al., 2019) and other existing research (Djongyang et al., 2012; Amos-Abanyie Samuel et al., 2013, Adaji et al., 2020), the development of weather files for various locations aids in the evaluation of many variables that can be investigated to improve building performance. For instance, weather files generated for various sites were used to evaluate different variables that can be explored to improve the performance of buildings under moderate and extreme weather conditions (Adekunle and Nikolopoulou, 2016). This was demonstrated in a recent study in which TMY weather files were developed to encourage further research into residential building performance simulation in Abuja, Nigeria (Adaji et al., 2019).

## 2. Literature review

In recent years, elevated temperatures were reported in many studies in tropical and temperate climates (Amorim and Dubreuil, 2017; Nematchoua et al 2021; Indraganti, 2010; Adaji et al., 2019; Adekunle, 2020). Different investigations have assessed the most efficient sustainable intervention that will improve occupants' comfort and minimise overheating within indoor spaces (Adekunle and Nikolopoulou, 2016; Adaji et al., 2019). However, construction of residential building envelopes in tropical regions like sub-Saharan Africa, predominantly employs structural sandcrete hollow blocks (SSHB) that are of low thermal mass (Amos-Abanyie et al., 2013). To date, there is limited or no empirical study that has been carried out to assess its performance regarding the heat stress experienced by occupants of this type of building in the region. Existing studies on thermal comfort in buildings explained that occupants of SSHB buildings are vulnerable to rising temperatures in warm periods, especially in dry seasons (Adaji et al., 2020; Amos-Abanyie et al., 2013). Therefore, additional studies are required to understand the performance of SSHB buildings in different weather conditions and climate.

### 2.1. Thermal comfort and overheating studies in tropical regions

Various investigations on thermal comfort have been carried out in tropical regions, especially in hot humid climates with most results showing a wide range of temperatures at which people feel comfortable (comfort or neutral temperature) measured in air-conditioned (AC) and naturally ventilated (NV) buildings (Zain et al., 2017; Wong et al., 2003; Kwok, 1998; de Dear, Leow et al., 1991; Djongyang et al., 2012; Adaji et al., 2019). The neutral temperatures reported in these studies ranged from 28-32°C in the naturally ventilated buildings while a range of 26-29 °C was reported in the air-conditioned buildings. Studies of occupant comfort in hot climates in tropical regions around the world reveal a broad range of comfort temperatures and various adaptive measures to make them more thermally comfortable (Zain et al., 2007; Adaji et al. 2019; Zepeda-Rivas & Rodríguez-Álvarez, 2020). Air-conditioning is often seen as the way to lower internal temperatures and improve occupants' comfort. However, this is a procedure that involves additional money and energy, which many individuals in developing nations cannot afford.

This development leads to serious indoor environmental conditions like heat stress, thermal discomfort, and poor indoor air quality (Zain et al., 2007). The importance of the interaction between the occupants' and their surroundings in attaining thermal comfort is often overlooked by comfort standards based on climate chambers. Indoor thermal comfort and expression of satisfaction with the thermal environment have been determined by researchers using EN16798-1, EN ISO 7730 and ASHRAE Standard 55 indoor thermal measurements. The standards are critical for assessing the building's occupants' health, comfort, satisfaction, and well-being. The operative temperature recommended by ASHRAE Standard 55 (ANSI/ASHRAE Standard 55, 2017) could vary from 19.5°C (67°F) to 27.8°C (82°F). The values obtained from the Standard 55 (ANSI/ASHRAE Standard 55, 2017) suggest that temperatures below the lower thresholds could indicate cold discomfort while temperatures above the upper thresholds could indicate warm discomfort in buildings.

### 2.2. Review of heat indices

Heat stress is defined as a condition in which a human body's ability to remove excess heat is hampered, and it typically occurs when the body's core temperature and heart rate rise

(NIOSH, 2018). Heat stress can also be defined as a situation in which the human body absorbs excessive amounts of heat, which is often produced by overheating (NEHC, 2007; OSHA, 2016). Mathematical models for the calculation of stress indices in various temperature conditions have been proposed in previous research (Lemke & Kjellstrom, 2012; Stull, 2011). This study uses the Wet-Bulb Globe Temperature Heat (WBGT) and the Universal Thermal Climate Index (UTCI) mathematical models, the Apparent Temperature (AT), as well as the Standard Effective Temperature (SET), to calculate the stress indices in the areas in the case study. The present study's findings are compared to the outcomes of other studies in the field to see whether the estimated temperatures are higher than the thresholds suggested by the thermal comfort models. The research also suggests design modifications and recommendations to enhance occupants' overall thermal comfort, health, and well-being in school buildings.

To date, heat stress and occupant comfort in timber buildings have both been studied (Adekunle, 2018). Heat stress has also been studied in non-timber building functional areas including operating spaces (Brode et al., 2010; Lemke & Kjellstrom 2012) and hospital wards (Giridharam, 2017). Workplaces and offices are also investigated for heat stress (NEHC, 2007; OSHA, 2016). The research cited above exclusively addressed heat stress in buildings in temperate climates. Therefore, the heat stress in structural sandcrete hollow block structures is investigated in this research.

## 3. Method – environmental monitoring and mathematical models

On-site monitoring was employed to collect environmental data that could be used to better understand and assess the thermal environment. Thermal comfort models were employed to determine whether occupants were experiencing hot or cold discomfort. The mathematical models were used to compute the stress indices and determine if occupants are susceptible to heat or cold stress in different seasons due to the thermal environment. The study also looked at the applicability and categories of numerous thermal standards (ASHRAE 2017; BSEN16798-1, 2019; CIBSE, 2015).

The CIBSE thermal comfort standard (2015) recommends the appropriate building range for determining maximum acceptable temperature ($T_{max}$). The CIBSE comfort standard states that buildings should be planned and developed to be within the Category II (suggested acceptable range is 3 K) bands. The CIBSE TM52 further stresses that the Category II upper band should be evaluated by using Equation (1). The equation (Equation (1)) also indicates the maximum acceptable temperature for the Category II TM52, and it specifies the running mean temperature ($T_{rm}$).

$$T_{max} = 0.33\, T_{rm} + 21.8 \qquad (1)$$

The EN16798-1 thermal comfort model examines a naturally ventilated thermal environment with physically controlled openings such as doors, windows, and so on, as well as mechanical ventilation. The Category II thermal envelope is the thermal environment occupied by users with a "normal level of expectations".

The EN16798-1 thermal comfort model considers and recommends the calculation of the running mean temperature. Similarly, the ASHRAE thermal comfort standard (ASHRAE, 2017) also follows a similar approach that other thermal comfort standards considered in this study for evaluating the thermal comfort of occupants and the performance of buildings. The thermal comfort models are applied to assess thermal comfort of occupants during the total hours of occupation during the on-site measurements, i.e., living areas occupied (08:00 – 22:00), and bedrooms occupied hours (23:00 – 07:00).

The applicability and limits of various standards (such as the CIBSE, the EN16798-1 and ASHRAE Standard 55 thermal comfort models) used for evaluation of the performance of spaces and the summary of the standards have been presented in existing research (Adekunle and Nikolopoulou, 2016; Giridharan, 2017; Adaji et al 2019).

### 3.1. Heat indices and on-site monitoring of environmental parameters

Heat index is defined as a condition of environmental parameters (such as temperature, relative humidity, dewpoint, solar radiation, etc.) taken at a particular interval using sensors at 1.1 m height above the floor level in line with ASHRAE 55 (ASHRAE, 2013). The sensors were mounted on the internal walls at 1.1 m height above the floor level to measure and log the parameters. The data recorded during the warm and non-warm periods were downloaded, checked, and analysed. For the warm dry season, the on-site monitoring was carried out from February to May 2015. All the spaces monitored have windows that can be manually operated. The windows were being used for ventilation during the field study, and mechanical ventilation systems were not operated when the indoor temperatures increase.

### 3.2. Computation of environmental variables not measured during the on-site monitoring

The surveys were carried out over a limited period, therefore simulation carried out over an extended period to include the whole warm dry season from 01 February to 30 April. The air temperature, operative and radiant temperatures, relative humidity and dew point were calculated. However, the indoor vapour pressure and dewpoint were not calculated. During the surveys, two of the data loggers used for the on-site monitoring recorded the indoor air temperature, relative humidity and dew point. Mathematical models were considered in this study to calculate the values of the environmental variables that were not measured during the on-site monitoring of the case study buildings. The mathematical models were also used to check and validate the calculated data. Vaisala (2013) explained that when relative humidity has been determined, saturation vapour pressure can also be calculated using Equation (2), while vapour pressure can be computed by applying Equation (2). In the equations, $P_{ws}$ stands for saturation vapour pressure (hPa), T is defined as temperature (°C), Pw is vapour pressure (kPa) and RH is relative humidity (%). In Equation (3), A, m, n are constants, and the values are defined in the existing study (Vaisala, 2013).

$$P_{ws} = A\,.\,10 \times \left(\frac{mT}{T+T_n}\right) \qquad (2)$$

$$P_w = \frac{1}{10} \times P_{ws} \times RH \qquad (3)$$

Given that air temperature and wind speed data are assessed at 10m level, the input data should be recalculated. Air temperature was approximated through applying a factor of 0.6 K/100m (Fr€ohlich and Matzarakis, 2013). Utilizing Hellman's exponential law, wind speed was recalculated for the height of 1.1m above the surface, Equation (4).

$$V_h = V_{10} \times \left(\frac{h}{h_{10}}\right)^{a} \qquad (4)$$

where $V_h$ is the wind speed (m/s) at height h = 1.1 m, $V_{10}$ is the wind speed (m/s) at height $h_{10}$ = 10 m, and α is the friction coefficient (Hellman exponent). However, in their study they selected, α is 0.34 (Urban and Kyselý, 2014; Blazejczyk et al., 2012). In this study α is 0.60 based on the suggestions in Table 1 illustrates the thermal threshold for this index. The Hellmann exponent depends upon the coastal location and the shape of the terrain on the ground, and the stability of the air. Examples of values of the Hellmann exponent are given in the table below:

Table 1: The Hellmann exponent value examples

| Location | α |
|---|---|
| Unstable air above open water surface: | 0.06 |
| Neutral air above open water surface: | 0.10 |
| **Unstable air above flat open coast:** | **0.11** |
| **Neutral air above flat open coast:** | **0.16** |
| **Stable air above open water surface:** | **0.27** |
| **Unstable air above human inhabited areas:** | **0.27** |
| **Neutral air above human inhabited areas:** | **0.34** |
| **Stable air above flat open coast:** | **0.40** |
| **Stable air above human inhabited areas:** | **0.60** |

## 4. The study location and Case Study Buildings

This study was conducted in Abuja, a city located at latitude 9.0765°N and longitude 7.3986°E. Abuja is at an elevation of 840 m (2760 ft.) above the sea-level. This city is the capital of Nigeria and has a hot-humid climate located in West Africa, a tropical region. The study was conducted during the warm dry season from February to early May 2015.

### 4.1. Case study description

For this paper, four prototypes are selected as representative case study buildings from eight different prototypes constructed at the Abuja location site. The study assesses selected residences in Dutse Alhaji (9.1448°N, 7.5356°E) and Lugbe (8.9868°N, 7.3626°E) within the Federal Capital Territory (FCT) in Abuja, Nigeria. The buildings were chosen because they were monitored and evaluated during the field study. The characteristics of the case study buildings are summarised in Table 2. All the case study buildings are built with the structural sandcrete hollow blocks as the walling material and aluminium sheets for the roof. The walling material comprises of a mixture of natural sand, water, and a binder usually cement (Oyelola and Abdullahi, 2006; Sholanke, et al., 2015). The case study buildings also have a similar U-values for the building components as presented in Table 2. However, the buildings do not have the same orientations, occupants' number and occupancy duration. The buildings were also chosen based on their orientation, the pattern of occupancy, location with respect to other adjoining buildings (semi-detached, detached) and design and construction parameters like the building material, wall height and window-to-wall ratio. The case studies are designated as follows, for the dwellings in Lugbe, LGH1 (3-bedroom, north facing detached bungalow) and LGH2, (2-bedroom, north-east facing, semi-detached bungalow). While DAH1 and DAH2 are for the dwellings in Dutse Alhaji (east facing one-bedroom terrace flat attached). In the warm dry season, the case study buildings are naturally ventilated (LGH1 and DAH1) but supplemented with cooling equipment such as portable fans and air-conditioning for LGH2 and DAH2. The thermo-physical properties of the main building components across all the case studies are highlighted in Table 2.

Table 2: Thermo-physical properties of the main building components.

| Building components | Materials | Estimated U-values (W/m2K) |
|---|---|---|
| **Internal walls** | **150mm structural sancrete hollow blocks (no bridging or insulation), finished with 20mm cement/plaster/mortar on surface.** | **2.02** |
| **External walls** | **230mm structural sancrete hollow blocks (no bridging or insulation) finished with 20mm cement/plaster/mortar on surface.** | **2.03** |
| **Floors** | **Ceramic clay floor tiles and 20mm cement screed on 150mm cast concrete** | **3.0** |
| **Roof** | **Aluminium Roofing sheets (no insultation below), rafters, heavy timber trusses** | **7.14** |
| **Windows** | **Windows single glazing, and low performance window frame (no insulation).** | **5.78** |
| **Ceiling** | **Cement Plasterboard** | **2.53** |

## 5. Data Analysis

The mean daily outdoor temperature ranged from 30.3°C-31.1°C (Table 3). The overall average daily outdoor temperature reported during the period of the survey was 30.7°C. The average maximum and minimum outdoor temperatures were 41.1°C and 23.5°C respectively for Lugbe. While Dutse Alhaji recorded an average maximum and minimum outdoor temperature of 38.4°C and 23.0°C respectively. The overall average daily outdoor dew-point temperature was 15.9°C, and the mean daily outdoor RH was 43%. The average running mean temperature ($T_{rm}$) of 30.4°C was computed for the dry season months. The mean daily running mean temperature during the survey varied from 30.3°C-32.76°C was recorded during the surveyed periods. The average atmospheric pressure at sea level was 95837.6Pa. The mean outdoor AT of 30.5°C and WBGT of 23.8°C were computed. The average outdoor UTCI was 29.3°C. The analysis showed that outdoor occupants would be thermally uncomfortable above the effective temperature index. The overall mean outdoor wind speed was approximately 2.0m/s. Table 3 provides a summary of the features of outdoor weather conditions. The study highlighted that moderate heat indices were reported within the outdoor thermal environment of the dwellings during the survey. When considering the WGBT, the investigation showed that the daily indices exceeded the 23°C baseline for strong heat stress for outdoor conditions during the whole survey period. The study showed that relationships exist between outdoor temperature and thermal indices. Concerning the analysis of indoor data, the mean values of the study period during the dry season are summarized in the table below (Table 3). The analysis showed that the mean temperatures within the spaces varied from 30.2°C-34.2°C, while the mean monthly RH ranged from 29%-61% for all the measured spaces in Lugbe (LGH1 & LGH2) and Dutse Alhaji (DAH1 & DAH2).

A comparative analysis between the mean indoor and outdoor revealed a similar pattern was noted in the simulated models during the survey periods. However, the major contrast was that all the mean temperatures in all the measured spaces were above 30°C, while 75% of the calculated air-conditioned spaces across all the dwellings recorded temperatures between 25.9°C 29°C. The study revealed that even though there was moderate to strong risk of heat stress regarding the outdoor data, the mean values of indoor thermal indices, especially in the case study dwellings suggest that occupants are prone to heat stress during extreme warm dry season temperatures or heatwaves.

Table 3: Features of the measured and simulated external temperatures for the surveyed period and the whole dry season (February – April).

| Outdoor Variables | Measured outdoor values Abuja | | Predicted outdoor values for the 2000s using TMY3 for Abuja | | |
|---|---|---|---|---|---|
| | Lugbe | Dutse Alhaji | Lugbe | Dutse Alhaji | Abuja (Lugbe & Dutse Alhaji) |
| | 18/03-24/03 | 11/4-17/04 | 18/03-24/03 | 11/4-17/04 | February - April |
| Predicted Max temp. (°C) | 41.1 | 38.4 | 44.0 | 42.8 | 44.7 |
| Predicted Min temp. (°C) | 23.5 | 23.0 | 20.8 | 22.0 | 15.4 |
| Predicted Mean temp. (°C) | 31.1 | 30.3 | 30.1 | 30.7 | 29.3 |
| Predicted Mean RH% | 56.1 | 30.3 | 47 | 52 | 48 |
| Predicted Mean Dewpoint temp. (°C) | 20.3 | 11.5 | 15.8 | 18 | 15.5 |
| Mean UTCI (°C) | 30.3 | 29.7 | 30.2 | 31.3 | 29.3 |
| Mean WGBT (°C) | 23.3 | 23.2 | 24.3 | 25.6 | 23.8 |
| Mean AT (°C) | 30.7 | 30.3 | 31.5 | 33.1 | 30.5 |
| Number of hours above 28°C | 71 | 64 | 55 | 64 | 48 |
| Number of hours above 30°C | 51 | 50 | 43 | 51 | 39 |

**Notes:** duration of simulations: Temperatures above 28°C are highlighted in yellow, Temperatures above 30°C are highlighted in amber.

### 5.1. Evaluation of the risk of overheating

The applicability and limits of various standards (such as the CIBSE, the BSEN15251 and ASHRAE Standard 55 thermal comfort models) used for evaluation of the performance of spaces and the summary of the standards have been presented in existing research (Adekunle and Nikolopoulou, 2016; Giridharan, 2017; Adaji et al., 2019). The results on the evaluation of the risk of overheating of this study using the CIBSE, EN16798 and ASHRAE models are presented below.

#### The Static CIBSE comfort model for measured and predicted data

The study showed that extreme overheating is noted during the dry period in all (100%) of the spaces (living areas and bedrooms) during the physical measurements in Lugbe and Dutse Alhaji. A similar finding is noted in the simulation as overheating is reported in 100% of the spaces at Lugbe and Bwari. The tables highlight the percentage of hours that exceeded 28ºC in the living areas during the day and evening as well as night-time in the bedrooms. In Lugbe and Bwari, the study revealed that simulated temperatures were above 28ºC for more than 1% of the time in all (100%) of the living areas. The research also showed that temperatures exceeded 28ºC above 1% of the time in 100% of the bedrooms in Lugbe and Bwari during the sleeping hours.

#### The EN16798-1 dynamic adaptive comfort model for measured and simulated temperatures

The measured and simulated temperatures during the day, and evening, in the naturally ventilated living areas in Lugbe exceeded the Cat. II upper benchmark for over 5% of the time. The simulated temperatures were almost the same percentage of the time as the outcomes obtained from the physical measurements. The study revealed occupants are susceptible to warm discomfort for a longer period in the dry season in Lugbe. The results showed warm discomfort also occurs in the naturally ventilated living area in Bwari. The findings agree with the outcomes of the evaluation of the overheating risk over the same timeline when measured temperatures were assessed. The outcomes also showed that the measured spaces are warmer than simulated spaces. The research also showed extreme indoor thermal conditions during the day, and evening, at Lugbe. The night-time analysis of the adaptive comfort in Lugbe revealed that temperatures exceeded the Cat. II upper benchmark. In comparison to the simulated internal temperatures for Lugbe and Bwari, the results showed extreme indoor thermal conditions during the day and evening. The results showed warm discomfort also occurs in the naturally ventilated living area. In the bedroom, the temperature exceeded the Cat. II upper benchmark for over 5% of the time showing warm discomfort occurs at night (Table 10.6).

**ASHRAE 55-2020 adaptive comfort model for measured and simulated temperatures**

The data from the study shows that none of the monitored spaces had thermal conditions that fall within the comfort zone of ASHRAE-55. The comfort zones for 80% acceptability were at 28.0–28.8◦C. The adaptive comfort range of the study area is wider than that of ASHRAE-55, and vice-versa in warm months, as such, it does not comply with ASHRAE Standard 55-2020. For the calculated temperatures during the same survey period and the whole dry season from February to April, all the spaces did not comply with the standard, thus aligning with the measured data. This is in contrast however with the data from the living room spaces it complied with ASHRAE Standard 55-2020 and the occupants were predicted to fall into the 80% acceptability mark to be neutral about their thermal environment.

Overall, the measured and predicted temperatures indoor temperatures exceeded the thresholds of moderately warm overheating risk. The predicted overheating risk results also show that the naturally ventilated living room and bedroom spaces in all case studies were warmer than the air-conditioned space for the daytime, evening, and night-time periods. The results agree with the monitored overheating results.

## 6. Results and Discussions

For the total duration of the survey, the study revealed that the mean indoor temperature varied from 30.3°C-31.1°C (Table 4). The measured mean temperatures for the hours of occupation in the living room spaces from 08:00-22:00 ranged from 31.7°C-34.2°C, while the measured mean temperature of the bedroom across all case studies recorded from 23:00-07:00. This suggests that the residents in the dwellings are experiencing warm conditions for sustained hours above EN16798-1 Cat II and Cat III thresholds for more than 80 hours across all case studies. The average indoor dew-point temperatures in all the spaces were between 11.7°C and 21.8°C. The mean indoor RH ranged from 29% to 61%. The mean air velocity of about 0.1 m/s.

On one hand, the results showed that higher mean temperatures were calculated in the naturally ventilated spaces in the dwellings agreeing with the measured results. On the other hand, lower mean temperatures were calculated in the air-conditioned living rooms in contrast to the high temperatures measured in the corresponding spaces. This contrast can be attributed to the respondents limited use of the air-conditioned units in the dwellings due to lack of electricity and high energy bills as indicated by the respondents during the survey period. Hence, may contribute to the higher temperatures reported in the spaces than the values calculated in the corresponding spaces. The study revealed that the temperatures were within the range of at least 2°C in all the naturally ventilated spaces. The findings also showed that a change in outdoor temperature results in temperature swings in the indoor spaces, especially in the LGH1. The observations made during the study showed that other design factors such as number and size of openings, building materials used (i.e. structural sandcrete hollow blocks), as well as the window to-wall ratio, might contribute to higher temperatures reported in the dwellings.

For the calculation of the stress indices, the following input parameters were applied to the mathematical models. The mean indoor air velocity of 0.1 m/s was considered for the calculation. Also, the mean metabolic rate was 1.0 met. The results revealed that higher mean indices were mostly computed in the naturally ventilated spaces when compared to the air-conditioned spaces. Similarly, the reported mean sensation in all the dwellings were on the 'warm' part of the scale for the measured spaces. However, the predicted mean sensation values in other spaces that were calculated were on the 'slightly warm' or 'warm' part of the scale, except for the air-conditioned spaces in the living rooms that were on the 'neutral' part of the scale. (Table 4 and 5). The findings on the mean AT showed that the measured spaces recorded heat indices above 33°C (Table 6). For the whole dry season simulation from February to April, the calculated AT showed temperatures were above 30°C, apart from the air-conditioned spaces that showed temperatures ranging from 26°C-29.6°C.

The observations made during the survey showed that microclimatic variables such as wind speed, solar radiation, surrounding vegetation might contribute to higher AT values than other indices considered in this study. The current study indicated that the occupants are subject to heat stress within the spaces in dry season. The occupants may be vulnerable to heat stress in some of the spaces (particularly in all the naturally ventilated spaces) during extreme dry season or heat wave than the remaining spaces. The results in the spaces during the survey showed the indices were within the same range with higher indices (at least 4°C) reported throughout the day. Regulation of energy consumption during the occupied, non-use of air-conditioning and the use of sliding windows that opens only 50% at its maximum use in the daytime/ evening periods may contribute to higher heat indices reported at the dwellings than the night-time periods. The PMV values for ASHRAE-55 and EN16798-1 were within the same range. Applying the ASHRAE-55 PPD and EN16798-1 PPD models to calculate the percentage of people that were satisfied with the thermal environment of the case study, the results revealed that more than 60% - 90% of the occupants were dissatisfied. The results aligned with the findings presented in the existing studies (Adaji et al., 2020) on thermal comfort in residential buildings. The mean values for temperature, RH, heat indices, PMV, and PPD for ASHRAE-55 and EN16798-1 are presented in Tables 15, 16 and 17.

Table 4. Mean values of indoor parameters measured in the spaces during the survey period

| **Variables** | **Mean temp (°C)** | **Mean Dew-point temp (°C)** | **Mean RH (%)** | **Mean WGBT (°C)** | **Mean UTCI (°C)** | **Mean AT (°C)** | **Mean PPD (%)** | **Mean PMV** | **Mean SET (°C)** | **% of hours above 28°C** | **% of hours above 30°C** | **Predicted Mean sensation (ASHRAE-55)** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **LGH1: Living room (08:00-22:00)** | **32.4** | **19.5** | **48** | **26.6** | **33.0** | **36.2** | **91** | **2.38** | **31.7** | **100** | **89** | **Warm** |
| **LGH2: Living room. (08:00-22:00)** | **31.7** | **20.5** | **52** | **26.4** | **32.6** | **35.8** | **83** | **2.16** | **31.3** | **100** | **98** | **Warm** |
| **DAH1: Living room) (08:00-22:00)** | **33.3** | **11.7** | **29** | **24.5** | **32.6** | **34.1** | **93** | **2.48** | **31.0** | **100** | **99** | **Warm** |
| **DAH2: Living room (08:00-22:00)** | **34.2** | **14.3** | **32** | **25.7** | **33.9** | **35.8** | **98** | **2.89** | **32.0** | **100** | **100** | **Hot** |
| **LGH1: Bedroom (23:00-07:00)** | **32.1** | **19.9** | **49** | **26.4** | **32.8** | **35.9** | **88** | **2.28** | **31.5** | **100** | **95** | **Warm** |
| **LGH2: Bedroom (23:00-07:00)** | **30.2** | **21.8** | **61** | **26.2** | **31.6** | **35.0** | **61** | **1.68** | **30.4** | **87** | **62** | **Warm** |
| **LGH1: Living room (08:00-22:00)** | **31.9** | **13.3** | **35** | **24.2** | **31.4** | **33.3** | **78** | **2.03** | **30.2** | **100** | **98** | **Warm** |
| **LGH2: Living room. (08:00-22:00)** | **31.7** | **14.7** | **38** | **24.5** | **31.4** | **33.5** | **76** | **1.99** | **30.2** | **100** | **86** | **Warm** |

**Notes:** Temperatures above 28°C are highlighted in yellow. Temperatures above 30°C are highlighted in amber.

Table 5. Mean values of indoor parameters calculated in the spaces during the survey period using the 2000s TMY3 weather file

| **Variables** | **Mean temp (°C)** | **Mean Dew-point temp (°C)** | **Mean RH (%)** | **Mean WGBT (°C)** | **Mean UTCI (°C)** | **Mean AT (°C)** | **Mean PPD (%)** | **Mean PMV** | **Mean SET (°C)** | **% of hours above 28°C** | **% of hours above 30°C** | **Predicted Mean sensation (ASHRAE-55)** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **LGH1: Living room (08:00-22:00)** | **32.0** | **16.2** | **41.2** | **25.0** | **31.6** | **34.1** | **78** | **2.03** | **30.4** | **100** | **72** | **Warm** |
| **LGH2: Living room. (08:00-22:00)** | **27.1** | **15.1** | **53** | **21.3** | **25.8** | **27.7** | **8** | **0.41** | **26.3** | **44** | **10** | **Neutral** |
| **DAH1: Living room) (08:00-22:00)** | **30.8** | **19.8** | **53** | **25.7** | **31.6** | **34.6** | **68** | **1.82** | **30.4** | **93** | **62** | **Warm** |
| **DAH2: Living room (08:00-22:00)** | **25.9** | **14.4** | **60** | **25.3** | **21.3** | **27.3** | **5** | **-0.30** | **25.2** | **19** | **3** | **Neutral** |
| **LGH1: Bedroom (23:00-07:00)** | **31.6** | **16.3** | **43** | **24.9** | **31.3** | **33.8** | **77** | **2.01** | **30.5** | **88** | **65** | **Warm** |
| **LGH2: Bedroom (23:00-07:00)** | **30.4** | **17.8** | **49** | **24.7** | **30.5** | **33.2** | **57** | **1.6** | **29.7** | **73** | **56** | **Warm** |
| **DAH1: Bedroom (23:00-07:00)** | **30.9** | **20.0** | **55** | **25.9** | **31.6** | **34.8** | **71** | **1.88** | **30.7** | **83** | **57** | **Warm** |
| **DAH2: Bedroom (23:00-07:00)** | **29.0** | **19.0** | **56** | **24.4** | **29.5** | **32.3** | **33** | **1.16** | **28.6** | **65** | **29** | **Slightly warm** |

**Notes:** Temperatures above 28°C are highlighted in yellow. Temperatures above 30°C are highlighted in amber.

Table 6. Mean values of indoor parameters calculated in the spaces from February – April using the 2000s TMY3 weather file

| Variables | Mean temp (°C) | Mean Dew-point temp (°C) | Mean RH (%) | Mean WGBT (°C) | Mean UTCI (°C) | Mean AT (°C) | Mean PPD (%) | Mean PMV | Mean SET (°C) | % of hours above 28°C | % of hours above 30°C | Predicted Mean sensation |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| LGH1: Living room (08:00-22:00) | 32.1 | 15.6 | 40 | 25.0 | 31.8 | 34.1 | 84 | 2.16 | 30.7 | 94 | 77 | Warm |
| LGH2: Living room. (08:00-22:00) | 26.8 | 14.6 | 54 | 21.0 | 25.3 | 27.1 | 7 | 0.30 | 25.6 | 38 | 11 | Neutral |
| DAH1: Living room) (08:00-22:00) | 30.4 | 17.3 | 49 | 24.7 | 30.5 | 33.2 | 57 | 1.62 | 29.7 | 81 | 59 | Warm |
| DAH2: Living room (08:00-22:00) | 25.6 | 14.4 | 56 | 20.4 | 24.6 | 26.0 | 5 | -0.13 | 24.8 | 16 | 2 | Neutral |
| LGH1: Bedroom (23:00-07:00) | 28.5 | 16.4 | 54 | 22.8 | 27.9 | 30.3 | 14 | 0.95 | 27.9 | 81 | 59 | Slightly warm |
| LGH2: Bedroom (23:00-07:00) | 26.9 | 17.9 | 63 | 22.9 | 27.1 | 29.6 | 9 | 0.43 | 26.5 | 64 | 43 | Neutral |
| DAH1: Bedroom (23:00-07:00) | 28.0 | 16.5 | 55 | 22.9 | 27.8 | 30.0 | 17 | 0.77 | 27.8 | 71 | 48 | Slightly warm |
| DAH2: Bedroom (23:00-07:00) | 27.0 | 15.5 | 52 | 22.2 | 27.0 | 29.0 | 8 | 0.36 | 26.2 | 53 | 22 | Neutral |

**Notes:** Temperatures above 28°C are highlighted in yellow. Temperatures above 30°C are highlighted in amber.

As outlined in the existing research, psychrometric analyses were also considered using the PMV method of ASHRAE-55 and EN16798-1 to understand the comfort zones during the period of the survey and various hours of occupation and non-occupation (Table 4 and 5). The results showed higher values of the computed variables were obtained during the extended hours of occupation (08:00-22:00) than the other periods considered in this study. The results revealed that occupants' comfort should also be taken into consideration during the regular hours of occupations for various users in residential buildings and other developments. The relationships between the indices, RH, outdoor and mean temperatures in all the dwellings were considered (Figure 1a). The outcomes revealed that associations exist between the indices, RH and mean temperatures. Similar results were also found between the variables when whole dry season simulated data from February-April were assessed (Figure 1b). The study showed an increase in the mean temperature significantly influences the indices especially AT and UTCI.

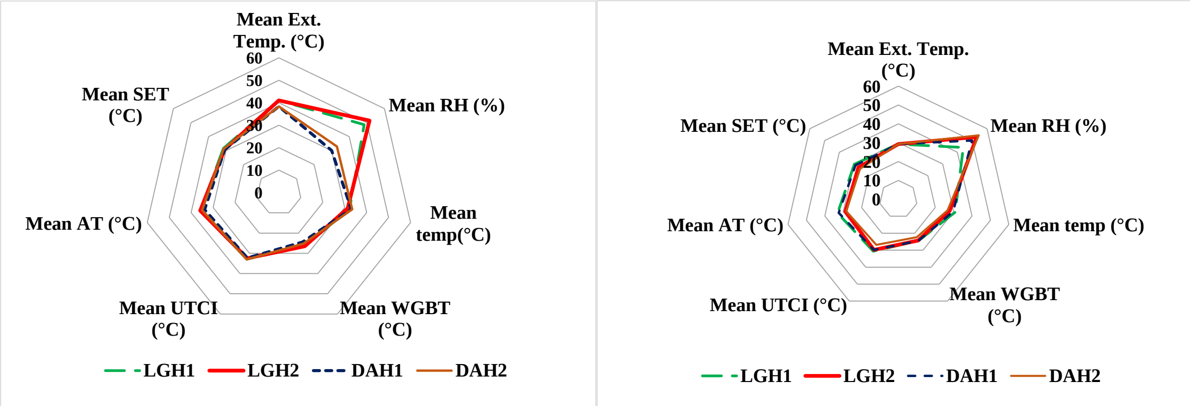


**Figure 1**: Charts showing the influence of External temperature, RH on mean indices and links between mean temperatures and mean indices during the period of the survey (left) and simulated whole dry season from February-April (Right).

The variables were also assessed using the adaptive approach. The results were compared by applying the ASHRAE-55 and EN16798-1 thermal comfort categories to evaluate the comfort temperatures and the risk of overheating within the spaces in the dry season. The results revealed the occupants were uncomfortable in dry season. The temperatures were not within the ASHRAE-55 and EN16798-1 applicable lower and upper limits for acceptable and comfort thresholds throughout the survey. The temperatures rose above the appropriate limits of both models (ASHRAE-55 and EN16798-1) for more than 5% of the total hours when different periods were considered. Additionally, when the CIBSE adaptive method of TM52 for assessing the risk of overheating in buildings was applied, all of the spaces were overheated. However, the study found out that occupants' comfort in the first few hours during the occupied hours should be a critical concern as additional energy would be required to adjust and improve the thermal environment of the development like using fan air and air-conditioning for cooling, in addition to occupants removing the top layer of their clothing. Considering all the applicable limits of the thermal comfort categories, higher values were computed in naturally ventilated spaces compared to the air-conditioned spaces, especially for the simulated spaces

Also, the comfort temperature within the spaces considered in this study was at least 3.0°C higher than the comfort temperature calculated from the adaptive models. The finding aligns with the outcome presented in the existing research (Efeoma and Uduku, 2016; Djongyang et al., 2012). Comparing the results of this research with the existing research on thermal comfort in residential buildings and other buildings, the mean temperature reported in this study was higher than the values reported in existing research.

The results revealed higher mean AT, UTCI, SET, and WBGT are predicted during the measurements for the monitoring period, the highest AT, WBGT and UTCI are predicted in the naturally ventilated dwelling LGH1 (Table 4). Regarding the simulations that considered the same period of measurements and the meteorological warm dry season months (February-April), the highest heat indices are predicted in LGH1 when the 2000s TMY3 weather file are considered (Table 5 and 6). The results showed 'moderate heat stress' to 'Strong heat stress' is predicted in all the measured spaces when WBGT indices was considered.

## 7. Conclusions

The study evaluated the performance, occupant comfort, apparent temperature (AT), and other indices of a residential building in warm dry season. In the warm dry season, the mean temperatures in the living spaces and bedrooms ranged from 31.7°C-33.6°C during the field survey at different periods. The occupants were found to be uncomfortable in the thermal environment based on physical assessments of environmental variables.

The PMV range and projected thermal sensation revealed that the occupants were uncomfortable, with around 80% of users not satisfied with the thermal environment. When the ASHRAE-55, CIBSE TM52, and EN16798-1 adaptive thermal models were used, the temperatures were not within acceptable comfort ranges. The study demonstrated that thermal comfort standards may be used to determine the danger of overheating in buildings throughout the summer. The results of the investigation show that the AT indices are consistent with the projected thermal sensation within the spaces at various times. The AT indices were higher than the UTCI, WBGT, and SET indices. The AT, UTCI, and SET indices had mean values ranging from 31.5°C to 35.5°C, while the WBGT had mean values ranging from 23.9-25.8°C.

The findings show that overheating and heat stress is predicted within the spaces during the warm dry season. The study suggests that different designers should incorporate heat stress analysis as well as thermal comfort evaluations to evaluate suitable interventions and local sustainable building materials to improve the thermal environment. The increased temperatures reported in the spaces could be due to a variety of design elements such as direction, construction materials (i.e. use of SSHB in this case study) and methods.

The study suggests that more research be done on occupants' comfort and stress indices in residential dwellings constructed with structural sandcrete hollow block (SSHB) and other building materials over long periods of time during the dry season to better understand what changes occupants can make to remove unwanted heat from the thermal environment. It is anticipated that this research can help the Nigerian government discuss and implement new legislation to improve the resilience of buildings in the region, to make informed and far-reaching decisions and policies, based on the need to passively, and simply, protect populations from the growing impacts of the changing climate.

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# A field investigation on thermal comfort in free-running school buildings during the summer season in the temperate climate of Nepal

**Mishan Shrestha[1] and H.B. Rijal[2]**

[1, 2] Graduate School of Environmental and Information Studies, Tokyo City University, Japan, 3-3-1 Ushikubo-nishi, Tsuzuki-Ku, Yokohama, Kanagawa 224-8551
Correspondence email: born2winmission123@gmail.com

**Abstract:** A healthy indoor environment is crucial for students' academic performance and health in schools. Nepal has dynamic environmental conditions according to geography and climate. The school buildings designed in these areas do not use any heating or cooling devices to maintain the thermal environment and, thereby, thermal comfort. As no serious concerns were raised about students' thermal comfort, this study examined the current condition of students' thermal comfort in school buildings in the temperate climatic region of Nepal, aiming to address how sensitive students are to temperature variations inside the school buildings. A survey was conducted on the indoor thermal environment and the associated thermal comfort survey was administered to 246 secondary level students between 12 to 18 years of age, 40% (n = 101) males and 60% (n = 145) females, in seven classrooms in three free-running schools during the summer season in 2019. They voted three times during the regular lecture: in the morning, midday, and afternoon. Under the free-running condition, the indoor globe temperatures were close to the outdoor air temperatures, and the indoor and outdoor water vapor concentrations were correlated with each other. The results showed that approximately 64% of the student's responses were within the central comfort zone of ASHRAE, indicating a preference for a cooler indoor environment. The Griffiths method predicts that the student's mean comfort temperature is 26.9 °C. This study explored the adaptive thermal comfort of students in free-running school buildings in Nepal during the summer.

**Keywords:** School building, free-running, students, thermal comfort, comfort temperature, adaptive behaviours

## 1. Introduction

Thermal comfort is one of the major indicators of indoor environmental quality, especially in school buildings. Thermal adaptation, human behaviours, and the use of the heating-cooling system are the most commonly used activities to optimize thermal comfort in the built environment. The former two cases are dominant in the buildings in developing countries like Nepal, which are free-running (naturally ventilated) with no heating and cooling devices. In free-running classrooms, the cognitive aspect of students' thermal perception could be different from that of those in air-conditioned classrooms. Depending on the variation of the outdoor local climate, the perception of the students is also different. This could be identified by the fundamental concept of adaptive principle; “If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort” (Nicol & Humphreys 2002). Psychologically, they could be prepared to face and adapt to higher or lower temperatures using behaviours. The behaviour may be either personal or environmental (Nicol & Humphreys 2012). Generally, it is not easy to use fully adaptive behaviour in school buildings because of the constraints exposed in schools, such as the dress code and other shifting activities.

School buildings are a specific type of building where more students are accommodated for an extended time. The thermal comfort perceived by students could be different as they tend to become passive recipients, creating comfortable conditions (de Dear et al. 2020). Thermal comfort studies have been conducted in temperate (Teli et al. 2012), sub-tropical (Kim & de Dear 2018), tropical (Hamzah et al. 2018), Mediterranean (Corgnati et al. 2009), and hot humid climates (Liang et al. 2012). They have identified the comfort temperature; an adaptive model that identifies the thermal comfort condition in school buildings in those respective areas.

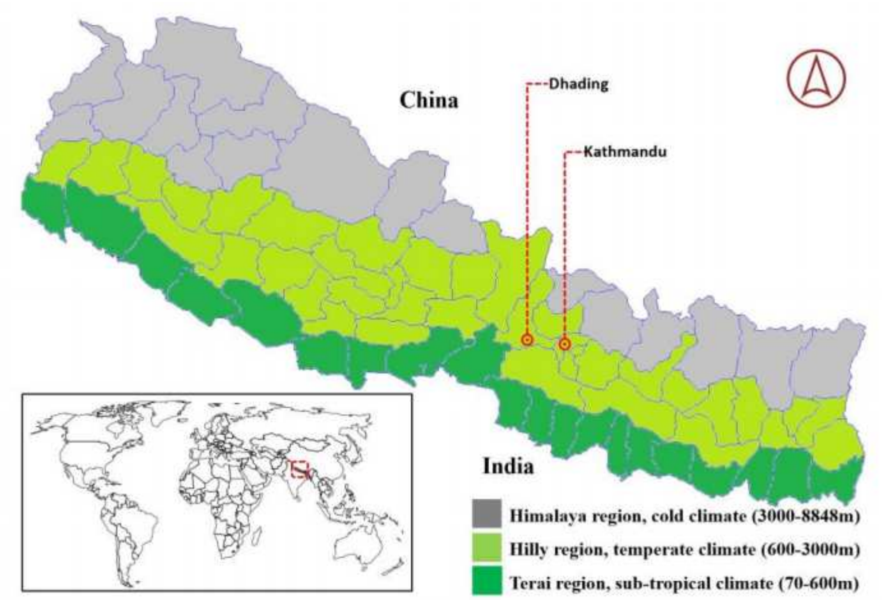
The development of effective infrastructure in most school buildings in Nepal, for example, the installation of building envelopes with insulation, which should play an important role in maintaining the classroom environment for thermal comfort within a desirable condition, has not yet been made (Shrestha et al. 2021). Mostly, they are constructed based on a community-driven approach without considering the effect of outdoor thermal environmental conditions on an incremental and non-engineering basis (Anwar et al, 2016), which lacks appropriate insulation levels in walls or roofs, ventilation, solar control, and other important thermal comfort features; they do not have mechanical heating and cooling systems. What would be the thermal environment and thermal comfort in those buildings? Through the literature, we came to know that even a systematic study has not been conducted to study thermal comfort in those during the summer. Thus, it is necessary to carry out thermal comfort studies in school buildings so that the impact of the thermal environment can be known for the improvement of the indoor thermal environment. To fill up the research gap and to answer the above-mentioned questions, this study was conducted. This paper aims to analyze the thermal environment, the thermal comfort of the students, and how students are adapting and maintaining their thermal comfort under the free-running condition during the summer in the school buildings in Nepal.

## 2. Methodology

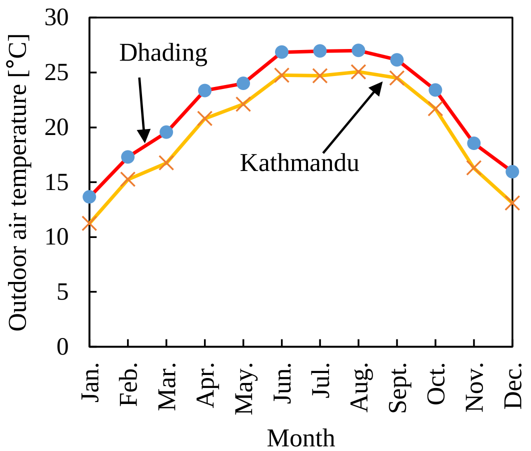
The methods cover field surveys of measurement and questionnaires. The field survey collects the thermal responses of students, building information, and indoor and outdoor thermal environmental quantities, which are used to understand the thermal condition.

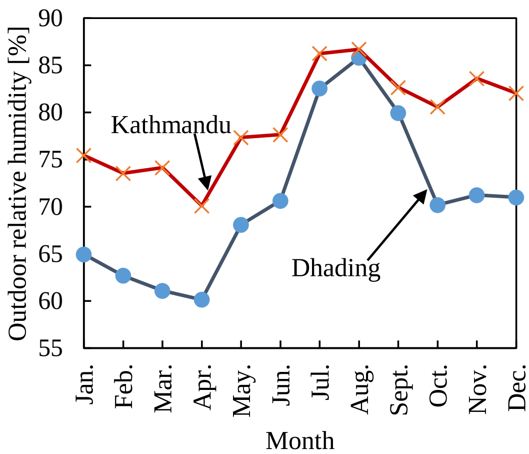
### 2.1. Description of geography, climatic condition, and buildings

Due to its geography and altitude variation, Nepal has an extremely varied climate from south to north. The country is divided into three topographic regions: the north is mountainous Himalayan with a cold climate, the middle is hilly with a temperate climate, and the south is Terai with a subtropical climate. The temperate climate is the most dominant climate type, with a dry winter and hot summer. Fig. 1 (a) shows the location of the investigated school buildings in a temperate climate on the map of Nepal. The outdoor air temperature in this area generally, decreases in October, reaching its minimum in January. June to September are the months with the hottest temperatures, rainfall, and high humidity. The relative humidity from June to September ranges between 70 and 83% (Shrestha et al. 2021). Fig. 1 (b, c) shows the variation in the monthly mean outdoor air temperature and humidity of the investigated areas. A series of field studies were carried out in three different school buildings, one in Kathmandu (S1) and two in Dhading district (S2 and S3). Fig. 1 (d, e, f) shows the general view of the school building and classrooms of S1, S2, & S3. All the buildings are uninsulated and naturally ventilated (free-running) by keeping windows and doors open. They were made of bricks, and the inner and outdoor wall surfaces were finished with mortar and plaster.




(a)




(b) (c)

(d) (e) (f)

Figure 1. (a) Location of the study areas, (b) Monthly mean outdoor air temperature, (c) monthly mean relative humidity, (d) outdoor view of the school building (S1), (e) study classroom (S2), and (f) study classroom (S3)

## 2.2. Thermal environmental measurement

The measurement of environmental quantities such as air temperature, globe temperature, and relative humidity was performed indoors and outdoors continuously in classrooms of all school buildings from May 21$^{st}$ to July 12$^{th}$, 2019 (from the 29th for S1). The data was recorded automatically at 10-minute intervals. The indoor measurement was performed at the center of each classroom away from the windows and doors at the height of approximately 1.1 m, minimizing the influence of the students nearby. Outdoor measurement sensors of the data logger were protected from the direct effect of sunlight and moisture sources. Table 1 shows the characteristics of the data loggers used. The purpose of using a black-painted globe thermometer with a 75 mm diameter in this study is that it has a higher response time for temperature measurement (Nicol 2012).

Table 1. Characteristics of the data logger used

| Description | Temperature-humidity sensor (TR-74Ui) | | Globe thermometer (TR-52i) | Anemometer Kanomax 6501 |
|---|---|---|---|---|
| Sensor | Thermistor | Polymer-resistance | Thermistor | Hotwire |
| Measurement range | 0 to 55 °C | 10 to 95%RH | -60 to 155 °C | 0.01 to 5 m/s |
| Accuracy | ±0.5 °C | 5%RH [at 25 °C, 50%RH] | ±0.3 °C | ±0.02 m/s |
| Resolution | 0.1 °C | 1%RH | 0.1 °C | 0.01 m/s |
| Response time (90%) | Approx. 7 min. | Approx. 7 min. | Approx. 80 sec. | Approx. 7 sec. |

### 2.3. Thermal comfort survey

In conjunction with the measurement of environmental quantities, subjective responses to environmental perception were asked. Altogether, 246 secondary level school students, 40% (n = 101) males, and 60% (n = 145) females participated in the whole survey, ranging in age from 12–18 years. Altogether, seven classrooms in three school buildings were visited. A seven-point thermal sensation and a five-point preference scale with Nepalese language translation were used (Rijal et al. 2010). The students were questioned about their thermal sensations and preferences as shown in Table 2. Besides the students' responses, their adaptive behaviours were also asked. In total, 737 responses were collected for each question. They voted in sedentary conditions without intervening in the regular lesson. Fig. 2 shows the timeline of the thermal comfort survey and environmental measurement in each classroom.

Table 2 Scales used for thermal comfort survey

| Scale assigned | Thermal sensation | Thermal preference |
|---|---|---|
| 1 | Very cold | Much warmer |
| 2 | Cold | A bit warmer |
| 3 | Slightly cold | No change |
| 4 | Neutral | A bit cooler |
| 5 | Slightly hot | Much cooler |
| 6 | Hot | |
| 7 | Very hot | |

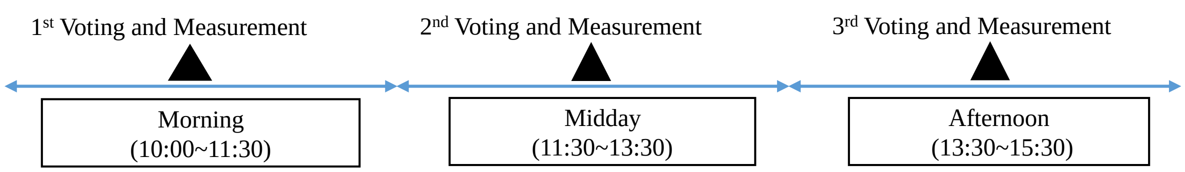



Figure 2. The procedure of questionnaire survey and environmental measurements.

## 3. Results and discussion

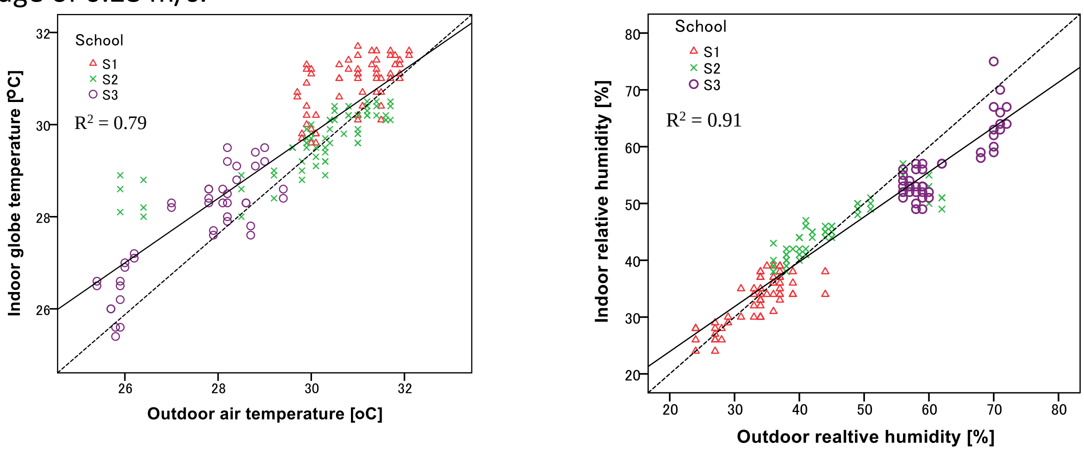
### 3.1. Thermal environment during the voting time

Environmental quantities such as temperature and relative humidity were measured in order to observe the thermal environmental conditions. The globe temperature was measured, as it represents the combined effect of radiation from indoor surfaces and the convection of space air. The measured indoor air and globe temperatures were quite close and did not vary much. Figure 3 (a) shows the relationship between the continuously measured indoor globe temperature and the outdoor air temperature during the voting time in each school building. The indoor globe temperature in S1 lies between 29.6 and 31.5 °C while the outdoor air temperature is between 29.7 °C and 32.1 °C. Both indoor globe and outdoor temperatures displayed a similar pattern of variation, as this must be due to the zinc roof and its effect on the indoor thermal environment in S1. The indoor and outdoor temperatures differed among buildings due to their architectural characteristics, orientation, geography, climatic conditions, and so on.

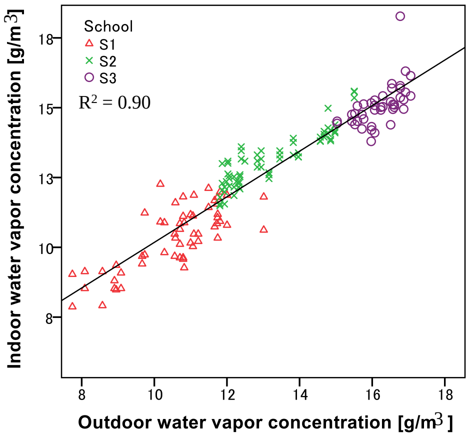
Fig. 3 (b) shows the variation of measured indoor and outdoor relative humidities in each school building. The indoor relative humidity follows the outdoor relative humidity. Among all school buildings, S1 and S3 have the lowest and highest relative humidity, respectively. The outdoor relative humidity lies between 24 and 44% and indoors between 27 and 39% during regular lessons during the survey time in S1. The high correlation value of temperature or humidity showed that the students are probably facing an indoor environment similar to an outdoor one.

Relative humidity cannot tell the moisture level for comfort and indoor air quality. Therefore, using the continuously measured air temperature and relative humidity, indoor and outdoor water vapor concentrations were calculated (Shukuya 2019). Fig. 3 (c) shows the relationship between the indoor and outdoor water vapor concentrations, indicating that they show a similar trend of variation. They fluctuated mostly between 8 and 18 g/m$^3$. The mean indoor and outdoor water vapor concentrations are 12.6 and 13 g/m$^3$, respectively. The indoors is higher during the daytime. This is because of the activities of the students and the moisture generated by respiration during the day. The higher the indoor air temperature, the more water vapor that the air can hold.

The measured average air velocity was between 0.19 to 0.37 m/s with an overall average of 0.28 m/s.




(a) (b)




(c)

Figure 3. Measured environmental quantities during the voting time in S1, S2, & S3 buildings: (a) indoor globe temperature and outdoor air temperature, (b) indoor and outdoor relative humidity, and (c) indoor water vapor concentration and outdoor water vapor concentration.

### 3.2. Thermal sensation and preference

This section examines students' perceptions of the thermal environment mentioned in the previous section 3.1. Fig. 4 (a, b) shows the overall distribution of thermal sensation and preference of the students in all three investigated school buildings. It shows that 75.9% of the responses were on the hotter side (responses for 5, 6, & 7), with most preferring a cooler environment. The results showed that 63.6% of the student's responses were within the central three categories (responses for 3, 4, and 5), which is representative of satisfaction and acceptance. Overall, the preference for "3. No change" was 21.8%. The responses of 75.8% were obtained towards the preference for cooler. The significant number of responses on the hotter side is probably due to unacceptable thermal environmental conditions in the classrooms. The reduction of the indoor temperature should be necessary to change the responses of the students toward the comfort side.

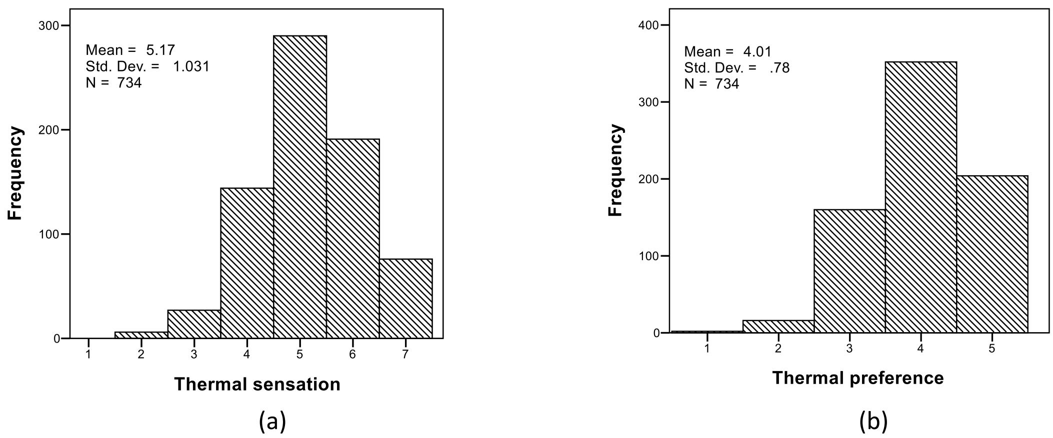
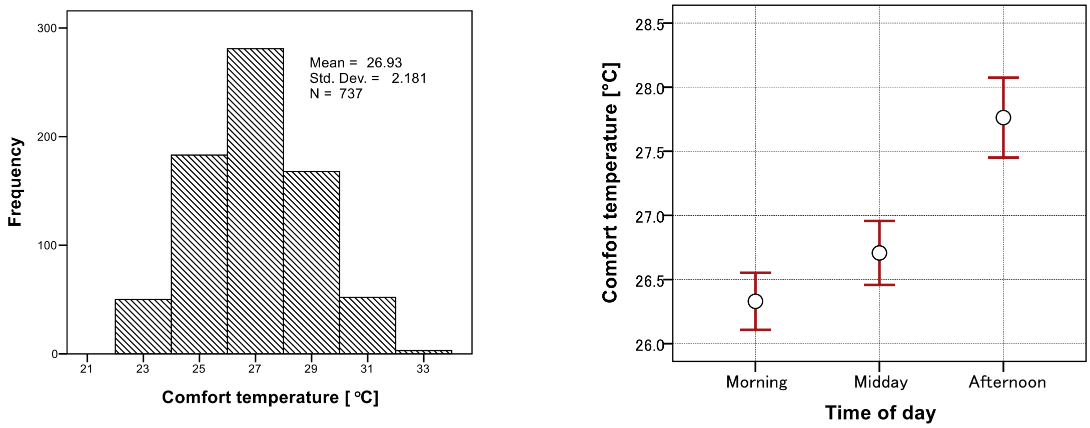



Figure 4. Overall distribution of (a) thermal sensation and (b) preference

### 3.3. Estimation and analysis of comfort temperature

The average comfort temperature of the students, based on their thermal sensation and measured indoor globe temperature, was estimated using the Griffiths method with a Griffiths constant of 0.50, which can estimate the individual comfort temperature (Griffiths

1990, Humphreys et al. 2013, & Shrestha et al. 2021). In the Griffiths method, it is assumed that there is no thermal adaptation of the occupants, therefore 0.5 is used to account for the effect of thermal adaptation (Nicol et al. 2012 & Jowkar et al. 2020). There is a negligible difference in comfort temperature even if the other Griffiths constants (0.25, 0.33) are used. Fig. 5 (a) shows the distribution of comfort temperature whose average is 26.9 °C. S1 school in Kathmandu has a higher average comfort temperature than S2 and S3 schools: 28 °C, 27.5 °C, and 25.5 °C, respectively. The S3 school is significantly lower than the remaining ones. Overall, the comfort temperatures are distributed over a wide range, but the values are mostly between 25 °C and 29 °C. These values are close to the findings of the studies conducted in naturally ventilated schools in temperate, hot-humid, and Mediterranean climates during the hot seasons (Shrestha et al. 2021, Talukdar et al. 2020, Heracleous & Michael. 2020, & Liang et al. 2012). An analysis made on adaptive thermal comfort by Humphreys et al, 2013 found that comfort achievement is possible in a free-running condition within a range of prevailing mean outdoor temperature from 10 to 30 °C. The comfort temperature perceived by the students is higher, which must be because of their greater status of adaptation and tolerance to the indoor thermal environment.
Fig. 5 (b) shows the error bar of comfort temperatures (Mean ± 2S.E.). Mean comfort temperatures estimated in the morning, midday, and afternoon are 26.3°C, 26.7°C, and 27.8°C, respectively. An independent sample T-test is applied to compare these estimated mean comfort temperatures. A statistically significant difference in comfort temperature is confirmed for the three-time periods ($p<0.001$). This must be because of the variation in the thermal environmental condition of the classroom due to varying outdoor environmental conditions throughout the day. Fanger et al. (1974) found no significant difference between ambient temperatures preferred by subjects in the morning and the evening, and they concluded that the same thermal comfort conditions can be used from morning to evening, which is contrary to the present study.




(a) (b)

Figure 5. (a) Distribution of comfort temperature (b) Comfort temperature with 95% confidence interval in the morning, midday, and afternoon

### 3.4. Relationship between comfort temperature and outdoor air temperature

The ASHRAE adaptive model (ASHRAE 2017) defines how the comfort temperature of occupants corresponds to the outdoor air temperature. Fig. 5 shows the morning, midday, and afternoon plots of comfort temperatures on the ASHRAE adaptive model. Most of the comfort temperatures are within the 80% acceptability limit range. However, the comfort temperature falls beyond the upper limits at higher outdoor temperatures during the day. This shows that students are showing wider adaptability behaviours to indoor temperatures.

Table 3 presents the adaptive thermal comfort equations given by previous systematic studies conducted in naturally ventilated buildings in different climates of Nepal. The adaptive slope of this study is close to the study conducted by Shrestha et al. 2021 in school buildings. Singh et al. 2019 found the adaptive comfort slopes of 0.22, 0.47, and 0.30 for primary, secondary, and university classrooms, respectively, which showed that the slope of the secondary level students is similar to that in our study. The difference in adaptive slope could be due to the thermal adaptation in the classrooms and its effect on students' perceptions.

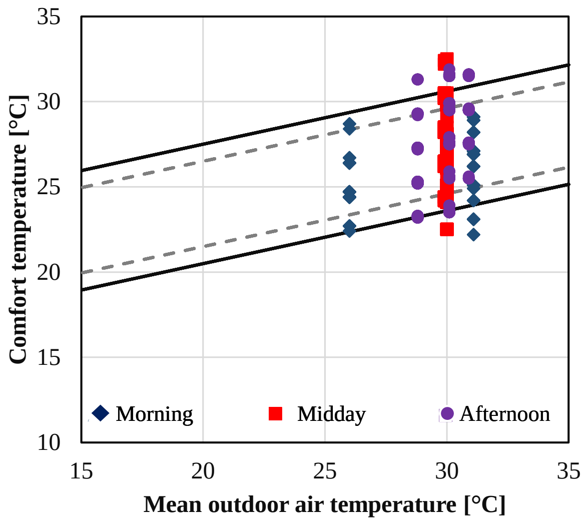



Figure 6. Comparison of comfort temperature with the ASHRAE adaptive model

Table 3 Summary of adaptive thermal comfort studies in Nepa

| References | Climate | Buildings | Survey period | Adaptive comfort model |
|---|---|---|---|---|
| Gautam et al, 2019 | Cold, temperate, & sub-tropical | Traditional | Winter | $T_c = 0.62T_o + 7.6$ |
| Pokharel et al, 2020 | Cold, temperate, & sub-tropical | Residential | Winter | $T_i = 0.49T_{om} + 4.8$ (cold)<br>$T_i = 0.45T_{om} + 9.1$ (temperate)<br>$T_i = 0.86T_{om} + 2.8$ (sub-tropical) |
| Shahi et al, 2021 | Cold, temperate, & sub-tropical | Residential | Winter | $T_c = 0.53T_{om} + 10.6$ (sub-tropical) |
| Gautam et al, 2020 | Sub-tropical | Residential | Summer | $T_c = 0.46T_o + 14.1$ (local people)<br>$T_c = 0.66T_o + 7.5$ (migrant people) |
| Shrestha et al. 2021 | Temperate | School | Autumn | $T_c = 0.50T_o + 13$ |
| This study | Temperate | School | Summer | $T_c = 0.54T_o + 10.86$ |
| Rijal, 2021 | cold | Traditional | Winter | $T_c = 0.81T_{rm} + 4.4$ |

$T_c$: Comfort temperature [°C], $T_o$: Outdoor air temperature [°C], $T_g$: mean globe temperature [°C], $T_{om}$: Mean monthly outdoor temperature [°C], $T_{rm}$: Outdoor running mean temperature, $T_i$: indoor air temperature [°C]

### 3.5. Adaptive behaviours of students

Students were asked to answer the behaviours they use to adapt or adjust to the indoor thermal environment of the classrooms. They were instructed to specify and write down the other control used by them if was not specified in the questionnaire. The responses to a couple of activities were obtained. Figure 7 shows the behaviours used for adaptation in the thermal environment of the classrooms. The maximum responses responded to by the students were obtained for the opening of windows and drinking water.

Rodríguez et al. (2021) investigated that the most frequent adaptive actions taken by the students were opening the door or windows regarding the environmental modifications and taking a cold drink regarding behavioural adaptations, which is very similar to this study. Aparicio-Ruiz et al. (2021) found that students prefer opening the windows and opening the doors as adaptive behaviours to feel comfortable, more than the use of fans, which were mainly turned on in the afternoon. Zaki et al. (2017) found that more adaptive actions are taken by university students under the free-running condition to remain thermally comfortable.

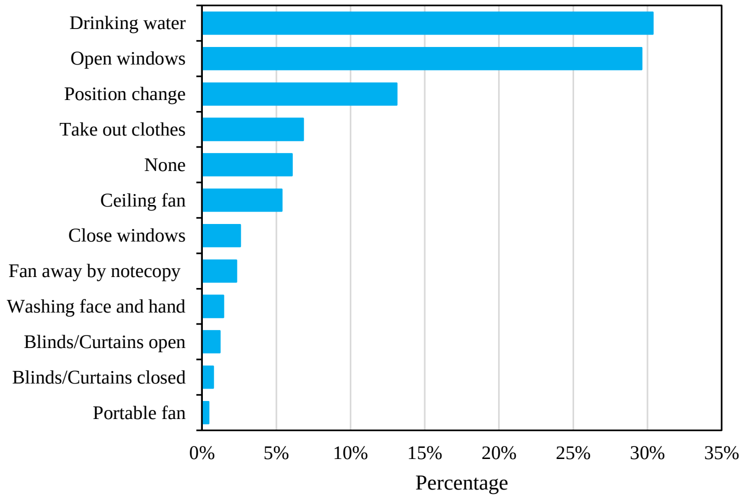


Figure 7. Adaptive behaviours used by students to adjust their thermal comfort or environment

## 4. Conclusions

This paper presents the results of a thermal comfort study conducted in free-running (naturally ventilated) Nepalese school buildings during the summer of 2019. The measurement of environmental survey and thermal comfort survey was conducted. The major findings are as follows

1. The indoor globe temperature and outdoor air temperature, as well as the indoor and outdoor water vapour concentrations, were strongly correlated.
2. Approximately 63% of the student's responses were within the central three categories of ASHRAE, indicating a preference for a cooler indoor environment.
3. The Griffiths method predicted a mean comfort temperature of 26.9 °C. The analysis of the comfort temperature based on the subjective responses of students shows that they sensed the different thermal environments from morning to afternoon and that the comfort temperature is high, especially during the afternoon of the school hour.
4. The comfort temperature showed adaptability to indoor air temperatures. They are adapting by using limited adaptive behaviours in those environments.

The results obtained in this study alone do not provide all the information needed to evaluate thermal comfort in school buildings in Nepal. In order to gain a deeper understanding of thermal comfort in Nepalese school buildings, further field studies should be conducted such as during the winter season and in other climates. Further research may help draw attention to thermal comfort and hence its improvements so that students can benefit from a more comfortable environment, thereby improving their academic performance.

## Acknowledgments

This work was supported by JST SPRING, Grant Number JPMJSP 2118. We would like to thank all the students and teachers for their cooperation in our field study despite their regular lessons.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# A Review on Adaptive Thermal Comfort and Energy Saving in Residential Buildings

**Naja Aqilah[1] and Hom B. Rijal[2]**

[1] Graduate School of Environmental and Information Studies, Tokyo City University, Yokohama, 224-8551, Japan, najaaqilah16@gmail.com
[2] Graduate School of Environmental and Information Studies, Tokyo City University, Yokohama, 224-8551, Japan, rijal@tcu.ac.jp

**Abstract:** The global temperature is expected to rise by 1.5°C or more over the next 20 years. This can cause thermal discomfort, especially in summers and highly-urbanized area. The heating, ventilation, and air-conditioning (HVAC) systems consume about 50% of building energy in order to provide a more comfortable indoor thermal environment. As the building plays a crucial role in creating a safe and comfortable living environment, ensuring a better trade-off between energy consumption and the comfortable indoor environment is important. It is urgent to reduce energy consumption without having to sacrifice occupant's thermal comfort and explore the applicability of thermal comfort standards while determining the impact on energy consumption in residential buildings. This paper aims to clarify the variation of comfort temperature, relationship between comfort temperature with indoor or outdoor temperature and the implication of thermal comfort to energy saving in residential building. As a result, this paper found out that the effects of humidity and air velocity were seldom discussed and the comfort temperature can be estimated from indoor or outdoor temperature. Thus, there is a need for future studies to investigate the effect of humidity and air velocity on residential thermal comfort. A standard approach in designing the future field measurement studies for a different types of built environments, climate, types of building and other factors also need to be considered.

**Keywords:** Thermal Comfort, Residential building, Comfort temperature, Adaptive model, Energy saving

## 1. Introduction

Over one-third of global final energy use and around 40% of total carbon dioxide ($CO_2$) emissions are attributed to the residential and service sectors [1]. Therefore, these sectors are expected to reduce their energy consumption and $CO_2$ emissions. Without any change to the current policies scenarios energy demand will increased by 1.3% each year to 2040 [2]. The heating, ventilation, and air-conditioning (HVAC) systems consume about 50% of building energy in order to provide a more comfortable indoor thermal environment [3]. Barreca *et al*. [4] in their study concluded that AC (air-conditioning) adoption increases the average residential electricity consumption by 11%. In addition, the greenhouse gas emissions from AC will account for about 0.5°C rise in global temperatures [5]. Chang *et al*. [6] highlighted that the amount of energy consumed for heating has seen a continuous upward trend with the growth of the building sector and the emphasis on the indoor thermal environment.

Based on American Society of Heating, Refrigerating, and Air-Conditioning Engineers ASHRAE-55 standard, thermal comfort is that state of mind that define the fulfillment of the thermal condition [7]. Thermal comfort also directly related to air temperature, radiant temperature, relative humidity, air velocity, human activity, and clothing insulation. Any changes in these factors will affect human thermal comfort. Due to the need to reduce the energy consumption in residential buildings, researches covering the issue of thermal comfort in indoor environment have been increasing.

Most of the researchers have established models by conducting field measurement studies to know how people will feel in a particular situation then estimate the temperature at which people will feel comfortable [14-18]. These type of temperature usually are being called 'comfort temperature' and 'neutral temperature' [8]. A variation of comfort temperatures can be observed from all previous studies. Jeong et al. [45] focused more on the comparison of respondent's perceived thermal comfort and the use of adaptive strategies in two different climates because the diversity in the climates across Australia might suggest that people may have different ranges of thermal acceptability and tolerance. Another study by Rijal et al. [18] mentioned that the comfort temperature and its seasonal range depend on the climate and building design. However, there is lack of review paper that described current condition of adaptive thermal comfort studies and energy saving in residential building.

This paper explores the residential field studies for thermal comfort in different country, climate, types of building and also operation modes. The objectives are to clarify the variation of comfort temperature and to identify the relationship between comfort temperature with indoor or outdoor temperature. Lastly, to investigate how thermal comfort strategies can effect the energy consumption in residential building.

## 2. Methodology

To proceed with this study, the keyword of "residential thermal comfort" was searched in Scopus database. A total of 3,243 journal papers were published. Then, we filtered to field measurement studies and the outcome is 184 results (Figure 1). From all reviewed papers, the relationship between comfort temperature with indoor or outdoor temperature has been extracted. Other than that, we also gather all information regarding energy saving from adaptive measures strategies.

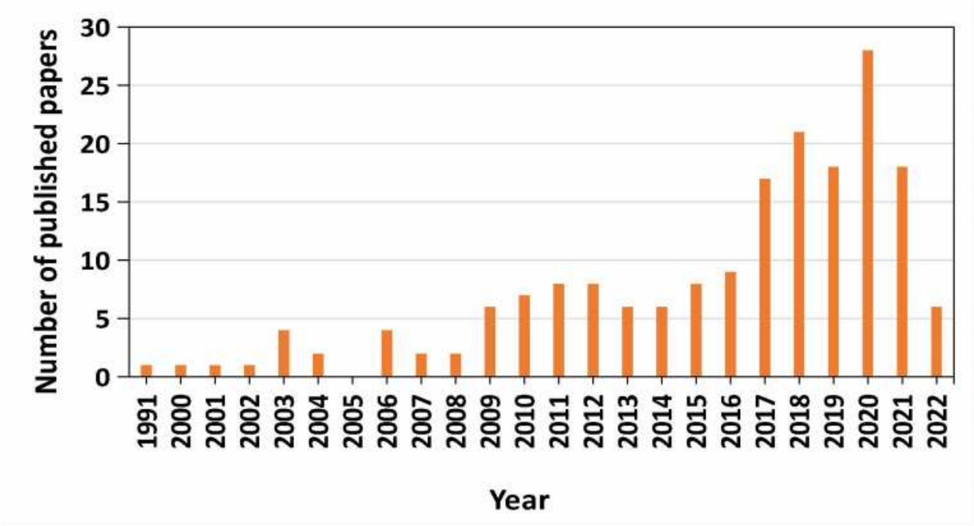

Figure 1. Number of published paper for thermal comfort field measurement studies in residential (Assessed on 13 June 2022)

Generally, linear regression method is used to find the relationship between thermal indices (indoor temperature, globe temperature, indoor mean radiant temperature, operative temperature and thermal sensation vote). By applying linear regression in the presence of adaptive behaviour, estimating the comfort temperature can be inaccurate [9]. Besides, comfort temperature ($T_c$) which predicted by using regression can be unreliable due to small number of samples [10]. Thus, Griffiths' method is preferably to be used for estimating comfort temperature. In this paper, both comfort temperature and neutral temperature are represented by $T_c$. The comfort temperatures are varied because of thermal adaption, buildings styles and also depend on the seasons [16]. These $T_c$ can be calculated using Griffiths' method as shown in Equation (1).

$$T_c = T + \frac{(0 - TSV)}{a} \quad (1)$$

Where T indicates any thermal index of indoor temperature such as indoor mean radiant temperature, operative temperature or globe temperature, '0' represent neutral condition, it can be replaced by '4' when using a seven-point thermal sensation scale (1 to 7) and α is the constant rate of thermal sensation change with room temperature which is equivalent to the regression coefficient. The Griffiths constant is about 0.440 in air-conditioning operation and 0.208 in naturally ventilated operation [18]. The average comfort temperature in Table 1 is estimated by using this method when only the information of thermal sensation votes were given in the paper.

## 3. Results and discussion

### 3.1. Variation of comfort temperature

In the field survey or field measurement method, the respondent will answer the questionnaires regarding the thermal sensation and thermal preference. This process are being conducted along with the simultaneous measurement of the indoor environmental variables such as air temperature, relative humidity and air velocity. Thus, these processes undertake adaptations of the occupants depending on the stimulation of the climatic condition. As a result, it is more accurate and hence can lead to more energy efficient building designs. A thermal comfort field measurement in hot-humid climate of China determined the thermal preferences inside residences with 22.0 - 25.9°C as an acceptable operative temperature range [14]. A study from Gong et al. [15] determined the thermal comfort range which observed at operative temperatures of 20.9 - 27.5°C in summer and 12.2 - 20.1°C in winter.

Table 1 lists several important points from previous residential field measurement studies including indoor air temperature and climatic data. Some of the studies did not provide the average data for indoor and outdoor temperature, and thus we try to calculate by picking up 10 different values from the related graph and find the mean from that.

Table 1. Previous thermal comfort field measurement studies

| Country | Reference | Duration of measurement | Number of samples | Variable used | Operation mode | $T_{oav}$ (°C) | $T_{omin}$ (°C) | $T_{omax}$ (°C) | $T_{iav}$ (°C) | $T_{imin}$ (°C) | $T_{imax}$ (°C) | $T_c$ (°C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| China | Yu et al. [16] | - 2013 (52 days)<br>- 1st 2014 (10 days)<br>- 2nd 2014 (51 days) | 527 | $T_{op}$ | CL<br>HT | - | -20 | 32.5 | - | 13.5<br>0.5 | 30.0<br>24.0 | 21.8<br>14.5 |
| China | Li et al. [19] | 6 years | 825 | $T_g$ | Mixed | - | - | - | - | 12.0 | 20.0 | 24.3 |
| Japan | Rijal et al. [18] | 2015 - 2016 | 69 | $T_{in}$ | FR<br>CL<br>HT | 16.8<br>27.4<br>8.3 | - | - | 23.1<br>27.3<br>19.9 | - | - | 23.0<br>26.8<br>20.2 |
| China | Song et al. [20] | - May 14th to November 20th in 2016 (191 days) | 43 | $T_{in}$ | Mixed | 21.3 | 10.7 | 31.7 | 24.1 | - | - | 25.4 |
| Ethiopia | Yadeta et al. [22] | During dry season (120 days) | 104 | $T_g$ | Mixed | 20.1 | 13.2 | 23.6 | 26.4 | 18.0 | 33.0 | 20.4 |
| India | Thapa and Indraganti [23] | 12 months | 5 | $T_{op}$ | CL<br>FR<br>FR | 26.4<br>15.5<br>17.8 | 18.5<br>5.7<br>5.7 | 31.3<br>24.0<br>31.3 | 28.2<br>18.9<br>20.9 | 22.4<br>9.0<br>9.0 | 35.1<br>26.9<br>35.1 | 28.3<br>19.4<br>21.3 |
| China | Wang [17] | 1 month | 66 | $T_{op}$ | FR | - | - | - | 20.1 | - | - | 21.4 |
| China | Han et al. [14] | 2003-2004 | 26 | $T_{op}$ | Mixed | 33.0 | 30.5 | 35.5 | 29.8 | 24.6 | 34.6 | 28.6 |
| China | Gong et al. [15] | 61 days (summer)<br>42 days (winter) | 144 | $T_{op}$ | CL<br>HT | 18.9 | 8.1 | 28.2 | 30.0<br>16.1 | 26.5<br>10.4 | 33.3<br>22.8 | 24.2<br>16.2 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Indonesia | Sujatmiko et al. [40] | 6 months | 5 | $T_{in}$ | Mixed (Bandung)<br>Mixed (Jakarta) | 23.5<br>27.8 | 13.0<br>21.0 | 36.0<br>37.0 | 27.5<br>29.2 | 24.2<br>21.8 | 31.0<br>35.2 | 25.1<br>26.6 |
| Nigeria | Adaji et al. [41] | 1 months | 8 | $T_g$ | Mixed (Lugbe)<br>Mixed (Dutse) | 31.1<br>30.3 | 23.5<br>23.0 | 41.1<br>38.4 | 31.7<br>33.6 | 29.1<br>31.0 | 34.1<br>36.4 | 29.6<br>28.2 |
| Madagascar | Nematchuoa et al. [42] | 1 year | 67 | $T_{in}$ | FR | 26.8 | 20 | 33.5 | - | 20.5 | 31.5 | 24.5 |
| Malaysia | Djamila et al. [43] | 1 year | 890 response | $T_{in}$ | FR | - | - | - | 30.7 | 26.5 | 35.3 | 30.2 |

$T_{oav}$: Average outdoor temperature; $T_{omax}$: Maximum outdoor temperature; $T_{omin}$: Minimum outdoor temperature; $T_{iav}$: Average indoor temperature; $T_{imax}$: Maxmum indoor temperature; $T_{imin}$: Minimum indoor temperature; CL: Cooling; FR: Free running; HT: Heating; $T_{mrt}$: Indoor mean radiant temperature; $T_{op}$: Operative temperature; $T_{in}$: Indoor temperature; $T_g$: Globe temperature; $T_c$: Comfort temperature

### 3.2 Relationship between comfort temperature and indoor temperature

Field studies should primarily be conducted to support evidence of relationship between comfort temperature with indoor air temperature in the built environment. As mentioned by Song et al. [20], a differentiated thermal environment with different air temperature and radiant temperature can influence human thermal comfort levels. Therefore, Rijal et al. [18] quantify the seasonal differences in the comfort temperature and develop a domestic adaptive model for highly insulated Japanese dwellings. Gong et al. [15] researched the possible correlations between the occupants' thermal sensations to on-site environmental monitoring and in situ measurements of multi-storey residential buildings under natural ventilation in the Guilin Karst area. However, there is not sufficient explanation of the effect of relative humidity and air velocity obtained by field studies [38].

Figure 2 shows the correlation between the comfort temperature and average indoor temperature of previous studies as shown in Table 1. Different points are represented for each operation modes (free running, mixed, cooling and heating). Each point represents the results of comfort temperature for each measured indoor temperature. It can be seen that the comfort temperature was close to the measured indoor temperature. This indicates that people will mostly adapting to the thermal environment and felt comfortable at the different indoor temperatures. Table 2 listed regression equation from several previous studies. Then, these equations are illustrated in Figure 3. The slope for the regression line during free running for traditional houses in the study of Nematchuoa et al. [42] is the lowest (0.25) compared with the slope for apartments (0.506) and single storey residential houses (0.752). This might be related to the differences in building design and thermal responses for each type of the building.

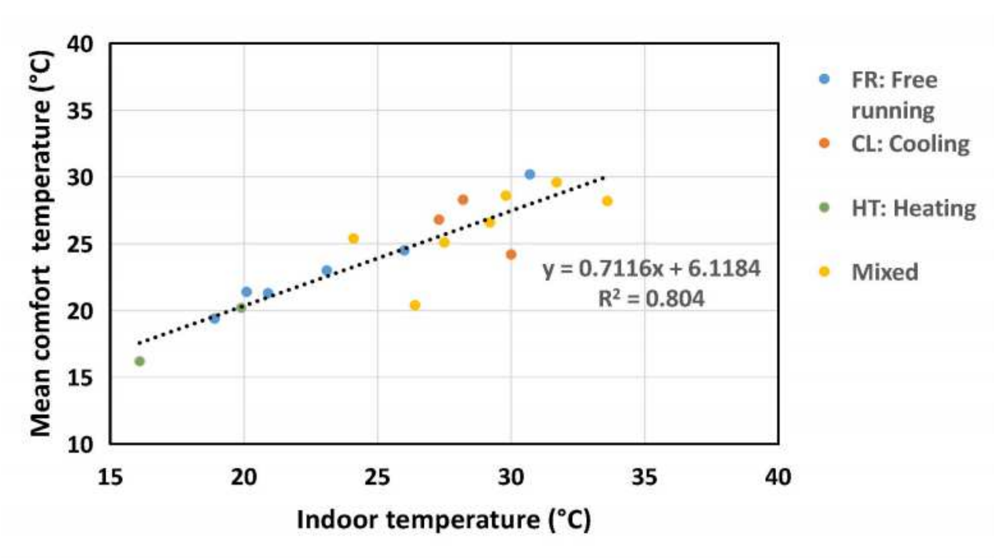


Figure 2. Correlation between the comfort temperature and average indoor temperature

Table 2. Regression equation from past studies

| Reference | Types of building | Operation modes | Regression equation |
|---|---|---|---|
| Nematchuoa et al. [42] | Traditional residence | FR | $T_c = 0.250T_{in} + 19.6$ |
| Indraganti et al. [24] | Apartments | FR | $T_c = 0.506T_g + 11.39$ |
| Thapa [26] | Single-storey residential houses | FR | $T_c = 0.752T_{op} + 4.419$ |
| Thapa and Indraganti [23] | Residential and college building | Mixed | $T_c = 0.658T_{op} + 9.769$ (warm and humid)<br>$T_c = 0.727T_{op} + 5.643$ (cold) |
| Manu et al. [44] | Offices and residential | Mixed | $T_c = 0.90T_{op} + 2.54$ |

CL: Cooling; FR: Free running; HT: Heating; $T_{op}$: Operative temperature (°C); $T_{in}$: Indoor temperature (°C); $T_g$: Globe temperature (°C); $T_c$: Comfort temperature (°C)

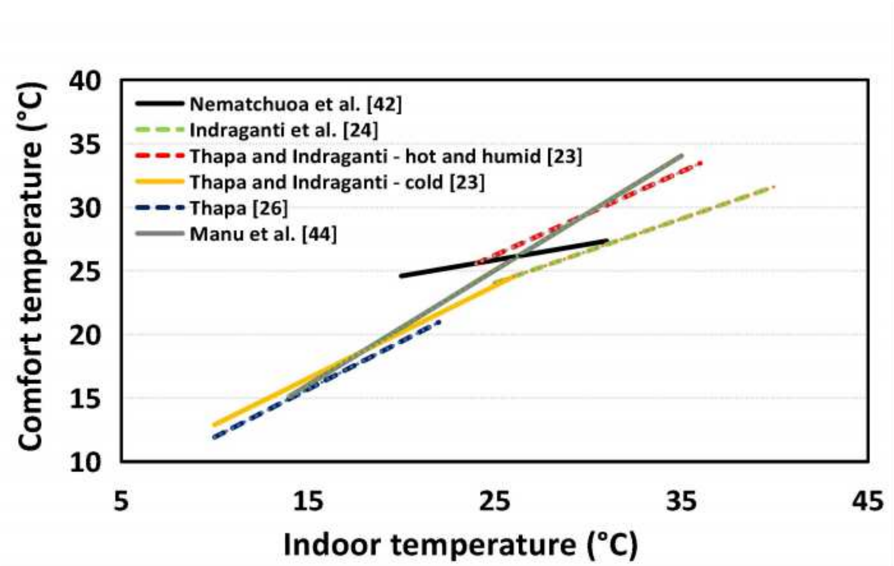


Figure 3. Regression line for comfort temperature with indoor temperature ranges

### 3.3. Relationship between comfort temperature and outdoor temperature

Most of the field studies on adaptive thermal comfort has mentioned about the strong relationship between the indoor comfort temperature and mean outdoor temperature as shown in Table 3. Safarova et al. [33] found out that the comfort temperature and the use of fans being correlated solely with outdoor temperature. This allow the effect of climate on indoor comfort temperature to be estimated.

These adaptive comfort equations from previous studies have been illustrated as regression line in Figure 4. For the operation modes of cooling and free running, the regression line of condominiums in the study of Rijal et al. [18] has the lowest slope (0.16) compared with homes with AC (0.26), regional vernacular dwelling (0.30), apartments and residential (0.31).

Table 3. Adaptive thermal comfort equation from past studies

| Reference | Types of building | Operation modes | Adaptive model |
|---|---|---|---|
| Rijal et al. [18] | Condominium | FR<br>CL<br>HT | $T_c = 0.37T_{rm} + 16.8$<br>$T_c = 0.16T_{rm} + 22.5$<br>$T_c = 0.31T_{rm} + 17.7$ |
| Humpreys and Nicol [28] | - | FR | $T_c = 0.534T_o + 11.9$ |
| Kim et al. [31] | Homes with AC | CL | $T_c = 0.26T_o + 16.75$ |
| Costa-Carrapico et al. [25] | Regional vernacular dwelling | CL<br>FR | $T_c = 0.30T_m + 17.9$<br>$T_c = 0.43T_m + 15.6$ |
| Udaykumar et al. [32] | Apartments | CL | $T_c = 0.31T_m + 17.8$ |
| Safarova et al. [33] | Residential | CL | $T_c = 0.31T_m + 17.6$ |

CL: Cooling; FR: Free running; HT: Heating; $T_m$: Mean monthly outdoor temperature (°C) ; $T_{rm}$: Running mean outdoor temperature (°C); $T_c$: Comfort temperature (°C);

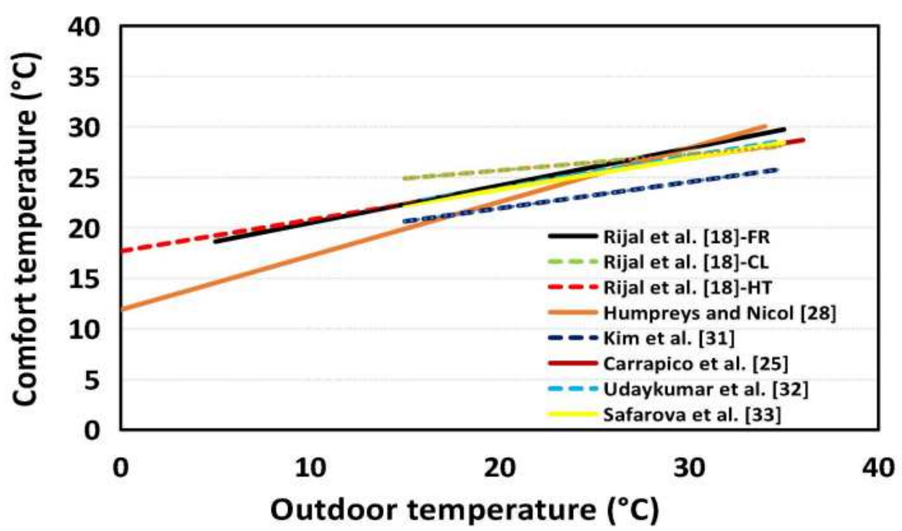


Figure 4. Comfort temperature with outdoor temperature ranges

### 3.4 Energy consumption implication

Human comfort usually been ignored when attempting to save energy [1]. For example, implementing load shedding would automatically shed load by directly modified the air handling unit fan speed and resulting in a poor air distribution and occupant discomfort [11]. Accordingly, there is a significant energy-saving potential coming by improving the thermal comfort level of the occupants. A reduction of 20% and 80% in heating and cooling requirement have been resulted from shifting the conventional fixed thresholds to the adaptive energy demand [12]. Other than that, a conservative energy savings rate of 13.2% can be obtained when improving the occupant's comfort to 24.4 – 27.2 °C at which 6°C increase in thermostat set point [13]. Thus, it is urgent to explore the applicability of thermal comfort standards and the use of adaptive behaviour to determine its implication on energy use in buildings. Table 4 described energy implication by natural ventilation and adaptive measures from previous studies.

Table 4. Energy implication by natural ventilation and adaptive measures from previous studies

| Country | Reference | Strategies | Energy implication |
|---|---|---|---|
| United States | Sadineni et al. [34] | Raise SST from 23.9°C to 26.1°C (during 16:00–19:00). | Peak electrical energy demand reduced by 69%. |
| Saudi Arabia | Al Sanea et al. [35] | Change yearly-fixed Thermostat setting (21–24.1 °C) to optimised monthly fixed settings (20.1–26.2°C). | Energy cost reduced by 26.8–33.6%. |
| Spain | González-Lezcano et al. [36] | Natural ventilation | 13% cooling energy saving by natural ventilation |
| Spain | Barbadilla-Martín et al. [37] | Implementation of the algorithm in the HVAC control system, both during the cooling and the heating period | Obtaining savings of 27.5% and 11.4% respectively |

## 4. Conclusions

This paper presents literature review and identified several areas of progress and points to form the basis information regarding the future thermal comfort field studies and the implication of energy saving. The following points can be concluded from this review:

1) The effects of humidity and air velocity were seldom discussed in the published papers. There is a need for future studies to investigate the effect of humidity and air velocity on residential thermal comfort.
2) The comfort temperature can be estimated from indoor or outdoor temperature. Thus, a standard approach in designing the future field studies for a different types of built environments, climate, types of building and other factors also need to be considered.
3) Adaptive comfort models tend to have a wider range of comfort temperature, which could have significant energy savings in both air-conditioned and naturally ventilated buildings. In summer, if people are willing to bear greater indoor temperatures, cooling systems will become less common. Aside from the potential for energy savings, raising the summer set point temperature could significantly minimize the peak electricity demand.

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# Study on winter comfort temperature based on daily survey in mixed-mode office buildings in Aichi prefecture of Japan

**Supriya Khadka[1], H.B. Rijal[2], Katsunori Amano[3], Teruyuki Saito[4], Hikaru Imagawa[5], Tomoko Uno[6], Kahori Genjo[7], Hiroshi Takata[8], Kazuyo Tsuzuki[9], Takashi Nakaya[10], Daisaku Nishina[11], Kenichi Hasegawa[12], Taro Mori[13]**

[1] PhD Student, Tokyo City University, Japan, supriyakhadka1996@gmail.com
[2] Prof., Tokyo City University, Japan, rijal@tcu.ac.jp
[3] Master Student, Nagoya University, Japan, amano.katsunori.x1@s.mail.nagoya-u.ac.jp
[4] Assoc. Prof., Nagoya University, Japan, saito@nuac.nagoya-u.ac.jp
[5] Assist. Prof., Osaka Institute of Technology, Japan, hikaru.imagawa@oit.ac.jp
[6] Assoc. Prof., Mukogawa Women's University, Japan, uno_tomo@mukogawa-u.ac.jp
[7] Prof., Nagasaki University, Japan, genjo@nagasaki-u.ac.jp
[8] Assoc. Prof., Hiroshima University, Japan, takatah@hiroshima-u.ac.jp
[9] Prof., Kansai University, Japan, ktsuzuki@kansai-u.ac.jp
[10] Assist. Prof., Shinshu University, Japan, t-nakaya@shinshu-u.ac.jp
[11] Prof., Hiroshima University, Japan, nishina@hiroshima-u.ac.jp
[12] Prof., Akita Prefectural University, Japan, haseken@akita-pu.ac.jp
[13] Prof., Hokkaido University, Japan, mori.taro@eng.hokudai.ac.jp

**Abstract:** People spend most of their life-time indoors where they expect the comfortable environment. Comfort temperature is important to investigate because the chosen office indoor temperatures affect the energy used in the building, and people in thermally comfortable environment are generally more productive. The effects of temperature on comfort are broadly recognized for thermal comfort. Japanese office buildings are well equipped with the air-conditioning systems to improve thermal comfort of the occupant. Various field studies conducted in different parts of Japan has given the comfort temperatures in Japanese offices. The main objectives of this research are to analyse the comfort temperature in Japanese offices in winter, and to investigate the relationship between the comfort temperature and the indoor air temperature.

This study measures the environmental conditions of the office buildings, the occupants' characteristics, objective data of thermal environment and the subjective questionnaires of the thermal comfort. The field data is collected in five office buildings located in Aichi prefecture. We collected 3364 votes for the winter season. Griffiths' method is used to calculate the comfort temperature.

The result suggests that the occupants were found to be highly satisfied with the thermal environment in their offices. Even though the Japanese government recommends the indoor temperature of 20 °C for heating, the comfort temperature was found to be 5 °C higher in mixed mode. The comfort temperature is related to the indoor air temperature. This indicates that the occupants are well adapted towards the given thermal environment of these mixed mode Japanese office buildings.

**Keywords:** Field survey, Mixed mode, Thermal sensation vote, Indoor air temperature, Griffiths' method, Comfort temperature.

## 1. INTRODUCTION

Office workers use a variety of "adaptive opportunities" to regulate their indoor thermal environment and secure their thermal comfort (Rijal et al. 2019). Today, people spend more time indoors, where they expect the level of thermal comfort that ensures comfort as well as wellbeing. Even gentle fluctuations in the indoor environment can cause discomfort, which may lead to a sudden change in the behaviour or the activity of the occupant (Humphreys and Nicol 1998). It is important to adjust the indoor environment of the office with natural ventilation as much as possible from the viewpoint of reducing COVID-19 infection in the future. The field survey especially in naturally ventilated buildings (NV), mixed mode (MM) and free running mode (FR) around the world proves that the comfort temperature varies with the outdoor air temperature. Therefore, it is important to provide better thermal environments, so-called "comfortable environments". Japanese office buildings are well equipped with air-conditioning (AC) systems to help in creating thermal comfort. Even though the Japanese office buildings do have AC systems, it seems that the various practices, such as opening doors and windows to allow air movement as much as possible, enable the occupants to be at their required thermal comfort in the office buildings.

The adaptive thermal comfort model is being established around the world as ASHRAE standard 55 (ASHRAE 2013) and European Standard EN 15251 (CEN 2007). The ASHRAE standard has accumulated the thermal comfort database in defining indoor thermal environment from the field study from across the world for different seasons (de Dear and Brager 1998). However, these standards do not include data from Japanese office buildings.

Comfort temperatures are important to investigate because the chosen office indoor temperatures affect the energy used in the building, and people who are in thermally comfortable environment are generally more productive. Based on field surveys, the comfort temperatures in Japanese offices have been investigated by several researchers. The comfort temperature was found to be 25.0 °C, 25.4 °C and 24.3 °C for free running mode (FR), cooling mode (CL) and heating mode (HT) respectively at Kanto area of Japan (Rijal et al. 2017). Khadka et al. (2022) found that the mean comfort temperature is 24.8 °C for MM and 25.0 °C for FR in the Japanese office buildings. Tanabe et al. (2007) found the comfort temperature is below 27 °C. These research are focused mostly for the summer season or a year around which did not analyse the comfort temperature in detail for winter season of mixed-modes office buildings. Japanese government introduced the "Warm Biz" programs that recommend an indoor temperature of 20 °C for heating in the year 2005 for energy saving (Enomoto et al. 2009). However, this value is not based on the field survey and lacks supporting evidences.

The main objectives of this research are to analyse the comfort temperature in Japanese office buildings in winter, and to investigate the relationship between the comfort temperature and the indoor air temperature. The findings can be used to create guidelines and standards for the cold climatic conditions allowing to design MM and FR mode buildings in the future. This understanding also aims to decrease in the temperature setting of heating of existing buildings during winter season so that will further help in energy saving in the buildings.

## 2. METHODOLOGY

The field study focuses on the environmental conditions of the office buildings, the occupant's characteristics, thermal measurement and the subjective questionnaires of the thermal comfort.

### 2.1. Study area and investigated buildings

The study site is located in Aichi prefecture of Japan (Rijal et al. 2022b). The location features a humid subtropical climate (Köppen climate classification: Cfa), which is characterized by hot and humid summer and cool winter. Figure 1 indicates the monthly mean outdoor air temperature and relative humidity of Nagoya meteorological station. The average annual temperature in Nagoya reaches 15.5 °C. The temperatures are highest on average in August, at around 27.8 °C, and lowest in January, at around 4.1 °C as shown in the Figure 1. The average relative humidity varies from 60 to 77 % in different months of the year.

The field survey is conducted in five mixed mode office buildings located in Aichi prefecture from December 2021 to February 2022. The five investigated office buildings were of change-over mixed-mode (CBE 2021) type having operable door/windows and the HVAC systems depending on the seasons or time of the day (Figure 2). We divided our data into two modes i.e. FR and HT as we are focused on the winter thermal comfort. FR mode is such type of mode which neither use heating nor cooling during the survey but the occupants use the passive controls that are available to them at the time of survey to regain their comfort (Nicol et al. 2012). Figure 2 shows the general overview of one of the investigated office buildings.

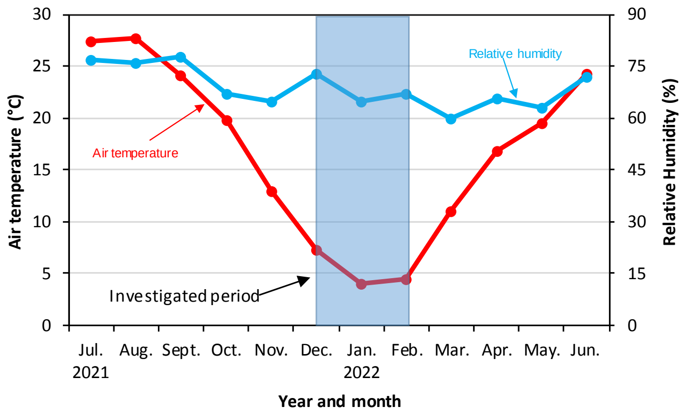


Figure 1. Monthly mean outdoor air temperature and relative humidity in Nagoya (Japan Meteorological Agency, 2022)

Figure 2. Overview of one of the Investigated office buildings

## 2.2. Thermal measurements

The environmental variables were measured by using instruments as shown in Table 1. The measurement of the environmental variables such as air temperature, globe temperature and relative humidity with the digital instrument sensor, which is placed 1.1 m above the floor level, away from direct sunlight at ten-minute interval. Two instruments set up was allocated in the same floor in two locations for buildings N1 and N5 (Table 2). The survey method was as same as the survey conducted in Kanto region (Rijal et al. 2022a). The climatic data were obtained from the Nagoya meteorological station of the Aichi prefecture.

Table 1. Description of the instrument used.

| Parameter measured | Name of the instruments | Range | Accuracy |
|---|---|---|---|
| Air temp., humidity, illuminance | TR-76Ui | 0 to 55 °C, 10% to 95% RH, 0 to 130 klx | ±0.5 °C, ±5%RH, ±5% |
| Globe temp. | Tr-52i SIBATA 080340- 75 | −60 to 155 °C Black painted 75 mm diameter globe | ±0.3 °C |
| $CO_2$ | TR-76Ui | 0 to 9,999 ppm | ±50 ppm |

Table 2. Description of buildings, instruments and occupants

| Building code | Investigated floor | Number of measurement points | Number of occupants | Number of female | Number of male | Number of votes |
|---|---|---|---|---|---|---|
| N1 | 2F | 2 | 4 | 2 | 2 | 522 |
| N2 | 1F, 2F | 2 | 8 | 5 | 3 | 939 |
| N4 | 2F | 1 | 8 | 3 | 5 | 839 |
| N5 | 4F | 2 | 10 | 1 | 9 | 764 |
| N7 | 5F | 1 | 5 | 2 | 3 | 300 |
| **Total** | | **8** | **35** | **13** | **22** | **3364** |

### 2.3. Thermal comfort survey

The questionnaire sheets were distributed to the office workers where the purpose of the survey and how to fill out the questionnaire were explained briefly. Also, one of the investigated office building carried out the survey through excel sheet on PC. Longitudinal survey is conducted each day by the respondents while digital instruments being installed at the office buildings for that periods of time. The thermal comfort survey was conducted with 35 occupants: 22 males and 13 females (Table 2). Generally, the occupants voted 4 times a day: 2 times in the morning and 2 times in the afternoon. The survey was conducted in Japanese language.

Table 3 shows the scale used for the thermal sensation vote. Each state of heating use, cooling use and window opening were recorded in binary form during the survey (0= heating/cooling off or window closed, 1= heating/cooling on or window open). We have collected 3364 votes from five mixed mode office buildings (FR= 209 votes and HT= 3155 votes).

Table 3. Scale of thermal sensation vote

| No. | Scale |
|---|---|
| 1 | Very cold |
| 2 | Cold |
| 3 | Slightly cold |
| 4 | Neutral |
| 5 | Slightly hot |
| 6 | Hot |
| 7 | Very hot |

## 3. Results and discussion

### 3.1. Distribution of the outdoor and indoor air temperatures during the voting

To know the investigated conditions during the voting, indoor and outdoor air temperature were analysed. The mean outdoor air temperature was 10.0 °C and 7.3 °C for free running mode (FR) and heating mode (HT) respectively.

The mean indoor air temperature during the voting were 23.7 °C and 24.6 °C for FR and HT modes respectively. Figure 3 shows the distribution of the indoor air temperature, and the mean was 24.5 °C. The result also suggests that the occupants are mostly maintaining the indoor air temperature at the range of 24 -26 °C in response to the low outdoor air temperature. The Japanese government recommends the indoor temperature of 20.0 °C for winter in "Warm Biz" condition. The results suggest that the mean indoor air temperature of the office buildings was significantly higher than that of the recommended value.

Figure 4 shows the relation between indoor and outdoor air temperature. The range of indoor air temperature was small compared to outdoor air temperatures. We have found the following regression equation from the regression analysis.

$T_i = 0.13\ T_{out} + 23.6$ (N=2909, $R^2$=0.078, S.E.=0.008, p<0.001) (1)

$T_i$: Indoor air temperature (°C), $T_{out}$: Outdoor air temperature (°C), N: Number of the sample, $R^2$: Coefficient of determination, S.E.: Standard error of the regression coefficient and p: Significant level of regression coefficient.

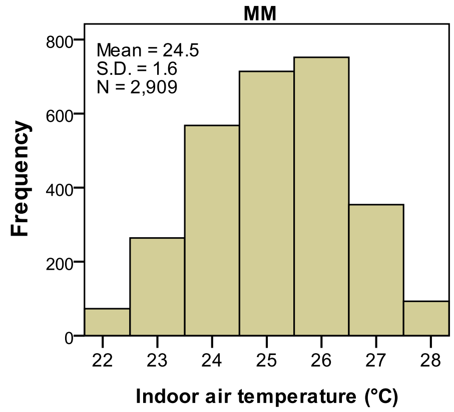


Figure 3. Distribution of indoor air temperature

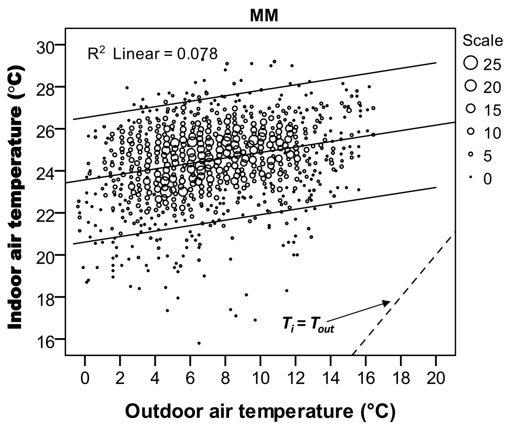


Figure 4. Relationship between the indoor and outdoor air temperature

Due to the heating use in MM buildings, the regression coefficient or correlation coefficient is significantly low. It is weak but the indoor air temperature is significantly correlated to the outdoor air temperature. The equation can be used to estimate the indoor temperature of the similar MM buildings.

### 3.2. Distribution of thermal sensation vote

In the previous section, we analysed the indoor and outdoor air temperatures. In this section we evaluate the thermal response of the office workers for the given thermal environmental condition. The subjective evaluation is required to understand the actual thermal comfort of the occupants in the office buildings.

Figure 5 shows the distribution of thermal sensation votes of the occupants. The mean thermal sensation vote is 3.8. The occupants mostly voted "4. Neutral" which accounts for the 72 % votes of the total. The results showed that the occupant were highly satisfied with the office thermal environment. Generally, thermal sensation votes "3. Slightly cold", "4. Neutral" and "5. Slightly hot" is considered as thermal comfort zone i.e. 98.5 %. About 4 % votes are "5. Slightly hot" in winter, and thus the energy can be saved by reducing the temperature setting in the offices.

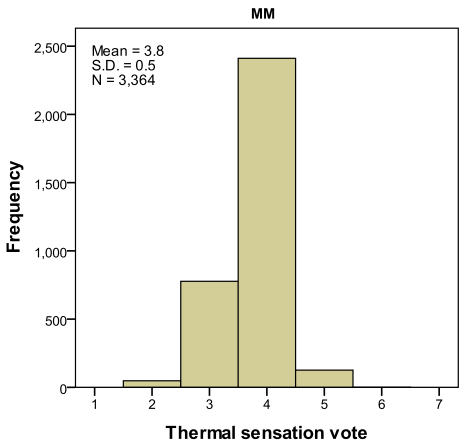


Figure 5. Distribution of thermal sensation votes

### 3.3. Comfort temperature

Comfort temperature is known as one of the key variable to understand the thermal comfort of the office workers. It is used as the standard to adjust the indoor thermal environment and to give satisfactory thermal comfort to the occupants. Humphreys (1978) found that the comfort temperature is varying according to the seasons. Later, de Dear and Brager (1998) confirmed this finding from field survey. In this section, we want to clarify and establish the winter comfort temperature in the Japanese MM office buildings.

#### 3.3.1 Regression method

In this section, we analyse the comfort temperature by regression method. The linear regression analysis of the thermal sensation vote *(TSV)* and indoor air temperature was conducted as shown in Figure 6. We have obtained the following regression equation.

$TSV = 0.107\, T_i + 1.15$ (N=2909, $R^2$=0.10, S.E.=0.006, $p<0.001$) (2)

The slope of equation (2) is 0.107/ °C which indicates that for every 9.3 °C change in indoor air temperature, thermal sensation vote will have a unit change which is similar to the other studies done in different areas (Kumar et al. 2016; Rijal et al. 2017; Nicol and Roaf 1996;

Karyono 2000). Kumar et al. (2016) narrated that the lower slope is indication of the higher adaptation of the occupant to the indoor environment.

When the comfort temperature is estimated by substituting “4. Neutral” in equation (2), it would be 26.6 °C. As shown in Figure 5, most of the “4. Neutral” votes are in the range of 23 - 26 °C. Hence, it is not suitable to estimate the comfort temperature by regression method. We then estimate the comfort temperature by Griffiths’ method in the next section.

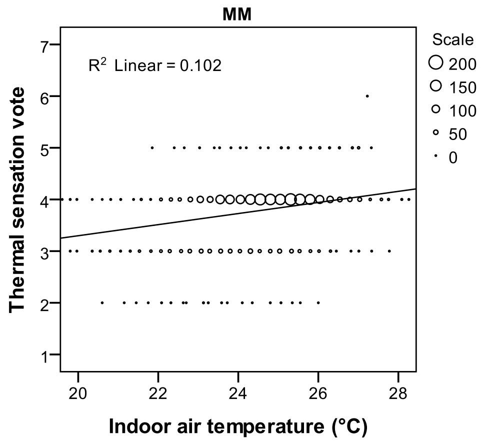


Figure 6. Relationship between thermal sensation vote and indoor air temperature

### 3.3.2 Griffiths’ method

The comfort temperature was estimated by the Griffiths’ method (Griffiths 1990; Nicol et al. 1994; Rijal et al. 2008; Humphreys et al. 2013). This method can be used to estimate comfort temperature with any single vote in the seven-point scale of thermal sensation given the assumption of equidistance in points. It is considered as useful when linear regression is not reliable to estimate the comfort temperature.

In this section, we applied the Griffiths’ method to calculate the comfort temperature in winter for avoiding the errors caused by regression method. Based on the respondents’ votes of thermal sensation and the corresponding values of measured indoor air temperature, we estimated the comfort temperature by using the following equation:

$$T_c = T_i + (4-TSV) / a \quad (3)$$

$T_c$: Comfort temperature (°C) and a: Griffiths’ constant (= 0.50).

When *TSV* is “4. Neutral”, the estimated comfort temperature equals the indoor air temperature otherwise they differ. Figure 7 shows the distribution of the comfort temperature. The mean comfort temperature in MM buildings is 25.0 °C and they are mostly distributed between 24 - 27 °C. The mean comfort temperature for FR and HT mode was 24.6 °C and 25.0 °C respectively. The result showed that the mean or range of comfort temperature is comparable to the indoor air temperature during the survey as shown in the Figure 3. Again, the comfort temperature of this study is significantly higher than the recommended temperature of 20 °C for “Warm Biz” condition.

When we compared the comfort temperature according to the gender and months, we found similar results. Figure 8 shows the mean of comfort temperature of five office buildings. The building wise there was maximum 1.3 °C differences in the comfort temperature.

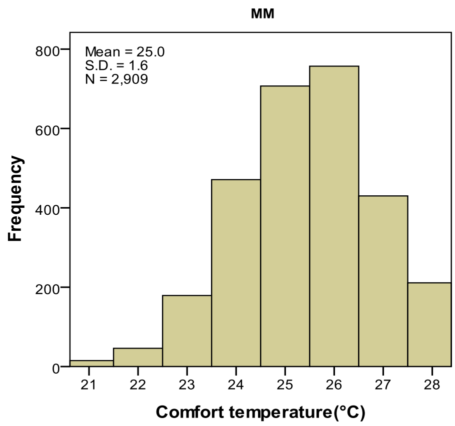


Figure 7. Distribution of comfort temperature

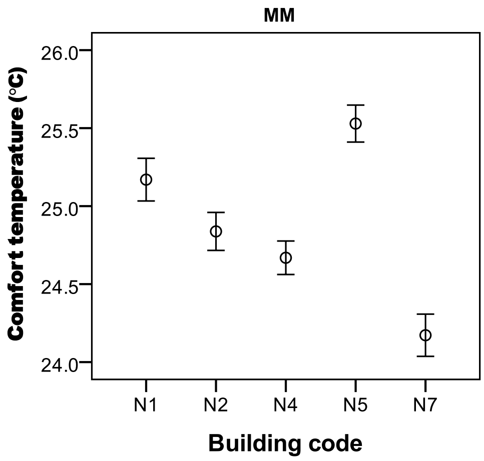


Figure 8. Comfort temperature according to office buildings with 95 % confidence interval (mean ± 2 S.E.)

We compared the comfort temperature with previous studies which used the regression and Griffiths' methods as shown in Table 4. For this study the mean comfort temperature observed were similar to the studies that were found in the Kanto (Japan) and India, whereas the comfort temperature was found to be lower as compared to Bangladesh, higher as compared to the China. The results indicated that the comfort temperature might be different by the climatic condition.

Table 4. Comparison of comfort temperature with previous studies

| **Reference study** | **Country** | **Building type** | **Mode of operation** | **Season** | **Index temp. (°C)** | **Comfort temp. (°C)** | **Method** |
|---|---|---|---|---|---|---|---|
| This study | Japan (Aichi prefecture) | Office buildings | MM | Winter | $T_i$ | 25.0 | Griffiths |
| Rijal et al. 2022a | Japan (Kanto region) | Office buildings | MM | All seasons | $T_g$ | FR=24.9<br>HT=24.3 | Griffiths |
| Kumar et al. 2020 | India | Workshop | NV | Autumn + Winter | $T_{op}$ | 25.9 | Griffiths |
| Hussain et al. 2019 | Bangladesh | Workshop | NV | Cool and dry season | $T_{op}$ | 25.9-26.1 | Regression |
| Kumar et al. 2016 | India | Office | NV | Winter | $T_g$ | 25.2 | Griffiths |
| Cao et al. 2011 | China | Classroom and offices of University | Space heating | Winter | $T_{op}$ | 20.7 | Regression |

$T_i$ : Indoor air temperature, $T_g$ : Indoor globe temperature, $T_{op}$: Operative temperature

### 3.4. Relationship between the comfort temperature and indoor air temperature

Regression analysis was used to examine the relationship between comfort temperature and indoor air temperature. Figure 9 shows the relationship between the comfort temperature and the indoor air temperature. Office workers are highly adapted to the indoor environment, and thus the comfort temperature is related to the indoor air temperature. We have found the following regression equation.

$T_c = 0.785\ T_i + 5.7$ (N=2909, $R^2$=0.60, S.E.=0.012, p<0.001) (4)

When indoor air temperature is low, the comfort temperature is slightly high, and when indoor air temperature is high, the comfort temperature is slightly low. People become adapted to the indoor temperatures they experience, while at the same time they adjust the indoor temperature to make themselves comfortable which is similar to the Rijal et al. (2017).

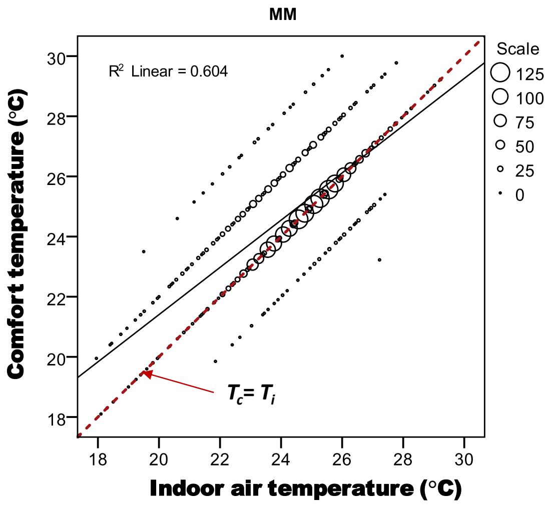


Figure 9. Relationship between comfort temperature and indoor air temperature

## 4. Conclusions

We have conducted the field survey on winter comfort temperature based on the daily survey in five mixed-mode office buildings in Aichi prefecture of Japan. We have found the following results:

1. The occupants are highly satisfied with their office environment as most of the thermal sensation votes were "Neutral".
2. The mean comfort temperature according to the Griffiths' method was found to be 25.0 °C in mixed mode. The comfort temperature is found to be 5.0 °C higher than the recommended value (20 °C) of Japanese government for winter.
3. The comfort temperature and indoor air temperature were highly correlated. The results indicated that the occupants are well adapted to the given thermal environment.

## ACKNOWLEDGEMENTS

We would like to sincerely thank to the Itsuwa Denki Kogyo Co., Ltd., Kimura Kohki Co., Ltd., SEEDS Co., Ltd., Shinwa Electric Co., Ltd., Yasui Architects & Engineers, Inc. and local government for their kind cooperation. This research is supported by the Grant-in-Aid for Scientific Research (B) (21H01496) of Japan Society for the Promotion of Science (JSPS).

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## Climate Change Adaptation Strategies - downtown Amman.

**Farah Z. Al-Atrash[1], Nibal Hameed[2]**

[1,2] Department of Architecture and Interior Architecture, School of Architecture and Built Environment, German Jordanian University, P.O. Box 35247, Amman 11180, Jordan, farah.alatrash@gju.edu.jo

**Abstract:**
In line with the climate challenges Amman is facing, innovative solutions should be implemented to uphold various effects and increase the city's adaptive capacity. This study aims to identify the role of Green Infrastructure in climate adaptation, Quraish street in Amman is chosen as a case study to represent a dense urban environment that has a high share of impermeable reflective surfaces and lacks proper vegetation. The research employed a dynamic simulation strategy using computational simulations to quantify the effects of different green infrastructure scenarios on heat mitigation, air pollutants reduction, and stormwater management. The scenario-based approach was used enabling community and expert participation along with site assessment and analysis in the design phase. Results indicate that using planters with dense trees has notable effects on heat mitigation but negligible effects on pollutants concentrations. In contrast, sparse tree canopies showed negligible effects on heat mitigation and also negligible effects on pollutants concentrations. The use of stormwater planters for runoff management showed minimal effects on runoff reductions. In contrast, the green envelope scenario showed notable effects on stormwater runoff reductions and negligible effects on heat mitigations and pollutants concentrations.

**Keywords:** outdoor thermal comfort, green infrastructure, climate adaptation, ENVI-met software, Quraish street/ Amman

## 1. Introduction

Amman is a densely populated city with 1,680 km² and is home to almost 4.5 million residents (DOS, 2020). Different parts of the city are susceptible to climate change. According to the Amman climate action plan of (Greater Amman Municipality, GAM), the city faces increased maximum temperatures and frequent heat waves, localized stormwater flooding due to heavy rainfall events, extended drought periods, and shortages in water resources. These events were accompanied by an increased population, deteriorated infrastructure, and increased demand for water and energy, especially in the poor central areas (GAM, 2019).

The central area of Amman resides on a buried stream and is characterized by its steep topography, which exacerbates the risk of localized flooding events. As a part of the Amman-Zarqa basin, the old stream of Amman formed as a receptor to the heavy rainfall events and used to flood, inundating the surrounding agricultural banks (Munif, 1994). Figure 1 (a) shows Amman stream basin and its associated elevations and natural stream flow. The basin has a total area of 103 km and resides to the city's northwest. Its elevations vary between 1040 meters to the north and 740 meters in the low-lying areas near the city centre.

Since 1987, the city's urban expansion headed toward the north and northwest of the basin as shown in Figure 1 (b). The expansion has resulted in altering natural stream flows and caused natural land degradation. These changes have negatively contributed to urban flooding events, as the high share of impermeable surfaces which replaced natural stream flows, increased the volume and velocity of stormwater runoff (Makhamreh & Al-Weshah, 2019).

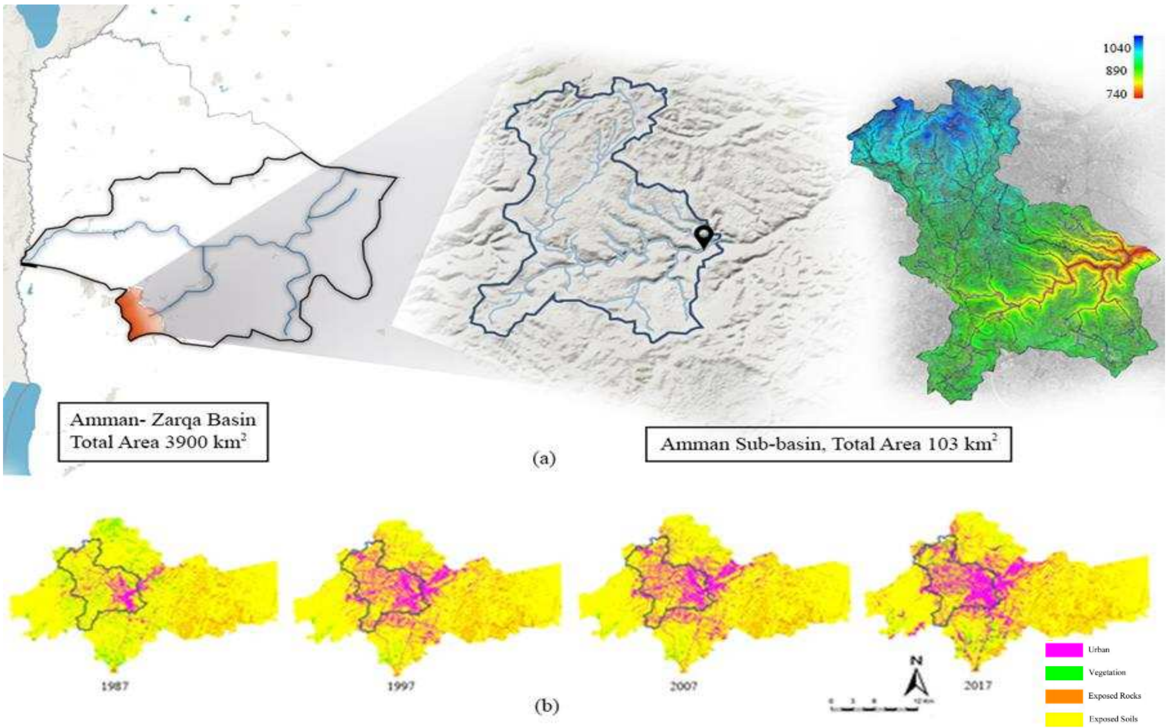


Figure 1. (a) Amman sub-basin elevations and natural stream flows. Source: (engicon, 2019) (b) Urban expansion in relation to the sub-basin. Source: (Al-Bilbisi, 2019)

The continuous urban development on the expanse of natural land has contributed to the rise in air temperatures as well. The increased share of urban surfaces that replaced natural vegetation cover had created an Urban Heat Island effect. There is strong evidence that the changes in land cover types had increased the local temperature of the city, as mean temperature values for Amman urban area have increased by 4°C since 1987 (Bani Doomi et al., 2016). Quraish street is chosen as a case study to represent an area with a high share of impermeable surfaces and a lack of proper vegetation, in order to identify the role of different Green Infrastructure scenarios in climate adaptation using computer simulations. Quraish street has formed a significant urban hub over the past decades. It was the first step for urbanization in the city of Amman and an important commercial street that encompasses a diversity of both uses and users.

Quraish street is located in a low-lying area surrounded by hilly plateaus (Jabals). Its location poses various effects on microclimate and stormwater runoff as well. Since its altitude is lower than its surroundings, temperatures during the day are usually warmer. Consequently, warming the air that sinks to the wadis as a result of temperature inversions. Cool air condenses and sinks to the lower elevations at night, but it heats up as the urban surfaces relieve absorbed heat at night. The urban development on the surrounding topography limits ventilation and airflow which increase air temperatures down the wadi. As the street is a high traffic volume road, air pollutants produced by vehicles get trapped by the surrounding hills due to limited ventilation, which lowers air quality in the area as shown in Figure 2.

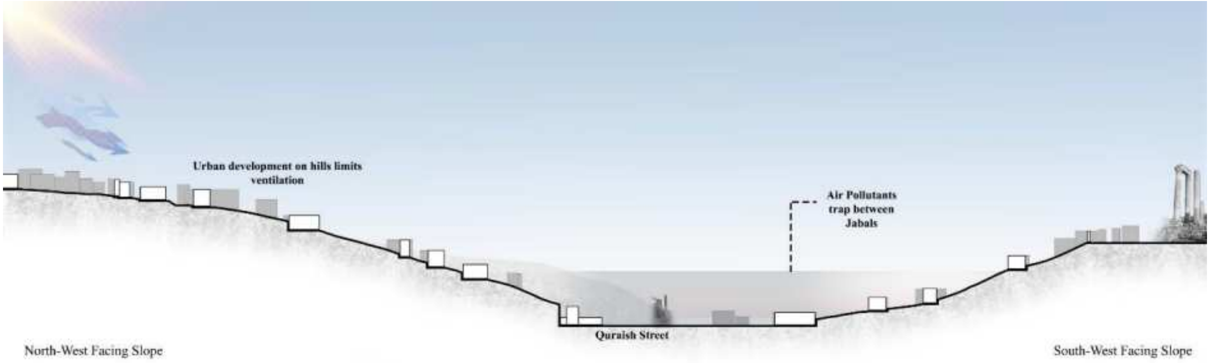



Figure 2. effects of topography on airflow and air pollution. Source: (Researcher, 2021)

The surrounding topography also increases stormwater runoff. Higher elevations usually have low infiltration rates. The urban development on the hills decreases infiltration and increases runoff velocity and volume. In rainfall events, runoff flows through the slopes directly to the low-lying area of Quraish street. The runoff flow from un-treated topography like Jabal el Jofeh creates landslides and usually holds debris and stones that block the drainage system and increase the hazard of flooding. According to the technical reports that reported the flooding events in the past years, many reasons have contributed to the flash floods in the area including 1. exceptional rainfall intensities as a result of climate change increased the hazard of water ponding down the valley 2. deteriorated drainage structures and blockages overwhelmed their storage capacity, as a result, water accumulates exceeding the holding capacity of the underground drainage system increasing the likelihood of flooding.

## 2. Literature Review

While cities and urban centres grow, they develop to accommodate more population and economic activities through increasing the share of built-up areas and impermeable surfaces. These continuous changes in the quantity and location of impermeable surfaces within the urban catchments significantly impact the hydrological characteristics of a catchment and increase the hazard of flooding. A study done by Hollis showed that continuous urbanization increases the probability of small floods up to 10 times, while complete urbanization of a catchment with at least 30% paving of the basin may double massive floods with return periods of 100 years in size (Hollis, 1975).

The urbanization process has altered natural ecosystems and reduced the system's flexibility to absorb excess water. Replacing natural land cover with sealed surfaces reduces the infiltration and storage capacity of the soil (Parkinson & Mark, 2006; Qin et al., 2013). The low drainage into the soil combined with an increasing number of intensive rainfall events leads to higher runoff into the sewage system and depletes its holding capacity exacerbating the hazard of urban flooding (EEA, 2012). Continuous soil sealing also reduces evapotranspiration because the urban surface does not retain water as vegetation cover does, preventing natural evapotranspiration from leaves and soils (Parkinson & Mark, 2006; Tucci, 2007).

Table 1. The potential asset that makes up green infrastructure grouped into three scale groups. Source: (EEA, 2011)

| The local, neighbourhood, and village-scale | Town, city, and district-scale | City-region, regional, and national scale |
|---|---|---|
| • Street trees, verges, and hedges<br>• Green roofs and walls<br>• Pocket parks<br>• Private gardens<br>• Urban plazas<br>• Town and village greens and commons<br>• Local rights of way<br>• Pedestrian and cycle routes<br>• Cemeteries, burial grounds, and churchyards<br>• Institutional open spaces<br>• Ponds and streams<br>• Small woodlands<br>• Play areas •Local nature reserves<br>• School grounds<br>• Sports pitches<br>• Swales (preferably grassed), ditches<br>• Allotments<br>• Vacant and derelict land | • Business settings<br>• City/district parks<br>• Urban canals<br>• Urban commons<br>• Forest parks<br>• Country parks<br>• Continuous waterfronts<br>• Municipal plazas<br>• Lakes<br>• Major recreational spaces<br>• Rivers and floodplains<br>• Brownfield land<br>• Community woodlands<br>• Former mineral extraction sites<br>• Agricultural land<br>• Landfill | • Regional parks<br>• Rivers and floodplains<br>• Shorelines<br>• Strategic and long-distance trails<br>• Forests, woodlands, and community forests<br>• Reservoirs<br>• Road and railway networks<br>• Designated greenbelt and strategic gaps<br>• Agricultural land<br>• National parks<br>• National, regional, or local landscape designations<br>• Canals<br>• Common lands<br>• Open countryside |

The continuous build-up of $CO_2$ generated from various human activities in the atmosphere accentuates the greenhouse effect. The continuous warming intensifies the global hydrological cycle (Milly et al., 2002). Due to the atmosphere's capability to hold more water vapor in warmer climates (ISDR, 2004; Jha et al., 2011). Therefore, an increase in humidity is expected, and more water moves through the hydrological cycle, changing the climatic patterns and leading to more precipitation per event, more variability, and more frequent climate extremes than the current climate ranges. (EEA, 2012; ISDR, 2004). Urbanization also contributes to climate change by altering the natural energy balance and causing an urban heat island effect (Akbari et al., 2016).

A more specific definition in the scope of stormwater management defines green infrastructure as a cost-effective technology that reduces the risk of urban flooding by controlling surface runoff allowing for groundwater recharge, and restoring hydrological processes to conditions before urban development as much as possible (Soz et al., 2016; Zeng et al., 2020), which is applied according to the US Clean Water Act through the use of plants or soil systems, permeable paving or other permeable surfaces, harvesting or re-use of stormwater. Landscaping for stormwater storage, infiltration or evapotranspiration, and reduction of flows to sewer systems. The European Environmental Agency classifies the green infrastructure practices in terms of scale as listed in Table 1 (EEA, 2011).

ENVI met software simulate climates in urban environments and assess the effects of atmosphere, vegetation, architecture, and materials interaction. It was used for this study as it covers the needed variables. Furthermore, Envi met allows calculating different thermal comfort indices using BIOMET, a post-processing tool that calculates human thermal comfort indices based on simulation data (Russo et al., 2016).

## 3. Methodology

This research sought to examine the performance of green infrastructure in the local context of Quraish street with the aim of developing a scenario-based approach to identify different possibilities for green infrastructure planning. The research questions investigated the adequate green infrastructure retrofits to be used in Quraish street, considering the location's spatial, geographical, and social contexts; and the impacts of these solutions in addressing climate challenges and improving urban resilience. The research objectives included planning green infrastructure integration with the site to achieve its multi-functional character and quantify the proposed scenarios' impacts on climate adaptation.

The dynamic simulation was adapted as the overall research strategy in conducting the research. A mixed-methods research design was adopted. Multiple sources of evidence, including official documents, experts and local community interviews, questionnaire surveys, field observations, and photo documentation, were used for data collection. The data analysis demonstrated the study area's spatial and social characteristics and evaluated the existing situation. Furthermore, it provided input for the preliminary simulation model. Building on the analysis results, the simulation models were developed to test three scenarios (Base Case, Design alternative one, and design alternative two), then the results were evaluated. Subsequently, the synergies and trade-offs between ecosystem services offered by each scenario were defined, and the recommendations for future implementation were proposed as shown in Figure 1.

The simulation models support the decision-making process by informing concerned policymakers of the best practices that make urban environments more resilient and adapted against different circumstances. Furthermore, they help in identifying the opportunities and restrictions in the design process without the need to alter the physical environment, which saves both effort and financial expenditures (Butler & Schütze, 2005). In ordr to select the approprriate simulation tool, differen softwares were compared. Figure 3 shows the Simulation tools selection procedure.

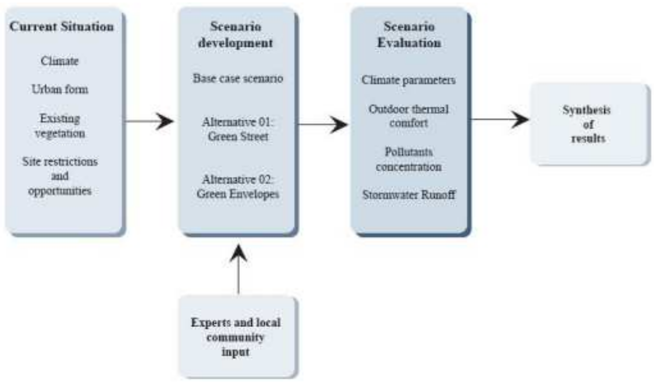



Figure 2. Dynamic simulation approach diagram. Source: (Researcher, 2022)

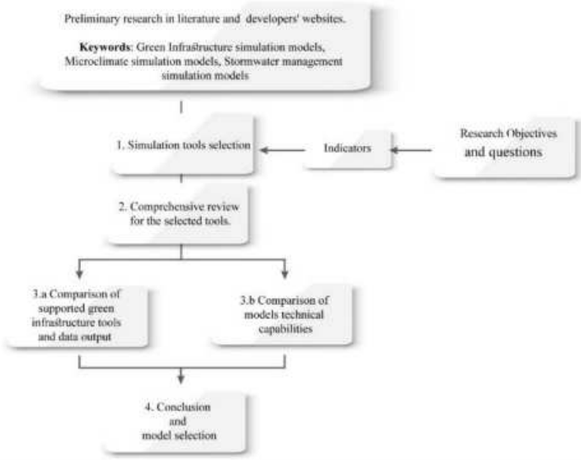


Figure 3. Simulation tools selection procedure. Source: (Researcher, 2021)

The first preliminary research process resulted in selecting eight simulation tools listed in Table 2. The table presents a comprehensive review of the selected tools and their general features, including their (Developer, Release Date, Availability, Aims, Spatial Scale, Temporal Scale, Architectural Software Integration, and Case Studies).

The models are classified under two main categories: stormwater management models, compared according to the capability to simulate runoff volume, infiltration assessment, facility retention, evaporation, and imperviousness. The second category is urban microclimate models, these models are compared according to the provided greenery services and their capability to simulate air temperature, solar radiation, relative humidity, Physiologically Equivalent Temperature (PET), and wind speed. Noting that some of the microclimates models can perform air quality simulations, models are also compared according to their capability to simulate carbon dioxide ($Co_2$), aerosols, and gas emissions. Based on the above comparison ENVI-met 5.0 was chosen as a simulation tool for this research as it offers the most appropriate features needed for this research.

Data Collection and Analysis from official data sources: data from relevant governmental institutions were gathered via (RFI letters) permitted by the university and through direct visits and phone calls. The information acquired consisted of maps, numerical data tables, and presentations. However, this step faced some challenges and limitations. Relevant data such as natural elevations, street profile, culvert and electricity network placement, and rainfall IDF curves could not be obtained due to lack of documentation or cooperation, among other issues related to confidentiality.

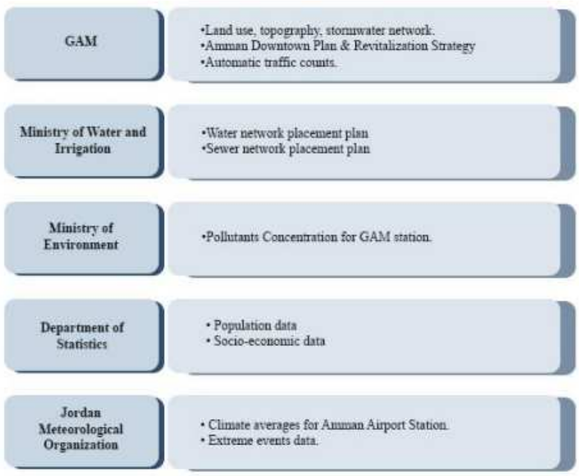


Figure 4. Official sources and types of collected data. Source: (Researcher, 2022)

Table 2. General feature of the selected simulation tools.

| Microclimate, Air Quality Models | | | | Stormwater Management Models | | | | |
|---|---|---|---|---|---|---|---|---|
| **ANSYS Fluent** | **Rayman** | **Urban Weather Generator** | **ENVI-met** | **RECARGA** | **Infraworks, (GSI)** | **Mike Urban** | **US EPA SWMM** | Model Name |
| Ansys Engineering Simulation Solutions | Andreas Matzarakis | Singapore National Research Foundation,<br><br>US Department of Energy | Micheal Bruse Envimet Company | The University of Wisconsin-Madison, water resources group | Autodesk Inc. | Danish Hydrological Institute (DHI) | The United States Environmental Protection Agency | Developer |
| 2005 | 2006 | 2015 | 1997 | 2002 | 2015 | 2007 | 1971 | Release Date |
| Commercial | Free- available to download | Free- available to download | Commercial version 5.0<br>Free- available to download version 3.1 | Free- available to download | Free- available to download for Autodesk 360 users | Commercial | Free- available to download | Availability |
| A computational fluid dynamics software package can simulate; 2D/3D flows, | Estimate the radiation fluxes and the effects of clouds and solid obstacles on short wave radiation fluxes. | Estimates the hourly urban canopy air temperature and humidity using weather data from a rural weather station. | Simulate climates in urban environments and assess the effects of atmosphere, vegetation, architecture, and materi- | Evaluate the performance of green infrastructure techniques. | Plan and design green infrastructure techniques and analyse their benefits to meet sus- | GIS integrated software models for urban water management practices, includ- | Tracks the quality and quantity of runoff generated within urban sub-catchment and flow | Model's Aims |
| Microscale-Mesoscale | Microscale | Microscale | Microscale | Single facility | A site to district scale | Neighbourhood to regional scale | Catchment Scale | Spatial Scale |
| Varies- depends on the equation | Varies- may reach to yearly simulations | Hourly | Up to 48 hours | Hourly, Single event, or long term | Single event | Sub-hourly | Single event or long-term | Temporal Scale |
| Allows for cad integration | No | Rhino | Already an architectural software | No | BIM software – can integrate with Revit. | No | No | Architectural Software Integration |
| (Adelia et al., 2020) | (Lee & Mayer, 2016)<br>(Fröhlich et al., 2019) | (Bueno et al., 2013)<br>(Street et al., 2013) | (Rasia & Krüger, 2010)<br>(Minella & Krüger, 2013)<br>(Hofman & Sam- | (Boancă et al., 2018) | (Choruengwiwat et al., 2019) | (Xiao et al., 2017)<br>(Hernes et al., 2020) | (Alfredo et al., 2010)<br>(Qin et al., 2013)<br>(Zhu et al., | Case Studies |

Thus, climate data were obtained for the nearest monitoring station to the study area where Amman Civil Airport station is the nearest within a 5.5 km radius and almost similar geographical coordinates and elevation.

Average daily traffic counts for Quraish street were obtained from the traffic directorate in Greater Amman Municipality. The average values for urban roads were not documented because these roads do not already have installed counters. Thus, data on the nearest traffic light (lanes 10-13, which directly head toward Quraish street) was obtained. The data records in Table 3 show an average number of 15681 vehicles. Due to the existence of multiple entrances and exits along the street from both sides, an estimated total number of 20,000 vehicles for 24 hours was proposed to be used in the simulations.

Table 3. Average daily vehicles that enter Quraish street. Source: (GAM Traffic Directorate, 2022)

| | Saturday | Sunday | Monday | Tuesday | Wednesday | Thursday | Friday | Daily Average |
|---|---|---|---|---|---|---|---|---|
| Number of Vehi-cles | 14157 | 16326 | 17387 | 17037 | 16238 | 15089 | 1354 | 15681 |

Qualitative Interviews: Online and face-to-face interviews were conducted from of hydrology, urban design, and archeology experts and group consisted of traders who work in the street. The Field Survey aimed to explore the local situation of Quraish street, starting from al-Misdar intersection and ending with Al Hashmi Street U-turn. To define the street's existing problems, built environment characteristics, and potential site threats. This survey was conducted using the instructions of literature and experts interview. The research employed simple random sampling. A random sample of 172 respondents was chosen to represent the study population. The targeted population was the visitors, facilities owners, and workers of Quraish street, as they would have a direct relationship with Green infrastructure retrofits in the area. The answers assigned by the respondents were averaged in order to present mean scores and presented in pie/ column charts presented in chapter 04. The charts were analyzed to understand the users' needs, views, and aspirations for the area and interpret their acceptance of green infrastructure strategy implementation in the area. The results were used as an input for the scenario development phase. The Scenario development phase focused on developing appropriate design scenarios based on the analysis results of the previous steps. The literature review, interviews, site analysis, and questionnaires were used to plan optimized green infrastructure retrofits within the study area. Due to limited available space, most interventions were planned for roofs and pavements with different scenarios' materials and applications. The interventions and justification are fully explained in chapter five. Table 4 summarizes the final scenarios that were used in the simulations

Table 4. Summary of the proposed scenarios for the simulation process.

| **Scenario** | **Interventions** |
|---|---|
| Base case | Existing situation with minimal vegetation. |
| Green Envelopes | Green roofs and green facades for buildings. Cool (permeable) pavement for the sidewalks and parking spaces. |
| Green street | Stormwater tree planters along the street. Impermeable pavements for the sidewalks and parking spaces. |

## 4. Results

### 4.1. Climatic Data

Climate forces and their potential climate impacts: According to Köppen-Geiger's climate classification, Amman has a Mediterranean hot summer climate (Csa), with relatively hot, dry summer and cold, wet winter seasons (Rubel et al. 2017). Winter extends through December until the end of February, with an average temperature record between 8°C and 10°C degrees. The coldest month of the winter season is January, with an average temperature of 8.4°C. Summer is moderately hot and extends through June, July, and August. With average temperatures ranges between 24°C and 27°C. The warmest month is August, with an average maximum temperature of 32.8º C. Spring and Autumn are short and characterized by comfortable weather conditions. Relative humidity ranges are relatively low during summer, between 42- 50%, and increase in winter up to 73.6%. Precipitation in Amman is highly dependent on rainfall, with a low possibility of snow once or twice annually. The mean annual rainfall in Amman is 250 mm (Amman Airport station, 2020).

Jordan is currently facing the impacts of changing climate. According to the Amman climate action plan, the country's annual maximum temperature has increased by 0.3° to 1.8°C since the 1960s. At the same time, rainfall patterns had varying trends in increasing and decreasing during the past decades, depending on the location (GAM, 2019). Since 2010 Amman has witnessed striking climate hazards. Changes in rainfall intensity had caused flash floods in the city centre in 2015, 2019, and 2020. Lengthy drought periods occur as a result of changing rainfall patterns. Maximum temperature in the summer has increased, and heatwaves are frequently occurring. These events are affecting the lives, economy, and public health of the poor, vulnerable communities of Amman (GAM, 2019).

### 4.2. Built Environment

Figure 5 shows that the morphological structure had transformed from scattered buildings with plenty of open, permeable spaces in 1918 to impermeable and dense structures. As a result, land use had also transformed from residential and agricultural in 1918 into mixed-use development and services after the coverage process to fulfil the vision of downtown in the 1960s as a central business district. The total number of surveyed structures directly facing the main road is 106; only 62 buildings are fully occupied, while 39 buildings are semi-vacant, with one vacant building and four construction locations.

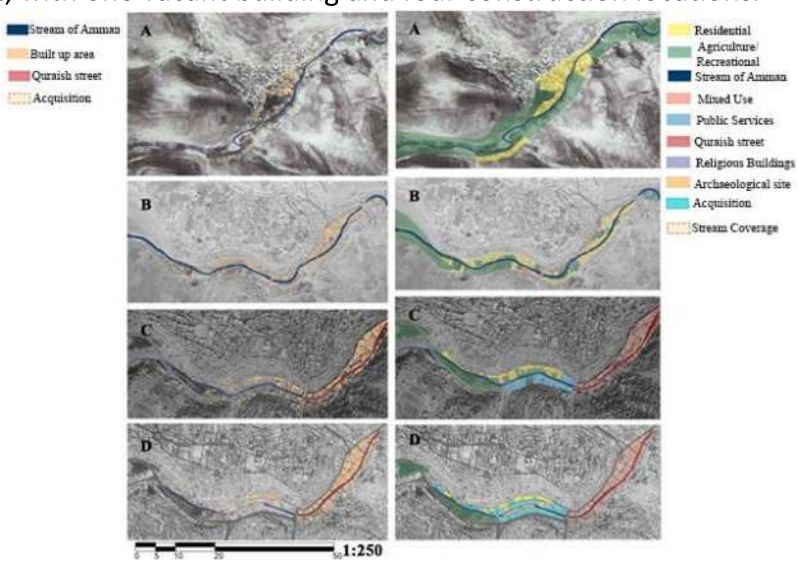



Figure 5. Urban Morphology and Land-use transformations of the stream banks. A. 1918, B. 1953, C. 1978, D. 1992. Source: (Gharaibeh et al., 2019)

Roads and traffic: The vehicular circulation pattern in Quraish street heads northeast towards al Hashmi street. It has two major gateways and one major exit. The one-way street suffers high traffic volume. It is a wide street with car dominancy and no safe pedestrian crossings. Public transportation vehicles have no proper stops or dedicated bus lanes. They occupy a considerable share of the street on the sides, increasing traffic congestion and disturbing mobility. There is an existing BRT station near the GAM building within 10 minutes walking distance and another BRT station in al Mahatta area. shows the existing Road Hierarchy and public transportation.

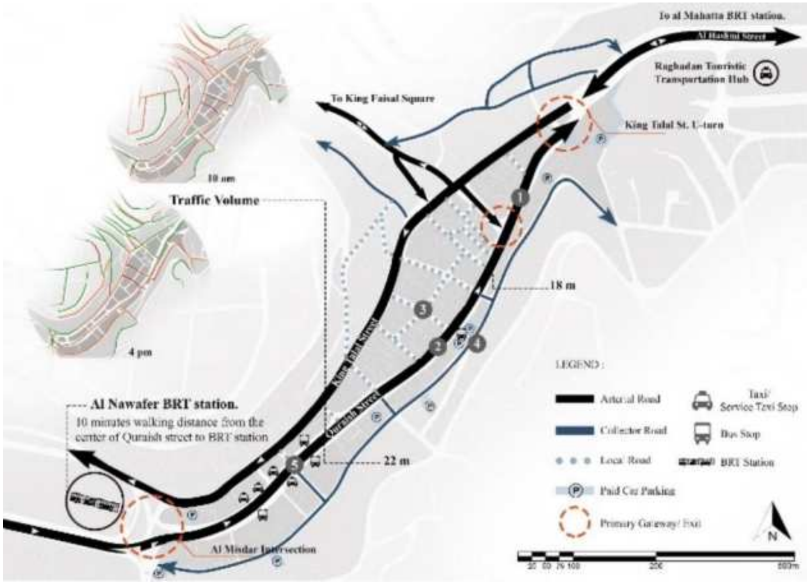



Figure 6. Road Hierarchy and public transportation. Source: (Researcher, 2021)

Utility networks: Major utility infrastructure exists beneath Quraish street, serving the surrounding area. An existing culvert with a cross-sectional area of almost 48 square meters passes towards al Jaish street, where it splits into two culverts. The existing utility networks in Figure 7 cross within the culvert pathways reducing its cross-sectional area, which affects the culvert's ability to drain stormwater and increases the possibility of flooding.

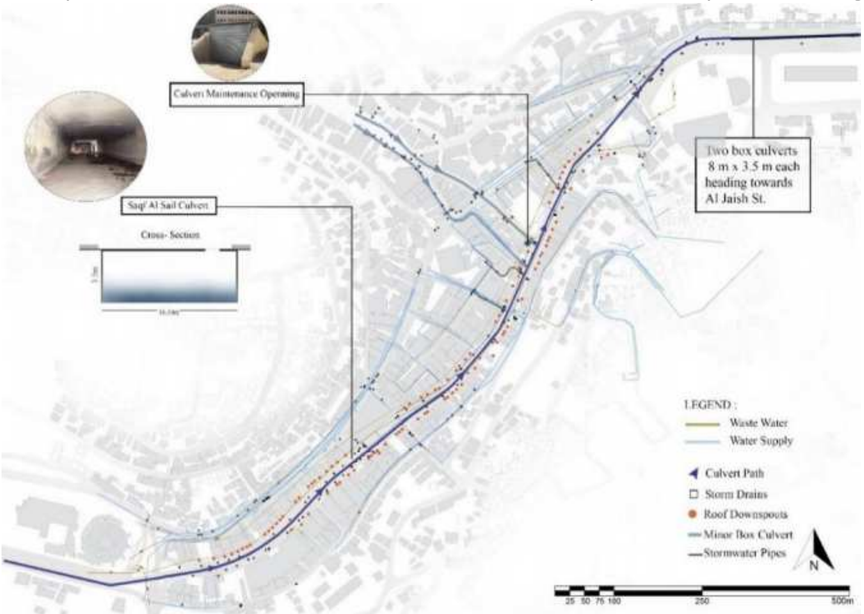



Figure 7. Existing utility network. Source: (Researcher, 2021, GAM,2021, MOWI,2021)

Vegetation and natural cover in Quraish street are relatively low in percentage due to the high urbanization. Vegetation provides various environmental benefits. It cools air temperature through evaporative cooling, retains rainwater through leaf interception, slows, and manages runoff through infiltration. In Quraish street, urban surfaces have higher percentages compared to vegetation cover. Only a few trees exist along the street, with a small park. Thus, the lack of vegetation in Quraish street contributed to warmer air temperature and increased stormwater runoff.

Pollution: various sources of pollution exist in Quraish street. Private and public transportation vehicles are the major source of air pollution. According to the Ministry of Environment, $PM_{10}$ is the most produced pollutant that exceeds the standard limits in al Madina area, especially during peak times (MOE, 2020). The site lacks solid waste management.

### 4.3. Quantitative analysis

selective results are introduced. 1- Assessment of the community's awareness of the recent urban; and climate changes occurring in Amman (Traders and Visitors) (Figure 8): results indicate that the majority of the respondents had observed an increasing trend in the summer mean temperatures and a changing trend in rainfall intensities for the past ten years (96%). Most of the respondents believe that the increasing number of vehicles and their associated emissions is the most significant factor that accompanies urban expansion and negatively affects climate change. Moreover, 97.7% of the respondents agree that excessive urban expansion on the expanses of green open spaces negatively affects psychological health.

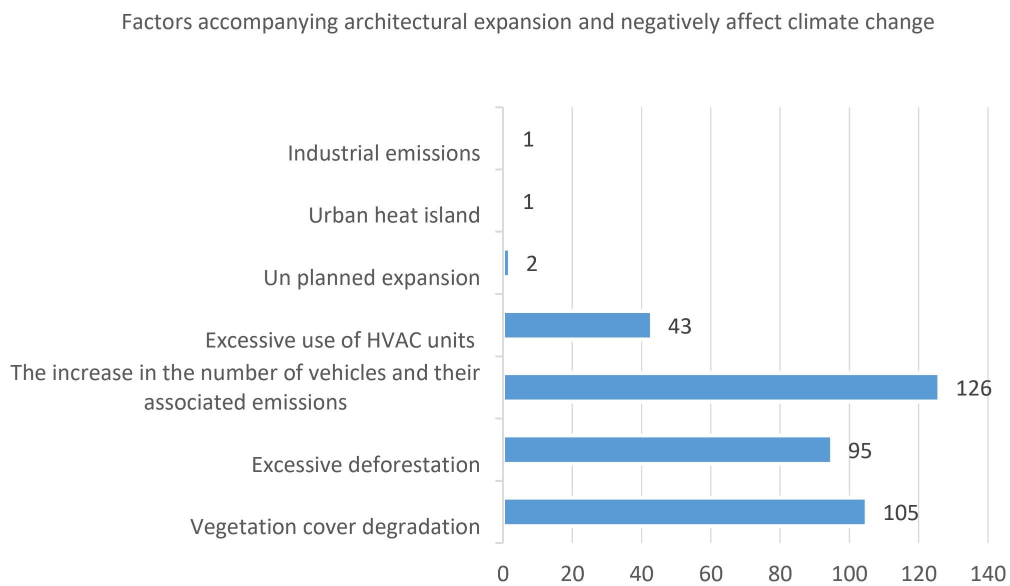



Figure 8. Assessment of the community's awareness of the recent urban; and climate changes occurring in Amman. Source: (Researcher, 2022)

2- Problem Identification on the local scale. Assessment of the significant problems visitors face in Quraish street. According to the respondents, the most significant problems in Quraish street are traffic congestion, smells, and flood risks as shown in Figure 9. While the most suitable solutions for the previous problems are organizing public transportation and increasing the green areas.

As shown in Figure 5-32, 75.2% of the respondents avoid visiting Quraish street in the winter due to flood risks. While 78.2 % of them avoid visiting Quraish street in summer during the day due to extreme heat. More than 90% of the respondents agree that the underneath culvert needs a support system, Quraish street lacks shaded places for rest, the street should have more green and open spaces, and vehicle emissions have a negative impact on air quality. Furthermore, 73.7% of the respondents agree that urban density in the area exacerbates the risk of flooding.

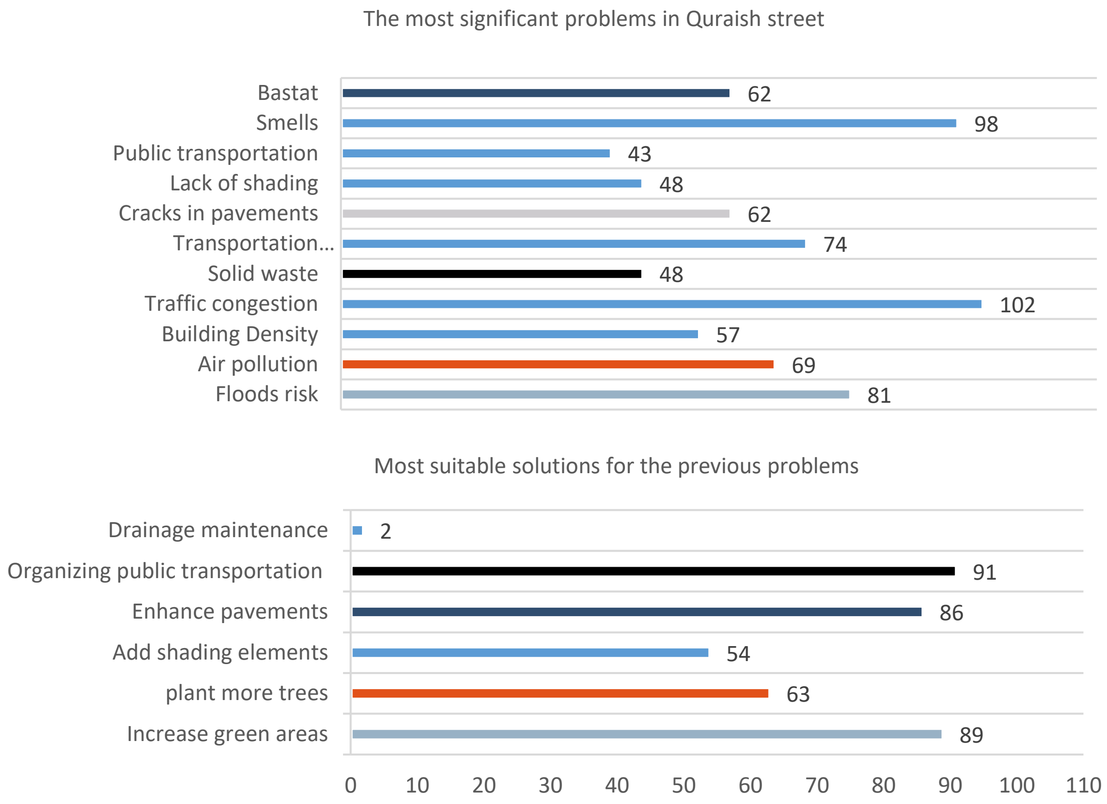
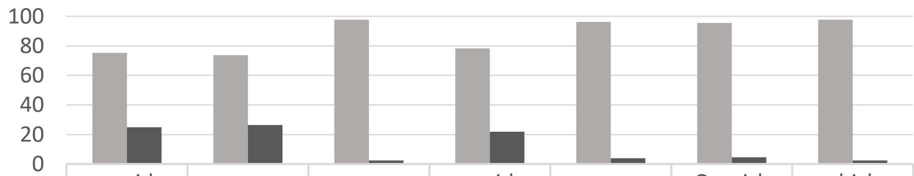



Figure 9. Significant problems visitors face in Quraish street and their proposed solutions. Source: (Researcher, 2022)




| | avoid visiting Quraish street in the winter due to flood risks. | urban density in the area exacerbates the risk of flooding. | underneath culvert needs a support system. | avoid visiting Quraish street in summer during the day due… | Quraish street lacks shaded places for rest. | Quraish street should have more green and open spaces. | vehicle emissions have a negative impact on air quality at… |
|---|---|---|---|---|---|---|---|
| Agree | 75.2 | 73.7 | 97.7 | 78.2 | 96.2 | 95.5 | 97.7 |
| Disagree | 24.8 | 26.3 | 2.3 | 21.8 | 3.8 | 4.5 | 2.3 |

Figure 10. Agree/ Disagree statements to assess significant problems in Quraish street. Source: (Researcher, 2022)

3- Assessing the acceptance of green infrastructure implementation. According to the respondents, the priorities of ecosystem services that should green infrastructure employ stormwater management and providing open and green spaces. Regarding the acceptance of Green Infrastructure solutions, 99.2% of the respondents think they would feel more comfortable visiting the street if the green infrastructure was implemented and 93.8 % of them think they would visit Quraish street more frequently if the green infrastructure were implemented. 99.2% of the respondents think green infrastructure will economically revive the street. While 97% of them think that green infrastructure will attract more tourists to the area. Finally, 98.5% of the respondents think that green infrastructure will enhance the urban scene of the area.

4- Assessing the traders' acceptance of green infrastructure implementation. According to the respondents, the priorities of ecosystem services that should Green Infrastructure employ are stormwater management and providing open and green spaces. Regarding Green Infrastructure acceptance, 68.3% of the respondents agree to use their facilities' facades/ roofs, and front sidewalks for green infrastructure implementation. However, 78% of the respondents believe that financial contribution to green infrastructure implementation will raise the burden on their financial status. Furthermore, more than 90% of the respondents believe that green infrastructure will contribute to economic growth and increase the number of visitors to the area.

Scenario development: Based on the expert's and users' interviews, site assessment, field survey, and questionnaire results. The following conclusions were summarized in Table 5, which contributed to the scenario development. It is worth mentioning that flood risk reduction requires watershed-scale solutions. Hence, the proposed solutions will only mitigate site-generated runoff.

Table 5. Scenario development considerations

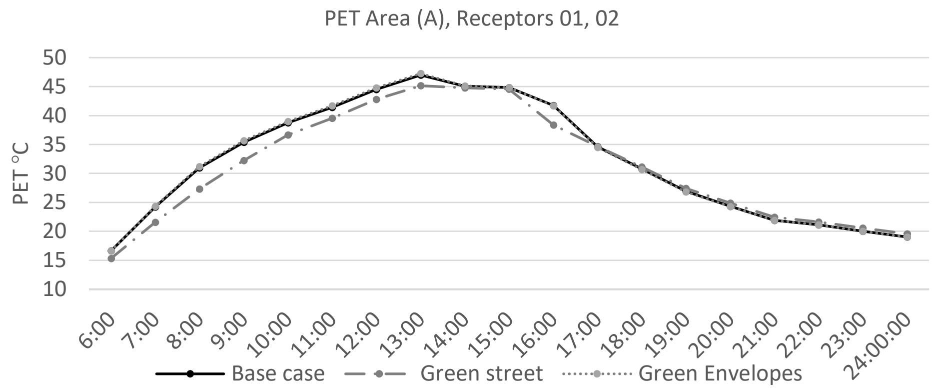
| Indicator | Proposed solutions |
|---|---|
| Lack of sufficient space for implementation | Interventions will take place on roofs, facades, sidewalks, and parking lots. |
| Due to the utility lines and dry springs under buildings, full infiltration is not allowed. | Partial infiltration using impermeable linear beneath. |
| Old buildings structure | Extensive green roofs due to lower loads |
| Vegetation selection | Using drought, shade-tolerant vegetation (sedum for green roofs, Ivy for green walls) |
| Tree placement (dense and sparse canopies) | Minimum 8 meters between tree canopies to allow ventilation |
| Green façade placement | Existing blank side elevations to preserve heritage identity |
| Green roof placement | Vacant roofs that allow considerable space |

### 4.4. ENVI-met simulation results

Outdoor Thermal comfort: The ability of green infrastructure scenarios to moderate the microclimate in Quraish street is explored based on the PET index (Physiologically equivalent temperature).

The PET values are calculated at pedestrian level (1.8) meters high for four receptors located in the two model areas. The diurnal PET values of all scenarios show moderate to extreme heat stress within the study area. Figure 11 shows the average PET in both model areas. In the morning, the intensity of PET ranges within comfortable sensation, while discomfort and extreme stress can be observed between 10 AM and 5 PM, noting that the distribution slightly varies between the model areas.

Air Pollution: Using green infrastructure for $CO_2$ sequestration showed different trends depending on the scenario. As shown in Figure 12, the use of dense crown trees with the green street scenario in the model area (A) showed a notable reduction in $CO_2$ values. In contrast, the use of sparse trees in the model area (B) and green envelopes in both areas had a negligible effect on $CO_2$ sequestration at the pedestrian level.



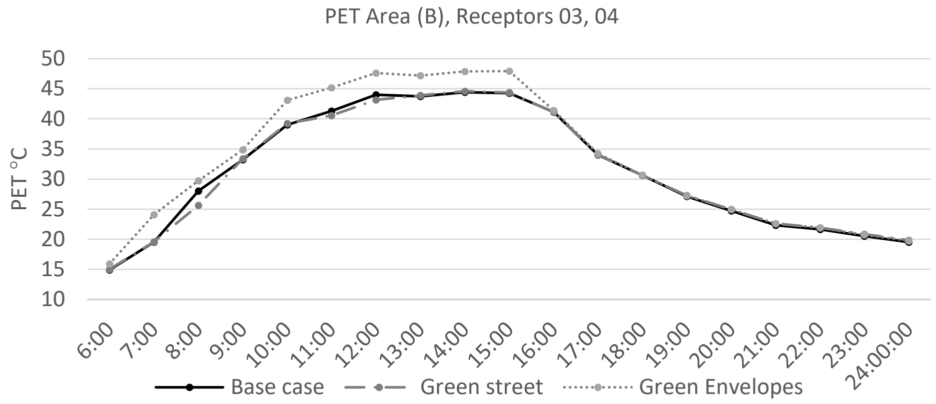
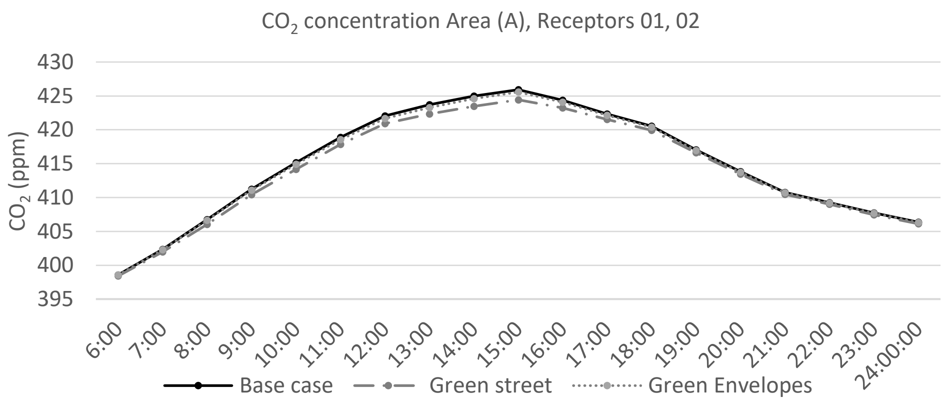




Figure 11. Average PET at 1.8 m height by four investigated receptors.



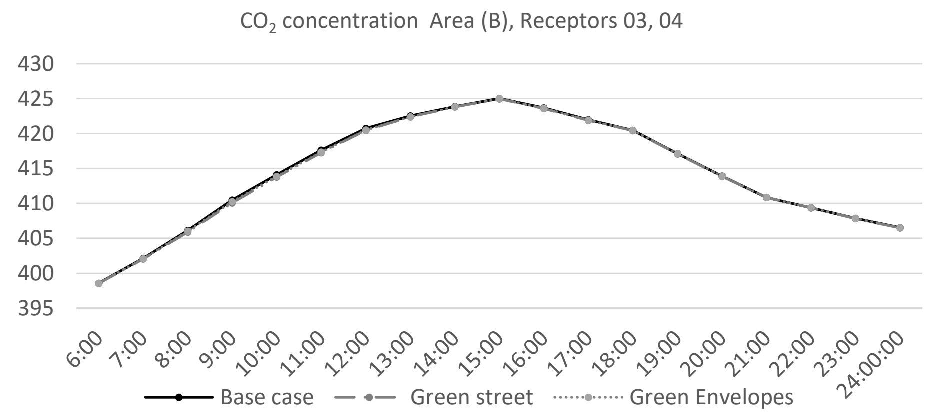




Figure 12. Average $CO_2$ at 1.8 m height by four investigated receptor

## 5. Conclusion

Urban centres play a significant role in climate adaptation future. Hence, Quraish street in Downtown Amman was chosen as a case study to represent an urban centre that has a high share of urban surfaces and lacks proper vegetation. Furthermore, it has a distinct location down the valleys that exacerbates various climatic risks. An urban retrofits strategy was chosen for Green Infrastructure planning in the study area. The urban retrofit strategy required an assessment of the site's physical and environmental characteristics and integration of community in problem identification and solutions acceptance. The research employed a scenario-based approach based on the site assessment and community participation. The research strategy focused on dynamic computer simulations using ENVI-met Model to quantify the effects of the proposed. Based on the field survey, the most significant problems in Quraish street are traffic congestion, smells, and flood risks while the most suitable solutions for the previous problems are organizing public transportation and increasing the green areas. The majority of the respondents believe in the Green Infrastructure solutions, and 99.2% of them would feel more comfortable visiting the street if the green infrastructure was implemented.

Results indicate that using dense tree canopies has shown notable effects on heat mitigation. In contrast, sparse tree canopies showed negligible effects on heat mitigation. Regarding pollutants concentration, tree canopies showed negligible reductions in $CO_2$ concentration but a notable increasing effect on vehicle emissions concentrations due to limited ventilation caused by tree canopies. The green envelope scenario showed negligible effects on heat mitigations at the pedestrian level but notable effects on roof podium levels and in the surrounding area. However, it has increased vehicle emissions concentrations because it has lowered the horizontal airflow. Heat stress is a significant outcome of increased solar radiation. In order to create thermally comfortable outdoor spaces, planners should incorporate vegetation in the urban environment to enhance the shading patterns and lower air temperatures through evaporative cooling. Using vegetation on roofs, and trees in enclosed street environments can reduce $CO_2$ concentrations. However, they limit ventilation and increase the concentration of traffic pollutants at pedestrian levels. Thus, planners and city authorities should implement policies to encourage electric vehicles, public transportation and walkability to reduce vehicle emissions. Incorporating street trees in enclosed urban environments should take into consideration their main intended function depending on canopy density, spacing, and tree structure. Trees' height should not exceed maximum building heights to allow proper solar access for buildings. Moreover, space between tree canopies should be sufficient in order to allow ventilation and proper airflow.

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# The effect of prevailing climate, outdoor pollution levels and ventilation rates on indoor air quality in social housing in Almaty, Kazakhstan

**Mainur Kurmanbekova*, Steve Sharples, Jiangtao Du**

School of Architecture, University of Liverpool, Liverpool L69 7ZN, UK;
*corresponding author: m.kurmanbekova@liverpool.ac.uk;

**Abstract:** Increased ventilation rates were one way of reducing Covid risks. However, there are some negative health effects associated with increased air flow rates if the external air is polluted. There have been very few studies of residential indoor air quality (IAQ) in Kazakhstan. For this research existing low-income, mid-rise and naturally ventilated social housing in the city of Almaty were modelled to simulate indoor contaminant levels for different ventilation rates and climatic conditions. CONTAM v3.4 was used to model indoor concentrations of gaseous nitrogen dioxide (NO2) and particulate matter ($PM_{2.5}$) – chosen for their negative impacts on cardio-respiratory health. Outdoor levels of NO2 and $PM_{2.5}$ were provided by an air quality monitoring station a few kilometres from the housing. NO2 and $PM_{2.5}$ levels were estimated to investigate how combinations of weather and ventilation rate might influence IAQ. Combinations of particular wind speeds and directions, coupled to window opening patterns, could lead to indoor levels of NO2 and $PM_{2.5}$ that were higher than are recommended in health standards. Further work will carry out field monitoring of indoor pollutants to calibrate the accuracy of the CONTAM model and provide data on existing IAQ levels in Kazakhstan's social housing stock.

**Keywords:** indoor air quality, health, weather

## 1. Introduction:

Indoor and outdoor air quality are well established determinants of population health and wellbeing. The World Health Organisation has established air quality guidelines for several air pollutants known to be harmful to human health (WHO 2021), including particulate matter ($PM_{2.5}$) and nitrogen dioxide (NO2). Based on population weighted, annual average $PM_{2.5}$ concentration (µg/m³) data from 2018 to 2021, Kazakhstan currently ranks 23rd among the world's most polluted countries (IQAir 2021). There has been evidence that elevated $PM_{2.5}$ and NO2 concentrations are associated with adverse health effects, like respiratory and cardiovascular diseases (Brook et al. 2010; Pope Iii et al. 2002; Yang et al. 2019; Zanobetti et al. 2009). Also, $PM_{2.5}$ concentrations are associated with an increased risk of contracting the COVID-19 virus and the likelihood of experiencing more severe symptoms, including death, if infected (Cole, Ozgen & Strobl 2020; Wu et al. 2020).

Indoor residential exposure to $PM_{2.5}$ and NO2 is becoming a public concern because most people spend majority of their time indoors. Indoor residential $PM_{2.5}$ is mostly produced by smoking and cooking (Dimitroulopoulou et al. 2006; Hu & Zhao 2022), as well as by ambient $PM_{2.5}$ entering the home through ventilation or envelope leakage. Indoor residential NO2 sources include gas stoves and outdoor concentrations. Total indoor concentrations of these pollutants are influenced by the relative distribution of outdoor and indoor sourced pollutants in the residence, which is dependent on housing characteristics. Indoor $PM_{2.5}$ and NO2 concentrations are also influenced by socio-demographic characteristics, which could lead to different exposure patterns and health hazards in specific populations (Rotko et al. 2000; Shrubsole et al. 2016). Low-income households, for example, may be more susceptible to these impacts as they are more likely to live in smaller apartments within multifamily residences, thereby increasing the influence of indoor sources within their unit or from neighbouring flats. Also, low-income urban inhabitants are more likely to smoke and cook using gas stoves (Glasser et al. 2022), both of which can raise indoor $PM_{2.5}$ and NO2 concentrations.

To date, a considerable number of existing social housing buildings in Kazakhstan are not equipped with mechanical ventilation systems, which results in natural ventilation being the only way to supply fresh air indoors. However, using natural ventilation for areas with high outdoor pollution levels could increase the risks of people being exposed to air pollutants. Over the last six years a stable high level of air pollution had been observed in Kazakhstan and ambient air pollution was a subject of numerous studies (Kerimray et al. 2020; Vinnikov, Tulekov & Raushanova 2020). However, little is known about the impact of ambient air pollution on indoor air quality in Kazakhstan.

The purpose of this study was to determine to what extent the ambient $PM_{2.5}$ and NO2 concentrations and indoor emitted particles contribute to indoor $PM_{2.5}$ and NO2 pollution in social housing apartment in Almaty, Kazakhstan, under differing meteorological conditions, particularly the prevailing wind direction for the analysed dates in summer and winter of 2021 as well as the steady state wind direction in relation to the orientation of the building. The results seek to contribute to a better understanding of how the outdoor air pollutants and occupants' behaviours impact indoor air quality (IAQ) in Kazakhstan's social housing. To achieve this objective, a naturally ventilated social housing apartment block in Almaty was simulated during the summer and winter seasons for different ventilation rates and prevailing climatic conditions. The outdoor $PM_{2.5}$ and NO2 concentrations were obtained from an actual monitoring station. The indoor sources emission rates were estimated from a literature review. The multizone airflow and contaminant transport program CONTAM v3.4 was used to model indoor and ambient concentrations of NO2 and $PM_{2.5}$.

## 2. Methodology

### 2.1 Study area

The study area was social housing apartments in Almaty (43.2220° N, 76.8512° E), which is a major city in southern Kazakhstan, with a population of 2 million people. Figure 1 shows the location of Almaty within Kazakhstan.


Figure 1. Location of Almaty within Kazakhstan

The average annual air temperature of Almaty is 9.4 $^0$C. The average air temperature fluctuates in January from -18.4 to -1 $^0$C and in July from 20.7 to 27.3 $^0$C. Extreme summer temperatures can reach up to 41.7 $^0$C, while winter temperatures can drop to -37.7 $^0$C. Almaty has a 'bowl-shaped' topography and is located in the wind shadow of the Ile Alatau mountain range, where stagnant weather conditions are frequent, which lead to adverse environmental conditions. The situation is aggravated by the fact that the "wind rose" has been distorted in the metropolis. According to the National Hydrometeorological Service RSE 'Kazhydromet', over the past 30 years, the average wind speed has decreased from 6 to 1-2 metres per second (Koshegulova & Kon 2021). Calm weather and strong inversion layers suppressing vertical exchange are major reasons for the high levels of air pollution over the city (Zakarin et al. 2021).

Almaty is one of the leading cities in terms of the amount of social housing commissioned there. As part of the implementation of the "Nurly Zher" state programme, 3,065 apartments, with a total area of 239,700 $m^2$, were put into operation in 2021, including, 1451 apartments to large families, working youth, and for socially vulnerable segments of the population (RK 2022). From 2012 the state program has been constructing affordable social housing corresponding to III and IV comfort classes in accordance with the requirements of state standards in the field of architecture, urban planning and construction (Mamin 2019). Economy class housing is distinguished by such parameters as the number of rooms, varying from 1 to 3 and about 15 $m^2$ per person.

### 2.2 Building

A low-income residential complex, classified as class IV (economy class) according to the Kazakhstan building code, and located in Almaty's North-west edge, was chosen for this study. This social housing building was commissioned in 2013 and includes a complex of 33 houses of different heights from four to nine storeys (Figure 2). Back in 2016-2017, cases of tilting houses were regularly detected due to the subsidence of the soil and violations of building standards. During cold periods, the building is supplied with district heating using solid fuel. The building is naturally ventilated, and outdoor air is supplied through window openings and infiltration. The complex is located within a two-kilometer radius of a combined heat and power CHP-2 central heating plant and a waste processing plant.

Figure 2. View of the residential social housing complex studied in this research.

## 2.3 Simulation parameters

The average floor area per tenant in the simulation parameters for economy-class (IV) apartments was 15 square metres. The class IV apartments have one to two living rooms at most, as well as a shared bathroom. There are up to 9 square metres in the kitchen. Finished apartment quality is referred to as the simplest in terms of interior finishes that use inexpensive building materials and fixtures (KAZGOR 2007). Also, in comparison to the higher classes, the finishing work's internal surfaces are where the most deviations are permitted. Rods, plastered surfaces, as well as window and door slopes, have the largest vertical and horizontal deviations (mm per 1 m) with a simple and budget quality building finishing for class IV compared to improved or high-quality comfort classes (Nuguzhinov et al. 2004).

CONTAM 3.4.03, which is an established and well-validated multi zone airflow and contaminant transport analysis program, was chosen as the primary tool for this study. A two-bedroom corner unit apartment with a total floor area of 54.84 $m^2$. Figure 3 shows the CONTAM schematic plan layout of the apartment, with the modelled area in green. The apartment is located on the ground floor of a 4-storey high building, with a basement below it. The height of the basement and residential floors is 2.8 m from the finished floor to the bottom of the floor slab. There are three apartments on each floor, and the studied one is located at the northwest corner of the floor with windows facing north and south. Building dimensions were based on the architectural plans.

Each zone contains an airflow path, represented as a 'rhombus/diamond' on the walls and floors, which is a CONTAM building component through which air can move between two adjacent zones. Each airflow path is provided with specific leakage value information that describes its flow characteristics. An even distribution of permeability was assumed across all surfaces. Leakage values were assigned to interior and exterior walls, wall joints, windows, doors, and ceilings based on ASHRAE's effective leakage area (ASHRAE 2001) and previous modelling studies (Fabian et al. 2016; Underhill et al. 2018). CONTAM deposition rate sink model was used to remove contaminants ($PM_{2.5}$ and NO2) from zones. $PM_{2.5}$ was modelled using a deposition rate of -0.19/h and -0.87/h for NO2 (Fabian, Adamkiewicz & Levy 2012; Long et al. 2001; Taylor et al. 2014).

Indoor air temperatures in summer and winter were set at 20 °C, according to the interstate standard GOST (GOST30494-2011 2013). Hourly values of weather conditions for a typical meteorological year (TMY) were obtained from the Meteonorm software in epw format. One week in August and one week in December were selected to represent hot and cold periods respectively. Hourly air pollution data from 'ПНЗN3 (S) Ice Arena' station located in the Alatau district of Almaty were obtained from KazHydroMet between 1$^{st}$ January 2021 and 31$^{st}$ December 2021.

CONTAM contaminant concentrations within the control area (living room) of an apartment were simulated using different combinations of airflow and contaminant state methods (Table1). Steady state and transient state airflow were simulated against transient contaminant concentrations, and this generated twenty scenario cases defined by season and window opening behaviour. Open windows are marked as 'O' and closed windows as 'X' in Table 1. The calculation time step in CONTAM allows the user to perform a combination of simulation method settings over a user-defined time period. For instance, to obtain a time history of contaminant concentrations under steady airflow conditions, "steady state airflow," which is a user-specified weather condition and in this study with a focus on changing the wind direction, was combined with "transient contaminant," which is a dynamic contaminant concentration from an external contaminant file simulation. Additionally, transient contaminant simulation and transient airflow simulation (Table 2) that use external weather data for the designated period are combined to produce time histories of contaminant concentrations ($PM_{2.5}$ and NO2) under changing weather conditions. All simulation types used a 5-minute time step interval.

Table 1. *Variable case scenarios representing changes in season, window opening and airflow simulation patterns.*

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Steady state airflow simulation** | | | | | | | | | | | | | | | | |
| **Season** | Winter | | | | | | | | Summer | | | | | | | |
| **Wind direction** | N/0° | | E/90° | | S/180° | | W/270° | | N/0° | | E/90° | | S/180° | | W/270° | |
| **Window*** | X | O | X | O | X | O | X | O | X | O | X | O | X | O | X | O |
| **Case** | *S1* | *S2* | *S3* | *S4* | *S5* | *S6* | *S7* | *S8* | *S9* | *S10* | *S11* | *S12* | *S13* | *S14* | *S15* | *S16* |
| **Transient airflow simulation** | | | | | | | | | | | | | | | | |
| **Season** | winter | | | | | | | | summer | | | | | | | |
| **Window*** | X | | | | O | | | | X | | | | O | | | |
| **Case** | *TW1* | | | | *TW2* | | | | *TS1* | | | | *TS2* | | | |

*- windows during the cold season were open for two times a day for 30 minutes and during summer were open for the whole day from 8 a.m. to 8 p.m.;

## 3. Results

Hourly average concentrations of total indoor $PM_{2.5}$ and NO2 in the living room of the corner apartment were simulated for one week each during winter heating and summer cooling periods across several window opening and airflow scenarios. Overall, indoor concentrations are the sum of the effects of all sources within the unit and infiltration from outdoors. Indoor $PM_{2.5}$ concentrations during the one-week winter period under transient contaminant simulation varied from 23.5 to 644.1 μg/m$^3$, with an average of 166.2 μg/m$^3$ for a closed window (TW1), and from 23.9 to 645.5 μg/m$^3$, with an average of 167.7 μg/m$^3$ for an open window (TW2) case (Figure 4). The mean outdoor modelled concentration of $PM_{2.5}$ during the winter heating season (209 μg/m$^3$) was significantly higher than the mean concentrations in the control area (166 μg/m$^3$). Results of the Pearson correlation indicated that there is a significant large positive relationship between ambient $PM_{2.5}$ concentration and indoor $PM_{2.5}$, ($r(167) = .944$, $p < .001$), as shown in Table 2. Concentrations of mean indoor $PM_{2.5}$ during the summer period varied from 4.4 to 48.0 μg/m$^3$, with an average of 19.2 μg/m$^3$ for both windows opening activity scenarios (Figure 5). Indoor $PM_{2.5}$ reflect outdoor concentration levels.

Average concentrations of ambient NO2 from the state monitors were stable across all studied seasons, ranging from 0.9 to 1.2 μg/m$^3$, with an average value of 1.0 μg/m$^3$ (Table 2). There was an increase of indoor NO2 concentrations during cold periods, coinciding with cooking activities and minimum window opening behaviour (Figure 6), and an indoor decrease of NO2 during the summer period (Figure 7) with occasional peaks reaching 4.2

µg/m$^3$. The NO2/TW1 and NO2/TW2 lines in Figure 6 overlap due to very small significant difference in NO2 pollutant concentration between window closed (*M* = 1.4, *SD* = 2.4) and window open condition (*M* = 1.4, *SD* = 2.4), *t*(168) = 2.5, *p* = .014, during cold season, according to the results of the paired t-test. Also, there is a non-significant NO2 concentration difference between window closed (*M* = 0.6, *SD* = 0.5) and window open state (*M* = 0.6, *SD* = 0.5), *t*(168) = 0.4, *p* = .683 for the summer period (Figure 7).

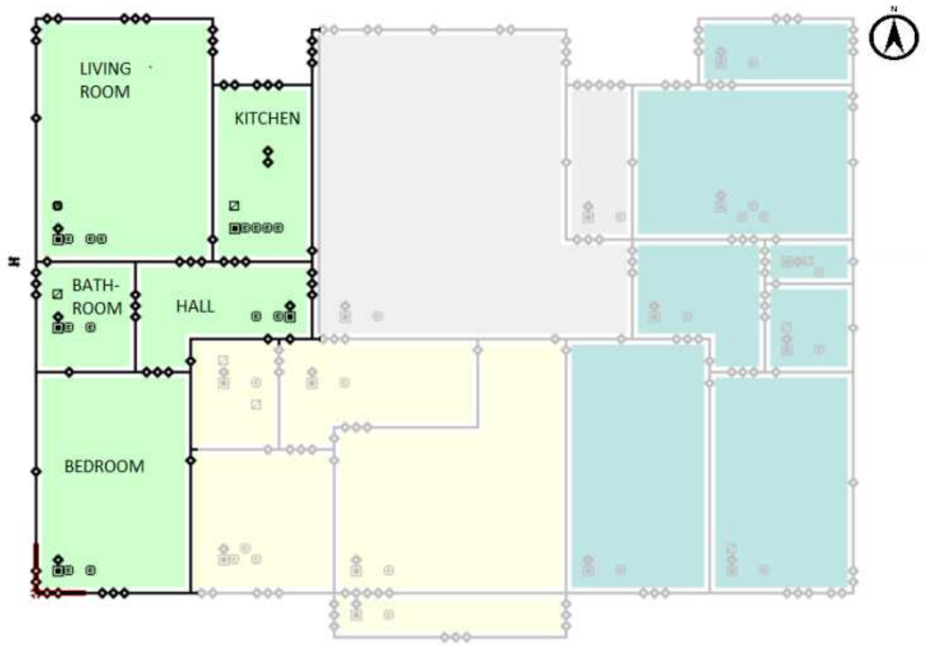



Figure 3. *CONTAM schematic floor layout, representing the Ground Floor apartments in a social housing building. Each apartment is divided into colour zones. Each zone contains airflow paths, pollutant sources and sinks which are represented as dots on walls and interior spaces.*

Table 2. Ambient *PM2.5 and NO2 concentrations for the specified period of 2021 and simulated values for indoor control area.*

| Transient airflows | Period | Values | Indoor $PM_{2.5}$ µg/m$^3$ | Outdoor $PM_{2.5}$ µg/m$^3$ | Indoor NO2 µg/m$^3$ | Outdoor NO2 µg/m$^3$ |
|---|---|---|---|---|---|---|
| **window open** (TW1) | **Winter:** Dec12-Dec18 | Mean | 166.2 | 208.7 | 1.4 | 1.0 |
| | | Max | 644.1 | 886.6 | 15.6 | 1.2 |
| | | Min | 23.5 | 16.5 | 0.4 | 0.9 |
| **window closed** (TW2) | **Winter:** Dec12-Dec18 | Mean | 167.7 | 208.7 | 1.4 | 1.0 |
| | | Max | 645.5 | 886.6 | 15.6 | 1.2 |
| | | Min | 23.9 | 16.5 | 0.4 | 0.9 |
| **window open** (TS1) | **Summer:** Aug12-Aug 18 | Mean | 19.2 | 26.1 | 0.5 | 1.0 |
| | | Max | 48.0 | 104.9 | 4.2 | 1.1 |
| | | Min | 4.7 | 1.0 | 0.2 | 0.9 |
| **window closed** (TS2) | **Summer:** Aug12-Aug 18 | Mean | 19.2 | 26.1 | 0.5 | 1.0 |
| | | Max | 48.0 | 104.9 | 4.2 | 1.1 |
| | | Min | 4.4 | 1.0 | 0.2 | 0.9 |

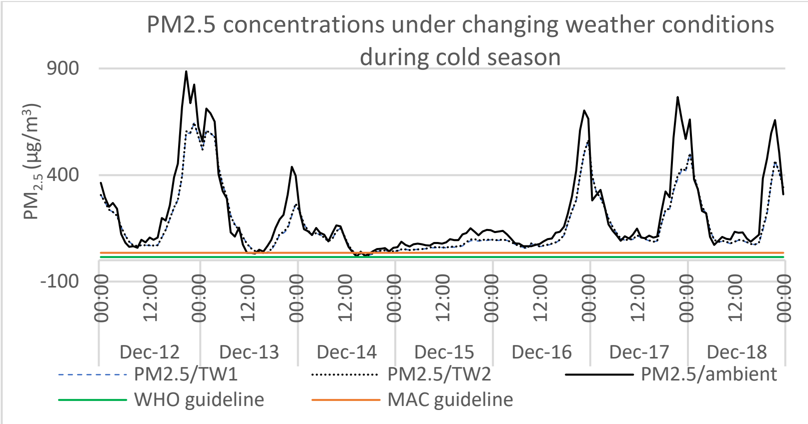



Figure 4. *Outdoor and indoor transient airflow and transient $PM_{2.5}$ pollutant simulation values during winter heating period.*

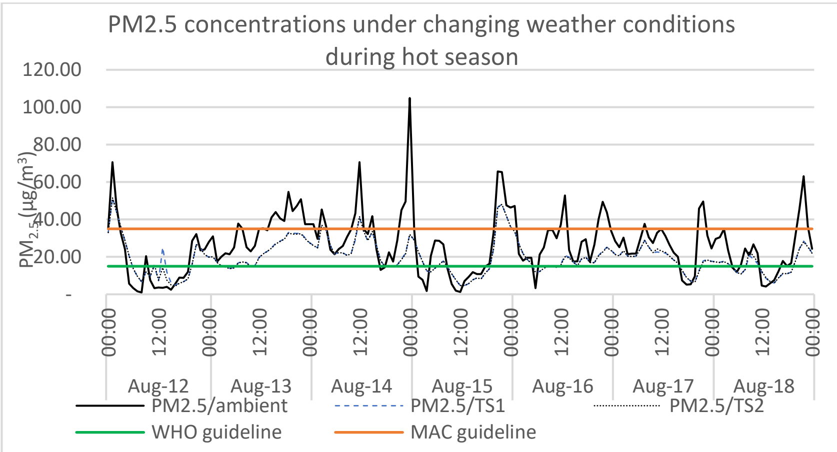



Figure 5. *Outdoor and indoor transient airflow and transient $PM_{2.5}$ pollutant simulation during summer cooling period.*

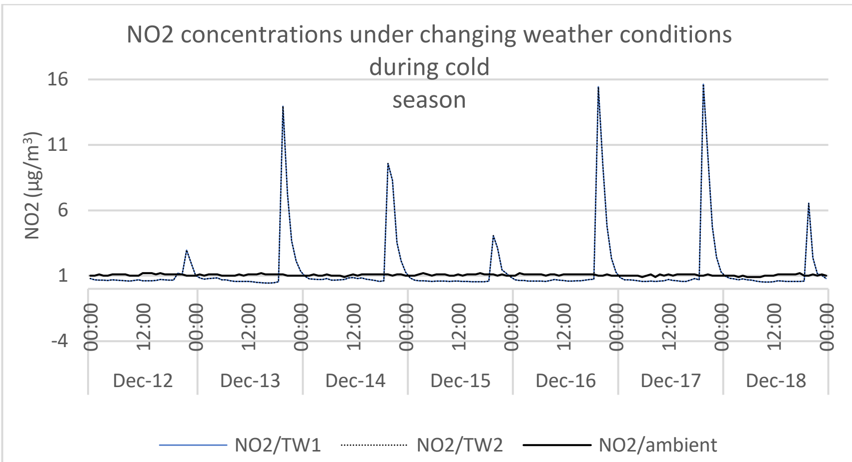



Figure 6. *Outdoor and indoor transient airflow and transient NO2 pollutant simulation during winter heating period.*

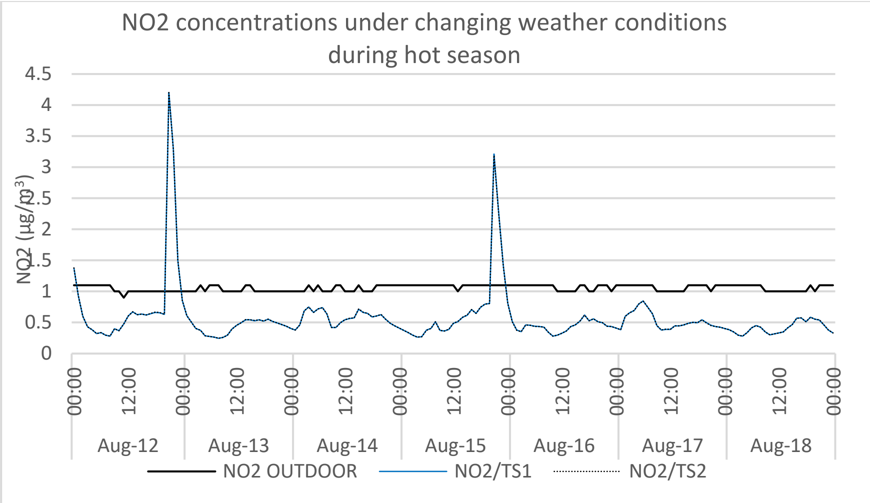
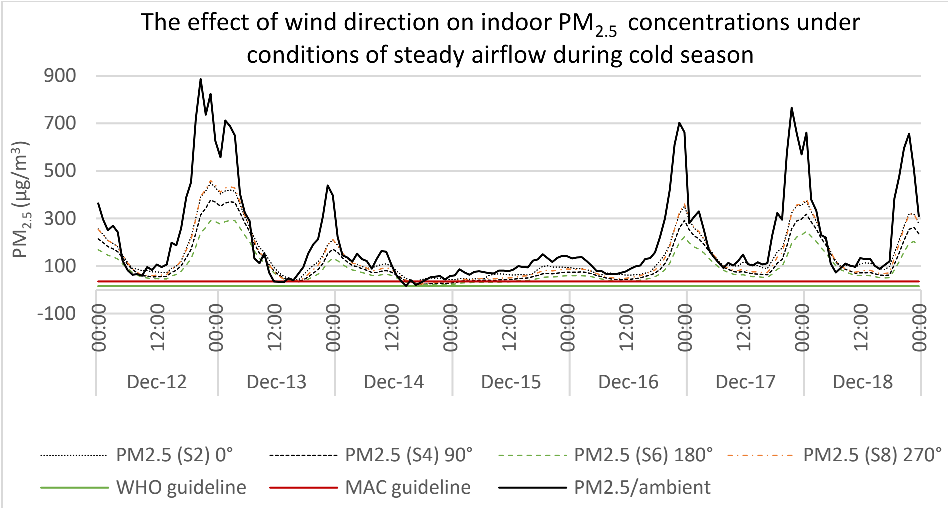
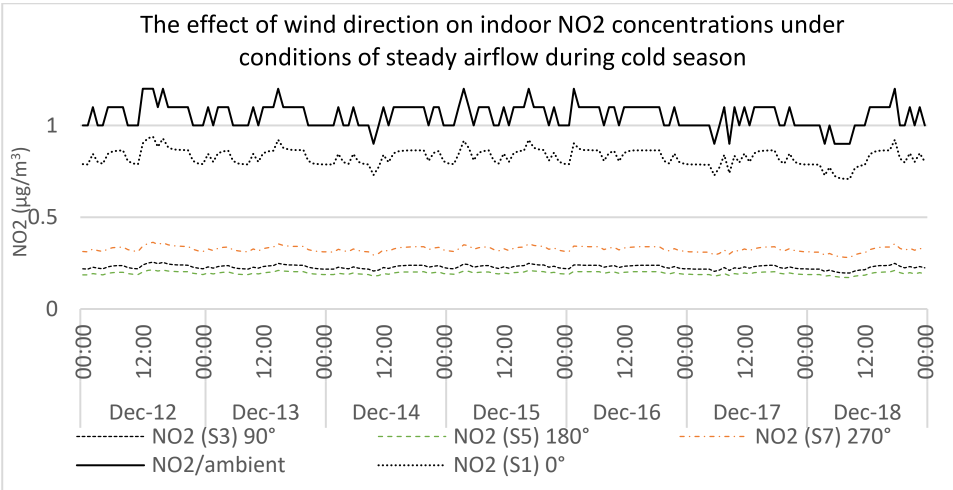



Figure 7. *Outdoor and indoor transient airflow and transient NO2 pollutant simulation during summer cooling period.*

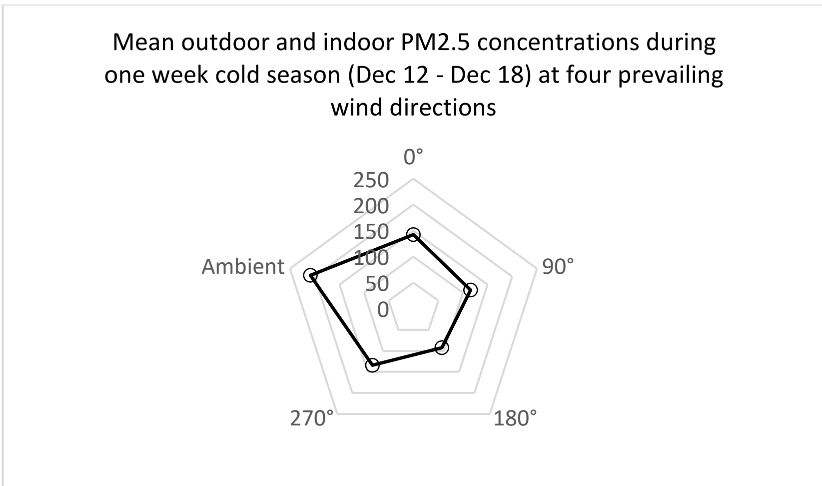
The indoor distributions of $PM_{2.5}$ and NO2 in the condition of natural ventilation for different wind directions were simulated in the control area. Steady state weather data with four prevailing wind directions, namely 0° (N), 90°(E), 180° (S), and 270°(W), with a wind speed of 1 m/s, were set against the transient contaminant files for winter and summer periods. Since the window is located on the north side, the prevailing wind direction from the north (0°) and west (270°) drove the largest number of ambient $PM_{2.5}$ particulates inside the control room during the heating period of the year. Conversely, the wind direction from the south (180°) gave the least effect due to the angular location of the simulated space (Figure 8). In the summer, the level of $PM_{2.5}$ (weekly average 29.7 µg/m$^3$) infiltrating through northern wind direction (0°) almost never lagged behind the external levels, and in some places exceeded them. This is because, while the level of $PM_{2.5}$ is within reasonable limits during the summer (weekly average 26.5 µg/m$^3$), the internal generation of suspended particles due to home cooking can exceed the concentration by several times (Figure 9). In the summer period the concentration of suspended particles inside the room were statistically significant ($r(167) = .732$, $p < .001$) according to the Pearson correlation for the direct direction of the wind from the north between the window open and closed scenarios for $PM_{2.5}$ concentrations (Figure 9a).




a)

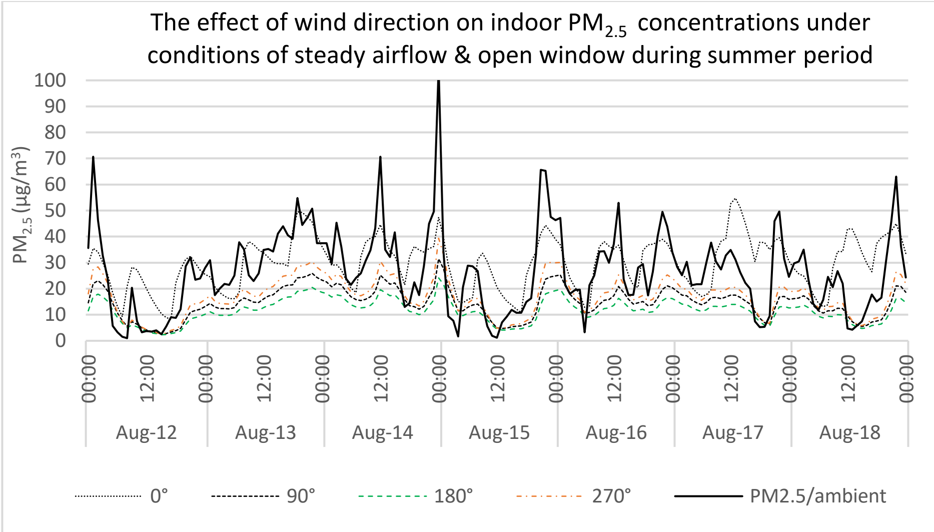



b)

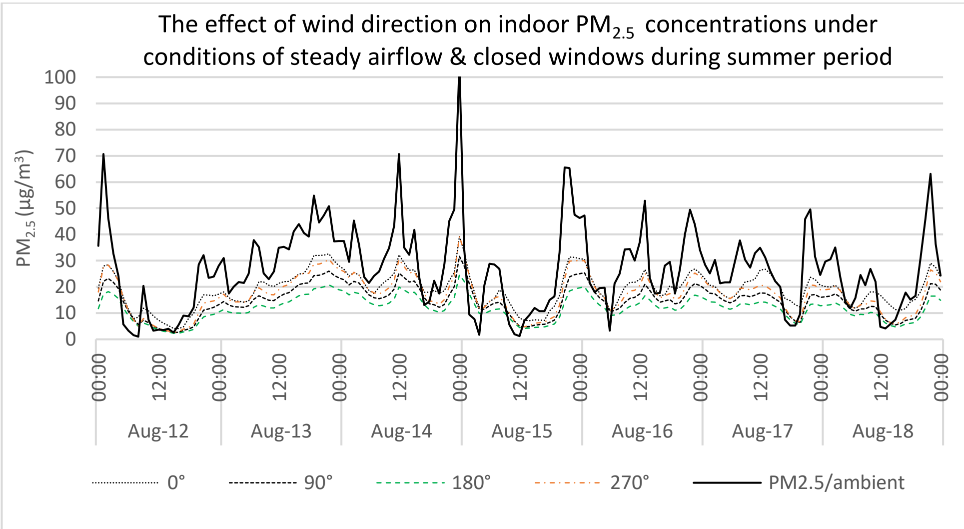



c)

Figure 8. *Distributions of transient PM2.5 (a), NO2 (b), and mean PM2.5 (c) contaminants in the ambient and indoor air throughout the winter season under steady state airflow conditions at four prevailing wind directions: 0° (N), 90° (E), 180° (S), and 270° (W).*




a)




b)

Figure 9. *Outdoor and indoor steady state airflow at four prevailing wind directions: 0° (N), 90° (E), 180° (S), and 270° (W), and transient $PM_{2.5}$ pollutant simulation during summer period for: a)-open window; b)-closed window.*

Figure 10 illustrates that a north prevailing wind direction contributes to the collection of a larger amount of NO2 pollutant inside the room during the summer period. There was *no* significant effect for indoor NO2 contaminants concentrations $t(336) = -0.15$, $p = 0.8841$, despite window open ($M = 0.8$, $SD = 0.04$) and window closed ($M = 0.8$, $SD = 0.04$) schedule conditions.

## 4. Discussion and Conclusion

Indoor $PM_{2.5}$ and NO2 concentrations were simulated across different airflow combinations and window opening behaviour. Overall, evidence of seasonal differences in both studied pollutants was found. The average mass concentration of transient airflow $PM_{2.5}$ particles (208.7 μg/m$^3$) during the winter period predicted for an indoor environment exceeded the average daily WHO (2021) of 15 μg/m$^3$ and Kazakhstan's average daily Maximum Allowable Concentration of 35 μg/m$^3$ guidelines by almost 1000% and 375% respectively. There are differences between WHO and Kazakhstan's air quality standards. WHO uses daily and annual average recommended guidelines to assess the air quality, whereas in Kazakhstan, the values of one-time maximum allowable concentration (MAC) are being used (KAZHYDROMET 2021). Dangerous indoor $PM_{2.5}$ concentrations in winter are attributed to high ambient pollution levels due to the proximity to the coal fired CHP plant and reduced winter air exchange rate (Assanov, Zapasnyi & Kerimray 2021).

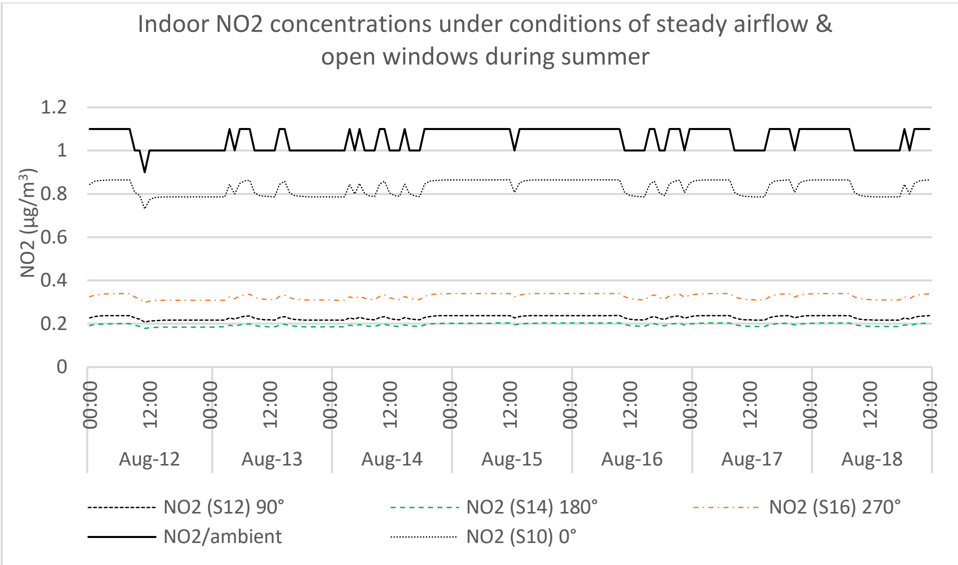



Figure 10. *Ambient and indoor steady state airflow and transient NO2 pollutant simulation during summer period under prevailing wind directions: 0° (N), 90° (E), 180° (S), and 270° (W)*

The concentrations of NO2 across the different scenarios do not exceed WHO's (25 μg/m$^3$) and local (40 μg/m$^3$) air quality guidelines (KAZHYDROMET 2021; WHO 2021); however, they are significantly above outdoor concentrations and are thus driven by indoor sources during both seasons. Also, there is a strong correlation on apartment location and infiltration within a building and season. The upper levels of the residential apartment building are more susceptible to higher concentrations of pollutants infiltrating from adjacent units during cold periods due to stack effect (Arku et al. 2015; Fabian et al. 2016). In addition, it was found that for the studied seasons, prevailing wind direction (Han et al. 2015) perpendicular to the opening, combined with the mechanical window opening during daytime, resulted in higher concentrations of indoor pollutants, especially $PM_{2.5}$, which may contribute to serious health risks for the socially disadvantaged population in Almaty, Kazakhstan.

Overall, the study investigated the concentrations of transient pollutants indoors and outdoors and concluded that internal air quality should be considered when estimating the population's exposure level. In addition, the ventilation patterns for various prevailing wind conditions may significantly change the indoor exposure for a given outdoor pollution level. However, no significant relationship was found between window opening patterns for both studied periods. Future field monitoring of indoor pollutants will be carried out to calibrate the accuracy of the CONTAM model and provide data on existing indoor air quality levels in Kazakhstan's social housing stock. Investigations will also consider the specific details of the building, the closest outdoor obstacles and distance of pollutant source from the façade.

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**Declaration of conflicting interests**

The authors declared no potential conflicts of interest with respect of the research, authorship, and/or publication of this article.

# The impact of local variations in climate on optimum design techniques and discomfort in dwellings of rural villages of SW China

**Adrian Pitts[1] and Yun Gao[2]**

[1] University of Huddersfield, UK, a.pitts@protonmail.com; or a.pitts@hud.ac.uk;
[2] University of Huddersfield, UK, y.gao@hud.ac.uk;

**Abstract:** This paper reports research to aid in the optimisation of redevelopment processes for rural villages in SW China. The stimulus for the paper came from observations of variable outcomes and from missed opportunities to incorporate better climate sensitive design. Issues arise from lack of awareness amongst some stakeholders. SW China, and particularly Yunnan Province, is taken as the focus because of the number of ethnic minorities present which affects how new skills and knowledge might be taken up in rural areas. A number of villages have been visited to collate data and observations. Villages that were identified in government programmes for potential redevelopment were chosen for study. Meteonorm Software was used to augment climate data for the sites and the Climate Consultant software used to identify most promising options for changes to design. Analysis was carried out for contemporary climate and for future climate with RCP 8.5 scenario. Outcomes suggest that new design solutions can be introduced into the palette of choices available to local stakeholder. Although climate can occasionally be extreme the design options can offer choices to avoid much discomfort, even following potential climate change. An important conclusion is the need for further support to the process to raise awareness and optimise outcomes amongst local stakeholders.

**Keywords:** rural villages; SW China; design options; climate variations; discomfort

## 1. Introduction

This paper describes research undertaken to aid the development of sustainability and climate sensitive design advice to support redevelopment of rural villages in China. Currently great effort and substantial financial resources are being directed towards redeveloping and revitalising rural dwellings as part of government programmes (Government of the People's Republic of China, 2012). The authors' experiences suggest there is room to enhance the environmental or 'green' design aspects and they have been working towards this end over a number of years, for example Pitts (2016). The paper first describes the background to the topic in relation to rural redevelopment in China, and then considers the barriers to adoption of better climate sensitive design. It then analyses opportunities that could be implemented and discusses process to achieve improved outcomes.

### 1.1. Chinese Rural Village Redevelopment

The rapid economic expansion of China in recent decades has owed much to the growth of cities and urbanisation alongside the development of industries employing many millions of workers. The balance towards cities has shifted dramatically though there are still many rural residents – almost 500 million currently, account about 36% of the whole population in China (Statista, 2022) and these inhabit more than 600,000 administrative villages. A distinction needs to be drawn between 'administrative' villages and actual or 'natural' villages as in SW China each administrative village normally incorporates several natural villages. In China there are about 1 million natural villages, and in this paper the authors are generally more concerned with activities within natural villages. Given the large numbers of the villages, although the cities are generally regarded as the economic drivers of the country, the countryside cannot be ignored and there is a substantial 'levelling-up' programme to allow rural areas to benefit from the improved economic situation normally associated with urban areas. This has resulted in funding for upgrading of housing, though with a number of different models of involvement and contribution.

Some support mechanisms have identified villages with special characteristics worthy of preservation or development; in some other cases a focus on the beauty of the area or on the potential for developing tourism have acted as the driver. There is certainly evidence that different models of support and stakeholder involvement are active (Gao, 2016). Unfortunately, the redevelopment process comes with less consideration of the needs of the users, but focuses more on the improvement of the energy and environmental performance according to the regulations, leading to some less well considered environmental choices by stakeholders.

### 1.2. Contemporary Building Design and Construction

The choice of materials in China is often limited by availability and by the skills and knowledge levels of the design and construction team. For instance, the scarcity of timber can restrict opportunities in some areas and natural materials are generally less frequently used compared to say concrete in its various forms. In rural areas there can be long histories of building with certain materials and with links to traditions and skills of ethnic nationality groups. The immediacy of available funding support or other forms of encouragement to redevelop dwellings has however led to a shift to favouring those designs which maximise space and modern amenities. Anecdotal evidence gathered by the authors indicates village owners want to replace old dwellings by new ones which imply or demonstrate a modern lifestyle.

In SW China the influence of ethnic minority groups in rural villages has also been felt more strongly and depending on the outcomes this can result in a significant shift from timber to concrete construction. One might therefor often find a dwelling of a style and construction shown in Figure 1 replaced by one as shown in Figure 2. These are both to be found in the same rural village in Xishuangbanna Prefecture in Yunnan.

### 1.3. Comfort and Climate

It seems quite clear that the traditional dwelling design of villages in rural China was to a significant degree affected by three things: expected ethnic and local styling; knowledge and skills of the local builders; and materials availability. These factors often also had a close relationship to the prevailing climate. However, the modern designs are more driven by contemporary construction practices and expectations for a newer style building with modern amenities, but with little consideration for climate. As a result, provision of comfortable indoor environments by natural means has not been a high priority and in fact some professionals as well as normal building users and owners do not have much knowledge of how to optimise design.

As a result of activities associated with a research network that had a number of stakeholder community members, a previous study of rural villages attempted to use techniques to optimise design through a parametric analysis (Pitts et al, 2019). EnergyPlus (EnergyPlus, n.d.) was the main software used in that analysis. However, in subsequent meetings with designers and dwelling occupants it was found that the design advice needed further simplification and this is, in part, what is reported in the paper here. The aim has been to produce easy-to-follow design guidance that can be used to supplement redevelopment.

Figure 1. Traditional village dwelling in Xishuangbanna

Figure 2. New village dwelling in Xishuangbanna

## 2. Villages Analysis

### 2.1. Choice of Villages

The choice of villages to be used for this research was determined from the need to derive and provide advice for specific villages that fell within certain government programmes. As a result, 14 were chosen and the first step was to identify their locations and to determine latitude, longitude and altitude (elevation above sea level); they are listed in Table 1. It was interesting to observe that the majority of the villages specified were at relatively high altitudes (above 1500m) although this is consistent with a large fraction of the Province of Yunnan being located on a high plateau geological form. The villages listed all fall within the Province of Yunnan though across spread locations. What they have in common is their selection as a special village worthy of development support.

Table 1. Villages chosen for analysis

| Village name | Latitude | Longitude | Altitude (m) |
|---|---|---|---|
| **Bisezhai** | **23.469 N** | **103.420 E** | **1366** |
| **Guyu** | **26.296 N** | **100.612 E** | **1375** |
| **Kunlushan** | **23.240 N** | **101.060 E** | **1206** |
| **Leju** | **25.097 N** | **101.520 E** | **2111** |
| **Manfeilong** | **21.596 N** | **100.696 E** | **617** |
| **Mingliu** | **23.454 N** | **103.650 E** | **1818** |
| **Nanben** | **22.631 N** | **100.686 E** | **1142** |
| **Nanlengtian** | **23.890 N** | **99.910 E** | **1931** |
| **Niru** | **27.946 N** | **100.790 E** | **2823** |
| **Take** | **23.820 N** | **100.030 E** | **1497** |
| **Wengding** | **23.284 N** | **99.170 E** | **1502** |
| **Xiguan** | **25.592 N** | **101.205 E** | **1875** |
| **Yubi** | **25.010 N** | **98.540 E** | **1670** |
| **Zhega** | **23.570 N** | **102.03 E** | **438** |

## 2.2. Building Design Features

Whilst a previous study had dealt with a complex multi-parametric analysis to suggest the optimum building design features (Pitts et al, 2019), feedback from users suggested a simpler interpretation was required. It was therefore decided to seek to limit the potential advice to those suggested design outcomes that arose from using the Climate Consultant Software (Climate Consultant, n.d.) and then to undertake a further review to ensure any recommendations can be adequately accommodated within typical design and construction activities. Such a choice provides a mid-way position between the very basic sorts of climate sensitive design advice which is based solely on generic options from the main climate classifications, and the more detailed advice that derives from a full dynamic simulation such as IESVE software (Integrated Environmental Solutions, n.d.)

An album/catalogue of design choices related to the production of a number or real and proposed schemes in SW China has previously been complied by the authors, and this provided insights into the potential for design change (Pitts and Gao, 2020).

## 2.3. Comfort and climate

The concept of linking building design features with climate so as to produce advice on suitable 'bioclimatic design' is one that began in the 1950's and has undergone several evolutions. The first exponents of such an approach were the Olgyay brothers with their first seminal work from the 1960s being updated (Olgyay, 2015).

Initially a number of graphical or decision-tree based methods were produced but over recent years this has transitioned into software tools. Whilst the software tools do not guarantee any higher degree of correct outcome, those tools have reduced the time needed to carry out the analyses. The Climate Consultant software produces graphical outputs which contain both numerous visualisations of the input data and also the representation on a psychrometric chart of the climate data along with control potential zones (CPZs). CPZs allow the user to see what external conditions can be made comfortable using a range of techniques. Climate consultant uses up to 16 techniques which are colour coded and an example is shown in Figure 3. The software also produces a number of design recommendations which are listed in order of most suitable for the location out a total list exceeding 60.

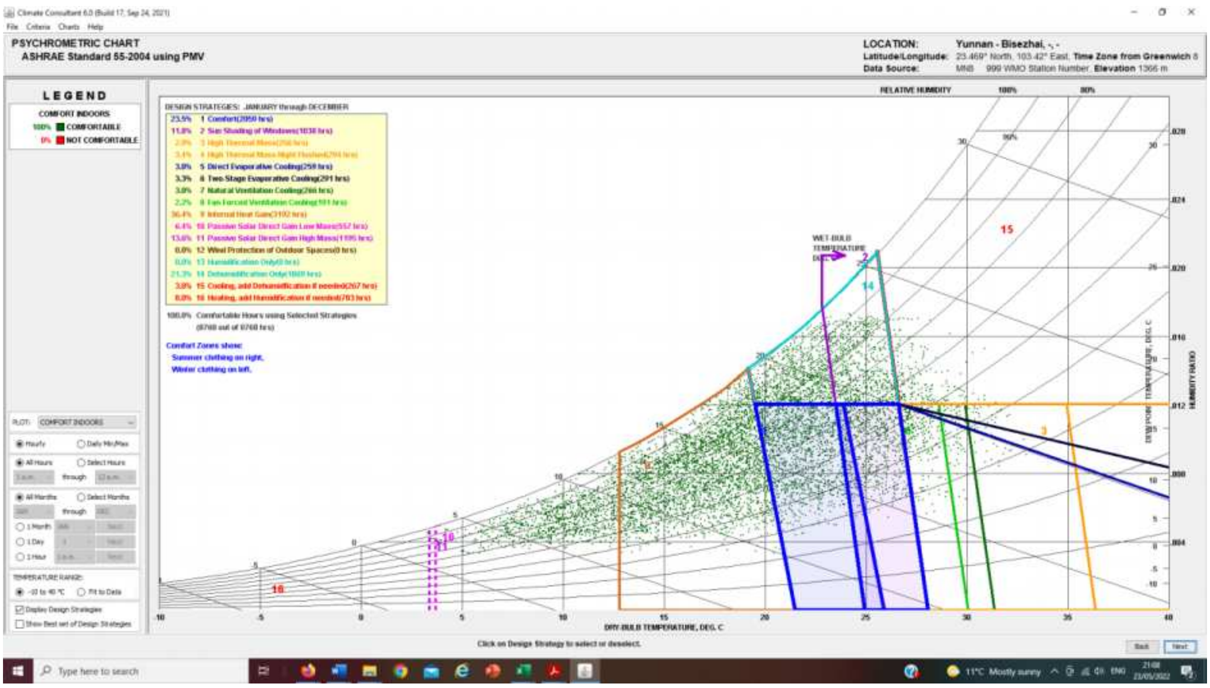


Figure 3: Example output from Climate Consult Software for one of the villages

## 2.4. Climate Data

Climate data is available for a number of locations in China and is normally access from the Energy Plus Weather data online resource. However, the availability of data for precise rural village locations away from the major cities is much more limited. It must also be recognised that there are substantial variations in local conditions partly caused by height above sea level and partly caused by local conditions. Since it was not possible to survey the sites in sufficient detail to acquire enough data to utilise in the analysis, the Meteonorm Software was used (Meteonorm, n.d.). The additional value brought by use of the software was the ability to generate not only contemporary climate data but also to generate future climate data based on different RCP expectations (RCPs are Representation Concentration Pathways and have been used by the Intergovernmental Panel on Climate Change to indicate greenhouse gas concentration ‘trajectories’).

In this study a future climate of RCP 8.5 was chosen so as to explore some of the potential for greater warming impacts. RCP 8.5 means warming created by the equivalent additional radiative heat gain of 8.5 $W/m^2$.

Meteonorm was therefore used to generate 28 weather data files – one for each location for contemporary times and one for the RCP 8.5 scenario.

## 2.5. Bioclimatic Design Choices

Whilst a previous study had dealt with a complex multi-parametric analysis to suggest the optimum building design features, feedback from users suggested a simpler interpretation was required. It was therefore decided to seek to limit the potential advice to the first 10 suggested design outcomes that arose from using the Climate Consultant Software.

The Climate Consultant programme was run for each of the 28 weather data files and then for each of those files two Comfort Models were used to derive outcomes: ASHRAE Standard 55 and Current Handbook of Fundamentals Model, and the Adaptive Comfort Model in ASHRAE Standard 55-2010. In addition, the choices for Design Strategies were considered for both all 16 strategies and for only the 'best' strategies as determined by Climate Consultant. An example of the design recommendations output is shown in Figure 4.

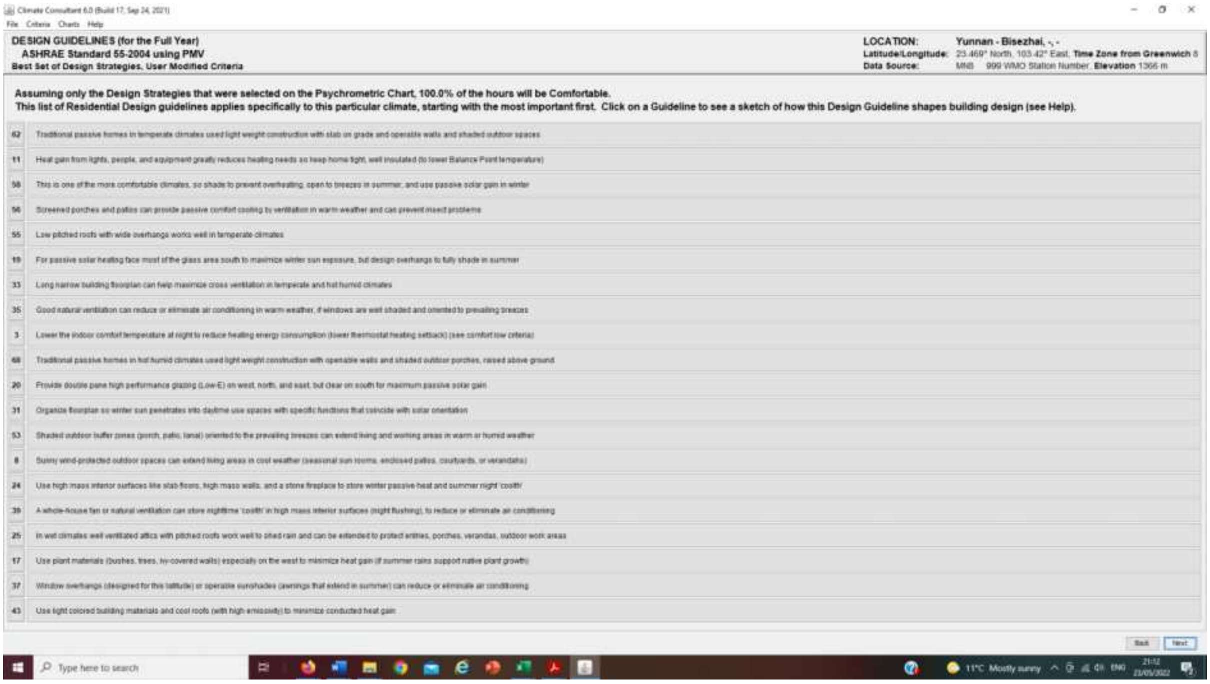


Figure 4: Example Design Guideline output from Climate Consult Software for one of the villages

## 2.6. Analysis Procedure

Once the Climate consultant software had been run for each of the 14 sites using each of 6 different comfort model and weather file option (84 cycles), the data were read off and stored in a spreadsheet for ease of analysis.

For each combination the ten highest rating techniques were identified. This resulted in a total of 30 commonly recommended techniques from the over 60 available. However, it was observable that of the 30 techniques a smaller number, 13, featured the most frequently. The observations of the frequency with which each technique in combination with comfort model and weather data were then used to derive some results and recommendations.

The list of basic design strategies is shown in Table 2.

Table 2. Villages chosen for analysis

| Strategy number | Strategy description |
|---|---|
| **1** | **Standard Comfort** |
| **2** | **Sun shading of windows** |
| **3** | **High thermal mass** |
| **4** | **High thermal mass with night 'air flushing'** |
| **5** | **Direct Evaporative cooling** |
| **6** | **Two-stage evaporative cooling** |
| **7** | **Natural ventilation cooling** |
| **8** | **Fan forced ventilation** |
| **9** | **Internal heat gains** |
| **10** | **Passive solar direct gain low thermal mass** |
| **11** | **Passive solar direct gain high thermal mass** |
| **12** | **Wind protection of outdoor spaces** |
| **13** | **Humidification only** |
| **14** | **Dehumidification only** |
| **15** | **Cooling, and dehumidification if needed** |
| **16** | **Heating, and humidification if needed** |

## 3. Results

### 3.1. Outcomes of climate analysis

The frequency calculation associated with the 30 possible design techniques was used to reduce the number to the most important. The criteria for selection were either: occurrence 5 or more times for the 14 villages in the top 5 recommendations; or occurrence 7 or more times in the top 10 recommendations. This was related to the three key issues: comfort associated with contemporary weather; comfort associated with RCP 8.5 weather; and comfort associated with use of adaptive comfort alone. It was observed from these data sets that the recommendations for techniques to be used with adaptive comfort alone, did not vary with the two weather scenarios. Table 3 summarises the outcomes of this analysis by indicating the 13 most common techniques and those most likely to be prescribed by contemporary weather data; by RCP 8.5 weather data; and by adaptive comfort alone.

### 3.2. Observations

Considering Table 3 it is clear that there are some variations between the three options. This indicates that design techniques which are most suitable for current climate may not be suitable in years to come when different climates and weather conditions may prevail. More in-depth analyses of the data are being undertaken to try to identify balance points where certain techniques become no longer viable or suitable, or conversely where new techniques may become more advantageous.

Table 3. Summary of potential design solutions across all villages to optimise climate sensitive design (taken from Climate Consultant software) – related to contemporary and RCP8.5 climates, and adaptive techniques

| Opt. no. | Description | Con-temp | RCP 8.5 | Adapt-ive |
|---|---|---|---|---|
| 1 | **Tiles or slate or a stone-faced fireplace to provide enough surface mass to store winter daytime solar gain and summer night-time coolth** | √ | √ | |
| 3 | **Lower indoor comfort temperature at night to reduce heating energy consumption (lower thermostat heating setback)** | √ | | |
| 11 | **Heat gain from lights, people, and equipment used to greatly reduce heating needs – keep home air tight and well-insulated** | √ | √ | |
| 19 | **For passive solar heating face most of glass area to south to maximise winter sun exposure but design overhangs to fully shade in summer** | √ | √ | |
| 20 | **Provide double pane high performance glazing - low-E on west, north and east, but clear on south for maximum passive solar gain** | √ | √ | |
| 31 | **Organise floorplan so winter sun penetrates into daytime us space with specific functions that coincide with solar orientation** | | √ | |
| 33 | **Long narrow building floorplan can help maximise cross ventilation in temperate and hot-humid climates** | | | √ |
| 35 | **Good natural ventilation can reduce or eliminate air conditioning in warm weather if windows are well shaded and orientated to prevailing breezes** | | √ | √ |
| 37 | **Window overhangs, designed for the latitude, or openable sunshades (awnings that extend in summer) can reduce to eliminate air conditioning** | | √ | |
| 55 | **Low pitched roofs with wide overhangs work well in temperate climates** | √ | | |
| 56 | **Screened porches and patios can provide passive comfort cooling by ventilation in warm weather and can prevent insect problems** | √ | √ | √ |
| 58 | **In a relatively comfortable climate: shade to prevent overheating; open building to breezes in summer; and use passive solar gain in winter** | √ | √ | √ |
| 62 | **Traditional passive homes in temperate climates use lightweight construction with slab-on-grade and openable walls and shaded outdoor spaces** | √ | √ | |

Though not immediately obvious however (and something needing more study) is that weather patterns associated with global warming would bring some benefits to some of the villages analysed. This is particularly the case where they are located at height and where the main concern is not for overheating but for impacts of cold/cool winters.

The technologies which most frequently occur as recommendations are:

- To take advantage of internal heat gains to offset heating requirements in cooler months;
- To employ passive solar heat gain for warmth and if necessary linked to high thermal mass and night-time ventilation;

- To use natural ventilation to provide for cooling in warm periods and when using adaptive thermal comfort approaches;
- To use shading of windows to limit solar overheating;
- Heating with humidification and cooling with dehumidification may be required as additional non-passive techniques in most locations;
- Evaporative cooling and humidification techniques may also be needed.

In order to consider these in more detail further information on the techniques to be used should be sought and this should be undertaken in conjunction with stakeholders.

## 4. Outcomes

### 4.1. Stakeholder Knowledge and Choices

The production of data and comments such as in the section above of course do not provide the complete answer to the issues introduces at the start of this paper. A very important aspect of the research, and one which was alluded to at the start, is the ability and willingness for the design techniques to be adopted. This is in part reflected by the level of knowledge of the techniques and implications amongst stakeholders, be they residents or professionals; and also, by the availability of materials or construction options.

In order to estimate some of the barriers and challenges to the introduction and use of new techniques an assessment was carried out using a small number of respondents with local knowledge and understanding. This attempted to rate and identify the techniques and technologies according to whether they would be possible to install/use and whether the stakeholders would fully comprehend the technique and therefore be able to use it effectively. The outcome of this exercise is shown in Table 4.

Based on this and previous research the authors consider the stakeholders in their various guises to be the key determinants of future progress. Some progress has been made within the wider remit of the research programme of which this forma part with additional guidance being provided in other circumstances and parts of China such as the greater Chongqing area.

### 4.2. Recommendations

The research undertaken leads to the following recommendations:

- Villages in rural areas of China require specific advice and support in terms of optimal progress towards climate sensitive design outcomes;
- In a region as large and variable as SW China and especially given the variations in topography, design recommendations need to be tuned to the specific climates and locations;

In terms of techniques that currently may be most promising on a general level the following list can be compiled;

- For passive solar heating face most of glass area to south to maximise winter sun exposure but design overhangs to fully shade in summer;
- Good natural ventilation can reduce or eliminate air conditioning in warm weather if windows are well shaded and orientated to prevailing breezes;
- Window overhangs, designed for the latitude, or openable sunshades (awnings that extend in summer) can reduce or eliminate air conditioning;
- Low pitched roofs with wide overhangs;
- Shade to prevent overheating; open building to breezes in summer; and use passive solar gain in winter

Table 4. Summary of potential design solutions assessed as 'can be used' and 'understood' in Yunnan. (Note: '√' indicates a positive response or potential, '?' indicates might be used or understood but may be affected by other considerations)

| Opt. no. | Description | Can be used | Under-stood |
|---|---|---|---|
| 1 | Tiles or slate or a stone-faced fireplace to provide enough surface mass to store winter daytime solar gain and summer night-time coolth | ? | |
| 3 | Lower indoor comfort temperature at night to reduce heating energy consumption (lower thermostat heating setback) | ? | |
| 11 | Heat gain from lights, people, and equipment used to greatly reduce heating needs – keep home tight and well-insulated | √ | ? |
| 19 | For passive solar heating face most of glass area to south to maximise winter sun exposure but design overhangs to fully shade in summer | √ | √ |
| 20 | Provide double pane high performance glazing - low-E on west, north and east, but clear on south for maximum passive solar gain | ? | |
| 31 | Organise floorplan so winter sun penetrates into daytime used space with specific functions that coincide with solar orientation | ? | |
| 33 | Long narrow building floorplan can help maximise cross ventilation in temperate and hot-humid climates | √ | ? |
| 35 | Good natural ventilation can reduce or eliminate air conditioning in warm weather if windows are well shaded and orientated to prevailing breezes | √ | √ |
| 37 | Window overhangs, designed for the latitude, or openable sunshades (awnings that extend in summer) can reduce or eliminate air conditioning | √ | √ |
| 55 | Low pitched roofs with wide overhangs work well in temperate climates | √ | √ |
| 56 | Screened porches and patios can provide passive comfort cooling by ventilation in warm weather and can prevent insect problems | √ | |
| 58 | In a relatively comfortable climate: shade to prevent overheating; open building to breezes in summer; and use passive solar gain in winter | √ | √ |
| 62 | Traditional passive homes in temperate climates use lightweight construction with slab-on-grade and openable walls and shaded outdoor spaces | √ | ? |

### 4.3. Further Work

Greater in-depth investigation is required on several fronts. Firstly, to establish with a greater degree of accuracy which technologies and techniques might be most useful in a more quantitative way. Secondly, in this research a step forward has been made to consider individual village circumstances, but this is a start point if greater optimisation is to be achieved. Thirdly, future climate and weather pattern changes may well vary from that illustrated here and a wider study would be welcome.

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# Influence of modern transitions in rural settlements on the thermal expectation of inhabitants

**Khadeeja Henna**

Indian Institute of Science, Bangalore, India. khadeejap@iisc.ac.in

**Abstract**
Rapid urbanization has led to the replacement of local traditional materials in rural dwellings with industry-manufactured materials like cement and steel. This transition in the building envelope directly influences the indoor thermal environment of the dwellings. While traditional dwellings relied predominantly on passive design for regulating the indoor thermal environment, modern dwellings are integrated with electro-mechanical appliances for the same. Rural inhabitants accustomed to wider temperature changes and attaining comfort through behavioral adaptation, now have access to active adaptative strategies. Long-term dependencies on these adaptive strategies could influence the thermal resilience of the inhabitants.
This study attempts to explore the changes in the thermal expectation of rural inhabitants subjected to modern transitions. A field study was conducted in a rural settlement in cold climate zone of India. Thermal sensation surveys of inhabitants living in traditional and modern dwellings were performed. The higher reliance of traditional and modern inhabitants on passive and adaptive strategies respectively, was evident from the survey. Comfort temperatures of the traditional occupant group was lower than the modern occupant group. In conclusion, the study found a significant distinction between the thermal expectation of the two groups in both their thermal sensation and adaptive behavior.

**Keywords:** thermal expectation, transitions, traditional occupants, modern occupants, thermal comfort

## 1. Introduction

Buildings and construction sector contribute almost 40% of energy- and process-related emissions and consume 36% of the global final energy use, with residential sector consuming nearly 22% (United Nations Environment Programme, 2021). Energy consumption pattern is not uniform across the world and tend to vary between modern and emerging economies. In 2018, when per capita residential energy consumption in the United States was over 10 MWh, the same in India was nearly 0.6 MWh (US Energy Information Administration, 2019). The energy disparity between rural and urban areas is also high, with per capita electricity consumption in rural and urban India reported as 8.9kWh and 25.8 kWh, respectively (NSS 68th Round, 2011-12). Building stock is also expected to double by 2050, much of this expected to be in Asia and Africa (United Nations Environment Programme, 2021). A growing number of these buildings would be constructed of modern industry-manufactured materials. Between 2001 and 2011, use of concrete and metal/asbestos roofing sheet in construction of houses had increased by 89% and 76%, respectively in India (Census of India, 2011, 2001). Such transitions in the building envelope are bound to alter the indoor thermal environment and resulting energy consumption in these dwellings. Several researchers have reported that modern material transitions often compromise the indoor thermal comfort in the dwellings (Henna et al., 2021; Shastry et al., 2014). Modern dwellings are often integrated with electro-mechanical appliances to improve the indoor thermal environment which was originally regulated using passive design features in traditional dwellings. Emerging countries like India, has witnessed a phenomenal increase in the use of air conditioners in residential buildings in recent years (Shakti Sustainable Energy Foundation, 2012). India's residential building energy consumption is expected to rise by eight folds between 2012 and 2050 (GBPN, 2014). Given the population densities in the emerging nations, energy consumption patterns tending to match that of developed countries will have huge ramifications on global emissions.

Studies report higher thermal comfort in traditional dwellings in comparison to modern dwellings (Dili et al., 2010; Nematchoua et al., 2014). Long-term exposure to active conditioning in modern buildings tend to influence the thermal perception of occupants and dependence on active conditioning (Buonocore et al., 2019; Ramos et al., 2021). This increases the dependence on electric controls for comfort and thereby the energy consumption in buildings. Whether the transition in housing, from traditional to modern, and the long-term exposure to the thermal conditions in these dwellings affect the thermal expectation of the occupants needs to be researched. Here, thermal expectation is being defined as the context in which an occupant feels comfortable. This could be a combination of the thermal environment, clothing and other behavioural adaptation. Existing thermal comfort studies explore the difference in thermal expectation of occupants due to their thermal history. The thermal history may be air-conditioned and naturally ventilated buildings (de Dear et al., 1991), office and home (Oseland, 1995), access to occupant controls (Fiala and Lomas, 2001), etc. The influence and experience of living in a traditional house designed to passively regulate indoor environment against a modern house that uses active involvement of fans, coolers, air conditioners to regulate indoor environment has not been investigated. This paper tries to understand the influence of thermal history with regard to the type of house, traditional or modern, on the thermal expectation of the occupant.

## 2. Literature Review

Thermal comfort of occupants have been central in climatic design of buildings as it is one of the most energy consuming end-use. American Society for American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) defines thermal comfort as that condition of mind that expresses satisfaction with the thermal environment (ASHRAE 55, 2010). One's past and current thermal experiences directly affects their response and acceptability of a thermal stimulus. Psychological adaptation springing from habituation and expectation plays a major role in regulating one's thermal expectation (Brager and de Dear, 1998). Several researchers have studied the influence of different factors like varying climate, active and passive conditioning, occupant controls, etc. on the thermal expectation of occupants. de Dear et al., 1991, found a discrepancy of approximately 3 K between neutral temperatures of occupants in naturally ventilated and air conditioned offices. Black and Milroy, 1966, studied occupants in air-conditioned and naturally ventilated office buildings in London, in which the former expressed more complaints about minor temperature fluctuations, although the latter was subjected to greater variability. Users of naturally ventilated buildings tend to have higher tolerance and thermal acceptability than that of airconditioned buildings (Frontczak and Wargocki, 2011). Cândido et al., 2010, studied occupants in naturally ventilated and air conditioned buildings and the effect of thermal history on their thermal expectation. The authors found that people subjected to steady thermal conditions had lower tolerance and adaptability to the dynamic conditions of naturally ventilated buildings. Zhang et al., 2017, carried out a climate chamber study between occupants from naturally ventilated buildings from rural and urban areas of South

China and found that though the two groups had similar neutral temperatures, the rural group had a wider acceptable temperature range attributed to local culture, expectations and environmental cognition. Oseland, 1995 studied the thermal sensation of UK occupants in their homes, offices and climate chambers and found that under identical indoor thermal environment, occupants felt warmer in their home than office and climate chamber.

The above studies explore the distinction in thermal expectation and perception among occupants attributed to their thermal history- active or passive conditioning, rural or urban areas, homes and offices. These indicate that people get accustomed to the thermal environment that they are in and this habituation influences their overall thermal expectation. Several researchers have explored the environmental parameters in traditional and modern dwellings to differentiate between their thermal performances. These investigations revealed that traditional dwellings provided more comfortable indoor environment than modern dwellings (Dili et al., 2011; Eyre et al., 2016; Shanthi Priya et al., 2012). Very few have studied the thermal responses of inhabitants to understand difference in thermal comfort in occupants accustomed to living in traditional and modern dwellings. Dili et al., 2010, reported a significant difference in thermal comfort experienced by occupants in traditional and modern dwelling. A questionnaire-based study conducted in traditional and modern homes in Cameroon also confirmed that traditional buildings were more comfortable than modern (Nematchoua et al., 2014). Though, experiences of occupants accustomed to living in traditional and modern houses were different, whether these long-term experiences in traditional and modern dwellings influence the thermal resilience/expectation of occupant need to be investigated. The current study investigates the thermal expectation of occupants accustomed to living in traditional and modern naturally ventilated dwellings.

## 3. Methodology

Thermal comfort assessment studies are broadly of two types- laboratory studies and field studies. In laboratory studies, usually conducted in climate chambers, all the environmental and personal (clothing and activity) parameters are controlled and measured before recording the thermal response of subjects. In field studies, on the other hand, subjects are engaged in their usual activities in the thermal environment they are accustomed to living in (Ballantyne et al., 1977). Environmental psychologists have often maintained that laboratory studies use a "reductionist" approach (McIntyre, 1982), oversimplifying the person-environment interactions (Proshansky, 1972) and are unable to capture the influence of context on thermal perception. Field studies recognize the integrity of the person-environment interaction which regulates thermal sensation and perception (Nicol and Humphreys, 1973).

Thermal expectation/perception of occupants in this study are studied through field assessments. A rural settlement in a village called Bisoi, near Dehradun, India was selected for the study. This village falls in cold climate zone of India and has an ample mix of both traditional and modern dwellings. All dwellings in this study are naturally ventilated buildings, with occasional use of electric fans and heaters. Survey of the inhabitants of the settlement, both men and women was conducted. Table 1 shows the details of the respondents that participated in the study. The survey was conducted in June. Most men wore t-shirts or shirts and pants or *kurta-pajamas*, while the women wore either blouses and skirts or *salwar-kameez*. More than 60% of the female respondents wore a sweater and all married women wore a headscarf, which was part of the culture. Majority of the inhabitants were farmers and both men and women worked on the field. The inhabitants were available for the survey when they returned home from the fields. When they returned the men would mostly take rest, while women would get engaged in household chores like cooking, winnowing, cleaning, etc., resulting in a higher met for female respondents.

Thermal sensation surveys of the occupants were conducted in two parts- point-in-time survey and general thermal sensation survey. The point-in-time survey involved taking the thermal sensation vote based on ASHRAE thermal sensation scale (ASHRAE 55, 2010), observations on clothing, metabolic activity, and measurement of the thermal environment at the time of the survey. General thermal sensation survey involved enquiries related to their preferred adaptive behaviours during warm and cold weather conditions. The respondents of the survey were segregated into two-

a) occupants living in traditional houses hereafter called traditional occupants. Here, traditional houses are classified as those made of local, traditional materials like slate and timber. These houses regulate the indoor environment predominantly through passive design features.
b) occupants living in modern houses hereafter called modern occupants. Modern houses are those houses that are constructed using modern, industry-manufactured materials like cement plastered brick wall and RCC roof.

The traditional occupants have been living in traditional houses predominantly and have little exposure to modern dwellings. Many of the modern occupants on the other hand have had experience of living in traditional houses in the past but have been living in the current houses for at least three years. Brager and de Dear, 1998, indicate that behavioural adaptation and expectation has a significant effect on thermal adaptation and the slower process of acclimatization is not very relevant, given the relatively moderate indoor conditions found in houses.

Table 1. Summary of respondents

| | | Gender | | |
|---|---|---|---|---|
| | | **Male** | **Female** | **All** |
| **Number of respondents** | | 12 | 14 | 26 |
| **Age** | **Min** | 31 | 10 | 10 |
| | **Max** | 90 | 80 | 90 |
| | **Mean** | 57.3 | 35.9 | 45.7 |
| | **SD** | 17.9 | 17.2 | 20.5 |
| **Clo** | **Min** | 0.38 | 0.53 | 0.38 |
| | **Max** | 0.6 | 0.9 | 0.9 |
| | **Mean** | 0.56 | 0.64 | 0.6 |
| | **SD** | 0.07 | 0.11 | 0.1 |
| **Met** | **Min** | 1.00 | 1.00 | 1.00 |
| | **Max** | 3.00 | 4.00 | 4.00 |
| | **Mean** | 1.17 | 1.79 | 1.50 |
| | **SD** | 0.58 | 0.87 | 0.80 |

Since thermal comfort is subjective and varies with individuals, statistical approaches using a sample of the population is often relied on (Ballantyne et al., 1977). The application of regression for thermal comfort analysis has been a usual method dating back to Bedford, 1936. Rohles and Nevins, 1971, used multiple regression analysis to estimate mean comfort vote in terms of temperature and relative humidity. Humphreys, 1978, used regression for relation between neutral temperature and outdoor air temperature. de Dear and Brager, 1998 used regression to derive relation between neutral temperatures and operative temperatures. Most field studies, including those based on which different adaptive thermal comfort standards are developed are based on regression analysis. In this paper, regression is often used for the analysis of the thermal sensation surveys. A confidence level of 90% is considered fair for this study as the study is being conducted in a smaller village and the variability in terms of thermal history is higher.

In addition to the thermal sensation survey, representative traditional and modern houses were selected in each of the village and real-time monitoring of indoor dry bulb temperature and outdoor dry bulb temperature were performed for summer and winter periods. Calibrated Resistance Temperature Detector data loggers with a resolution 0.05 °C and accuracy ± 1 °C were used to record temperatures at 30-minute intervals. The thermal performance of the two representative houses are compared in the following section.

## 4. Results and discussion

In this study, the difference in thermal expectation of traditional and modern occupants is being investigated by assessing the thermal behaviour and thermal sensation of the occupants based on the general thermal sensation survey and the point-in-time survey. Before venturing into that, it is important to recognize the difference in thermal performance of or the thermal environments in the traditional and modern houses subjected to the same external weather condition. This is important to understand the thermal environment each group of occupants are exposed to on a daily basis and grows accustomed to living in.

### 4.1. Thermal performance of dwellings

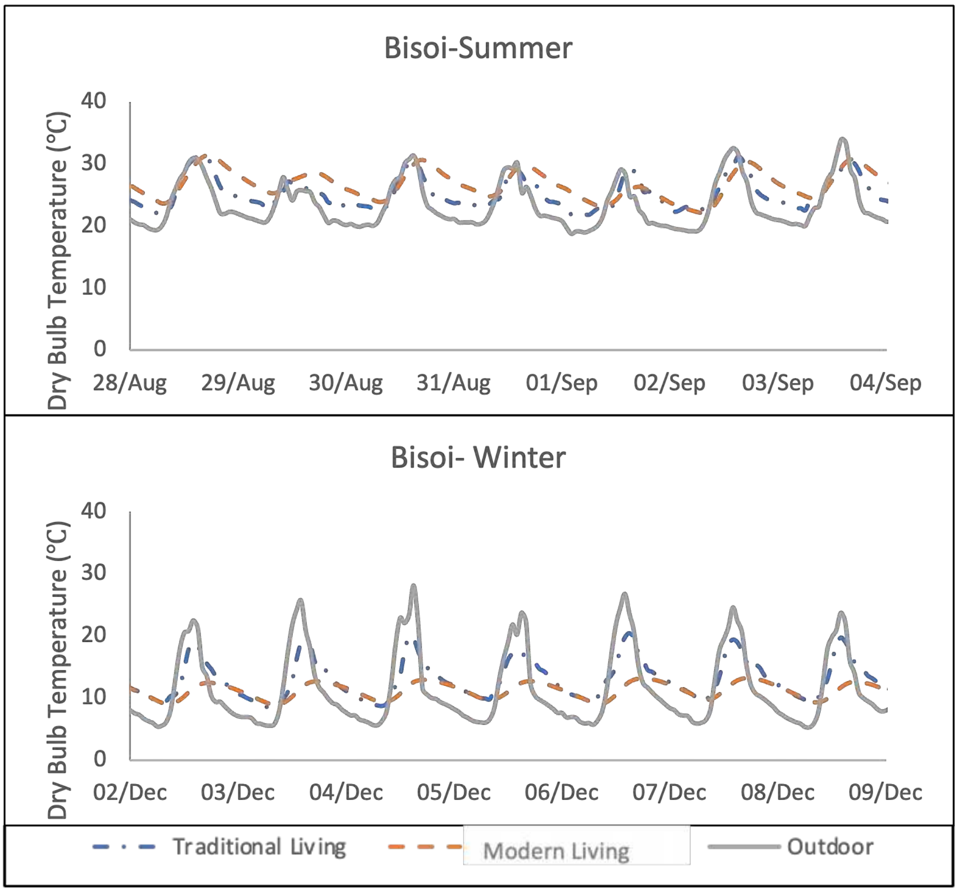


Figure 1. Summer and winter indoor and outdoor temperatures in representative traditional and modern dwellings in Bisoi

Figure 1 shows the recorded indoor dry bulb temperature readings for traditional and modern houses and outdoor dry bulb temperature during summer and winter months in Bisoi. In summer, both the houses maintain an indoor temperature range between 22 and 32 °C, when the outdoor temperature ranges between 18 and 34 °C. In winter, modern dwelling maintains a nearly constant indoor temperature between 9 ~ 12 °C, despite the outdoor temperature ranging between 6 ~ 28 °C. On the other hand, indoor winter temperature in traditional dwelling ranges between 9 ~ 20 °C. Throughout the day, modern dwelling maintains an indoor temperature lower than that can be perceived comfortable across winter season. The modern dwelling, is thus, less effective in winter in providing warmer and comfortable indoor environment, while traditional dwellings maintains warmth much better than modern dwelling. The time lag between outdoor and indoor air temperatures in modern house (3-4 hours) is greater than traditional (1-2 hours) house. This can be attributed to the 'openness' of traditional house through the dwelling envelope. The walls constructed using timber panelling allows for mixing of air through the joints as do the gaps between the slate roofing tiles, while the modern dwellings have relatively impervious walls and roof. The Pearson correlation coefficient between indoor temperatures in traditional dwelling and outdoor temperatures during summer and winter are 0.835 and 0.857, respectively. While that for modern dwelling during summer and winter are 0.537 and 0.579 respectively. The lower coefficient in modern dwelling can be attributed to its effectiveness in cordoning out the indoors from the outdoors. In traditional dwellings, outdoor environment has a greater bearing on the indoor thermal environment and is highly responsive to outdoor environment.

The above findings clearly show that the indoor thermal environment is different in traditional and modern dwelling subjected to the same weather. It must be noted that in Bisoi, situated in cold climate zone, modern dwellings tend to get much cooler in winter and warmer in summer. Modern dwelling is also able to separate out the outdoor thermal environment much more effectively than traditional dwelling. The traditional occupants are subjected to much wider range of temperature than modern occupants. This could be either considered as the poor thermal performance of traditional dwellings or as an opportunity for adaptation. Luo et al., 2016, studied the thermal perceptions of occupants accustomed to living in neutral and non-neutral thermal environment. They concluded that the long-term exposure to comfortable thermal environments raise occupants' thermal expectation while exposure to wider temperatures make avenue for thermal adaptation. Ivanova et al., 2021, studied the effect of drifting and fixed ambient temperatures on occupants' thermal physiology and perception. The researchers indicate that exposure to variability in indoor temperatures had the potential to improve human metabolic and cardiovascular health. Whether the exposure to wider indoor temperatures in traditional dwelling and narrow indoor temperatures in modern dwelling influences the thermal expectation of occupants needs to be studied. The following sections try to differentiate between the thermal behaviour and thermal sensation of traditional and modern occupants in order to explore possible changes in thermal response/expectation due to behavioural adjustment and adaptation.

### 4.2. Thermal behaviour of occupants

This section explores the thermal adaptive behaviour of both traditional and modern occupants. This includes clothing patterns and adaptive behaviour during cold and warm weather. Table *2* shows the summary of clo values (clothing resistance calculated based on ASHRAE 55, 2010) of clothing worn by the occupants during the point-in-time survey. Mean clo value was slightly higher for traditional occupants than modern occupants, while standard deviation of clo was higher for modern occupants, for both male and female respondents. This suggests that clothing adjustment is one of the behavioural adaptation methods predominantly and consistently adopted by the traditional occupants to attain thermal comfort.

Table 2. Calculated clo values of traditional and modern occupants during point-in-time survey

| | **Traditional** | | | | **Modern** | | | |
|---|---|---|---|---|---|---|---|---|
| | **Min** | **Max** | **Mean** | **SD** | **Min** | **Max** | **Mean** | **SD** |
| **Male** | 0.54 | 0.60 | 0.57 | 0.03 | 0.38 | 0.60 | 0.56 | 0.07 |
| **Female** | 0.53 | 0.70 | 0.66 | 0.07 | 0.53 | 0.90 | 0.65 | 0.11 |
| **All** | 0.53 | 0.70 | 0.63 | 0.07 | 0.38 | 0.90 | 0.61 | 0.10 |

Figure *2* shows the relation between thermal sensation votes (TSV) and clo value during the point-in-time survey. The coefficient of determination, $R^2$, between TSV and clo is 0.93 and 0.15 for traditional and modern occupants, respectively. The higher $R^2$ for traditional occupants suggests the thermal response of traditional occupants has greater bearing on the clothing adaptation while the TSV of modern occupants are relatively independent of their clothing. This confirms the observation made from Table *2* that traditional occupants rely on clothing adjustment for thermal comfort. Moreover, clo is slightly higher among traditional inhabitants for the same TSV. This indicate that at the same level of thermal sensation, traditional occupants needed more clothing resistance, while modern occupants probably relied on other methods for comfort.

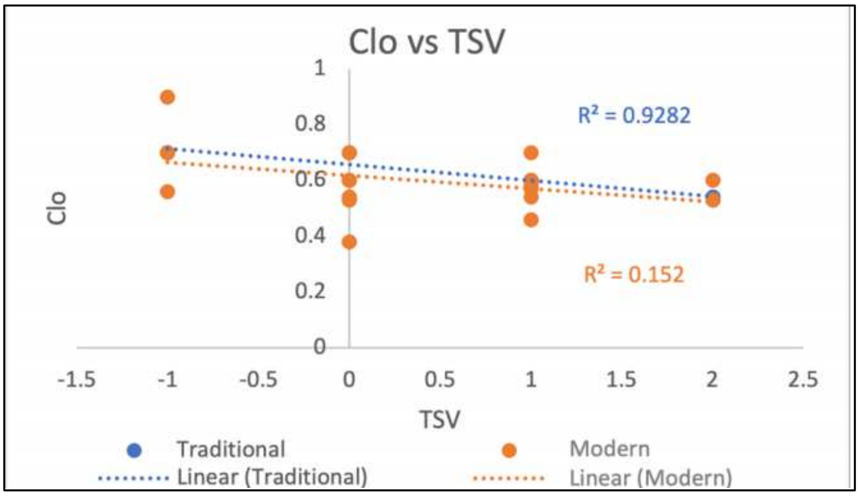


Figure 2. Clo against TSV for traditional and modern occupants

Figure *3* summarises the adaptive behaviour of both occupant groups during warm and cold weather. Occupants reported adaptive strategies like switching on fans, moving outdoors when the indoor gets warmer, wearing lighter clothing, opening windows, staying indoors when it is sunny outside and sitting in shade during warm weather. While, increasing layers of clothing, using room heaters, burning firewood, staying indoors, closing windows to prevent loss of warmth, sitting in the sun or moving to warmer village were the common adaptive strategies adopted during cold weather. Passive, behavioural adaptative strategies like opening windows in warm weather, closing windows during cold weather, lighter clothing in warm weather and increasing clothing layers during cold weather were more predominant among traditional inhabitants than modern. Active adaptation strategies like switching on fans during warm weather and using room heaters or burning firewood in cold weather are more common among modern inhabitants. This suggests that traditional occupants are accustomed to adopting traditional passive adaptive strategies and attaining comfort without requiring active electro-mechanical appliances. Effect of transition in the building envelope on the thermal behaviour of the occupants is apparent in the adoption and dependence on active adaptive strategies for thermal comfort. This is evident from the thermal behaviour of modern occupants as can be seen from Figure 3. Modern dwellings often come with modern active conditioning facilities embedded during commissioning itself. The inhabitants thus get habituated in relying on them for comfort. Switching on heaters are more convenient than wearing multiple layers of clothing.

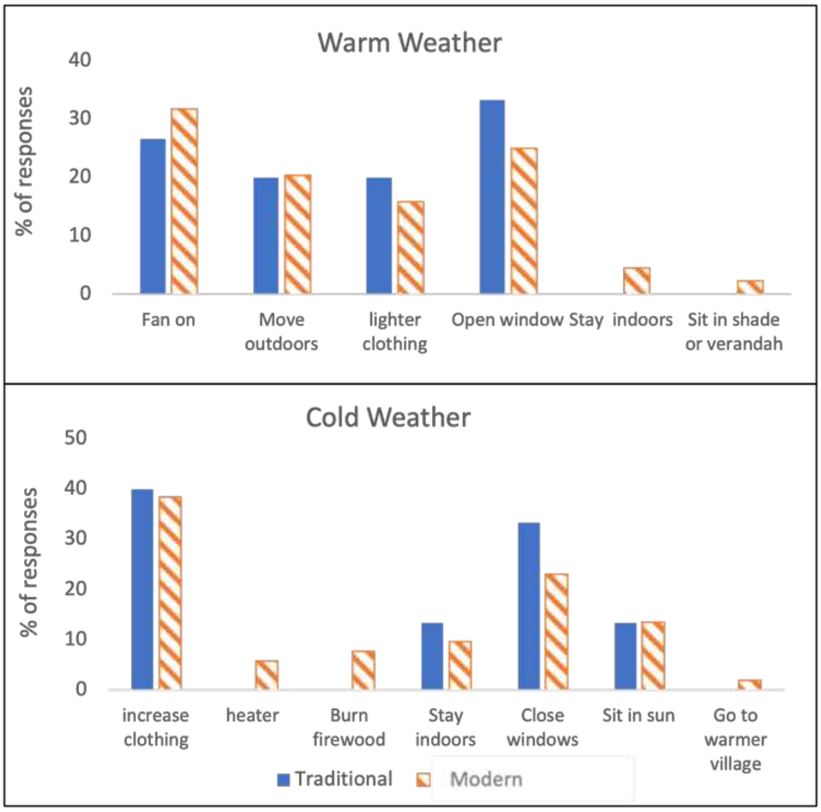


Figure 3. Behavioural adaptation of traditional and modern occupants during warm and cold weather

### 4.3. Thermal sensation of occupants

This section analyses the thermal sensation votes of the traditional and modern occupants during the point-in-time survey. The thermal sensation were marked based on the AHSRAE thermal sensation scale. In Figure 4, the distribution of percentage of comfort votes were plotted against the indoor dry bulb temperature marked during the point-in-time survey. In this paper, TSVs between -1 to +1 are considered comfort votes, the range in between which occupants do not experience much discomfort. Busch, 1992, defines this range of votes as the votes at thermal acceptability. Singh et al., 2010, suggests the use of range of comfort temperatures corresponding to comfort votes -1 and +1 on the ASHRAE thermal sensation scale rather than just comfort temperature, considering the avenue for physiological, psychological and behavioural adaptations of the occupants. Figure 4 shows the proportion of occupants comfortable at different indoor temperatures. The comfort votes of traditional occupants were higher at a temperature range of 25 ~ 27°C. The frequency of comfort votes peak at the comfort temperature for the group. For the traditional occupants, the relative frequency of comfort votes was highest at an indoor temperature of 26 °C, while that for modern occupants was at 28 °C. The modern occupants need higher indoor temperature to feel comfortable than traditional occupants. This implies that the long-term exposure to the thermal environment in modern dwelling and the dependency on active intervention has pushed the comfort temperature of occupants by 2 °C . This further increases the dependency of modern occupants on active adaptation strategies like room heaters and air-conditioners for comfort.

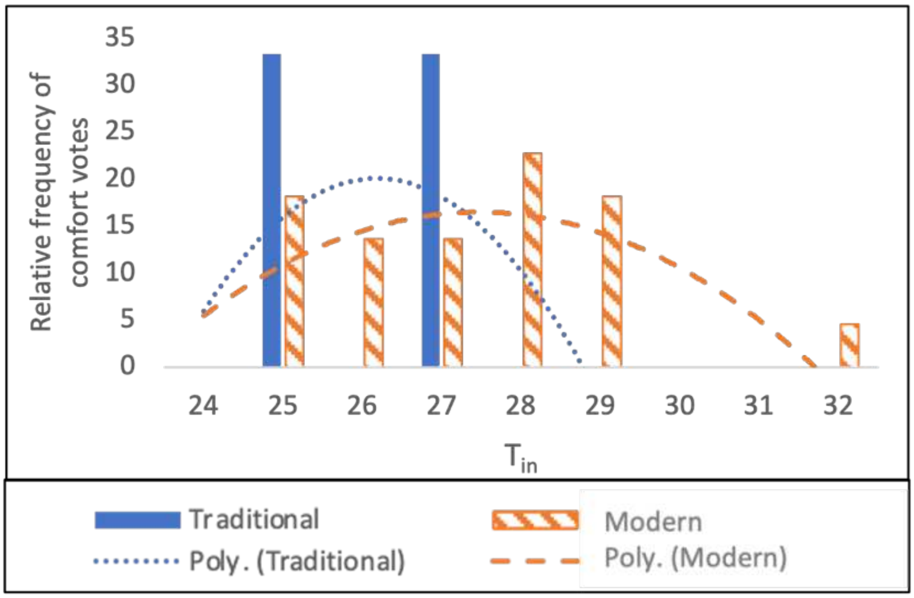


Figure 4. Relative frequency of comfort votes against indoor temperature

## 5. Conclusion

Long-term exposure to a given thermal environment and behavioural adjustment in that environment influences the thermal expectation and perception of occupants. This paper investigated the influence of modern transitions in dwellings on the thermal expectation of occupants. A field study was conducted in Bisoi, a village in Uttarakhand, India which falls in cold climate zone. Thermal sensation surveys of occupants accustomed to living in traditional and modern dwellings were conducted. From the analysis, the following conclusions could be drawn:

- The thermal environment in traditional and modern dwellings varied, especially in winter. Indoors in traditional dwellings maintained a wider range of temperature, while temperature variation in modern dwellings were quite narrow, especially during winter.
- Mean Clo value of occupant clothing was slightly higher among traditional occupants, while standard deviation of clo among traditional occupants was small in comparison to modern occupants. This suggests greater adoption of behavioural adjustment through clothing among traditional occupants.
- Traditional occupants tend to depend predominantly on passive adaptive behaviours while modern occupants are mostly dependent on active adaptation strategies
- Comfort temperature was lower for traditional inhabitants compared to modern inhabitants. In cold climate zone like Bisoi, this increases the dependency of modern occupants on active space heating strategies.

Based on the study, the influence of transitions in the building envelope was evident on the thermal behaviour and thermal perception of the occupant. The long-term exposure to the wider thermal environment in the traditional dwelling accompanied by adoption of traditional passive adaptive strategies make the traditional occupants more resilient to the wider temperature changes. Transitions in the building envelope accompanied by the introduction of active adaptive strategies allow the modern occupant to depend on the electro-mechanical appliances to attain comfort. Increased dependency on active adaptive strategies affect the thermal resilience of occupants, evident from the higher comfort temperature for the modern occupant group. Transitions in the building envelope, thus have the potential to influence the thermal expectation of occupants. This could have a domino effect on the energy consumption patterns and greenhouse gas emissions of transitioning communities. Increasing energy consumption and emissions associated with transitions in these communities, the rate and scale of such transitions in emerging countries could seriously impact global energy consumption and emissions, considering the population densities in these countries. Global climate change mitigation and adaptation strategies should take into account the effect of transitions in the built environment and associated change in thermal expectation and energy demand for thermal comfort.

## 6. Limitations and scope for future work

- This research was conducted in the field with the occupants involved in their day-to-day activities. The nature of field studies are such that, on one hand, they help study the occupants in their natural habitat, on the other hand, they often bring in wide variability in terms of the physical environment, clothing, metabolism of occupants, period of exposure to given thermal environment, etc. In addition, thermal experience immediately prior to the period of study is crucial in understanding the thermal perceptions of occupants. Controlling the immediate thermal experience is difficult in a field study. A controlled experiment with occupants with a thermal history of living in traditional or modern house need to be conducted in a climate chamber to eliminate any variabilities that could influence the thermal sensation of occupants and understand the thermal perception and thermo-regulatory behaviour of participants and variations, if any. Studying the thermal sensation and response of each respondent exposed to different indoor temperatures will further shed light on the thermal resilience of each occupant groups.
- The study was conducted in a small village with a very small population. During the analysis of the survey, some of the relationships could not be explored in depth as the data was not sufficient ($p$ > .05) to make a conclusion. Those relationships, for instance, thermal sensation votes against indoor temperatures for the traditional and modern inhabitants could not be studied effectively. These relationships are not included in this paper, but need to be explored further in depth using case studies with larger population sizes.
- During this study, real-time indoor temperature and humidity were monitored at regular intervals. Monitoring the operation of space conditioning appliances and windows would help in better understanding the dependence of inhabitants on different active and passive adaptive strategies.
- The study was conducted in a village situated in cold climate zone in India. The findings from this study need to be validated in other climatic conditions.

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# A brief overview of assessment frameworks and instruments related to well-being and productivity in relation to indoor environmental quality research

**Sanyogita Manu and Adam Rysanek**

Faculty of Applied Science, University of British Columbia, Vancouver, Canada

**Abstract:** This paper presents an overview of frameworks, instruments and tools used for subjective and objective assessment of well-being and productivity (or work performance). These instruments have been drawn and collated from a wide range of studies, including those that focus on factors unrelated to indoor environmental quality (IEQ). However, we perform a qualitative review of these instruments from the lens of IEQ domain, and with the objective that they may be used to observe, document, analyse and understand the relatively less-explored facets of IEQ research.

**Keywords:** literature review, questionnaires, well-being, health, productivity

## 1. Introduction

Subjective assessments, in the forms of questionnaires, are one of the most important tools used in investigations where building occupants are involved and are especially integral to indoor environmental quality (IEQ) studies. These questionnaires are either paired with the objective measurement of IEQ variables or used as stand-alone instruments in both field and laboratory experiments. Most of these subjective assessment instruments focus on occupant comfort and satisfaction with overall IEQ or specific IEQ variables, such as temperature, or humidity. Many others aim to gather occupant's perception of their well-being and work performance either in relation to IEQ conditions, or with respect to other non-IEQ related variables.

While reviews that focus on instruments pertaining to specific health problems or specific health-related productivity loss have been done, we found that a broad overview of these instruments within the realm of IEQ research was missing. The main purpose of this review, therefore, was to identify some of the most widely used instruments to assess occupant well-being and work performance and articulate our findings through a visual map. In the process of searching for and studying these instruments, we also found a wide range of tools that have been used for objective assessment of well-being and productivity. In order to present a more well-rounded overview, we decided to include them in this review as well.

## 2. IEQ and well-being

Several studies have documented health problems in buildings. The documentation of health-related issues ranges from overall assessments of general health to more detailed assessments related to specific health problems. The physical health findings were dominated by problems related to nose (Wong *et al.* 2009, Huang *et al.* 2011, Wang *et al.* 2018, Kamaruzzaman and Azmal 2019, Vakalis *et al.* 2019, Nitmetawong *et al.* 2020), followed by fatigue (Wong *et al.* 2009, Wang *et al.* 2018, Kamaruzzaman and Azmal 2019, Vakalis *et al.* 2019, Nitmetawong *et al.* 2020) and skin issues (Wong *et al.* 2009, Huang *et al.* 2011, Wang *et al.* 2018, Vakalis *et al.* 2019, Nitmetawong *et al.* 2020). While these may not be the most prevalent issues, they are certainly the most frequently documented. Fisk argues, more than once (Fisk and Rosenfeld 1997, Fisk 2000, n.d.), that strong evidence exists of the link between indoor environments and occurrence of communicable respiratory illness, allergy and asthma symptoms. Associations between lower ventilation rates and indicators of inflammation, rates of communicable respiratory infections, frequency of asthma symptoms and rates of short-term sick leave increase have also been made although the nature of this relationship is not entirely clear. For other health issues indicated in Table 1, their associations with IEQ do not seem to be conclusive. Psychological health or mental well-being have been less documented in IEQ studies. We found only one study that included stress as a health parameter and assigned it a mean score of 2.6 (between "rarely" and "sometimes") based on the survey results (Kamaruzzaman and Azmal 2019).

Table 1. Prevalence of health issues from studies included in the literature review

| Health issue | Study | Findings |
|---|---|---|
| *General health* | | |
| Overall | (Du *et al.* 2015) | 72% respondents reported good or fairly good health in Finnish residences; 32% thought their health symptoms were building-related [a] |
| | (Du *et al.* 2015) | 56% respondents reported good or fairly good health in Lithuanian residences; 25% thought their health symptoms were building-related [b] |
| *Physical health* | | |
| Headache | (Bluyssen 2000) | Reported by 15.9% respondents [c] |
| | (Vakalis *et al.* 2019) | Respondents in ~30% suites reported "occasional" and ~20% reported "every few days" occurrence [d] |
| | (Kamaruzzaman and Azmal 2019) | Mean score of 2.7 [e] |
| | (Nitmetawong *et al.* 2020) | Reported by ~54% respondents [f] |
| Eye | (Bluyssen 2000) | 13.1% reported having eye/throat irritation [c] |
| | (Vakalis *et al.* 2019) | Respondents in ~20% suites reported "occasional" and ~20% reported "every few days" occurrence of itching, burning, irritation of eyes [d] |
| | (Nitmetawong *et al.* 2020) | ~37% respondents reported irritation, dry eyes [f] |
| Throat | (Wang *et al.* 2018) | 48.6% respondents reported having dry and irritated throat [g,h] |
| | (Vakalis *et al.* 2019) | Respondents in ~25% suites reported "occasional" and ~20% reported "every few days" occurrence of hoarseness and dry throat [d] |
| | (Nitmetawong *et al.* 2020) | Reported by ~37% respondents [f] |
| Nose | (Wong *et al.* 2009) | Reported by 16% respondents [j] as repeating at least weekly; 62% of these respondents thought it was building-related |
| | (Huang *et al.* 2011) | Mean score of ~6.0 (p<0.001) (airway/mucous membrane) [k] |
| | (Wang *et al.* 2018) | 11.4% respondents reported having blocked or stuffy nose [g] |
| | (Vakalis *et al.* 2019) | Respondents in ~20% suites reported "occasional" and ~30% reported "every few days" occurrence of irritated, **stuffy,** or runny nose [d] |
| | (Kamaruzzaman and Azmal 2019) | Mean score of 2.5 (sneezing, stuffy nose) [e] |
| | (Nitmetawong *et al.* 2020) | Reported by ~57% respondents (sneezing) [f] |

| Health issue | Study | Findings |
|---|---|---|
| | | Reported by ≈45% respondents (runny nose, congestion) [f] |
| Skin | (Wong *et al.* 2009) | Reported by 12% respondents [j] as repeating at least weekly; 68% of these respondents thought it was not building-related |
| | (Huang *et al.* 2011) | Mean score of ~7.0 ($p<0.001$) [k] |
| | (Wang *et al.* 2018) | 40% reported having dry skin and itchiness [g,h] |
| | (Vakalis *et al.* 2019) | Respondents in ~15% suites reported "occasional" and 25% reported "every few days" occurrence of dry or flushed skin on the face [d] |
| | (Nitmetawong *et al.* 2020) | ~37% respondents reported itchiness [f] |
| Coughing | (Vakalis *et al.* 2019) | Respondents in ~30% suites reported "occasional" and 15% reported "every few days" occurrence of cough [d] |
| | (Kamaruzzaman and Azmal 2019) | Mean score of 2.5 [e] |
| Dizziness | (Kamaruzzaman and Azmal 2019) | Mean score of 2.7 [e] |
| Sleep issues | (Kamaruzzaman and Azmal 2019) | Mean score of 2.6 [e] |
| Fatigue | (Wong *et al.* 2009) | Reported by 19% respondents [j] as repeating at least weekly; 66% of these respondents thought it was not building-related |
| | (Wang *et al.* 2018) | 8.6% reported feeling lethargic or tired [g,i] |
| | (Vakalis *et al.* 2019) | Respondents in ~30% suites reported "occasional" and 20% reported "every few days" occurrence of fatigue, tiredness, exhaustion [d] |
| | (Kamaruzzaman and Azmal 2019) | Mean score of 3.07 [e] |
| | (Nitmetawong *et al.* 2020) | Reported by ~55% respondents [f] |
| *Mental health* | | |
| Stress | (Kamaruzzaman and Azmal 2019) | Mean score of 2.6 [e] |

[a] Based on a total of 83 respondents
[b] Based on a total of 56 respondents
[c] Based on a total of 403 respondents; a complaint was considered relevant if the percentage of complaints was equal or larger than 20%.
[d] based on a total of 180 suites; duration of interest was last three months
[e] Scale: 1=never, 5=very often; uncertainty not reported
[f] Based on a total of 93 respondents
[g] Based on a total of 73 respondents
[h] Attributed by the authors to low humidity levels indoors
[i] Attributed by the authors to high temperature and low humidity levels indoors
[j] Based on a total of 748 respondents
[k] Scale: 0=unaffected, 5=medium, 10=severely affected (65 respondents)

### 2.1. Subjective assessment of well-being

The range of available frameworks for subjective assessments is as wide as the scope and understanding of the term “well-being.” We identified some of the most widely used, and validated survey instruments and classified them broadly into two categories: instruments for assessment of physical well-being and those for assessment of mental well-being. Figure 1 shows a conceptual map of these frameworks in relation to the primary domains they address, namely, well-being and productivity. This map also indicates the overlaps between these domains and that of comfort/ satisfaction with IEQ conditions, which was not the primary focus of this review. In the process of performing this review, we also found that several of these questionnaires were originally developed as long versions to gather more extensive and detailed responses and tested extensively for validity and reliability. One or more "short forms" of these questionnaires were developed and evaluated later for ease of administration.

Within the physical well-being domain, three distinct types of self-assessment instruments were found. The first type was designed as instruments to specifically address physical fitness or activity; some examples are the International Physical Activity Questionnaire (IPAQ) (Craig *et al.* 2003, Lee *et al.* 2011) and the Standardized Nordic questionnaire for musculoskeletal symptoms (Kuorinka *et al.* 1987). The second type, such as the Cohen-Hoberman Inventory of Physical Symptoms (CHIPS) questionnaire (Cohen and Hoberman 1983, Allen *et al.* 2017), focus on learning about the respondents' experience of a range of health symptoms and their frequency. The third type of questionnaires deal with problems related to sleep – the Athens Insomnia Scale (AIS) (Soldatos *et al.* 2000, 2003) and the Pittsburgh Sleep Quality Index (PSQI) (Buysse *et al.* 1989).

The instruments used for assessing mental well-being may be sub-categorized into one-time evaluation of personality traits, such as the Big Five Inventory (BFI) (John and Srivastava 1999) that has 44 items to measure the five main dimensions of personality and the Revised Life Orientation Test (LOT-R) (Scheier *et al.* 1994) which is a10-item scale to measure level of optimism or pessimism about the future; or periodic evaluation (based on the recall of past week or month) of mood, stress, depression and other psychological distress. Some examples for the latter category are the Profile of Mood States (POMS) (McNair *et al.* 1971), the Center for Epidemiologic Studies Depression Scale (CES-D) (Radloff 1977), the Perceived Stress Scale (PSS) (Cohen 1988) and the short-screening scales K10 and K6 (Kessler *et al.* 2002).

We also found examples of instruments where the domains of physical health and mental well-being overlapped. In some cases, the overlaps were minor, such as in the Psychological General Well-being Index (PGWBI) (Dupuy 1984), while in others, for instance the 36-Item Short Form Survey Instrument (MOS SF-36) (Stewart and Ware 1992, RAND Corporation 2021), the overlaps were more substantial.

### 2.2. Objective assessment of well-being

Back in 1970, Fanger's model of Predicted Mean Vote accounted for human physiology in terms of mean skin temperature and sweating rate associated to thermal comfort perception in a given environment with known clothing resistance and metabolic rate (Fanger 1970). Such models assume constant values of physiological inputs, however, leading to unprecise prediction of comfort. With advancements in biotechnology, it now seems easier to measure some of these physiological variables, several of which also fall within the scope of the definition of biological markers. The variability in biomarkers is now increasingly being used as an indicator of change in comfort and well-being, which, in turn, affects productivity, even though medical research shows that a biomarker "does not necessarily associate with a patient's experience and sense of well-being" (Mouhieddine *et al.* 2015).

Researchers, especially in thermal comfort domain, are coming up with novel approaches to document physiological variables. In their experimental study to understand the effects of IEQ on productivity, Lan and Lian (Lan and Lian 2009) measured electroencephalogram (EEG) signal, electrocardiogram (ECG) signal, skin resistance, respiration rate, and finger blood flow. They do not discuss in detail the instruments used or the results related to these measurements. In a more recent lab-based study (Pigliautile et al. 2020), the authors used three wearable systems to measure selected biomarkers. The EEG signal was measured using a wireless neural headset, ECG signal was measured through a Zephyr BioHarness 3.0 and the electrodermal activity (EDA) was measured using a BITalino acquisition board developed by the authors. They concluded that using more heart rate variability (HRV) indices, in addition to the environmental variables, would improve the accuracy of thermal comfort prediction to 82%.

For field studies, wearable devices that are less conspicuous and less intrusive, such as smartwatches are being used for physiological monitoring (Buller et al. 2018), but such studies are very scarce. Nazarian et al. (Nazarian et al. 2021) used Fitbit smartwatches to obtain microclimate parameters in the immediate environment of the individuals, their physiological responses to heat (heart rate, skin temperature and humidity) and their subjective feedback regarding the thermal environment and tested them in both controlled and semi-controlled environments. An iButton Hygrochron temperature/humidity data loggers (DS1923) (Overview of iButton® Sensors and Temperature/Humidity Data Loggers 2021) was attached on the inner and outer face of the watch strap to collect temperature and humidity of skin and air. The PurePulse technology integrated with Fitbit was used for heart rate monitoring. Lastly, an app called Cozie (Jayathissa et al. 2019) for Fitbit was developed to gather what have been termed as micro ecological momentary assessments (EMAs) as a user-friendly way to collect large amounts of longitudinal data from a respondent (Jayathissa et al. 2020). Using wearable sensors for physiological monitoring in a non-intrusive yet quantitative way, especially in a field study context is a very novel methodology that is still emerging.

## 3. IEQ and productivity

Human performance in buildings has been of much interest for many years now not only for building energy researchers, but also for those working in the domains of behavior, psychology, cognitive science, and health economics. Based on a rule-of-thumb for office buildings, nearly 90% of the money spent will go towards employee costs, followed by rent (9%) and energy and utilities (1%) (Jamrozik and Clements 2019), which shows that the impact of buildings on human performance is a serious matter.

Several studies documenting associations between IEQ and performance/productivity in an office setting were found. For instance, studies have shown that thermal discomfort may lead to quantifiable loss in productivity (Wargocki 2006), that higher concentrations of CO2 and VOCs (reported in some of the studies included in this review) may result in reduced cognitive function (Allen *et al.* 2016); that short-term memory and verbal-logical reasoning may be disturbed by highly intelligible background speech (Liebl *et al.* 2012); and that “environmental stressors” (IEQ factors deemed inadequate) may indirectly disrupt high-functioning work performance by reducing motivation and increasing tiredness, and distractibility (Lamb and Kwok 2016). (Bueno *et al.* 2021) lists several algorithms, based on literature review, that have been developed to calculate productivity, or productivity loss from variables related to thermal environment.

We did not come across a standard usage in research for the terms “productivity” and “performance”. According to Jamrozik and Clements (Jamrozik and Clements 2019), use of these terms interchangeably has caused much confusion. For office-type work, they define performance as “success at accomplishing work tasks” and productivity as the “amount of work produced per unit time”. It may seem from these definitions that performance is a more subjective variable in that it requires some self-assessment of how “success” may be defined. While productivity may seem like a more objective variable, quantifiable using “amount of work” and “time” quantities, in non-standardized office work, defining the “amount of work” also becomes a subjective assessment. So, for this review, we use “productivity” as an umbrella term that includes both the definitions of productivity and performance, while we differentiate between the subjective and objective assessments of productivity in the following sections. Subjective assessment involves self-appraisals, which are respondents’ own judgment of their productivity. Studies have argued that this “perceived” productivity may not be a true indicator of actual productivity (Sensharma *et al.* 1998, Byrd and Rasheed 2016, Rasheed and Byrd 2017), while others argue that “the self-assessed measure of productivity is better than no measure of productivity” (Haynes 2007) or go as far as concluding that perceived productivity could be as important as actual productivity (Leaman and Bordass 1999, Oseland 1999). (Wargocki 2019) provides a list of methods, both subjective and objective, to use for estimating productivity and performance.

**3.1. Subjective assessment of productivity**

Some subjective assessments focus specifically on self-appraisal of productivity, such as the Endicott Work Productivity Scale (EWPS) (Endicott and Nee 1997), the Subjective Workload Assessment Technique (SWAT) (Reid and Nygren 1988) and the National Aeronautics and Space Administration-Task Load Index (NASA-TLX) (Hart and Staveland 1988, Hart 2006). Other short instruments focus on different aspects of productivity, such as absenteeism and presenteeism. Absenteeism is a measure of time missed from work, usually based on a recall period ranging from one week to one month, while presenteeism is used as a measure of actual performance in relation to possible performance. The Work Limitations Questionnaire (WLQ) Time Loss Module (Lerner *et al.* 2001), the Stanford Presenteeism Scale (SPS-6) (Koopman *et al.* 2002) and the absenteeism and presenteeism questions of the World Health Organization’s Health and Work Performance Questionnaire (HPQ) (Kessler *et al.* 2003, 2004) are a few examples.

While workplace environment has been known to directly influence productivity, and affects absenteeism and presenteeism, health and well-being are considered to affect productivity indirectly. Several health and well-being factors have been identified in the literature as indicators of productivity. This is also the reason we see so much overlap between well-being and productivity in most subjective assessment frameworks for the latter. Instruments such as the Work Functioning Impairment Scale (WFun) (Fujino *et al.* 2015), the Utrecht Work Engagement Scale (UWES) (Schaufeli *et al.* 2002, 2006), the Work Productivity and Activity Impairment Questionnaire - General Health (WPAI-GH) (Reilly *et al.* 1993), the Health and Work Questionnaire (HWQ) (Shikiar *et al.* 2004) and the Work Limitations Questionnaire (WLQ) (Lerner *et al.* 2001) focus on assessing the work-related impairments caused by problems related to physical and mental well-being. Then there are more detailed questionnaires that delve into the specific health problems that cause these impairments at work, such as the Finnish Institute of Occupational Health Work Ability Index (FIOH WAI) (Tuomi *et al.* 1998), the WHO Health and Work Survey (HPQ) (Kessler *et al.* 2003) and the NIOSH Generic Job Stress Questionnaire (NIOSH GJSQ) (Hurrell and McLaney 1988). The last one is an example of am instruments designed as a battery of questionnaires, comprising of more than 190 items organized under 22 form modules, related to work conflict, general health, mental well-being and demands from work, job requirements and satisfaction, physical environment, workload, and responsibilities, etc.

Several post-occupancy evaluation instruments, that focus primarily on satisfaction with IEQ conditions, also include a few self-appraisal questions related to productivity. Some examples are the Building Occupants Survey System AustraliA (BOSSA) (Candido *et al.* 2016), CBE Occupant Indoor Environmental Quality Survey (CBE n.d.), Building Use Studies (BUS) questionnaire (BUS Methodology 2021), Checklist of Work Related Experiences (CWRE) (Wilson 1990), AMA Workware (Usable Buildings 2021a), Office Productivity Network (OPN) Survey (Usable Buildings 2021b) and Work Environment Diagnosis Instrument (WEDI/WODI) (Center for People and Buildings 2021).

### 3.2. Objective assessment of productivity

Computer-based neurobehavioral testing has been used in fields of neurotoxicology, neuropsychology and occupational and environmental epidemiology since the 1980s (Williamson 1996). In their experiment-based study to evaluate the effects of room temperature on the productivity of office workers, Lan et al. (Lan *et al.* 2009) explain the framework of neurobehavioral functions which forms the basis for their battery of tests. They conceptualize behaviour in terms of three functional systems of cognition, emotionality, and executive functions. Cognition, which is the information-handling aspect of behaviour may be divided into four classes of functions, namely, perception (analogous to input in terms of information-processing in computer operations), memory and learning (storage), thinking (processing) and expressive functions (output). The authors differentiate between cognitive functions (those which involve specific functions or functional area) and executive functions (those that apply globally and affect all aspects of behaviour. Jamrozik and Clements (Jamrozik and Clements 2019), on the other hand, consider executive functions to be “domain-general” cognitive functions, and suggest focusing on tests related to executive functions since the range of cognitive functions and the available measures for each is so vast.

Executive functions refer to top-down mental processes needed for tasks that require concentration and attention. There are three core executive functions: inhibition (or inhibitory control), working memory and cognitive flexibility (or task switching) (Diamond 2013). In a systematic review, the authors found that attention, perception, memory, language function, and higher order cognitive skills were the most commonly studied cognitive functions when considering associations with IEQ (Wang *et al.* 2021). Based on their review, they compiled a list of tasks to assess these cognitive functions. Jamrozik and Clements (Jamrozik and Clements 2019) suggest focusing on tests related to the aforementioned core executive functions since the range of cognitive functions and the available measures for each is so vast.

In our review of literature, we found six studies where performance tasks were used to measure productivity. Of these, only one was a field study (Gupta *et al.* 2020) and the rest were studies conducted in controlled environments. The field study used numerical tests, proofreading tasks and Stroop test to test cognitive capability in order to understand the relationship between indoor environment and workplace productivity (Gupta *et al.* 2020). The authors could not find any meaningful correlations between the Stroop test data and the IEQ conditions due to the lack of spread of the test scores since the tests scores were consistently high and test durations were consistently short but the distribution of scores for the other tests was wider. The experimental studies used a range of tasks, the most common of which were addition (Tsutsumi *et al.* 2007, Lan *et al.* 2009, Geng *et al.* 2017), text typing (Tsutsumi *et al.* 2007) or transcription (Kuorinka *et al.* 1987) and text memory (Lan *et al.* 2009, Geng *et al.* 2017).

## 4. Discussion

This review involved an appraisal of more than 50 instruments at different levels of detail, based on the availability of the complete questionnaires. We classified the instruments into several themes and sub-themes based on the specific well-being and productivity metrics used. The overlaps between the themes were also visualized on the map.

In general, the most common outcome of interest or "dependent variable" in IEQ studies were comfort, satisfaction, and acceptability in relation to overall IEQ or IEQ domains/ attributes. This is to say that the relationship between IEQ and these variables has been firmly established through numerous field and lab-based studies, although the attributes for this relationship have not been standardized. Similarly, associations between IEQ and well-being have been made, especially the link between indoor environments and occurrence of communicable respiratory illness, allergy and asthma symptoms (Fisk 2000) although the nature of this relationship is not entirely clear. Associations of other health issues we identified in the first phase of the literature review, such as headaches, dizziness, sleep issues, fatigue, etc., with IEQ do not seem to be conclusive.

We also found that most productivity studies used either the subjective self-assessment (Tanabe *et al.* 2015) or quantitative assessments from cognitive/performance tasks scores (Gupta *et al.* 2020). In absence of a standard measure of productivity, it seems that either of these methods alone may not capture actual productivity (Sun *et al.* 2021). And while it has been argued that "perceived" productivity is not a true measure (Sensharma *et al.* 1998), we feel that the objective assessment, using performance-based tasks/cognitive tests, does not quite capture actual productivity either because the tasks designed for such assessments are likely different from the tasks performed by the respondents on a regular basis. The other potential drawback with these cognitive tests may be that the likely report productivity or performance at the time of deployment, which raises concerns about the reliability of these scores as a measure of general productivity. In order to "measure" the latter, these tests would, arguably, have to be deployed multiple times in a day, daily, for the duration of the study, increasing the likelihood of inducing survey fatigue. On the other hand, it is conceivable that self-appraisals allow respondents to recall and report their productivity over a period of time, such as past 24 hours, or past seven days. We found very few studies where both kinds of assessment methods were used, especially in a field study setting (Gupta *et al.* 2020).

In the process of reviewing these instruments, we found that quite a few of them were originally developed as long versions to gather more extensive and detailed responses and tested extensively for validity and reliability. One or more "short forms" of these questionnaires were developed and tested later for ease of administration. We also found that the instruments used for assessing mental well-being may be categorized into one-time evaluation of personality traits and periodic evaluation (based on the recall of past week or month) of mood, stress, depression, and other psychological distress factors.

Several subjective assessments related to work performance focused on self-appraisal of productivity, while other short instruments focused on proxy measures such as absenteeism and presenteeism. We found considerable overlaps between well-being and performance in many subjective assessment instruments for the latter, which is plausible since several health and well-being factors have been identified in the literature as indicators of productivity.

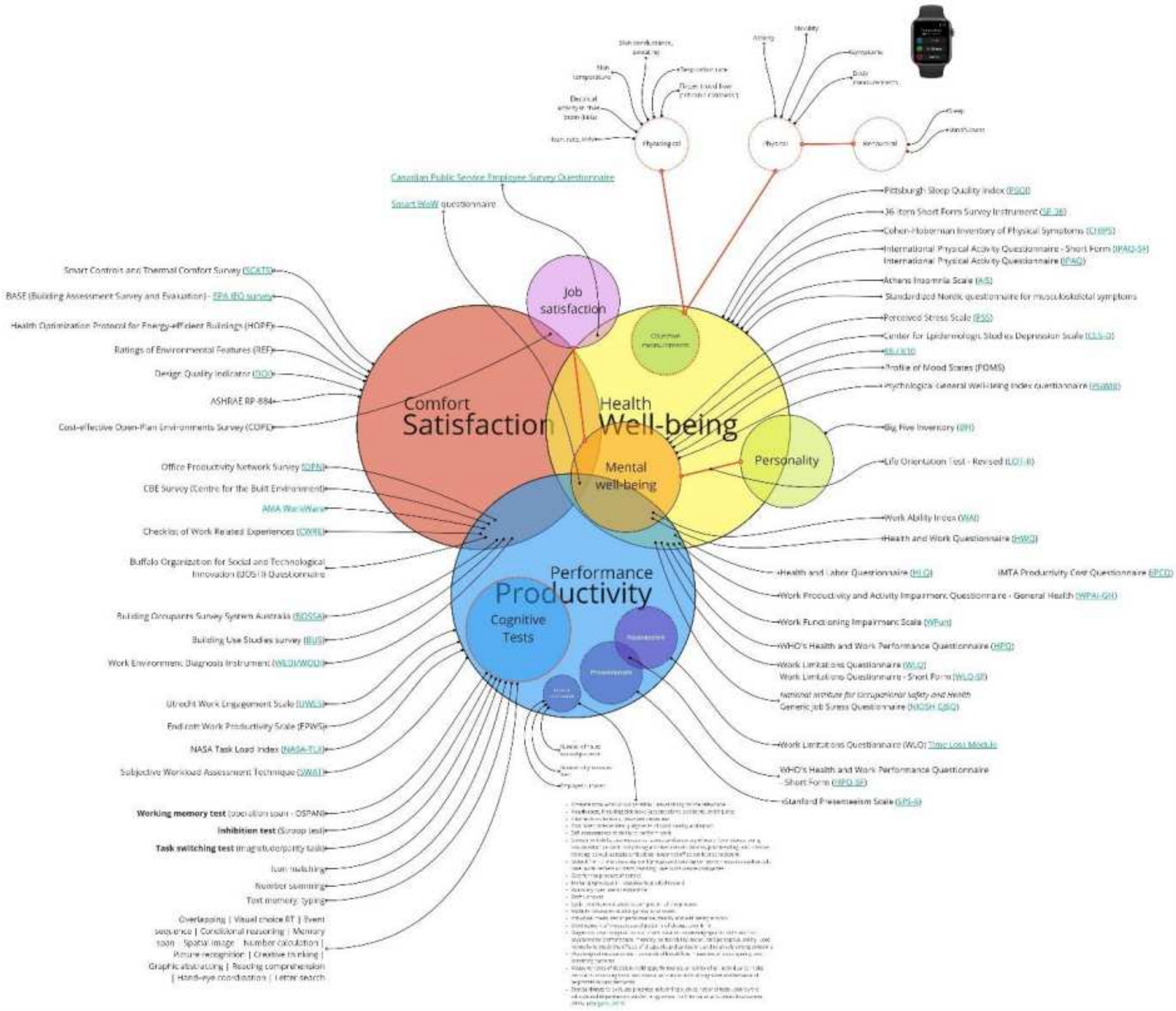


Figure 1. A map of the subjective and objective assessment frameworks for well-being and productivity based on this brief review of literature

## 5. Conclusions

From our review of instruments related to well-being and productivity that have been used in IEQ studies, we found that the range of such instruments is wide and varied, addressing different aspects of well-being and productivity. The most common outcome of interest or "dependent variable" in IEQ studies were found to be comfort, satisfaction, and acceptability in relation to overall IEQ or IEQ domains/ attributes. The most commonly used methods of assessing productivity were subjective self-assessment through questionnaires or quantitative assessments from cognitive/performance tasks scores. We also found that several questionnaires meant for assessment of performance/productivity also had a component related to worker's well-being.

This review will form the basis on which we will conduct a more comprehensive and systematic review of such instruments. We hope these reviews will help researchers and professionals to identify instruments that best align with their objectives, in the way of a "lookup" map, of sorts.

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## Health-related heat and cold adaptive capacity: projections under the UK Shared Socioeconomic Pathways

Kai Wan[1], Zhiqiang Feng[12], Shakoor Hajat[34], Matt Lane[5], Ruth Doherty[1]

1. School of Geosciences, University of Edinburgh, UK
2. Scottish Centre for Administrative Data Research, School of Geosciences, University of Edinburgh, UK
3. Department of Public Health, Environments and Society, London School of Hygiene & Tropical Medicine, UK
4. Centre on Climate Change and Planetary Health, London School of Hygiene & Tropical Medicine, UK
5. Department of Geography, University College London, UK

Abstract

High and low ambient temperatures can have adverse health effects on human beings. Previous health impact assessments projecting future health burdens under climate change scenarios usually focus solely on the change in climate, leaving the contribution of potential societal adaptive capacity on future health burdens an under researched area. This study contributes to this topic by projecting adaptive capacities to heat and cold in the UK under the five Shared Socio-Economic Pathways (SSP). The mechanisms of key factors affecting adaptive capacities are reviewed, including economic status, inequality, social cohesion, health care, behavioural changes, urban management and population, greenspace and energy efficiency. Heat and cold adaptive capacity indices are constructed using proxy variables and data from the UK-SSP project semi-quantitative projections. The results show a strong increase in adaptive capacities under SSP1, stable or slightly increased adaptive capacities under SSP2 and 5, and strong maladaptation under SSP3 and 4. Adaptive capacity to heat is generally lower than for cold, driven by the negative effect of increasing urbanisation on heat adaptation due to an increased urban heat-island effect, and the positive effect of improved energy efficiency measures on cold adaptation.

Keywords: heat, cold, adaptive capacity, shared socio-economic pathways (SSP), UK

### 1. Introduction

Increased mortality risk and hospitalisation under high and low ambient temperatures have been found in many cities and regions by epidemiological studies (Hajat et al, 2007; Vardoulakis et al, 2014; Gasparrini et al, 2015). A global study found that the mortality risk is generally the lowest when the ambient temperature is around the 80$^{th}$ to the 90$^{th}$ percentiles of daily temperature distribution for most countries (Gasparrini et al, 2015). For example, the ambient temperature corresponding to the lowest mortality risk (hereafter optimal temperature) has been found to be around 21-25°C in London (Armstrong, 2006; Hajat et al, 2006; Baccini et al, 2008; Gasparrini et al, 2015). The increased health risks under high and low temperatures may be due to the direct physiological impacts of high and low temperatures, such as hyperthermia and hypothermia at the very extremes and increased stress on the cardiovascular and respiratory systems (Kenney et al, 2014; Borg et al, 2017; Arbuthnott et al, 2018). High and low temperatures can also affect health indirectly for example by increasing the accidents of drowning under high temperatures and the transmission of respiratory diseases due to people gathering indoors under low temperatures (Arbuthnott et al, 2018; Dahl et al, 2019).

The optimal temperature and the health risk associated with non-optimal temperatures varies by city and region and changes over time. For example, higher cold-related mortality risk was found in warmer regions than in colder regions in Europe (Keatinge et al, 1997) and the US (Curriero et al, 2002; Anderson & Bell, 2009). There was a decrease in the mortality risk associated with heat in Italy between 1999 and 2016 (De'Donato et al, 2018) and in Spain between 1980 and 2016 (Achebak et al, 2019). This regional variation and long-term temporal change (e.g. decadal) may be due to acclimatisation and a series of interrelated aspects that affect the people’s exposure to temperatures and their vulnerability to high and low temperatures (Lindley et al, 2011; Anderson et al, 2019).

Apart from biophysical sensitivity (e.g. age and underlying health conditions), vulnerability is largely affected by the physical environment such as urban/rural environments and various socioeconomic factors, e.g. income, social network and availability of health services which affect people’s exposure and ability to prepare for, respond to and recover from non-optimal temperatures, which are referred as the adaptive capacity in this study (Lindley et al, 2011; Ellena et al, 2020). Compound indices can be constructed to reflect socio-spatial vulnerabilities or adaptive capacities to non-optimal temperatures (Johnson et al, 2012; Wolf & McGregor, 2013; Bao et al, 2015). For example, a heat vulnerability index was developed through stakeholder consultation in the UK, which was mapped for neighbourhood level areas using data mainly derived from Census 2001 and other administrative and environmental service data (Lindley et al, 2011).

Understanding future health burdens attributable to ambient temperatures under climate change could help policy-makers be more prepared for future risks and, making planning, take adaptive actions and interventions. The future burdens are affected by three aspects — hazard (i.e. temperature under climate change in this context), exposed population and vulnerability (biophysical sensitivity and adaptive capacity) (IPCC, 2014). Future temperature-related health burdens have been widely projected considering the change in temperature under climate change scenarios (Hajat et al, 2014; Gasparrini et al, 2017; Huber et al, 2020; Martínez-Solanas et al, 2021; Yang et al, 2021). The change in vulnerability can have a large influence on the estimated health burden (Gosling et al, 2017), whereas it has been less considered in health burden projection studies compared to temperature change (Anderson et al, 2019).

Trajectories of Greenhouse Gap and air pollutant emission, concentration and land-use have been widely used to assess probable climate outcomes under climate change, such as the Special Report on Emissions Scenarios (SRES) and Representative Concentration Pathways, which are used for the Intergovernmental Panel on Climate Change (IPCC) Fourth and Fifth Assessment Report respectively (IPCC, 2000; Van Vuuren et al, 2011). In recent years, the Shared Socio-Economic Pathways (SSP) are developed with five potential futures of how global society, demographics and economics might change over the next century which are used for the latest IPCC assessment reports (O’Neill et al, 2017; IPCC, 2021; 2022). Land use change and resulting GHG emissions and atmospheric concentrations are also derived from the SSPs in consistent to the socio-economic assumptions (O'Neill et al, 2016). In addition to global SSPs, country-specific SSPs have been developed which are both in consistent with the global SSPs and reflects country-specific features (Steininger et al, 2016; Wear & Prestemon, 2019; Chen et al, 2020). For example, the UK-SSP project provides qualitative narratives, semi-quantitative and quantitative projection data on a range of demographic and socio-economic indicators specific to the UK while under the global SSP framework (Pedde et al, 2021).

This study focuses on the overlooked area of the projection of future changes in the health-related adaptive capacity to heat and cold in the UK making use of the outputs from the UK-SSP project. The result of this study provides opportunities for exploring future health burdens attributable to heat and cold considering changes in temperature, population and vulnerability under consistent climate and socio-economic scenarios. In this study, factors affecting heat and cold adaptive capacities were identified through a rapid review. A focus group was conducted to assess the results from the rapid review and discuss methods to project the adaptive capacities under future scenarios. In the following sections, the methods are firstly introduced, followed by the results on the main factors affecting the health-related adaptive capacities to heat and cold, and the projection of the adaptive capacities under the UK-SSPs. In the end, the findings are discussed and concluded.

**2. Data and Methods**

A rapid review (Tricco et al, 2015) on the factors that affect health-related adaptive capacities to heat and cold was conducted. Literature was searched through Web of Science Core Collection with the key words ("heat" or "cold") and ("health" or "mortality" or "morbidity") and ("vulnerability" or "adaptation"). Relevant publications in the reference list of the retrieved papers were also included. The review stopped when there is little new information gained on the factors affecting the adaptive capacities to heat and cold by reviewing more papers. This method of determining the end of the review is borrowed from the methodological principal of "data saturation" in qualitative research (Saunders et al, 2018).

A focus group was conducted to assess and supplement the review results and to explore methods to project the adaptive capacities under future scenarios. The focus group was held online via Zoom on 27th April 2022 and organised by the Adaptation Community of Practice, Edinburgh Climate Change Institute. There were seven participants who are academics and environmental consultants working on climate change risk and adaptation. The review results on the factors affecting the adaptive capacities to heat and cold were presented to the participants and they were invited to express their opinions on the importance of these factors and additional factors that are not included. Two methods to project future adaptive capacities were given: 1) projecting the overall adaptive capacity level based on the qualitative narratives of each UK-SSP; 2) constructing compound indices for heat and cold adaptive capacities and using proxy variables and data from the UK-SSP project. The participants expressed their preference for these methods and their reasoning. The adaptive capacities to heat and cold were projected using the second method introduced above (see the focus group result in Section 4). Adaptive capacity indices were constructed for heat-health risks and cold-health risks separately using the key factors identified from the rapid review. The indicators of these factors and their projection data in the UK were identified and obtained from the UK-SSP project's output on semi-quantitative projections for 50 socio-economic variables (Harrison et al, 2021). The UK-SSPs (section 1) provides a consistent starting point for climate change impact, risk and adaptation studies in the UK that is in line with the global SSP framework. Hence these SSPs are fully compatible with other global assessments. The UK-SSP narratives were downscaled from the global SSPs and elaborated to include more details of sectoral development at three time periods up to the end of the 21st century (present to 2040, 2040-2070 and 2070-2100) (Stenning et al, 2021). Moreover, they were further developed through participatory processes including workshops, semi-structured interviews and questionnaires with stakeholders from academia, policy, practice and business (Stenning et al, 2021). In addition to the qualitative narratives, semi-quantitative trends for 50 socio-economic variables (e.g. availability of health service per capita, public spending on infrastructure) was created as result of the workshops and on previous work (Harrison et al, 2021; Pedde et al, 2021). These semi-quantitative projections are on a seven-point scale (strong, moderate or small decrease, no change, and small, moderate or strong increase) for three time periods up to the end of the century (Harrison et al, 2021).

An equal-weight additive approach is applied in this study to construct the heat and cold adaptive indices for pragmatic reasons (Lindley et al, 2011). Sensitivity analyses were conducted to assess the sensitivity of the projection result to the choice of indicators from the UK-SSP project by replacing indicators identified in the main indices with other closely related UK-SSP socio-economic variables. Alternative indicators and projection results are shown in Section 4 and Table 1.3.

**3. Factors that affect heat and cold adaptive capacities**

A variety of factors can affect the health-related adaptive capacities to heat and cold, ranging from economic and social, to behavioural and natural and built environmental factors (Mcgeehin & Mirabelli, 2001; Lindley et al, 2011). The rapid review and focus group results on the key factors are presented here.

**3.1. Economic status**

Being in low income, poverty or material deprivation affects multiple aspects of people's lives and their ability to prepare for, respond to and recover from non-optimal temperatures. Low income is also a main cause of fuel poverty, where households struggle to pay for energy bills to make their homes warm enough and hence affect their adaptive capacity to cold (Scottish Government, 2016). As the temperature is projected to keep increasing in the UK under climate change (Murphy et al, 2019), there may be an increasing need for fan or air conditioning, whereas those who are in low income or material deprivation may not be able to afford them or the associated energy bills (Thomson et al, 2019). Households with lower income or in deprived areas also have a lower access rate to the internet, which affects their ability to access information, such as heatwave and cold spell warnings and take preventive actions (Scottish Government, 2020; 2022).

In addition to income, the cost of living such as fuel and food are also important factors as mentioned by the focus group participants because the minimum income needed for a healthy living is dependent on the cost of living (Morris et al, 2007).

**3.2. Inequality**

Apart from the impact of absolute income as discussed above, health can also be affected by the relative socio-economic status and standard of living (Wilkinson, 1996). Countries with smaller income inequality generally have a higher life expectancy, and reduction in income inequality is also associated with increases in life expectancy over time (Wilkinson, 1996). In addition, crime, drugs and violence are also associated with inequality, and hence a lower level of inequality may increase societal security and hence improve the health of all (Pratt & Cullen, 2005). During heatwaves, opening windows is an efficient way of cooling, particularly at night time when the outdoor temperature is lower than the indoor temperature, however, worries about noise and security may prevent people from opening windows and hence people experience sustained heat stress at night (Morgan et al, 2017;

Murage et al, 2017). Huge inequality may also lead to social fragmentation and worsen social cohesion, which further reduce the adaptive capacity to non-optimal temperature and health (Scambler, 2012). The importance of social cohesion on adaptive capacities to heat and cold will be discussed below in more detail.

**3.3. Social network and cohesion**

The availability and support from social network and the cohesion of neighbourhoods are other factors that affect both people's underlying health conditions and their adaptive abilities to non-optimal temperatures (Berkman et al, 2000; Nicholson, 2012). A study that interviewed 19 elderly swedes on their experience of a heatwave found social isolation as the strongest driver of heat vulnerability (Malmquist et al, 2022). Those who lived alone during a 1999 heatwave in Chicago, US has been identified to experience a strong increase in mortality risk (Naughton et al, 2002). This may be because social support could provide information support on cold/heat warning and coping measures, and instrumental support such as obtaining medical help when getting a heat stroke or help with getting medicines and groceries when the temperature is too extreme for those who are vulnerable to go out (Berkman et al, 2000). Emotional support through social networks is also important for mental health, especially when people are confined indoors or having difficulties going out alone due to extreme ambient temperatures (Malmquist et al, 2022).

**3.4. Health care**

The availability of health and social care services is essential to population health and the adaptive capacity to non-optimal temperatures. In addition to responding to increased demand for the health and social care service by having enough resources to treat those who are affected, it is also crucial to be prepared for extreme temperatures to prevent the major avoidable health effects during extreme temperature by providing extreme temperature early warning, information and guidance and long-term planning through multi-sector and agency collaboration (WHO Europe, 2008; 2021). For example, a Heat-Health Plan has been effective in England since 2004 and a Cold Weather Plan since 2011 (Public Health England, 2021; Health Security Agency, 2022). Future adaptive capacities are affected by how these services change in the future.

**3.5. Adaptive behaviour**

Adaptive behaviours can affect heat and cold health risks ranging from the choice of clothes to the control of windows, shutters, fans and heating and water intake and diet (Fabi et al, 2012). For example, a survey in Europe found people in colder regions (e.g. south Finland) took better protective measures such as having higher living-room temperatures and wearing hats and gloves when being outdoors than in warmer regions (e.g. Athens), which may have contributed to the lower cold-related mortality risk in cooler regions (Keatinge et al, 1997). Adaptive behaviour is important because there is a difference between the availability of a measure and its effective use of it, which may be due to various reasons such as the worries of noise, insects and security, the cost of the utility bill, cultural customs and lack of knowledge (Abrahamson et al, 2008; Gupta et al, 2012). A lack of the power of control, such as window-opening and adjusting the temperature of thermostats particularly in care settings or nursing homes also affects the adaptive capacity of the residents, who are often very vulnerable to extreme temperatures (Gupta et al, 2017; Malmquist et al, 2022).

### 3.6. Urban management and population

Urban environments affect the adaptive capacity to heat due to a general warming temperature in urban than surrounding rural areas, i.e. the Urban Heat Island effect (UHI). Heaviside et al (2016) found that during the August 2003 heatwave in West Midlands, UK, urban areas are around 3 °C warmer than rural areas, and the UHI effect contributed to around half of the excess mortality during the heatwave. The UHI can be mitigated through strategies such as modifying the albedo of urban surfaces including cool roofs and pavements, increasing green space, decreasing anthropogenic heat and using natural heat sinks such as ground cooling (Santamouris, 2015). A study in the UK shows that the cooling potential of cool roofs is around 3 °C in summer, which is greatly larger than the cooling effect of 0.5°C in winter and hence has a minimal impact on intensifying cold risks (Macintyre et al, 2021). General infrastructure which could provide cool and warm places such as libraries and community centres provides another adaptation measure during sustained heat and cold weather (Lindley et al, 2011). Greenspace is also a strong modifier of the UHI effect and the impact of it on health, which will be discussed in the next section.

### 3.7. Greenspace

Increasing green space is highly effective in providing shade from solar radiation and cooling the environment, which can extend beyond the border of the green space due to the pressure difference and hence airflow between the greenspace and the nearby urban areas (Santamouris, 2015). For example, the Queen's Park in London with an area of 12 ha has been found to provide a cooling effect of 1 °C in the park with the cooling effect extending to around 330 m beyond the park (Vaz Monteiro et al, 2016). Higher vegetation cover has been found as a strong protective effect on heat-related mortality in London, UK, which may be due to its cooling effect and health benefits by promoting mental health and healthy behaviour (Mavrogianni et al, 2009; Murage et al, 2020). It is not only the presence of greenspace, the quality of greenspace is also important for its health benefits, such as its tranquillity, greenness and perceived safety (Baka & Mabon, 2020).

### 3.8. Housing and energy efficiency

People spend a long time indoors and hence the adaptive capacity to non-optimal outdoor temperatures is mediated by building thermal performance. Increasing energy efficiency is a key focus of the UK government, which is another core element in tackling fuel poverty (UK Government, 2022). Benefits such as the Winter Fuel Payment, Cold Weather Payments and Warm Home Discount Scheme are also available for those who need help in keeping their homes warm. The current focus of energy efficiency improvement in the UK mainly relates to space heating with insulation as a key intervention (UK Government, 2021).

A survey by the Building Research Establishment (2013) on behalf of the Department of Energy and Climate Change of the UK Government found that around 20% of households reported at least one room being overheated during summer 2011. Insulation and airtightness may have mixed effects on indoor overheating from reduced heat loss due to lack of ventilation and shading equipment, and the heat gained through solar radiation, outdoor environment and internally generated being trapped inside (Peacock et al, 2010; Gupta & Gregg, 2018). This can be managed by strengthening building regulations and improving individual behaviours as discussed above (Tabatabaei Sameni et al, 2015).

Housing tenure has been mentioned as a crucial factor affecting people's adaptive capacity to heat and cold by a focus group participant. People who rent their homes have generally poorer health and higher mortality rates, which may be due to various reasons including low income and material deprivation, fuel poverty, overcrowding, dampness and mould, noise, security, neighbourliness (Ellaway & Macintyre, 1998). In addition, people who rent a house are less able or less willing to modify their living environments to prepare for non-optimal temperatures, e.g. installing shutters (Lindley et al, 2011).

The focus group participants stressed that these factors are not mutually exclusive. For example, high income can increase investments in education and health care, people with low income are more likely to rent their homes (Scottish Government, 2022), inequality can impact social cohesion (Section 3.3), and the quality of greenspace is negatively correlated with neighbourhoods deprivation (Baka & Mabon, 2020). Other factors mentioned by the focus group participants include immigration status, job type, and government and council budget, which have overlapping effects with the factors discussed above.

**4. Projections under the UK SSPs**

The narratives of the five UK-SSP scenarios are summarised in Figure 1 focusing on the changes that may affect the heat and cold adaptive capacities as discussed in Section 3 (Pedde et al, 2021). Details of narratives on the UK-SSP product webpage can be found at UK Climate Resilience Programme (n.d. ).

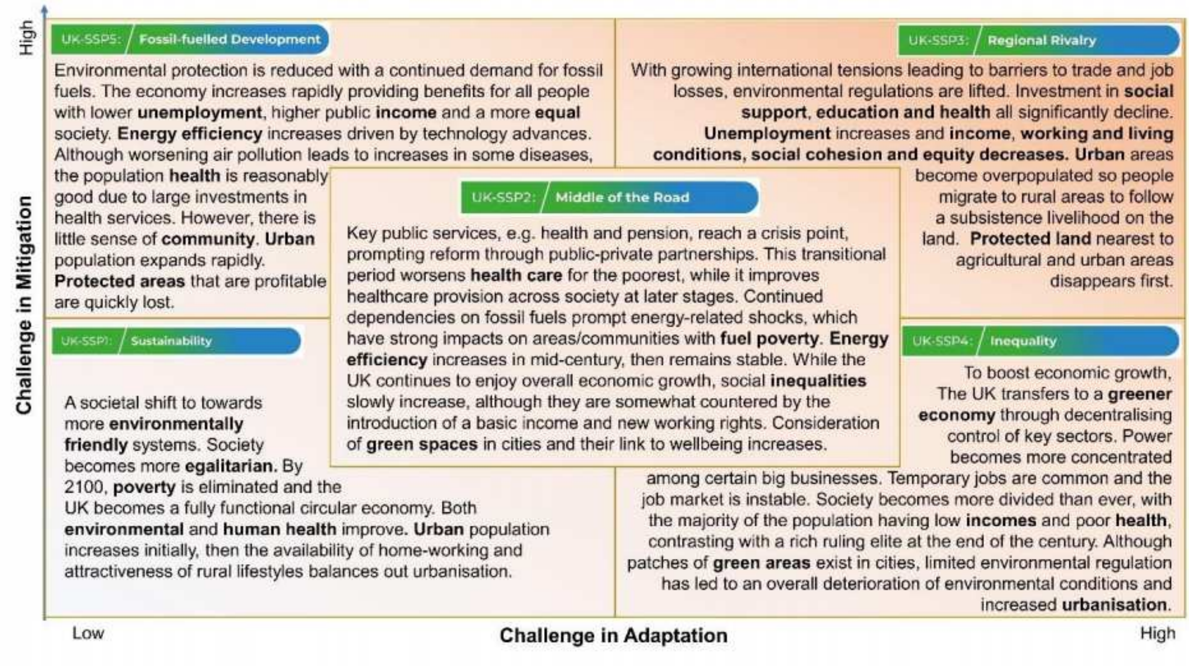


*Figure 1. UK-SSP narratives related to the adaptive capacities to heat and cold (UK Climate Resilience Programme, n.d.).*

Most of the focus group participants (four out of six) preferred the second method of projecting heat and cold adaptive capacities by constructing heat and cold adaptive capacity indices using indicators from the UK-SSP project (Section 2). Transparency was mentioned as the primary advantage of this method. However, one participant who preferred the first method by projecting the overall adaptive capacities based on the SSP narratives expressed that "I'm writing a paper at the moment about vulnerability indicators and becoming increasingly cynical of the actual worth and value. It's very easy to get fixated data on certain proxy indicators. The problem is when you choose certain proxy indicators to represent a large scale of different people and a large geographical scale and the diversity of people, you kind of end up making massive assumptions. (That's why I prefer) basing it on the narrative overall and being able to tailor it."

The second method is adopted for this study because it is preferred by most focus group participants for its transparency. Separate heat and cold adaptive indices are constructed (Section 2). Indicators and projection data for the key factors identified in Section 3 are identified and extracted from the UK-SSP project's output on semi-quantitative projections for 50 socio-economic variables(Section 2). Some factors have a negative effect, which is represented as a deduction sign. The heat and cold adaptive capacity indices are:

**Heat adaptive capacity** = average (income – income inequality + social cohesion + health care + public awareness – urban population + protected area)

**Cold adaptive capacity** = average (income – income inequality + social cohesion + health care + public awareness + energy efficiency)

Alternative indicators for the sensitivity analysis (Section 2) are shown in Table 1.

*Table 1. Sensitivity analysis of the choice of UK-SSP variables.*

| ID | UK-SSP variable in the main index | Alternative UK-SSP variable |
|---|---|---|
| 1 | Social cohesion | Social capital |
| 2 | Public awareness | Education investment |
| 3 | Health care | Human capital[1] |

*Note: 1. Human capital: the health, knowledge, skills and motivation of a country's population emotional and spiritual capacities (covering areas of education, job experience, skills and health). (Harrison et al, 2021)*

The indicators household income per capita and income inequality from the UK-SSP project are selected to represent economic status and inequality. There are two variables from the UK-SSP project that may represent social network and cohesion (Section 3.3)—social cohesion and social capital. These two terms are closely linked. Social cohesion describes the state of society concerning the interactions of the members "characterised by a set of attitudes and norms that include trust, a sense of belonging and the willingness to participate and help, as well as their behavioural manifestations" (Chan et al, 2006). Social capital is "the structures, institutions, networks and social relationships of a country's population that enable individuals to maintain and develop their human capital in partnership with others, and to be more productive when working together than in isolation", which is one of the key elements of social cohesion (Cloete, 2014). Therefore, social cohesion is selected as a component of the adaptive capacity indices in this study, and social capital is used in the sensitivity analysis. Adaptive behaviour is represented by the public awareness from the UK-SSP project, which indicates "the level of public awareness of health-related, environmental and sustainability issues" (Harrison et al, 2021).

The most relevant UK-SSP variable to greenspace is protected area. Granting protected status to certain areas can reveal the overall level of environmental protection and management, and communities may be given powers to protect locally important greenspaces (UK Government, 2011; Wheeler et al, 2015). Protected area and urban population are only used to composite the heat adaptive capacity and energy efficiency is only used as an indicator for the cold adaptive capacity due to the mixed effects of these factors (Section 3).

The calculated semi-quantitative projections of the heat and cold adaptive capacity indices are shown in Figure 2. The results show that the adaptive capacities to heat and cold are both projected to increase under SSP1. Under SSP2, the cold adaptive capacity increases slightly while heat adaptive capacity remains largely unchanged. Under SSP3 and SSP4, heat and cold adaptive capacities all decrease strongly. Under SSP5, the heat adaptive capacity decreases slightly whereas the cold adaptive capacity increases. It is also found that among all scenarios, heat adaptive capacity is generally lower than cold adaptive capacity under the same scenario (Figure 2). The sensitivity analysis result (the grey shade in Figure 2) shows that the projected heat and cold adaptive capacities remain robust when using alternative indicators. The drivers of the changes in the adaptive capacities will be discussed in the next section.

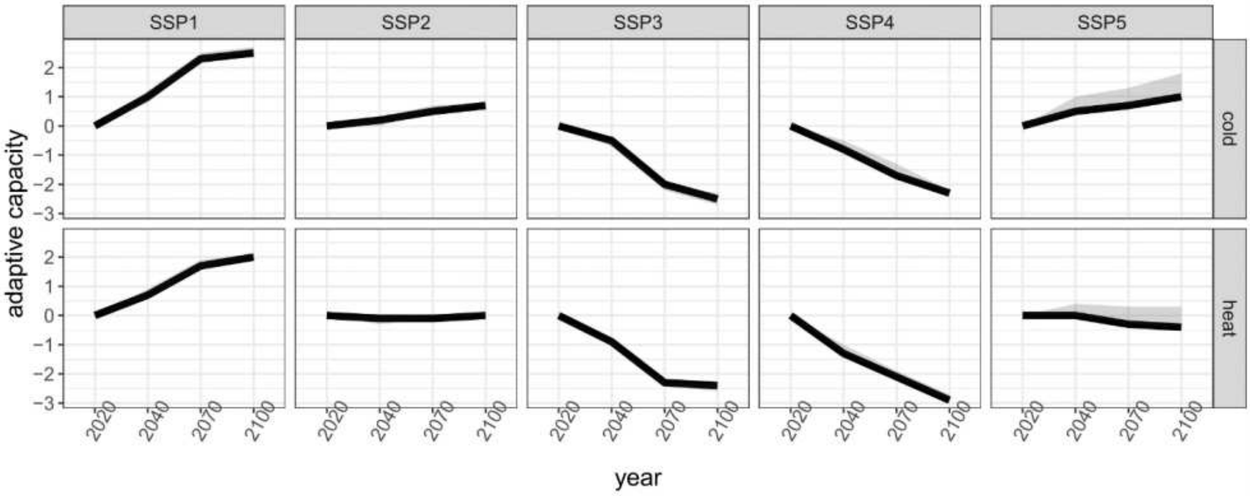


*Figure 2. Semi-quantitative projections of the heat and cold adaptive capacities. The solid lines shows results from the main indices, and the shading represents the range from the result of the sensitivity analyses.*

**5. Discussion**

Under SSP1, the UK shifts to a more egalitarian and sustainable society, accompanied by a huge decrease in income inequality, increases in social cohesion, health care availability and public awareness of health and the environment (UK Climate Resilience Programme, 2021a), which are the main factors driving the high adaptive capacities under SSP1 (Figure 2).

Under SSP2, the adaptive capacity to cold increases slightly and the adaptive capacity to heat remains unchanged. These small changes are likely due to the small changes and mix effects of different indicators. Under SSP2, although the economy grows slightly, inequality also increases because key public services such as the health sector reach a turning point of being privatised under this scenario, leading to a compromised healthcare service to the poor (UK Climate Resilience Programme, 2021b).

The adaptive capacities are projected to decrease strongly under both SSP3 and SSP4 (Figure 2). This is likely to be driven by the worsening of almost all indicators of the adaptive capacity indices under these two scenarios (Harrison et al, 2021). SSP3 has a slightly higher heat adaptive capacity than SSP4 (Figure 2), which may be because some people leave cities for the surrounding rural areas because urban is poorly planned and overcrowded under SSP3 which leads to a decrease in urban population (UK Climate Resilience Programme, 2021c). However, the indicator of the proportion of the urban population cannot capture all enhanced vulnerabilities of the urban population because urban management and conditions are also crucial (Section 3.6). Therefore, caution is needed when comparing the heat adaptive capacity between SSP3 and 4. Although almost all indicators are projected to worsen under SSP3 and SSP4, these are driven by different societal situations. The socio-economic and living situation declined for everyone due to a shift of public spending towards the defence sector under SSP3 (UK Climate Resilience Programme, 2021c). Under

SSP4, the decline is largely driven by extreme inequality between a few elite and a large body of poor (UK Climate Resilience Programme, 2021d).

Under SSP5, the economy increases rapidly for all with high availability of health care, high energy efficiency and very low inequalities, which are beneficial to an improved adaptive capacity (UK Climate Resilience Programme, 2021e). However, social cohesion decreases slightly due to individualistic lifestyles and poor public awareness of environment and health. Protected area, a proxy for the quantity and quality of greenspace, also decreases strongly because of weakened regulation on environmental protection, which counteracts some of the positive effects of economic growth (UK Climate Resilience Programme, 2021e).

The cold adaptive capacity is projected to be slightly higher than the heat adaptive capacity under all scenarios. This is determined by the difference between the indicators used to composite the two indices. The distinctive indicators for the heat adaptive capacity index are urban population and protected areas, with the former increasing in all scenarios and the latter decreasing markedly in SSP3, SSP4 and SSP5, which contributes to the increased challenge to heat adaptation (Harrison et al, 2021). In contrast, energy efficiency, the distinctive indicator for the adaptive capacity to cold generally increases apart from in SSP3 (Harrison et al, 2021).

There are several limitations of this study. Apart from the indicators selected, there are a variety of other factors that may affect the heat and cold adaptive capacities, which are not represented in the semi-quantitative projections of the adaptive capacities. However, as discussed in Section 3, these factors have overlapping effects and hence the overall effect can be largely reflected by the result. Different factors may have a different level of impact on the overall adaptive capacity, but for pragmatic reasons, an equal weight strategy is used to construct the adaptive capacities. One way of assigning the weights of indicators is expert elicitation (Lindley et al, 2011). However, it is often very challenging to obtain a consensus among experts and stakeholders due to the uncertainties of the different factors on the adaptive capacity (Lindley et al, 2011). Statistical techniques such as principal component analysis (PCA) have also been used to derive indicator weights (Wolf & McGregor, 2013). The suitability of using PCA to derive the weight is also controversial. On one hand, the method is useful to identify independent components among a large number of interrelated factors (Reckien, 2018). On the other hand, the meanings of the principal components generated are often difficult to interpret and the weight is often derived from the variance that is explained by the components, which do not necessarily represent their contribution to vulnerability or adaptive capacity (Reckien, 2018). Another limitation is that the semi-quantitative data provided by the UK-SSP project are UK-wide, whereas there might be variations across the nations, e.g. due to the devolution of policies such as climate change, health and energy efficiency to each nation. Although there are also uncertainties associated with the narratives and semi-quantitative projections of the UK-SSP variables, they are still very useful to explore the range of uncertainties from the change in future socio-economic conditions.

**6. Conclusion**

This study reviews and identifies key factors affecting the health-related adaptive capacities to heat and cold. Compound heat- and cold-health adaptive capacity indices are constructed based on these factors using indicators and data from the UK-SSP project, which are projected under the UK-SSPs up to 2100. The results show that both the heat and cold adaptive capacities are the highest under the SSP1, followed by the SSP2 and 5 due to mixed

effects of different indicators. The adaptive capacities are lowest in SSP3 and 4. The heat adaptive capacity is generally lower than the cold adaptive capacity under the same scenario, driven by the impact of increasing urban population on the challenges to the heat adaptive capacity and the increase in energy efficiency on the improvement of the cold adaptive capacity. The pattern of the adaptive capacity level under different scenarios largely corresponds to the level of challenge to adaptation represented by the SSPs.
The result can be further combined with temperature and population projections to project future heat/cold-related health burdens under consistent climate and socio-economic scenarios. The results are of potential use to the UK Government, and the health and climate change sectors in understanding and managing potential future health impacts of heat and cold.

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# Adopting Passivhaus Principles in Residential Buildings in the Extremely Hot and Dry Climate of Saudi Arabia

**Ebaa Khan[1], Steve Sharples[2], Haniyeh Mohammadpourkarbasi[2]**

[1]School of Architecture, University of Liverpool, United Kingdom, E.Khan2@liverpool.ac.uk;
[2]School of Architecture, University of Liverpool, United Kingdom

**Abstract:** Energy consumption per capita in Saudi Arabia is three times higher than the global average. The residential sector accounts for about 50% of the total national energy consumption. In 2016, Saudi Arabia established a new socio-political plan, Vision 2030, to diversify the economy and mitigate energy usage, particularly in residential buildings. This research assesses energy-efficient measures to help reduce energy consumption in Saudi residential buildings. The city of Makkah, with an extremely hot climate year round, is selected for the analysis. This research considers the feasibility of meeting a rigorous energy efficiency standards, Passivhaus, in Saudi Arabia. The emphasis was on improving the building envelope and using high-performance windows in an existing two-storey residential villa. This house type and occupancy level represent the most typical type in Makkah. The dynamic thermal simulation software DesignBuilder was used to compare the energy performance of the villa built to meet theSaudi Building Code (SBC) and built to meet Passivhaus standard requirements under the current and 2050 climate scenarios. Results indicate that meeting the Passivhaus standard for the building envelope can significantly reduce the cooling demand by 57%, and that the Passivhaus model was more effective than the SBC model in facing the challenges of future climate change.

**Keywords:** Cooling Energy, Saudi Building Code, Passivhaus retrofit, Climate Change

## 1. Introduction

Energy is an essential and indispensable element of human life, and when generated by non-renewable energy sources, such as fossil fuels, it causes global warming and, consequently, climate change. Hence, it is essential to reduce energy consumption. According to the United Nations Development Programme (2020), greenhouse gas emission levels are currently over 50% higher than 1990 levels. Furthermore, according to the US Energy Information Administration's (EIA) statistics (2015), the overall consumption of energy by the residential sector in the year 2015 was calculated at 7.823 trillion kWh. Therefore, the concept of green buildings for energy efficiency has emerged as a solution to help to reduce energy demands in the building sector, which is considered a key contributor to energy consumption and carbon emissions.

The main aim of this study was to find sustainable solutions that will help reduce energy consumption in residential buildings in the Kingdom of Saudi Arabia (KSA). The Passivhaus concept is considered, which will help to explore the possibility of achieving the objectives for the current climatic situation and future climate change projections. The expected results include reducing the risks associated with high energy consumption and carbon dioxide emissions.

## 1.1. The Trend of Climate Change in Saudi Arabia

The climate of Saudi Arabia has been defined as extremely hot and hyper-arid.The average summer temperature reaches around 45°C, while the average winter temperature ranges from 20-30 °C (Al-Ahmadi and Al-Ahmadi, 2013). Furthermore, the country is considered deficient in yearly rainfall (Meteoblue n.d). According to the 2018 Presidency of Meteorology and Environment (PME), Saudi Arabia's average temperature will rise by 0.72°C every decade, and the expected average warming in Saudi Arabia by 2041 will be higher than the global average. As shown in Figure 1, by 2050, temperatures are expected to rise by 2.0–2.75°C (Almazroui et al., 2012). As a result, the residential construction industry will face significant challenges in mitigating climate change.

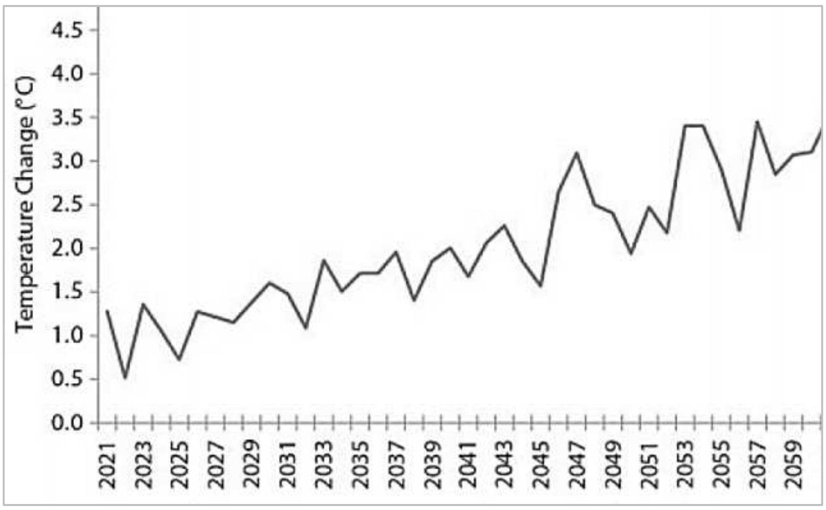


Figure 1. The annual outdoor mean air temperature of KSA changes from 2021 to 2059 (Almazroui et al., 2012).

## 1.2. The Saudi Arabia Energy Challenge and Government Response

Energy consumption per capita in Saudi Arabia is three times higher than the global average (SEEC, 2018). The residential sector is a significant contributor, accounting for about 50% of the total annual national energy consumption (SEEC, 2018). In 2016, Saudi Arabia established a new socio-political plan, entitled Vision 2030, to diversify the economy and mitigate energy usage, particularly in residential buildings. Saudi Arabia's Vision 2030 reforms call for pressure on the economy and the environment to improve energy consumption patterns (Abuhussain et al., 2019).

## 1.3. Saudi Building Code

In response to high energy consumption resulting from the fast-paced growth in the building sector, the government of KSA announced Royal Decree No.6927 in 2012 regarding building thermal insulation levels to improve their energy efficiency (Abuhussain et al., 2019). Furthermore, in 2013, the Saudi Standards, Metrology and Quality Organization distributed a new standard, known as standard No.2856/2014 Thermal Transmittance Values for Residential Buildings, based upon Saudi Building Code (SBC)-Chapter 602 (Energy Conservation Code, 2018). This standard (SBC) aimed to reduce the total electricity consumption by 30%–40% (Abuhussain et al., 2019) by controlling the maximum thermal transmission U-values for residential building envelope elements such as walls, roofs, and window glazing (Energy Conservation, 2018). The fabric U-value requirements are presented in Table 1. They proved to be useful and were made obligatory for all residential buildings in two stages (Code 1 and Code 2). Code 1 was applied to all residential buildings built after 2013, and then Code 2 was compulsory for all residential buildings built after January 2017. The code requires using insulation materials with low thermal conductivity, such as polystyrene and polyurethane, with a thickness of not less than 50 mm and a U-value of less than 0.25 W/m$^2$K for external walls and roofs. Additionally, the U-value of windows should not exceed 2.5 W/m$^2$K, with a solar heat gain coefficient (SHGC) of less than 50%. Moreover, the building should have an airtightness of better than 5.0 ac/h@50pa (Energy Conservation, 2018).

Table 1. U-values for Passivhaus standard and SBC

| **U-Value (W/m2K)** | **Passivhaus standard (Europe)** | **Passivhaus standard in hot zone** | **Saudi building code** |
|---|---|---|---|
| External Walls | 0.15 | 0.25 | 0.34 |
| Roofs | 0.15 | 0.25 | 0.20 |
| Windows | >0.80<br>SHGC->50% | 1.0-1.20<br>SHGC – 0.25 | 2.67<br>SHGC – 0.25 |
| Air tightness (@ 50 Pa) | < 0.6 | < 0.6 | 5.0 |

### 1.4. Passivhaus house in Hot Regions

The concept of the Passivhaus standard emerged during the 1990s as a response to the ongoing energy situation that began in the 1970s when the Yom Kippur War and the Iranian Revolution disrupted global oil supplies. The Passivhaus concept was developed by a Swede, Bo Adamson, and a German, Wolfgang Feist. The standard is generally used in Germany, Netherlands, Austria, and North America. The building technique for these houses is based on well-insulated and airtight building envelope (Tyler et al., 2019).

There are several rules upon which a Passivhaus building should be based, with the five most important being: thermal insulation, free from thermal bridges design, airtightness, mechanical ventilation with heat recovery, and efficient windows (Dalbem et al., 2016). Furthermore, the building's envelope must have a low thermal transmittance value (U-value) with the application of these rules (Dalbem et al., 2016). Overall, opaque building materials must be well insulated, with U-values not exceeding 0.15 W/m$^2$K. An airtight building will provide good ventilation and temperature while preventing humidity loss. The acceptable airtightness cannot exceed 0.6 ac/h@50pa (Passivhaus Institute, n.d). Furthermore, the entire window (including the frame) must have a U-value of 0.80 W/m$^2$K or less. In hot climates, higher U-values may be acceptable, and windows must have a U-value of no more than 0.85 W/m$^2$K. In the cold zone, total solar transmittance (SHGC) must be at least 50% for a net heat gain to be likely in the winter. However, In hot climates, a lower SHGC may be enough (iPHA, n.d.).

Studies have indicated how effective the Passivhaus standard reduces energy consumption - in cold areas by up to 90 percent (Passivhaus trust 2012). However, the same energy reductions may not be achieved in regions with warmer climates (Schnieders et al. 2019). In countries with very hot climates, such as those prevalent in the Middle East, there is still a lack of research about the applicability of the Passivhaus standard. It is also apparent that these principles cannot simply be applied without adapting them to the different meteorological conditions present in these hot climates. However, these regions might use various passive cooling strategies, such as evaporative cooling, which could save between 30 and 40 percent of energy (Lechner and Andrasik, 2021). However, passive cooling with direct natural ventilation cannot be employed in buildings that need to be airtight, such as those that follow the principles of the Passivhaus standard.

Therefore, the development and expansion of Passivhaus principles for use in hot and dry climates to achieve higher performance needs more study. This would involve a direct implementation that might not realise the same level of effectiveness as in cold climates (Passivhaus Institute, n.d). Nevertheless, case studies in arid climates demonstrate that the implementation of Passivhaus principles can significantly reduce energy consumption. Some relevant examples are the Desert Passive House in Hereford, Arizona (PHIUS, 2020) and Qatar's Passivhaus buildings (Khalfan, 2019). In addition, there is a passive office building in Dubai (the Space Centre) located in an extremely hot and humid weather area (Sifferlen, 2017). The results of these case studies in Qatar and the UAE have shown impressive proof of how implementing a well-made building meeting Passivhaus requirements can substantially decrease the cooling energy load, which is the most significant source of energy consumption in houses in hot and dry regions.

The Qatar Passivhaus building shows that, by applying all the Passivhaus standards and strategies, the project had a mission to achieve a 50% decrease in annual energy use, water usage, and $CO_2$ emissions compared with the standard villa (Khalfan, 2019). However, the project cannot achieve the required energy consumption levels in the Passivhaus standard due to the high cooling loads and the lack of airtightness in the building. (Khalfan, 2019). Qatar and the UAE have very similar climates to parts of Saudi Arabia. Therefore, all of the Passivhaus design approaches utilised in these examples can be applied to a building in Saudi Arabia. Other lessons that can be learned from these cases concern the effectiveness of wall, roof, and floor insulation materials. The Passivhaus standard for hot climate zones states that the U-value for opaque surfaces should be 0.25 W/m$^2$K, and for glazing surfaces it is 1.0-1.20 W/m$^2$K with an SHGC value of <50% and with an airtightness <0.6 ac/h@50pa (Khalfan, 2019). Table 1 compares the thermal U-values required by the Passivhaus standard and SBC.

## 2. Methodology

### 2.1. Case Study

Makkah, one of the most significant cities in Saudi Arabia, is also one of the hottest and driest cities in the world. The average temperature in Makkah is excessively high, with peak temperatures exceeding 45°C during summer and winter temperatures reaching 30°C on average (see Figure 2). This location has been selected for the evaluation of the Passivhaus principle. To assess the effectiveness of the envelope for residential buildings, an existing building (villa) was selected as a case study, which is shown in Figure 3. The building was constructed to meet SBC in 2021. Although the local authority approved the SBC for this building, it could not meet the minimum U-values required by the Saudi Energy Conservation Code, as shown in Table 1. The U-values were reviewed according to the construction materials profile, and Table 2 shows the thermal properties of the building.

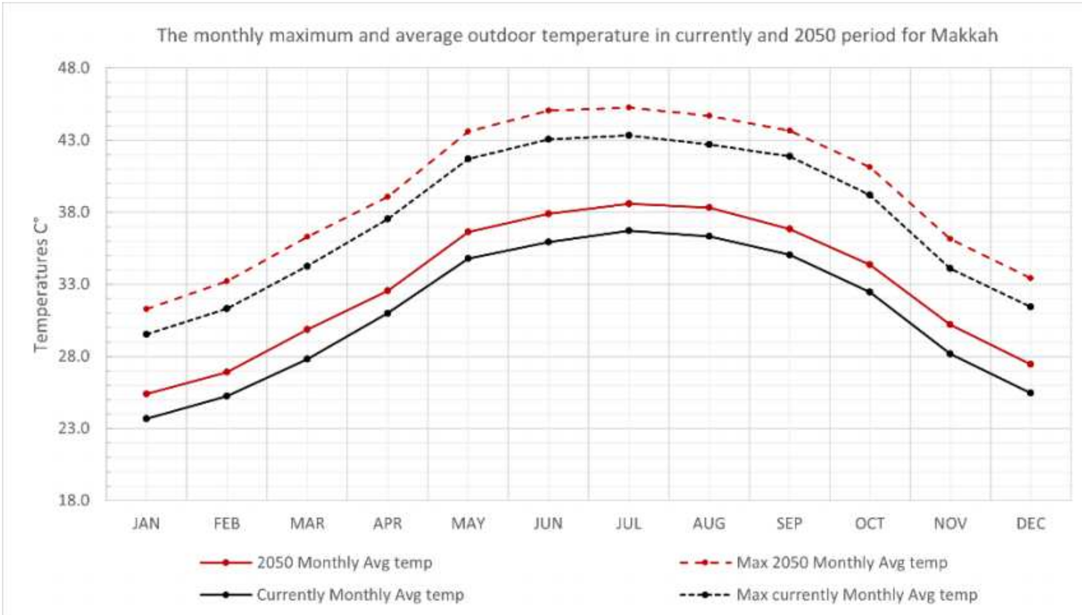

Figure 2. The monthly Max and Avg outdoor temperature over the current and 2050 period for Makkah

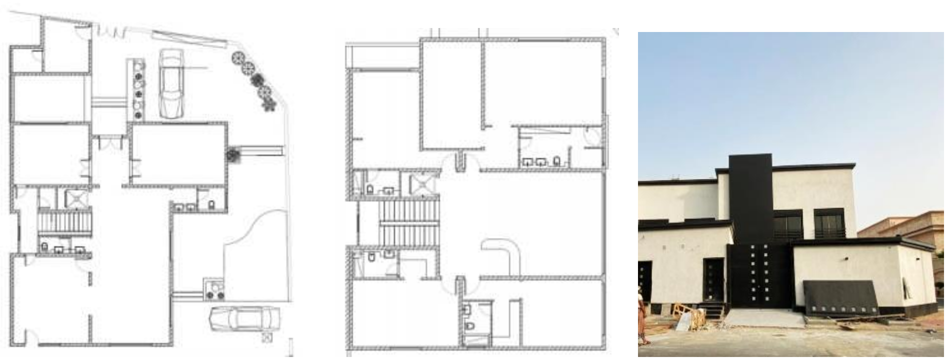
Figure 3. The SBC building under study

**Table 2.** Thermal properties of the SBC building

| Elements | Construction | U-Value (W/m²K) |
|---|---|---|
| Total area | 528.55 m² | |
| External walls | 0.02 m mortar + 0. 10 m concrete block + EPS Expanded Polystyrene 0.05 m + 0. 10 m concrete block + plaster 0.02 m | 0.478 |
| Roofs | Terrazzo .025 m + Mortar 0.25 m + Concrete, cast - foam slag 0.5 m+ EPS Expanded Polystyrene (Standard) 0.07 m + Bitumen layers 0.02 m + Reinforced Concrete 0.20 m. | 0.427 |
| Window glazing | 6mm/6mm Air gap double clear glazing | 3.157 / SHGC (0.7) |
| Occupancy | 0.0183 person/m2 | |
| Airtightness | 5.0 ac/h | |
| HVAC system | | Split no fresh air |

## 2.2. Modelling

The DesignBuilder simulation software was used as the primary method of investigation to assess the performance of the residential building envelope for SBC and non-SBC in the context of current and future climate change. Using DesignBuilder simulation software, three-dimensional models of the building were created based on the architectural drawings. Based on actual site visits and surveys, the building's thermal properties, such as construction materials, cooling system types, lighting, and appliances, of the existing villa were applied and modelled in DesignBuilder with appropriate occupancy schedules and activity profiles.

## 2.3. Models' calibration and simulations

Temperature and relative humidity data loggers (Rotronic HW4) were used to record the indoor temperature in each room in the SBC building, located at positions away from any direct heat sources. The monitoring process was carried out by distributing the devices inside the building to receive data from all orientations; North (Bedroom), East (Kitchen), South (Saloon), and West (Living room). In addition, a Kestrel 5700 data logger was fixed on the building roof to record the outdoor temperature. The device was sheltered from direct sun rays and rainfall. Figure 4 shows the equipment that was used for on-site measurements. The process of field measurements was divided into two periods. The first began in August 2021 and ended in November 2021, and the second started in December 2021 and ended in February 2022.


Figure 4. The measurement equipment used on site

Data collected during the monitoring were used for calibrating the DesignBuilder model. The average indoor operative temperature was determined by comparing the monitored indoor and outdoor temperatures at regular intervals of 15 minutes for a period of 7 days while the building was unoccupied, free running and not subjected to any additional electrical loads. In addition, the average indoor and outdoor temperatures were modelled and simulated using weather files obtained from the Meteonorm software and DesignBuilder. The calibration results showed that the difference in temperature between the simulated and measured temperatures was less than 4%. According to Taleb (2014), for a researcher to consider a model valid, the difference between simulated and measured results must be less than 5%. Royapoor and Roskilly (2015) propose that the ASHRAE 14 specification for the Mean Bias Error (MBE) to be +/-10% and Coefficient of Variation of the Root Mean Squared Error (CV_RMSE) be reduced from 30% to +/-5% and 20%, respectively when hourly annual data is available. This would bring the specifications in line with current industry standards. In situations where hourly data is not available, the ASHRAE 14 limits are a reasonable choice.

In addition, in order to guarantee the accuracy of the findings obtained from the annual simulation analysis, the setpoint temperature for the cooling system in the simulation models had been specified to be 25.5 ° C. This is stated in the Saudi Building Code 2017, Chapter 601: Energy Conservation. The Saudi building code stipulates two design temperatures for summer and winter in every climate and type of building, and for Makkah those temperatures are 25.5°C in the summer and 20°C in the winter (SBC, 2017). Moreover, the daily schedule of lighting, air conditioning, equipment, and occupant schedule was observed and obtained from previous monitoring and from the study by Monawar (2001), which depicts the behaviours of most Saudi Arabian residents inside buildings.

### 2.4. Meeting the Passivhaus requirement

This research aimed to find solutions that contribute to reducing the high cooling demand in the hot climate in Saudi Arabia. Consequently, the SBC model was developed and adjusted to meet the requirements of the Passivhaus standard U-values for the building envelope. In this case, U values were determined to be below the Passivhaus average for hot and dry climates and similar to the cold climate requirement to see if this helped decrease the thermal transfer for the building, effectively reducing cooling loads. A high-efficiency glass with a lower thermal U-value of 1.49 and a SHGC of 0.7 was applied. A higher level of airtightness than the SBC model, was modelled. To achieve a U-value of 0.15 or lower for the opaque surfaces, the thermal insulation thickness of the external walls and roofs in this model was increased to approximately three times that of the two models. See Table 3 for more details of the modelled building.

**Table 3.** Thermal properties of Passive model and SBC model U-Value

| Elements | Construction | U-Value (W/m$^2$K) | SBC U-Value (W/m$^2$K) |
|---|---|---|---|
| External walls | 0.02 m mortar + 0. 15 m block concreate + XPS Extruded Polystyrene 0.2 m + 0. 10 m block concreate + plaster 0.02 m | 0.15 | 0.478 |
| Roofs | Terrazzo .025 m + Mortar 0.25 m + Concrete, cast - foam slag 0.05 m + XPS Extruded Polystyrene 0.20 m + Bitumen layers 0.02 m + Concrete, Reinforced (with 2% steel) 0.20 m | 0.148 | 0.427 |
| Window glazing | Dbl Elec Ref Coloured 6mm/13mm Arg | 1.491 (SHGC 0.144) | 3.157 SHGC (0.7) |
| Occupancy | 0.0183 person/m$^2$ | | |
| Airtightness | 0.3 ac/h (estimated) | | 5.0 ac/h |

## 3. Results and discussion

Figure 5 shows the monthly cooling energy consumption for the SBC model under the current and the future climate 2050 scenarios. It can be seen that the monthly cooling loads with the SBC model under the current climate increase from 11.2 kWh/m$^2$ in January to a peak cooling load of 38.6 kWh/m$^2$ in August. With the 2050 scenario, the cooling load increases from 14.6 kWh/m$^2$ in January to 50.2 kWh/m$^2$ in August. This means the cooling load will be increased in the future 2050 scenario by around 30% in both winter and summer.

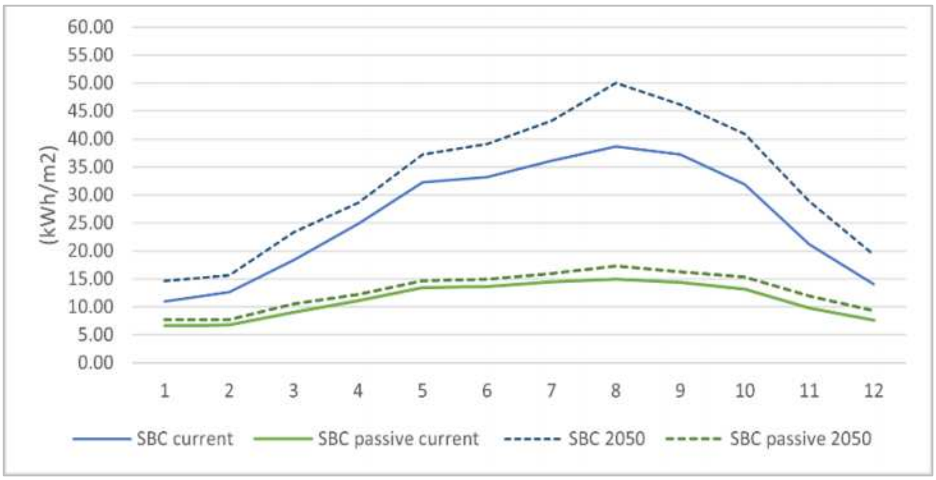


Figure 5. SBC Model Monthly Cooling Energy Consumption with retrofit to Passivhaus standard

Figure 5 also shows that the cooling load will be reduced by retrofitting the model to the Passivhaus standard. It can be clearly seen that the monthly cooling loads with the Passivhaus model under the current climate extend from 6.6 kWh/m$^2$ in January to a peak cooling load of 15.1 kWh/m$^2$ in August. With the 2050 scenario, the cooling load increases from 7.7 kWh/m$^2$ in January to 17.3 kWh/m$^2$ in August. The results shown in Figure 6 indicate that the cooling energy consumption reduces by around 56% annually after applying retrofitting measures. The total cooling loads will be 135.0 kWh/m$^2$ while the SBC model consume 311.4 kWh/m$^2$. Moreover, in 2050 scenario, the Passivhaus model's total consumption rises by 14% compared with the SBC model, which increases by 25%, an increase of approximately 75.9 kWh/m$^2$, while the total amount of cooling loads increases by about 19.0 kWh/m$^2$ with the Passivhaus model.

In addition, the simulation was rerun with shading activated. According to the findings, there was only a slight drop in Passivhaus model consumption, but that had no significant effect on the overall average. The Passivhaus model uses Double Electrochromic Reflective Coloured 6mm–13mm Arg glass. According to Aldawoud (2017), the energy performance of different types of glass varies. The results show that the Absorbent Double Electrochromic Coloured glass has the best energy performance of all the glazing systems examined, with the potential to save up to 60% when compared to single-glazed energy performance. Furthermore, glass with a gap width of 13 mm is preferable than glass with a gap width of 3 mm or 6 mm. Compared to the energy performance of a single glass, reflective low-E glass reduces energy transmission by 37% (Aldawoud, 2017). Moreover, Argon gas-filled glazing performs better than other types of gases, with a reduction potential of roughly 33%. Low solar heat gain coefficients and low U-value glass, according to Aldawoud (2017), are most effective in reducing the amount of heat entering the building. As a result, the shading has a small effect on the overall performance. On the other hand, the SBC model shows the reduced cooling demand in the annual total by more than 3000 kWh/$m^2$.

In general, meeting the Passivhaus standard requirements for the building envelope has significantly contributed to a reduction in the total amount of cooling required, as is clearly apparent compared to the current condition of the SBC building. The simulation results showed that the Passivhaus model was more effective than the SBC building for facing the challenges of climate change in the future. However, the retrofit model cannot meet the energy consumption requirement of the Passivhaus standard, which is 120 kWh/$m^2$ for total energy use, including domestic hot water, heating, cooling, auxiliary, and household electricity (International Passive House Association | The Difference, 2022). This suggests that more development of the building envelope needs to be investigated for further solutions to meet energy performance requirements.

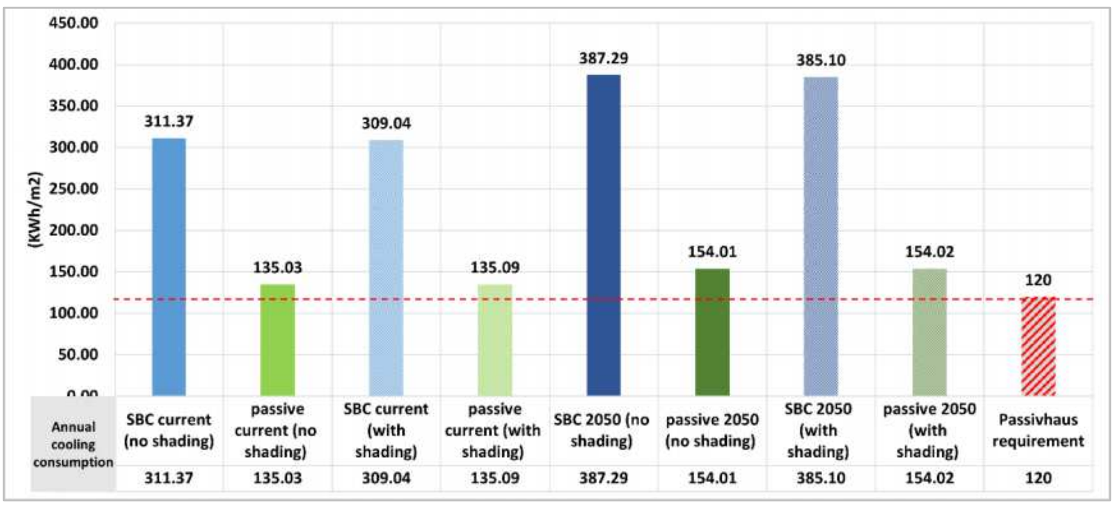

Figure 6. SBC Model's Annual Cooling Energy Consumption with Passivhaus standard retrofit

## 4. Conclusion

This study aimed to find a suitable solution for reducing energy consumption in the arid climates that characterise most Saudi regions. Studies have shown that climate change is an undisputed fact and results from the increase in greenhouse gas levels, which currently stand at 50% over those in 1990. Alongside many other countries, KSA is facing the challenges of climate change due to its high dependence on fossil fuels. KSA is considered the most significant fossil fuel consumer in the Middle East. The building sector is responsible for more than 50% of the total energy consumed in KSA, and cooling loads account for about 70% of this total energy consumption (Alshenaifi, 2015, p. 72). According to the Statistics Authority (2017), the population growth rate will rise by approximately 32% over the next 15 years. This means the country will face a serious problem due to increased energy demands by 2032 unless immediate, sustainable solutions are implemented (Abuhussain et al., 2019). Therefore, the KSA government aims to implement strategies to address increased energy usage and find potential solutions for sustainable and renewable sources of energy under the 2030 Vision. The SBC has been developed as a solution to reduce energy use in residential buildings. Although the SBC had the expectation of reducing energy consumption by up to 40%, it has not achieved the optimum level of reduction. Meanwhile, the Passivhaus standard has successfully reduced total building energy consumption by up to 80% in Europe. This study also aimed to investigate how the SBC performs under current climate conditions and in future climate change scenarios. The DesignBuilder software was used primarily as a simulation and investigation tool to evaluate the efficiency of the SBC for residential buildings. The findings indicate that the existing SBC model requirements will not be able to significantly resolve the impact of global warming in the future, as cooling is a major concern due to the harsh weather conditions in KSA.

The emphasis of this research was on developing a building envelope for the SBC model to meet the requirements of the Passivhaus standard by increasing the thermal insulation proportion for both external walls and roofs to achieve a U-value of <0.15 W/m²K. The type of glass used in building openings was also improved, considering the conditions needed to withstand warm and harsh climatic conditions; the type used has an SGHC of <0.5. By applying the Passivhaus requirements to the SBC model, a 57% reduction in the cooling demand was achieved. The total energy consumption of the Passivhaus model amounted to 135 kWh/m$^2$ per year, compared to 311.3 kWh/m$^2$ for the SBC model. The Passivhaus principles could, therefore, reduce the effects of potential climate change. However, an increase in demand for cooling energy due to climate change in the future was observed at around 14%. Also, more investigative and passive strategies that are not included in this study, such as shading devices, green roofs, and some architectural solutions, could help to reduce energy consumption further, in order to reduce the effects of future climate challenges and carbon dioxide emissions.

A limitation of this study is that it has focussed just on the envelope insulation and airtightness criteria set by SBC and Passivhaus. Other approaches to reducing enegy demand, such as the impact of increased thermal mass, or the use of natural ventilation instead of air conditioning for cooler periods of the year, have not been considered. Despite the potential of low energy natural ventilation, all recent buildings in Saudi Arabia are basically designed to be artificially cooled on a 24 hours a day, 7 day a week basis, to provide indoor thermal comfort (Alshaikh, 2016), which makes designing the building envelope to be thermally efficient all the more important.

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# Correlation model to evaluate two European climates' impacts on thermal comfort and indoor air quality in houses

**May Zune[1] and Maria Kolokotroni[1]**

[1] College of Engineering, Design and Physical Sciences, Brunel University London, UK.
Correspondence email: may.zune@brunel.ac.uk

**Abstract:** This study presents the development of a climate correlation model encompassing the impacts of diverse climatic parameters for the indoor conditions prediction concerning thermal comfort and indoor air quality (IAQ). We investigated the relationship between outdoor and indoor conditions in free-standing small houses, and compared the results of two contrasting European climates - Nordic and Mediterranean. The impacts of ventilation modes on the IAQ - infiltration and natural ventilation through window openings - were compared using a black-box model generated in the CONTAM and EnergyPlus simulation engines. The effects of ventilation and heating schedules, model size, and orientation for prevailing wind were tested considering factors that could statistically change correlation equations. The correlations between dry bulb temperature, operative temperature, temperature differences between indoor and outdoor, and airflow were analysed to identify significant patterns or trends between variables without controlling or manipulating any of them. The results were evaluated using adaptive thermal comfort equations and equations to estimate space-specific indoor $CO_2$ concentrations. The study informed the importance of user-driven decision-making processes for predicting the indoor conditions from outdoor climatic parameters which could encourage behavioural change for building operation to improve building thermal comfort and IAQ through natural ventilation strategies.

**Keywords:** Climate correlation; Indoor air quality; Adaptive thermal comfort; Indoor condition prediction; Residential building.

## 1 Introduction

Rethinking thermal comfort and indoor air quality (Nicol, J. Fergus & Roaf, 2017), adapting buildings and cities to changing climate conditions (Roaf et al., 2009), and learning to live in a smart home with behaviour change strategies (Hargreaves et al., 2017) have been dominant themes in the field of adaptive thermal comfort in building research in the most recent decade to date. Empirical research in the field of adaptive thermal comfort in buildings has been documented across the globe for different climates (Jeong et al., 2022)(Nicol, Fergus & Humphreys, 2010)(Humphreys et al., 2007)(DeDear & Brager, 1998) observing warming climates in various buildings. Despite abundant evidence that the external climates affect indoor building comfort, indoor air quality (IAQ) and health (Institute of Medicine, 2011), the relationships between outdoor climatic variables and indoor building parameters are less clear although weather and seasons exert a pervasive influence on building occupants' behavioural adaptations to the thermal environment (Bluyssen, 2009). Ambient temperature and outdoor pollutants are contributors to IAQ (Schenck et al., 2010); however, the implications of outdoor climatic parameters in the prediction of indoor conditions are still not well investigated. Furthermore, the correlation model of a specific outdoor climate and its related indoor condition needs to be investigated explicitly considering the context of different climates. This work, therefore, aims to contribute to the development of the indoor-outdoor correlation studies for residential settings carried out in the two different European climates: Nordic and Mediterranean climates.

A recent comprehensive impact assessment for European residential building stocks reports that the outdoor climates cause differences in energy demand and variation in thermal comfort between zones and cities while there will be larger needs for cooling demands and less heating demand in the future (Yang et al., 2021). Whilst the relationship between the outdoor climates and building energy consumption for heating and cooling is notably linked, the rise of outdoor temperature does not directly affect the indoor air carbon dioxide ($CO_2$) concentration, which is often used as an indicator of the IAQ and one of the main drivers for ventilation requirements. On the other hand, increasing building airtightness to reduce energy demand and control indoor temperature asks the building designers to consider the acceptable IAQ and $CO_2$ concentration in a building due to the dependency on mechanical ventilation for IAQ in those airtight buildings (McGill et al., 2017). The rate of indoor $CO_2$ concentration depends on a number of parameters: (i) ambient concentration and outdoor weather (ii) its generation source (e.g., number of occupants and their respiratory rate), (iii) ventilation rate and efficiency (air change via mechanical or natural ventilation), (iv) source control via the ventilation system, maintenance, air cleaning and activity control, and (v) building factors (building form and window design) (Iwashita & Akasaka, 1997) (Bluyssen, 2009) (Dimitroulopoulou et al., 2005). Hence, the indoor environmental factors, parameters, control and their relation to a residential setting are essential to consider in the development of indoor-outdoor correlation studies.

Two contrasting locations were selected in the present study to investigate the relationships between outdoor climate and indoor building parameters in developing the climate correlation models. The Nordic climate of Ry in Denmark represents the oceanic, temperate climate with full humid and warm summer while the Mediterranean climate of Athens in Greece represents the subtropical climate with dry and hot summer [Figure 1].

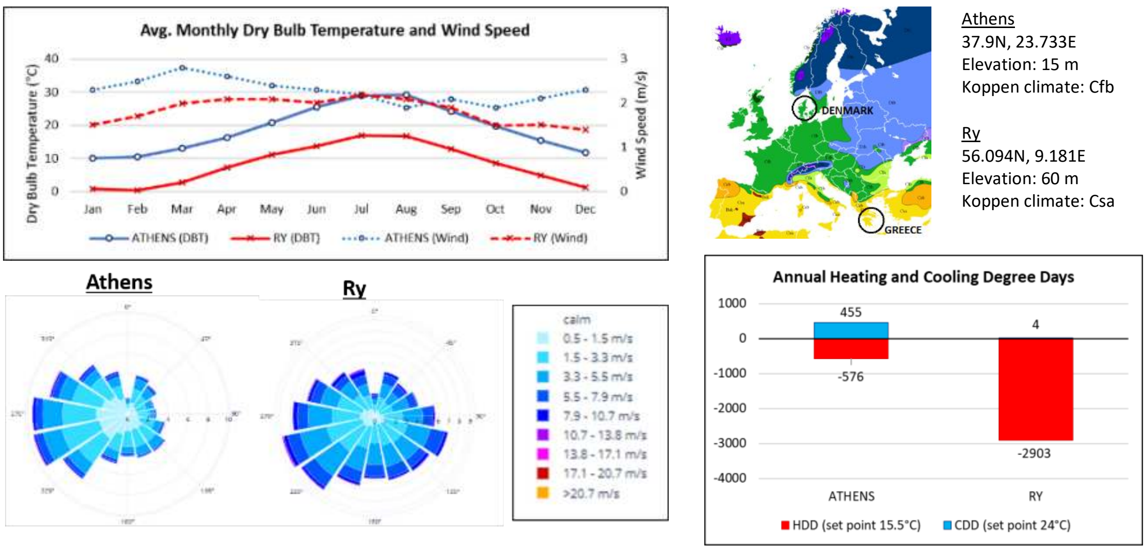


Figure 1. Characteristic of Athens and Ry climates

The typical weather file of Ry and Athens (Meteotest, 2020), which spanned from 2000 to 2010, showed that Ry had 2903 hours of heating degree days (HDD) while Athens had 576 hours of HDD and 455 hours of cooling degree days (CDD) due to higher outdoor dry bulb temperatures (DBT) found in Athens [Figure 1]. The values of monthly temperature profiles caused different results of HDD and CDD significantly in the two climates as monthly average DBT of Ry was below 20°C while Athens was approximately above 20°C. The comparison of typical weather years for two climates showed dominant south-west wind directions with higher wind speeds (WS) in Athens throughout the year, whereas lower WS and different wind directions were found in Ry.

Considering differences in outdoor climatic parameters, the following sections attempt to present how the building occupants from two contrasting climates can adjust their building thermal comfort and IAQ by means of window opening for natural ventilation which can be informed by the climate correlation model coupled with the weather forecast for the next day's temperatures and wind speed.

## 2 Method

The indoor-outdoor correlation model was developed from simulation experiments, correlation studies, and evaluation methods. The simulation experiments were generated from EnergyPlus (DesignBuilder, 2021) (United States Department of Energy, 2001) and CONTAM (NIST, 2012) programs. The correlation studies were developed by investigating the relationships between the climatic parameters and indoor condition parameters using scatter plots to generate linear and polynomial correlation equations. The results of simulation studies were evaluated using adaptive thermal comfort equations, single-zone mass balance equations and equations to estimate space-specific $CO_2$ concentrations. Whilst the comparative study can be informed in predicting the ventilation rate and indoor operative temperature ($T_{OT}$) according to their outdoor climates and indoor building parameters, the implementation of the correlation model for respective scenarios and climates could be different in the decision-making process due to the demand for heating and cooling due to the exposure to the ambient of the external elements and ventilation due to the location of the house in an exposed or urban site. Therefore, this study further discussed why the occupants need to understand the impacts of outdoor temperatures and prevailing wind directions, and how they can adjust their indoor environment using natural ventilation through window openings and heating schedules (supported by findings of the PRELUDE project (Prelude, 2022)).

### 2.1 Simulation models

A box-shaped model with a squared plan of 6m x 6m x 3m was introduced into both studied locations to observe the impact of outdoor climatic parameters on the indoor environment. Single-sided ventilation was considered through the use of a window, which had a 1.2m x 3m (3.6 $m^2$) area, and 20% of the window glazing area was considered for the openable area. A small window with 0.5m x 0.3m (0.15 $m^2$) was then introduced to compare the results of single-sided and cross-ventilations. The internal floor area and air volume of the two models were different due to their locally defined construction for thermal resistance (U-values), however, the model was close enough to the occupant density for a residential apartment which is defined as about 28.3 $m^2$/person (BS EN 16798-1, 2019). The internal room area and internal volume of the models were defined the same in both simulation engines for each location; however, the internal geometry sizes were different between Athens and Ry due to the thickness defined for the building envelope. Fixing the internal measurements across all models could be an option; however, each location might have different requirements for occupancy density. Furthermore, adding interior insulation is often assumed to be a cost-effective retrofit action despite it could reduce usable space. Hence, the external measurement of the models was fixed for both locations considering the ease of modelling processes which affect the number of simulations used in this study. Figure 2 and Table 1 present the illustration and construction of simulation models. The same typical weather files

(Meteotest, 2020), which were used in the climate study [Figure 1], were used for both simulation engines.

**EnergyPlus simulation model** **CONTAM simulation model**

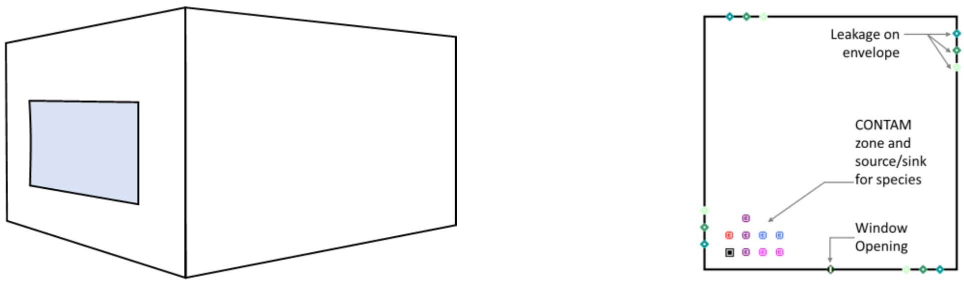


Figure 2. Illustration of the simulation model with single-sided ventilation from a window

Table 1. Construction and their thermal resistances (U-values) used in simulation models

| Type | | Construction used in EnergyPlus simulation model | U-values | Internal size |
|---|---|---|---|---|
| Athens | Roof | Concrete roof with insulation, cement plaster and render | 0.647 | Internal floor area = 30.9 m$^2$, Internal air volume = 85.9 m$^3$ |
| | Wall | Perforated block wall with cement plaster and render | 1.960 | |
| | Floor | Concrete floor with screed and tile above gravel-based soil | 0.735 | |
| | Window | Glazing with SHGC = 0.704 | 2.552 | |
| Ry | Roof | Roofing cardboard with insulation and plasterboard ceiling | 0.090 | Internal floor area = 26.4 m$^2$, Internal air volume = 64.9 m$^3$. |
| | Wall | Brick and aerated concrete wall with insulation and render | 0.150 | |
| | Floor | Concrete floor with screed and tile above gravel-based soil | 0.085 | |
| | Window | Glazing with SHGC = 0.462 | 0.541 | |

The envelope airtightness values in the EnergyPlus were assumed based on the discharge coefficient, flow exponent, and pressure differences in leakage and openings. Regarding the infiltration, following the CONTAM case studies that were prepared for the National Institute of Standards and Technology (NIST), the stack effect was captured in the CONTAM by dividing exterior wall leakage into three portions, representing the lower third, middle third, and upper third of each wall (Ng et al., 2012). The heating and cooling setpoints, ventilation setpoint for window opening, outdoor $CO_2$ concentration, and internal gains values, which are shown in Table 2 were assigned to all EnergyPlus simulation models to calculate the combined heat and mass transfer process between outdoor and indoor environments. While the prevailing mean outdoor temperatures are acceptable range, the value of the ventilation setpoint which affects the ventilative cooling comfort zone could be adjusted for summer and winter comfort zones (Emmerich et al., 2001) (ASHRAE, 2021); however, the ventilation setpoint was fixed at 22°C of $T_{OT}$ in this study. The schedule for occupant presence and the operation time for equipment were defined in the simulations using hourly fractions from 0 to 1; 1 represents the schedule is fully operated for the whole one hour (BS EN 16798-1, 2019).

In addition to the schedule defined for the residential setting in the BS EN 16798-1, the time profiles of heating and window opening hours were considered following the pre-defined scenarios. Hourly internal temperatures of the defined zone were considered in the CONTAM simulation, based on the results of the EnergyPlus simulation. Both EnergyPlus and CONTAM IAQ simulations for Athens and Ry were run to investigate the indoor $CO_2$

concentrations generated from occupancy metabolic rates using hourly time steps for interaction between thermal zones and the environment; the results were set to generate for the whole year in the EnergyPlus models and selected winter and summer days in the CONTAM models.

Table 2. Simulation input data used in EnergyPlus simulations

| Simulation Parameters | Values | References |
|---|---|---|
| Heating setpoint | 20°C (for Category II); Heating control by schedule | (BS EN 16798-1, 2019) |
| Cooling setpoint | 28°C (for Category II); No cooling application | (BS EN 16798-1, 2019) |
| Ventilation setpoint for adaptive comfort | 22°C | (ANSI/ASHRAE Standard 55-2013, 2013) |
| Outdoor ambient $CO_2$ concentration | 400 ppm | |
| Metabolic - Activity | Metabolic rate 130W (approximately 1.2 met) per person | (ASHRAE, 2021) |
| $CO_2$ generation rate | 0.005 L/s per person | (ASHRAE, 2021) |
| Internal gain | 3 W/m$^2$ for power density residential, apartment | (BS EN 16798-1, 2019) Annex C. |

Table 3. Simulation scenario used in this study

| Scenario | Description | Heating and ventilation |
|---|---|---|
| #1S | Infiltration only (no window ventilation) | Continuous heating |
| #3S | A window can open (South Facing Window) | Heating from 06:00 to 09:00, 10:00 to 17:00, and 18:00 to 23:00; Window open from 09:00 to 10:00 and 17:00 to 18:00, no temperature limit |
| #3N | A window can open (North Facing Window) | |
| #3E | A window can open (East Facing Window) | |
| #3W | A window can open (West Facing Window) | |
| #3C-NS | Two windows can open (North / South Windows) | |
| #3C-EW | Two windows can open (East / West Windows) | |
| #4S-V60* | Larger window (Openable Window Area = 60% of Area) | |
| #4S-1HR | Window open 1 hr (Window opening: 09:00-10:00am) | Heating from 6:00 to 09:00, 10:00 to 23:00 |
| * 20% of window openable areas for other scenarios. | | |

The first group represents a base scenario without natural ventilation, therfore, ventilation was applied only from infiltration for air change as windows were closed, and heating was operated continuously at a set point of 20°C throughout the year. In the second group, a scenario with summer ventilation was considered; however, this scenario was excluded due to the weak correlation results. In the third group, ventilation was applied for two hours by the opening window without temperature limits. During window opening hours, the heating was turned off despite the lower outdoor temperature at that time, and the heating was operated again when the window was closed. The effects of orientations, which could impact wind direction and solar hour, were tested from four cardinal directions by placing a window for single-sided ventilation. In addition, cross ventilation was introduced by adding a small window. For instance, by adding a small window on the north side, a scenario with the south-facing window was changed to a north-south ventilation scenario with cross-ventilation mode. In the fourth group, additional variants were considered using the same schedules as the third group. The differences between the third and fourth groups of simulation scenarios were openable window area and window opening hour. In the CONTAM models, the scenarios presented in the third group were tested to align with the EnergyPlus simulation studies.

## 2.2 Correlation and evaluation studies

We evaluated the internal operative temperature using the adaptive thermal comfort equations, and the derived correlations because the models used in this study were naturally ventilated. The adaptive thermal comfort model gives a range of operative temperatures that a person would be comfortable with for a given external temperature. If the temperature is the spread of the values within the lower and upper limits of adaptive thermal comfort temperatures, the predicted operative temperature from the correlation equation can be considered an acceptable result for indoor building thermal comfort at that condition. The equations to be used for the calculation of the operative temperature from the correlations with ambient temperatures are as follows (BS EN 16798-1, 2019):

$$\Theta_c = \mathbf{0.33}\Theta_{rm} + \mathbf{18.8} \quad \text{Equation 1}$$

$$\Theta_{rm} = \frac{\Theta_{ed-1} + \mathbf{0.8}\Theta_{ed-2} + \mathbf{0.6}\Theta_{id-3} + \mathbf{0.5}\Theta_{ed-4} + \mathbf{0.4}\Theta_{ed-5} + \mathbf{0.3}\Theta_{ed-6} + \mathbf{0.2}\Theta_{ed-7}}{\mathbf{3.8}} \quad \text{Equation 2}$$

Where,

| | | |
|---|---|---|
| $\Theta_c$ | = | Optimal operative temperature |
| $\Theta_{rm}$ | = | The exponentially weighted running mean of the daily mean outdoor air temperature |
| $\Theta_{(ed-1)}$ | = | External outdoor air temperature of the day before. |

The single-zone mass balance equations which give the relationship between ventilation rate and wind/temperature differences can be described as follows:

$$\boldsymbol{Q} = \boldsymbol{C_d A}\left[\frac{2}{\rho}\Delta \boldsymbol{p}\right]^{\frac{1}{2}} \quad \text{Equation 3}$$

$$\boldsymbol{p_s} = -\boldsymbol{\rho_o g 273}(\boldsymbol{h_2} - \boldsymbol{h_1})\left[\frac{1}{\theta_e} - \frac{1}{\theta_i}\right] \quad \text{Equation 4}$$

$$\boldsymbol{p_w} = \frac{\rho}{2}\boldsymbol{C_p v^2} \quad \text{Equation 5}$$

Where,

| | | |
|---|---|---|
| Q | = | Ventilation rate or airflow rate ($m^3/s$) |
| Cd | = | Discharge coefficient |
| ρ | = | Air density ($kg/m^3$) |
| Δp | = | The pressure difference across the opening (Pa) |
| A | = | Area of opening ($m^2$) |
| $P_s$ | = | Static pressure (Pa) due to temperature difference |
| g | = | Acceleration due to gravity ($m/s^2$) |
| h | = | Height above datum (ground) (m) |
| $\rho_o$ | = | Air density at absolute zero temperature ($kg/m^3$) |
| $\theta_e$ | = | The absolute temperature of the outdoor air (K) |
| $\theta_i$ | = | The absolute temperature of the indoor air (K) |
| $p_w$ | = | Wind-induced pressure (Pa) |
| $C_p$ | = | Wind pressure coefficient |
| v | = | Wind speed at a datum level (usually building height) (m/s). |

After the airflow rate was obtained from equation 3 and the predicted airflow rate was known, we calculated the pollutant concentrations using the well-known Pettenkofer-Seidel equation which has been adapted for many applications including buildings to predict species concentration from known emission and ventilation rates (Persily & Polidoro, 2019). The space-specific indoor $CO_2$ concentration can be calculated using the equations for a steady-state (Persily & Polidoro, 2019):

$$C_{(t)} = C_{(0)}\, e^{-\frac{q_v}{V_r} t} + Css\left(1 - e^{-\frac{q_v}{V_r} t}\right) \quad \text{Equation 6}$$

$$Css = C_{out} + \frac{G}{q_v} \quad \text{Equation 7}$$

Where,

| | | |
|---|---|---|
| $C_{(t)}$ | = | the concentration in the room at time t in mg $m^{-3}$ |
| $C_{(0)}$ | = | the indoor concentration at time 0 in mg $m^{-3}$ |
| $q_v$ | = | the volume flow rate of supply air in $m^3\ s^{-1}$ |
| V | = | the volume of air in the room in $m^3$ |
| t | = | the time in s |
| $C_{(out)}$ | = | the outdoor concentration |
| G | = | the mass flow rate of emission in the room in mg $s^{-1}$ |

## 3 Results

The results of indoor-outdoor correlation models for Athens and Ry were presented in two sections: correlation and evaluation.

### 3.1 Correlation studies

An example of the derived correlations is presented in Figure 3 and Tables 4 and 5 with the coefficient of determination ($R^2$), which is a statistical measurement that examines the close relationships between two correlated variables. The scatter plots, which display the relationship between two variables: outdoor climatic parameters (variable appears on the horizontal axis) and indoor thermal and IAQ-related parameters (variable appears on the vertical axis), present the results in linear and polynomial correlation equations. Correlating two variables based on hourly time step data could be varied by the compound effects of outdoor climate and indoor activities. If the correlation time was separated into two contrast conditions - naturally ventilated condition (by opening windows, NV time) and window closed condition (no NV time) - strong correlations were observed by temperature-pressure and wind-pressure differences.

It was observed that the ventilation rate depends on the area of the opening and the pressure difference across this opening. The temperature-pressure difference is dependent on the height difference between two openings and the inverse of the temperature difference outside and inside the models ($I_T$). The wind pressure difference depends on the wind pressure coefficient (which depends on the wind direction) and the WS. The parameters of these equations were explored as correlation parameters and it was found that the WS gives a strong correlation when windows were closed, while the $I_T$ gives strong correlations when windows were open in both models. There were no direct relationships between indoor $CO_2$ concentration and outdoor climate because the $CO_2$ concentration is dependent on the compound values of the occupancy and airflow. Although the heating energy requirements were varied by the outdoor climates, there was a weak correlation between zone hourly heating rate, DBT, and WS. After a series of comparisons using correlation scatter plots, DBT and WS parameters were then selected as the main outdoor climatic parameters as climate KPI for the correlation studies. The $T_{OT}$, $I_T$ and airflow from the indoor condition were selected as indoor condition parameters for further analysis and evaluation studies presented below.

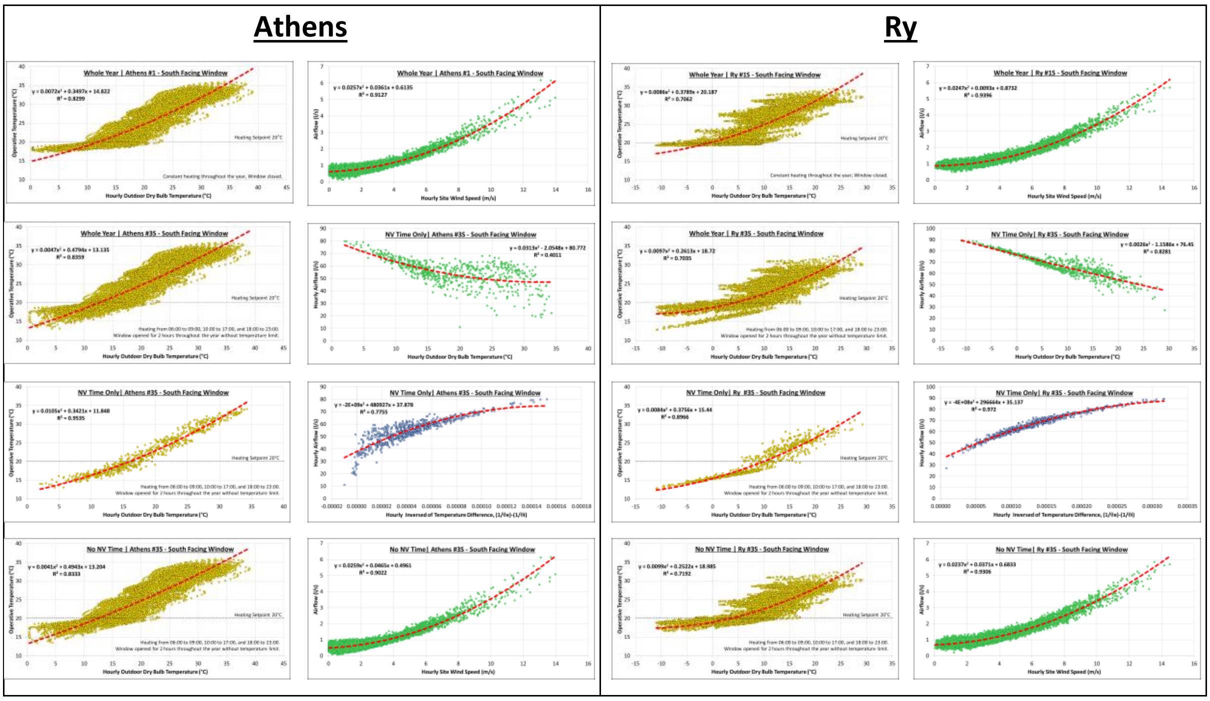


Figure 3. Correlations of Athens and Ry with selected KPI for outdoor climates and indoor condition parameters

Figure 3 presents the scenarios with infiltration only (window close continuously) and single-sided natural ventilation by opening a south-facing window for 2 hours. When the window was closed continuously throughout the year, the hourly temperature data results on scatter plots were varied by pressure differences on envelopes; annual temperature correlations of $R^2$ values were found as 0.83 in Athens and 0.71 in Ry. When the window was opened for 2 hours daily, the hourly temperature data results on scatter plots were varied by wind-driven ventilation; annual temperature correlations of $R^2$ values were then found as 0.95 in Athens and 0.89 in Ry when natural ventilation was allowed. Therefore, a strong correlation between DBT and $T_{OT}$ was found in the model with less fabric efficiency for building envelopes used in the Mediterranean climate.

When the window was closed continuously throughout the year, the $R^2$ values of annual correlations between WS and model airflow were found as 0.91 in Athens and 0.94 in Ry. When the window was opened for 2 hours daily, the $R^2$ values of correlations of WS and model airflow were found as 0.4 for Athens and 0.83 for Ry; the $R^2$ values of the $I_T$ and model airflow were also found as 0.77 for Athens and 0.97 for Ry. Therefore, strong correlations between WS, $I_T$ and model airflow were found in the model with high fabric efficiency for building envelopes used in the Nordic climate. A comparison of Athens and Ry models for all other scenarios also showed similar correlation patterns of scatter plots with slightly different values in their $R^2$ values; the outcome variable 'y' of the indoor condition values will be therefore different when the same predictor variable from the outdoor climate was used in the equations of Tables 4 and 5.

Table 4. Thermal and IAQ correlations for the Athens studies

| Athens PRELUDE pilot | Parameters | | Coefficient of determination ($R^2$) | | | Correlation Equation for Thermal Comfort and Ventilation | | |
|---|---|---|---|---|---|---|---|---|
| | Outdoor | Indoor | Annual | NV time Only | No-NV time | Annual | NV time Only | No-NV time |
| **Infiltration only (Sc 1)** | Dry Bulb Temperature | Operative Temperature | 0.8299 | n/a | n/a | $y = 0.0072x^2 + 0.3497x + 14.822$ | n/a | n/a |
| | Wind Speed | Airflow (L/s) | 0.9127 | | | $y = 0.0257x^2 + 0.0361x + 0.6135$ | | |
| | Inversed of Temp. Diff. | Airflow (L/s) | 0.0036 | | | $y = 744.34x + 0.8976$ | | |
| **Window can open (Sc 3)** | Dry Bulb Temperature | Operative Temperature | 0.8359 | 0.9535 | 0.8333 | $y = 0.0047x^2 + 0.4794x + 13.135$ | $y = 0.0105x^2 + 0.3421x + 11.848$ | $y = 0.0041x^2 + 0.4943x + 13.204$ |
| (South Facing Window) | Wind Speed | Airflow (L/s) | n/a | n/a | 0.9022 | n/a | n/a | $y = 0.0259x^2 + 0.0465x + 0.4961$ |
| | Inversed of Temp. Diff. | Airflow (L/s) | n/a | 0.7755 | n/a | n/a | $y = -2E+09x^2 + 480927x + 37.878$ | n/a |
| **Window can open (Sc 3)** | Dry Bulb Temperature | Operative Temperature | 0.8196 | 0.9528 | 0.8161 | $y = 0.0054x^2 + 0.4457x + 13.088$ | $y = 0.0129x^2 + 0.2711x + 11.878$ | $y = 0.0048x^2 + 0.4594x + 13.18$ |
| (North Facing Window) | Wind Speed | Airflow (L/s) | n/a | n/a | 0.8816 | n/a | n/a | $y = 0.0259x^2 + 0.0487x + 0.4859$ |
| | Inversed of Temp. Diff. | Airflow (L/s) | n/a | 0.7542 | n/a | n/a | $y = -2E+09x^2 + 512393x + 37.177$ | n/a |
| **Window can open (Sc 3)** | Dry Bulb Temperature | Operative Temperature | 0.8249 | 0.9336 | 0.8214 | $y = 0.0055x^2 + 0.4781x + 12.889$ | $y = 0.0105x^2 + 0.3774x + 11.323$ | $y = 0.005x^2 + 0.49x + 12.979$ |
| (East Facing Window) | Wind Speed | Airflow (L/s) | n/a | n/a | 0.8959 | n/a | n/a | $y = 0.0256x^2 + 0.051x + 0.5001$ |
| | Inversed of Temp. Diff. | Airflow (L/s) | n/a | 0.7957 | n/a | n/a | $y = -2E+09x^2 + 559628x + 35.734$ | n/a |
| **Window can open (Sc 3)** | Dry Bulb Temperature | Operative Temperature | 0.8257 | 0.9548 | 0.8208 | $y = 0.0058x^2 + 0.4673x + 12.954$ | $y = 0.0098x^2 + 0.4014x + 11.003$ | $y = 0.0053x^2 + 0.4791x + 13.054$ |
| (West Facing Window) | Wind Speed | Airflow (L/s) | n/a | n/a | 0.9046 | n/a | n/a | $y = 0.0285x^2 + 0.0459x + 0.4984$ |
| | Inversed of Temp. Diff. | Airflow (L/s) | n/a | 0.7606 | n/a | n/a | $y = -2E+09x^2 + 476126x + 38.358$ | n/a |
| **Two windows can open (Sc 3)** | Dry Bulb Temperature | Operative Temperature | 0.8204 | 0.9533 | 0.8170 | $y = 0.0054x^2 + 0.4465x + 13.081$ | $y = 0.0126x^2 + 0.2822x + 11.769$ | $y = 0.0048x^2 + 0.4601x + 13.176$ |
| (North / South Windows) | Wind Speed | Airflow (L/s) | n/a | n/a | 0.8826 | n/a | n/a | $y = 0.0263x^2 + 0.0501x + 0.4876$ |
| | Inversed of Temp. Diff. | Airflow (L/s) | n/a | 0.7011 | n/a | n/a | $y = -2E+09x^2 + 522024x + 40.08$ | n/a |
| **Two windows can open (Sc 3)** | Dry Bulb Temperature | Operative Temperature | 0.8255 | 0.9345 | 0.8221 | $y = 0.0055x^2 + 0.4783x + 12.882$ | $y = 0.0105x^2 + 0.3796x + 11.274$ | $y = 0.005x^2 + 0.4902x + 12.975$ |
| (East / West Windows) | Wind Speed | Airflow (L/s) | n/a | n/a | 0.8988 | n/a | n/a | $y = 0.0264x^2 + 0.0519x + 0.5022$ |
| | Inversed of Temp. Diff. | Airflow (L/s) | n/a | 0.7040 | n/a | n/a | $y = -2E+09x^2 + 510869x + 40.652$ | n/a |
| **Larger window (Sc 4)** | Dry Bulb Temperature | Operative Temperature | 0.8336 | 0.9656 | 0.8333 | $y = 0.0047x^2 + 0.4807x + 13.01$ | $y = 0.0092x^2 + 0.4231x + 10.344$ | $y = 0.0042x^2 + 0.4924x + 13.162$ |
| (Openable Window Area = | Wind Speed | Airflow (L/s) | n/a | n/a | 0.8959 | n/a | n/a | $y = 0.0256x^2 + 0.0517x + 0.4657$ |
| 60% of Window) | Inversed of Temp. Diff. | Airflow (L/s) | n/a | 0.8801 | n/a | n/a | $y = -5E+09x^2 + 2E+06x + 78.328$ | n/a |
| **Window open 1 hr (Sc 4)** | Dry Bulb Temperature | Operative Temperature | 0.8362 | 0.9558 | 0.8340 | $y = 0.0048x^2 + 0.4698x + 13.308$ | $y = 0.0129x^2 + 0.3071x + 11.962$ | $y = 0.0047x^2 + 0.4691x + 13.426$ |
| (Window opening: 09:00-10:00am | Wind Speed | Airflow (L/s) | n/a | n/a | 0.8992 | n/a | n/a | $y = 0.0259x^2 + 0.0434x + 0.5189$ |
| 1 hour only) | Inversed of Temp. Diff. | Airflow (L/s) | n/a | 0.7425 | n/a | n/a | $y = -1E+09x^2 + 381981x + 43.573$ | n/a |

Table 5. Thermal and IAQ correlations for the Ry studies

| Ry PRELUDE pilot | Parameters | | Coefficient of determination ($R^2$) | | | Correlation Equation for Thermal Comfort and Ventilation | | |
|---|---|---|---|---|---|---|---|---|
| | Outdoor | Indoor | Annual | NV time Only | No-NV time | Annual | NV time Only | No-NV time |
| **Infiltration only (Sc 1)** | Dry Bulb Temperature | Operative Temperature | 0.7062 | n/a | n/a | $y = 0.0086x^2 + 0.3789x + 20.187$ | n/a | n/a |
| | Wind Speed | Airflow (L/s) | 0.9396 | | | $y = 0.0247x^2 + 0.0093x + 0.8732$ | | |
| | Inversed of Temp. Diff. | Airflow (L/s) | 0.0412 | | | $y = 1E+07x^2 - 2347.6x + 1.4318$ | | |
| **Window can open (Sc 3)** | Dry Bulb Temperature | Operative Temperature | 0.7035 | 0.8966 | 0.7192 | $y = 0.0097x^2 + 0.2613x + 18.72$ | $y = 0.0084x^2 + 0.3756x + 15.44$ | $y = 0.0099x^2 + 0.2522x + 18.985$ |
| (South Facing Window) | Wind Speed | Airflow (L/s) | n/a | n/a | 0.9306 | n/a | n/a | $y = 0.0237x^2 + 0.0371x + 0.6833$ |
| | Inversed of Temp. Diff. | Airflow (L/s) | n/a | 0.972 | n/a | n/a | $y = -4E+08x^2 + 296664x + 35.137$ | n/a |
| **Window can open (Sc 3)** | Dry Bulb Temperature | Operative Temperature | 0.6329 | 0.8775 | 0.6493 | $y = 0.0096x^2 + 0.1601x + 18.338$ | $y = 0.0086x^2 + 0.2847x + 15.162$ | $y = 0.0097x^2 + 0.1506x + 18.596$ |
| (North Facing Window) | Wind Speed | Airflow (L/s) | n/a | n/a | 0.9176 | n/a | n/a | $y = 0.0236x^2 + 0.0412x + 0.639$ |
| | Inversed of Temp. Diff. | Airflow (L/s) | n/a | 0.9794 | n/a | n/a | $y = -5E+08x^2 + 342927x + 31.369$ | n/a |
| **Window can open (Sc 3)** | Dry Bulb Temperature | Operative Temperature | 0.6586 | 0.8451 | 0.6682 | $y = 0.0109x^2 + 0.2437x + 18.512$ | $y = 0.0089x^2 + 0.3718x + 15.33$ | $y = 0.0113x^2 + 0.2333x + 18.768$ |
| (East Facing Window) | Wind Speed | Airflow (L/s) | n/a | n/a | 0.9268 | n/a | n/a | $y = 0.0217x^2 + 0.0523x + 0.6642$ |
| | Inversed of Temp. Diff. | Airflow (L/s) | n/a | 0.9784 | n/a | n/a | $y = -5E+08x^2 + 313690x + 33.507$ | n/a |
| **Window can open (Sc 3)** | Dry Bulb Temperature | Operative Temperature | 0.6696 | 0.8854 | 0.6767 | $y = 0.0122x^2 + 0.24x + 18.488$ | $y = 0.0113x^2 + 0.3518x + 15.2$ | $y = 0.0124x^2 + 0.2312x + 18.754$ |
| (West Facing Window) | Wind Speed | Airflow (L/s) | n/a | n/a | 0.9297 | n/a | n/a | $y = 0.0234x^2 + 0.04x + 0.6819$ |
| | Inversed of Temp. Diff. | Airflow (L/s) | n/a | 0.9738 | n/a | n/a | $y = -4E+08x^2 + 301860x + 34.765$ | n/a |
| **Two windows can open (Sc 3)** | Dry Bulb Temperature | Operative Temperature | 0.7017 | 0.8981 | 0.7192 | $y = 0.0098x^2 + 0.2579x + 18.678$ | $y = 0.0084x^2 + 0.3774x + 15.294$ | $y = 0.01x^2 + 0.2484x + 18.952$ |
| (North / South Windows) | Wind Speed | Airflow (L/s) | n/a | n/a | 0.9332 | n/a | n/a | $y = 0.0243x^2 + 0.0366x + 0.684$ |
| | Inversed of Temp. Diff. | Airflow (L/s) | n/a | 0.8522 | n/a | n/a | $y = -4E+08x^2 + 279715x + 40.536$ | n/a |
| **Two windows can open (Sc 3)** | Dry Bulb Temperature | Operative Temperature | 0.6583 | 0.8482 | 0.6692 | $y = 0.011x^2 + 0.2431x + 18.481$ | $y = 0.0088x^2 + 0.3764x + 15.192$ | $y = 0.0113x^2 + 0.2323x + 18.746$ |
| (East / West Windows) | Wind Speed | Airflow (L/s) | n/a | n/a | 0.93 | n/a | n/a | $y = 0.0223x^2 + 0.0521x + 0.6656$ |
| | Inversed of Temp. Diff. | Airflow (L/s) | n/a | 0.8586 | n/a | n/a | $y = -4E+08x^2 + 283343x + 40.303$ | n/a |
| **Larger window (Sc 4)** | Dry Bulb Temperature | Operative Temperature | 0.6546 | 0.9434 | 0.7127 | $y = 0.0096x^2 + 0.2161x + 18.148$ | $y = 0.0068x^2 + 0.4416x + 12.965$ | $y = 0.01x^2 + 0.1984x + 18.569$ |
| (Openable Window Area = | Wind Speed | Airflow (L/s) | n/a | n/a | 0.9266 | n/a | n/a | $y = 0.0233x^2 + 0.045x + 0.6354$ |
| 60% of Window) | Inversed of Temp. Diff. | Airflow (L/s) | n/a | 0.9796 | n/a | n/a | $y = -2E+09x^2 + 949270x + 79.115$ | n/a |
| **Window open 1 hr (Sc 4)** | Dry Bulb Temperature | Operative Temperature | 0.7104 | 0.8959 | 0.7146 | $y = 0.0093x^2 + 0.2962x + 19.202$ | $y = 0.0137x^2 + 0.4006x + 15.682$ | $y = 0.0092x^2 + 0.2887x + 19.369$ |
| (Window opening: 09:00-10:00am | Wind Speed | Airflow (L/s) | n/a | n/a | 0.9308 | n/a | n/a | $y = 0.0238x^2 + 0.0313x + 0.7266$ |
| 1 hour only) | Inversed of Temp. Diff. | Airflow (L/s) | n/a | 0.9401 | n/a | n/a | $y = -4E+08x^2 + 278873x + 37.919$ | n/a |

## 3.2 Evaluation studies

A prediction of $T_{OT}$ or airflow can be calculated using the linear and polynomial correlation equations if outdoor climatic parameters - DBT and WS - are known. If the DBT of the previous days is known, the optimal $T_{OT}$ of a room or unit can be calculated for adaptive comfort temperature using equations 1-2. Using the correlation equations, the values of indoor airflow can be calculated from its relation to the outdoor wind speed when the window was closed or from its relation to the inversed temperature difference when the window was opened. The ventilation rate can be calculated from equations 3-5, from which the indoor $CO_2$ concentration in the room at time t can be calculated using equations 6-7. On the other hand, hourly results of the indoor $CO_2$ concentration can be obtained by running EnergyPlus and CONTAM simulations. A comparison of correlation equations with the single-zone mass balance equations and adaptive thermal comfort equations is presented in Figure 4 for Athens and Ry for summer and winter days to investigate seasonal differences in two contrast climates.

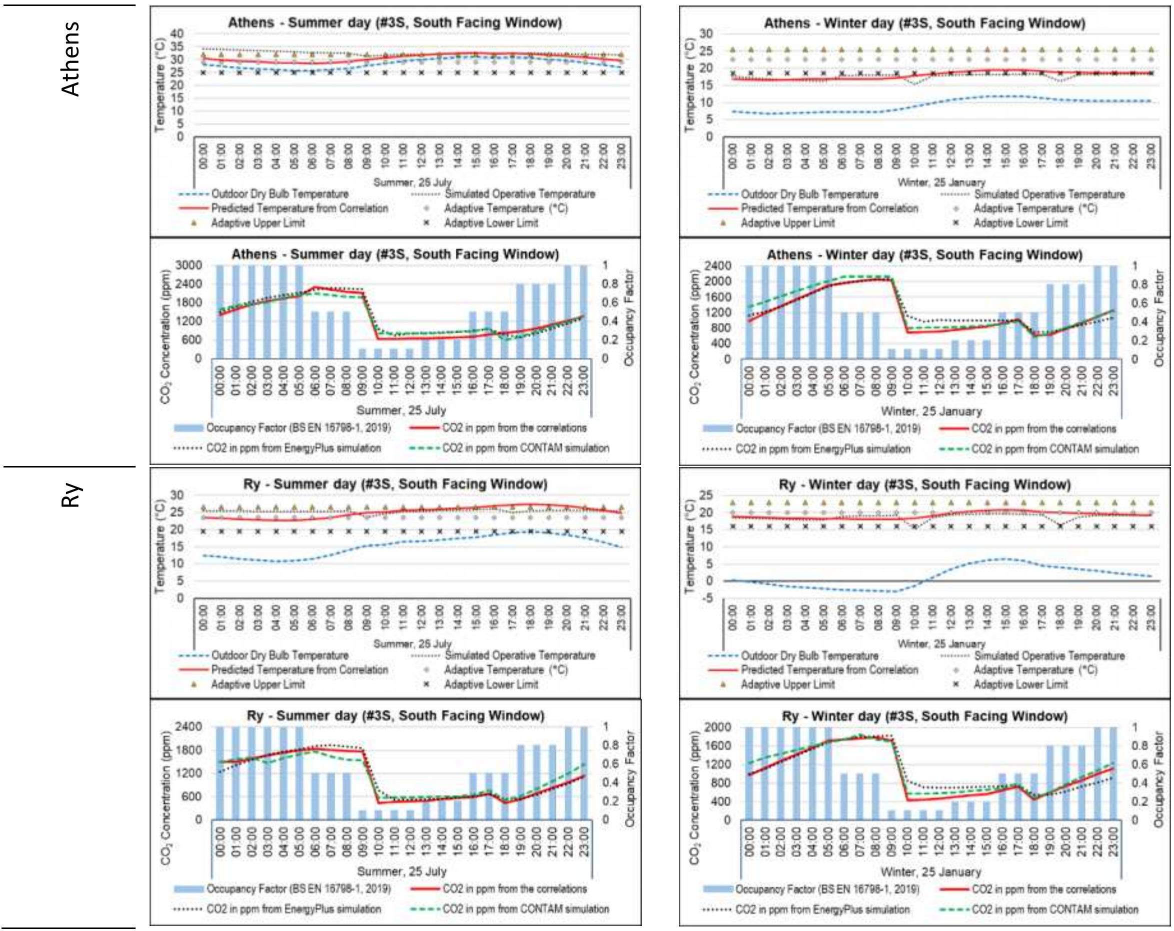


Figure 4. Example of indoor-outdoor module prediction compared to simulations and the equations 3-7

The DBT of Ry (almost the whole year) and Athens (during the wintertime) were found as lower than 20°C and the heating was turned off if the $T_{OT}$ were above 20°C in the EnergyPlus simulation. A comparison of simulated $T_{OT}$ and predicted $T_{OT}$ from the correlation equations showed that there was a reasonably close agreement between simulation and prediction results if the DBT were lower than the heating setpoints, defining the fact that the building fabric efficiency could play a role in $T_{OT}$. On the contrary, if the DBT were higher than the heating setpoints during the summer days in Athens, discrepancies between simulation and prediction results were found. Whilst the temperature correlations were found to be dependent on the temperature-pressure differences and wind pressure differences, the predicted $T_{OT}$ were found within the range of adaptive temperature limits for summer and winter days of both climates.

Unlike the temperature correlations, there is no direct relationship between indoor $CO_2$ concentration and outdoor climate. Figure 4 presents a comparison of the results of simulations and the equations used for the evaluation. In CONTAM simulations, the zone temperatures, which are known as $T_{OT}$ in EnergyPlus simulations, were assumed using user-defined schedules; the schedule was based on the results of the EnergyPlus simulation. Therefore, zone pressures due to temperature changes were able to be considered in CONTAM simulations. A reasonably good agreement was found between simulated values from EnergyPlus and CONTAM. It is important to stress that the assumption of previous day $CO_2$ concentrations and volume airflow were decided to calculate the indoor $CO_2$ concentrations using equations 6-7; therefore, there were discrepancies between the results of the EnergyPlus simulation and the calculated values from the equations. Apart from this, a good agreement can be made between simulation results and the prediction of indoor $CO_2$ concentration using the correlation models for both climates.

## 4 Discussion

The development of the indoor-outdoor correlation model was presented in the previous section for a free-standing housing unit, whereas the practicality and usefulness of the climate correlation model need to be discussed for its implementation. In the implementation process of the climate correlation model, understanding the effect of the climate on thermal comfort, IAQ and the building-related indoor parameter is important for the occupants to adjust their indoor environment by means of behavioural change and the use of smart home technologies or weather forecast. Hence, this section is further extended by discussing the above concerns.

### 4.1 Climate correlation for indoor thermal comfort

Natural ventilation would not be required if thermal comfort alone was concerned with the buildings located in cold climates because opening the window could cause a higher heating load and decreased $T_{OT}$. Natural ventilation is often considered for the IAQ in cold climates, therefore, window opening times of 2 hours daily were considered in this study to remove the indoor $CO_2$ concentration by allowing a high airflow rate and turning off the heating at that time despite the lower DBT were found. In Figure 1, 5.2% of annual hours (455 hours) were calculated for cooling degree days for Athens with a CDD setpoint 24°C, while the CDD values for Ry were negligible.

If the heating was constantly applied for a winter day in both climates, the simulated $T_{OT}$ was found at about 20°C heating setpoint; however, the simulated $T_{OT}$ rapidly dropped when the window was opened for two hours as the heating was turned off to reduce the heating load at that time [Figure 3]. Similarly, the simulated $T_{OT}$ was rapidly dropped on the summer day in Ry when the window was opened. Before the window was opened, the model can be assumed to be a heat-balance mode where the indoor condition can be controlled thermal comfort within a narrow range of acceptable temperatures by applying to heat (Nicol, J. F. & Humphreys, 2002). During window opening hours, the model was changed to a free-running mode where the indoor condition was controlled adaptive thermal comfort by naturally ventilating with a wide range of acceptable temperatures to avoid consuming energy for cooling (Nicol & Humphreys, 2002). However, opening the window for 2 hours on a summer day in Athens only reduced $T_{OT}$ rather than dropping the temperature rapidly at that hour because the heating was not applied on that day as the DBT was above 20°C, which could also cause higher $T_{OT}$. Unlike the temperature drop found in the EnergyPlus simulation results, similar patterns of DBT and predicted $T_{OT}$ were found as the prediction was calculated using the linear and polynomial correlation equations. In this study, the range of acceptable temperature was used as +3°C and – 4°C for the category II level of expectation medium, which is the most appropriate for retrofit buildings (BS EN 16798-1, 2019). The width of adaptive thermal comfort upper and lower limits shown in Figure 4 also revealed differences between a heat-balance mode and a free-running mode.

Using climate correlation equations, the $T_{OT}$ can be easily predicted if the DBT is known, and the outdoor weather data can be obtained by a smart home weather station or other weather forecasting sources. As the predicted $T_{OT}$ from the correlation model will be within the adaptive thermal comfort range, these narrow range in winter and wide range in summer for adaptive thermal comfort limits in two contrast climates are essential for the occupants to understand and adapt their thermal comfort to improve IAQ and reduce concentration by using natural ventilation through the window opening suggested by the correlation model.

It should be noted that if the housing unit has less exposed walls to the ambient because of neighbouring apartments the solar heat as well as heat losses or heat gains are impacted and therefore resulting internal conditions could be different which could influence the correlation equations. Therefore, more accurate results for a specific apartment simulation should be performed considering its exposure.

### 4.2 Climate correlation with building-related parameters

The concentration in the room at time t can be calculated when the ventilation rate (indoor airflow) is known, and a more accurate indoor airflow can be calculated using the correlation equations if the WS is known and there is a stronger correlation $R^2$ value. In the correlation studies, strong correlations between WS and model airflow were found in the unventilated airtight models (models #1S), but weak correlations were found while trickle vents were added to supply fresh air without mechanical ventilation. When the model airflow was correlated to the DBT or $I_T$, strong correlations were found in the wind-driven airtight models in Ry when the windows were opened. The values of $R^2$ were slightly varied by switching model orientation, adding cross-ventilation, increasing window openable area, and reducing window open time; the values of $R^2$ were slightly weaker in the Athens model.

In this study, the Ry models were defined with high airtightness, while the Athens models were found to infiltrate the building envelope against the Ry models. Adventitious gaps and cracks in the building envelope contribute to unintentional air exchange through infiltration and exfiltration by means of positive or negative pressures that cause less fabric efficiency with poor airtightness (Kukadia & Upton, 2019). It is important to stress that ventilations – both mechanical and natural ventilation - are required to design carefully in airtight buildings as the health costs of airtightness without adequate ventilation are harder to estimate. For instance, summer overheating is observed in the Passivhaus buildings (Mitchell & Natarajan, 2019). Likewise, poor IAQ results can be expected if the mechanical ventilation system is not well functioned in an airtight building. On the other hand, it is important both for the occupants and correlation model designers to pay attention to the condition of the correlation equations as the boundary condition of a model could affect the accuracy of correlation both in its $R^2$ values and further calculation of the concentration in the room at time t.

Similar to the thermal comfort predictions, the IAQ would be influenced by the local wind patterns, which could be affected by the location of the housing unit. For a housing unit in an urban area within an urban canyon, the wind speed and direction will be different from an exposed unit. Therefore, for more accurate results, specific simulations should be performed considering its exposure.

### 4.3 Climate correlation for indoor $CO_2$ concentration

The airflow in a building is often driven by pressure differences which originate from temperature differences, wind, and forced-air HVAC systems. The differences in the intensity of DBT and WS between day and night were small in both climates, while seasonal variation in temperatures and wind directions were large. The effects of wind pressure differences were insignificant while the windows were closed. Hence, it is critical for the occupant to pay attention to understanding temperature differences between indoors and outdoors to achieve a sufficient and fresh airflow rate in removing concentration from the indoors.

In the results, large temperature differences between indoors and outdoors were found in the wintertime, whereas slightly small differences were found in the summer. Due to the temperature differences, the airflow rates decreased during the summer days in Athens and increased concentrations. On the contrary, differences in the intensity of airflow rates between the summer and winter days of the Ry models were less profound. In Figure 4, significant drops in indoor $CO_2$ concentration were found when the windows were opened and the occupancy activities were reduced at 09:00 am; however, indoor $CO_2$ concentrations escalated again after the windows were closed at 19:00 when the occupancy activities were increased.

It is important to highlight that the occupancy schedule in this study was considered from the BS EN 16798-1, and the correlation equations were then generated. In the post-analysis, the forecasted occupancy data can be used to calculate the indoor $CO_2$ concentration using equations 6-7 including the previous day's $CO_2$ concentration. The calculation of the previous day's $CO_2$ concentration could be varied by the airflow and occupancy of the previous day. This study, therefore, revealed that the assumption of the previous day's concentration is critical as it could accumulate the concentration for the next day, which could also improve IAQ by window opening alone. The heating loads were slightly increased because the outdoor fresh air caused heat loss; therefore, careful time planning is crucial in adjusting heating and ventilation schedules. A study of a residential building in Japan showed that 87% of the total air change rate was caused by the behaviour of the occupants that also inform the setting of window opening time (Iwashita & Akasaka, 1997). Hence, the impacts of occupancy hours and the use of natural ventilation to allow sufficient air change rate in removing indoor $CO_2$ concentration are critical for the end-users knowledge of behaviour change strategy.

### 4.4 Limitations of the present study and further development

As mentioned before, specific simulations should be run for more accurate predictions for specific housing units also considering their exposure to ambient and their location to consider external temperatures and wind patterns. For housing units in urban locations, a methodology has been developed for performing simulations which consider the urban heat island and wind patterns in urban canyons (Salvati et al., 2020). Within the PRELUDE project, a platform is being developed through which such simulations will be possible for specific housing units so that correlations can be developed for specific cases. This will be an on-demand service which will produce guidelines for the occupants for manual operation and/or rules which can be implemented in a simple control system.

## 5 Conclusion

The development of the indoor-outdoor correlation module for residential settings was presented in this study using dynamic thermal and IAQ modelling. A simplified black-box model was employed in EnergyPlus and CONTAM studies for two different European climates: Nordic and Mediterranean climates. Considering differences in outdoor climatic parameters, the methodology of this work was set to compare annual and seasonal differences in the climate correlation models and to answer how the building occupants from two contrasting climates can adjust their indoor environment by means of behavioural change and the use of smart home technologies or weather forecast based on the results of the climate correlation model. The simulation scenarios were cautiously structured to investigate the benefit of natural ventilation through window openings and the impacts of ventilation and building operation schedules on the IAQ. The outcome of simulation studies was evaluated using adaptive thermal comfort equations, single-zone mass balance equations and equations to estimate space-specific $CO_2$ concentrations.

A strong temperature correlation between DBT and $T_{OT}$ was found in the less fabric efficiency for building envelopes model used in the Mediterranean climate while a strong airflow correlation between WS, $I_T$ and model airflow was found in the high fabric efficiency for building envelopes model used in the Nordic climate. A reasonably good agreement was found between simulated values from EnergyPlus and CONTAM, where the comparison between simulation results and the prediction of indoor $CO_2$ concentration using equations 1-7 were found acceptable results.

The Fogg Behaviour Model highlights that behaviour will only happen when three elements occur simultaneously: motivation, ability and trigger (Fogg, 2009). This study provides a simplified application and calculation for occupant-centred actions that encourage the 'ability' of the occupants to improve internal environmental conditions in their space using simple correlation equations which are comparable with the results of comprehensive scientific equations and a sophisticated simulation database. A wide engagement to inform and educate building occupants about the process and the application of the correlation model is essential in developing 'motivation' and 'trigger' to occur behaviour change. Therefore, further discussions were extended in this study to inform the occupants of the necessary knowledge of using the correlation model, which requires understanding the impacts of climatic parameters, fabric energy efficiency for ventilation and acceptable adaptive thermal comfort range in two contrast European climates.

**Acknowledgements**
This study was funded by the European Union's Horizon 2020 research and innovation programme under Grant Agreement N° 958345 for the PRELUDE project (https://prelude-project.eu).

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# Urban heating, lack of green and lack of space: the contribution of urban vegetation to the improvement of environmental quality in open urban spaces in the city of São Paulo, Brazil

**Luiza Sobhie Muñoz[1], Leticia Crevatin[2], Pedro Casara Luz[3], Paula Shinzato[4] and Denise Helena Silva Duarte[5]**

[1] PhD Candidate in Architecture and Urbanism at the School of Architecture and Urbanism of the University of São Paulo/FAUUSP.
[2] Undergraduate student in Architecture and Urbanism at the School of Architecture and Urbanism of the University of São Paulo/FAUUSP.
[3] Undergraduate student in Civil Engineering at the Polytechnic School of the University of São Paulo/EPUSP.
[4] Postdoctoral fellow at the School of Architecture and Urbanism of the University of São Paulo/ FAUUSP
[5] Full Professor in Architecture and Urbanism at the School of Architecture and Urbanism of the University of São Paulo/FAUUSP.

**Abstract:** The suppression of urban vegetation and the increase in built density and impervious surfaces are one of the main factors for the aggravation of local climate change effects. This lack of green decreases the environmental quality of open urban spaces and undermines their role in sociability, walkability, and inhabitants' health. This becomes more evident after the emergence of the COVID-19 pandemic, since the availability of adequate open urban spaces is essential to reduce the risk of contamination. In the city of São Paulo, the local Climate Action Plan (PlanClima SP) points out some strategies and actions that should be implemented to increase urban spaces' quality, many related to nature-based solutions. However, there is a lack of public spaces available for vegetation implementation, especially in the city centre. Thus, this work aims to develop urban redesign patterns that enable the insertion of vegetation in the Santa Ifigênia, a densely built-up area located in the centre of São Paulo, and contribute to the implementation of the PlanClima SP, regarding green adaptation measures and nature-based solutions. The results showed that it is possible to redesign the urban spaces to increase the urban vegetation, to improve the environmental quality and resilience of densely built areas and land surface temperature reductions up to 18 K were registered.

**Keywords:** Nature-based solutions, Urban Design, Adaptation, Climate Change, São Paulo.

## 1. Introduction

The world is experiencing a environmental crisis, including climate change, which will worsen in case the Greenhouse Gases emissions (GHG) are not controlled. The global mean temperature in 2021 was, roughly, 1.1 °C higher than the pre-industrial (1850-1900) average, which represents the sixth warmest year in this period, and the extreme events, such as exceptional heat waves, have broken records in many areas across the globe (WMO, 2022).

Regarding climate change, it is important to understand the global and local scale phenomena and how they overlap. For the former, the GHG emissions are the main cause of accelerating and aggravating climate change effects, while on the local scale, anthropogenic actions (IPCC, 2018) cause the energy imbalance (Oke et al, 2017), the main driver of urban heating. Anthropogenic actions are mainly related to vegetation suppression and to the change of ground properties, which leads to an increase in the emission of longwave radiation (Stone, 2012) and in the presence of impervious surfaces, which causes a decrease in the latent heat available (Erell et al, 2011). Regarding urban warming, the temperature rise is caused by four main characteristics of the cities: (i) a lack of evaporative cooling; (ii) the reabsorption of reflected radiation; (iii) low surface reflectivity; (iv) generated heat (Duarte, 2016). However, the climate change effects in cities are not only related to warming, but also to floodings, landslides, droughts, changes in the precipitation patterns and other different disasters that the cities must tackle (UN Environment, 2021), sometimes compounded.

The presence of all types of vegetation throughout the urban fabric is an imperative strategy to tackle and to adapt to all these environmental issues, and must be implemented even in places where, at a glance, it seems impossible. In this context, nature-based solutions[1] (NBS) are essential elements to climate adaptation, once provide economic, social and environmental benefits, decrease the population vulnerability and are cheaper than engineering works (UN Environment, 2021). These strategies can counteract drainage problems, urban heating and loss of biodiversity (IPCC, 2022; UK GBC, 2022)

Vegetation is also essential to the urban energy balance regulation due to its shading potential, evapotranspiration function and interaction with the wind. According to Santamouris et al (2018), trees are the most effective types of urban greening to manage the temperature rise. Under the tree crowns the air temperature is lower due to the reduction of surface temperatures promoted by shading and evapotranspiration effects (Coutts and Tapper, 2017). However, the tree effects in the microclimate are more related to the reduction of radiant energy than to the reduction of air temperature (Erell et al, 2011), once the reduction of surface temperature is more significant (Erell, 2017).

The combination of trees and pervious surfaces increases the thermal attenuation potential at the pedestrian level (Chang and Li, 2014). This is due to the fact that the more presence of vegetation the more water is transferred from the soil to the atmosphere (Aflaki et al, 2016), once trees not only promote shading, but also increase the humidity in its surroundings (Erell et al, 2011). In addition to these, NBS are also important to manage the urban drainage and to fight one of the most important environmental challenges: urban floodings. The increase of pervious surfaces is the key answer to tackle it.

The implementation and increase of urban vegetation are not only a challenge for the thermal regulation (Stone, 2012) and climate adaptation, but also essential for the urban environment quality improvement and to increase the use of open urban spaces and social life (NG et al, 2012). Since the beginning of COVID-19 pandemic, the importance of open urban spaces has become even more significant as a place which presents less risk of contagion. However, the quality of these open urban spaces must be improved and, for this, public policies and urban design are essential and must be connected, potentialized by effective governance.

The way how people use these spaces is directly related to the climate and cultural matters and facilitating and enabling its use is the main tropical design challenge (Emmanuel, 2016). Also, for this author, a climate-sensitive design is the key to climate adaptation and essential for making life in outdoor spaces possible. According to Emmanuel and Simath (2021), when climate matters are prioritised, government’s spendings to manage the natural

[1] Inspired and supported by nature, NBS are cost-effective, provide social, economic and environmental benefits and contribute to resilience (European Commission, 2015). In addition, these solutions must benefit biodiversity and support ecosystem services (European Commission, 2020).

disasters and vulnerability are reduced, and this is directly related to sustainable development. NBS must be implemented in every scale (Herzog, 2013), these different scales - local, regional, national and even international - should cross each other (Emmanuel and Simath, 2021), and its planning must consider public and private elements.

In the city of São Paulo, the spatial distribution of green is unequal, whereas some big and densely populated areas present less vegetation than those smaller and less populated ones. This fact highlights profound social and economic inequalities and shows that the presence of vegetation is also a social matter. Besides some municipal green plans, the city of São Paulo has an urban instrument in the zoning law that aims to increase the presence of urban vegetation, the Environmental Quota (São Paulo, 2016), focused only on private and over 500m² lots, which is a starting point, for sure, but not sufficient, once the public and open urban spaces also need attention. Recently, the PlanClima was released, which points out some strategies and actions to improve the urban spaces' quality in the city of São Paulo, many of them focused on green measures (São Paulo, 2021b).

The city centre, a consolidated area, holds the districts with one of the highest built and population densities: Bela Vista, República and Santa Cecília, respectively. Beyond being highly populated and built, these districts also show a massive lack of vegetation. Still, areas that have presented fast transformation, like the surroundings of Rebouças Avenue, located at Jardim Paulista and Pinheiros, must be controlled. In these areas, real estate developments have suppressed the vegetation in order to build skyscrapers (Figure 1). It is interesting to observe that even facing these transformations, Jardim Paulista and Pinheiros are areas way more vegetated than the city centre, and this is due to being wealthier areas than the city centre.

In particular, the city centre presents several challenges as a densely built area, with apparently little space available for urban vegetation and comparatively high surface temperatures throughout the year. It has also been a place of great historical, economic and cultural significance for the city. Historically, it holds much of the city's commerce and job offers, especially for the lower income people, and provides ample access to public transportation.

This, this paper aimed to develop proposals of urban redesign that enable the increase of vegetation in the city centre of São Paulo, especially in Santa Ifigênia region. These proposals considered the space available in the streets and within the blocks for these interventions and the land use in these areas, as well the pedestrian and cyclist security. These proposals were focused on NBS implementation, particularly street trees, in order to improve pedestrian comfort and walkability, and ground vegetated surfaces, to increase the rainwater infiltration for both areas: in the streets and within the blocks.

## 2. Objective

This work aims to examine the urban morphology of the city centre of São Paulo in the microscale, at street level, to propose the development of urban redesign patterns that enable the insertion and increase of vegetation in a densely built-up area, contributing to the implementation of the local Climate Action Plan (PlanClima), regarding, especially, green adaptation measures - such as street trees, retention gardens and sidewalks with rainwater infiltration areas.

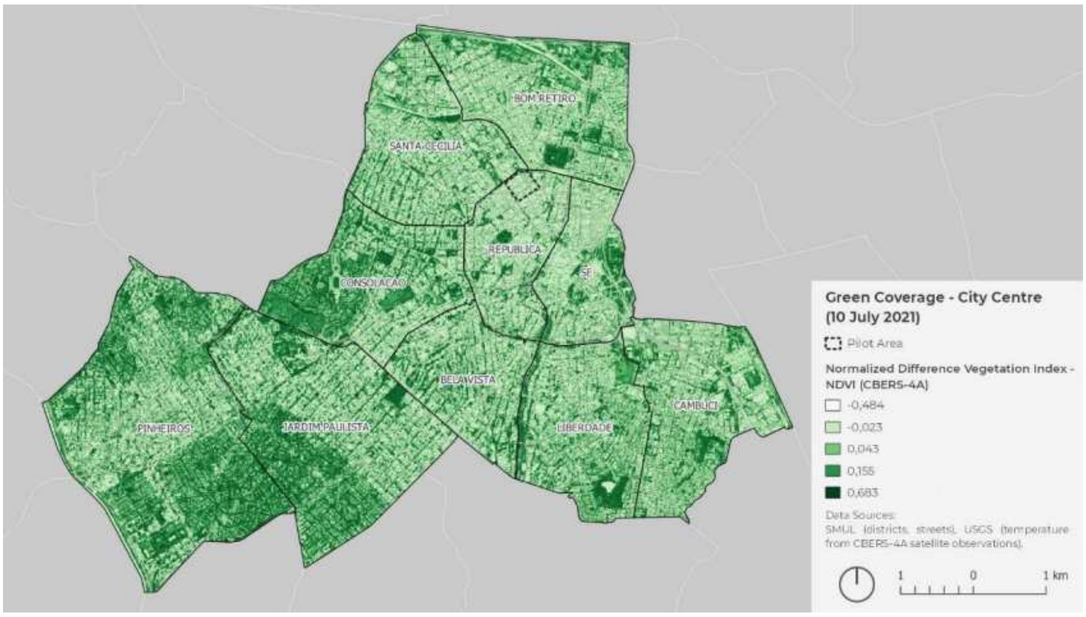


Figure 1. The presence of vegetation (NDVI index) for São Paulo's city centre, Pinheiros and Jardim Paulista districts.

## 3. Methodology

The first stage of this study's method was reviewing the existing literature on urban density, urban heating, nature-based solutions and its application. This included all kinds of reliable data available, such as official reports, case studies and urban planning instruments related to the expansion of urban green areas. In São Paulo, particular attention was given to the local Climate Action Plan – PlanClima (São Paulo, 2021b) and to the existing public programs, such as the Urban Amenities Program (São Paulo, 2021a), responsible for implementing several green infrastructure measures in the Sé district, located at the city centre of São Paulo. As for foreign references, examples include Hong Kong's Greening Master Plan (Hong Kong, 2019) and Australia's Cooperative Research Centre for Water Sensitive Cities guidelines for optimized tree placement (Coutts and Tapper, 2017).

This stage was followed by an assessment of the districts located at the centre of the city of São Paulo and in its surroundings, Pinheiros e Jardim Paulista, important areas of verticalization and new buildings, in order to select a specific pilot area for this paper. This process was due to previous results from Ferreira and Duarte (2019), developed for the entire metropolitan region of São Paulo, which showed a massive lack of urban vegetation in this area and, consequently, high values of land surface temperature. The parameters involved in this district assessment were related to the urgency of increasing urban vegetation, which were: density (both built-up and population); NDVI (Normalized Difference Vegetation Index) for the green coverage pattern; and land surface temperature. The assessment of these parameters made possible to check where the implementation of the urban green was more urgent. Lastly, several proposals of urban redesign that enable the implementation of urban green were made for the selected area.

### 3.1. Pilot Area Selection

The city of São Paulo is located in the southeast region of Brazil, at a latitude and longitude of, approximately, 23°.5" S and 46°38" W and altitudes varying around 760 m. Its climate is subtropical – Cfa according to Köppen classification (Beck et al, 2020) –, with mild to high temperatures: between 22 °C and 30 °C during summer and 10 °C and 22° C in winter. Precipitation is highest during summer, from December to March. Although São Paulo is the most populated city in the country, its population density of an average 73.98 inhab/ha (Instituto Brasileiro de Geografia e Estatística[2], 2022, based on the 2010 census) is relatively low compared to other large cities in the world, such as Mumbai, Istanbul and Shanghai (Gusson et al 2012).

To verify the values of built and population densities of the city centre, maps were developed on the 3.22.7 (Long Term Release) version of the software QGIS®[3]. To do so, all shapefiles used in the maps were obtained from GEOSAMPA[4] platform. For the population density, the data was obtained from projections made by Observa Sampa[5]. This was due to the fact that the Brazilian official demographic census, developed by IBGE, is outdated. This calculus was made by a simple equation based on dividing the number of inhabitants of a district by its area (Equation 1), and then the districts were classified according to the results (Figure 2).

$$\text{Population density} = POP/DA \quad (1)$$

Where: POP - number of inhabitants of the district;
DA - district area (ha)

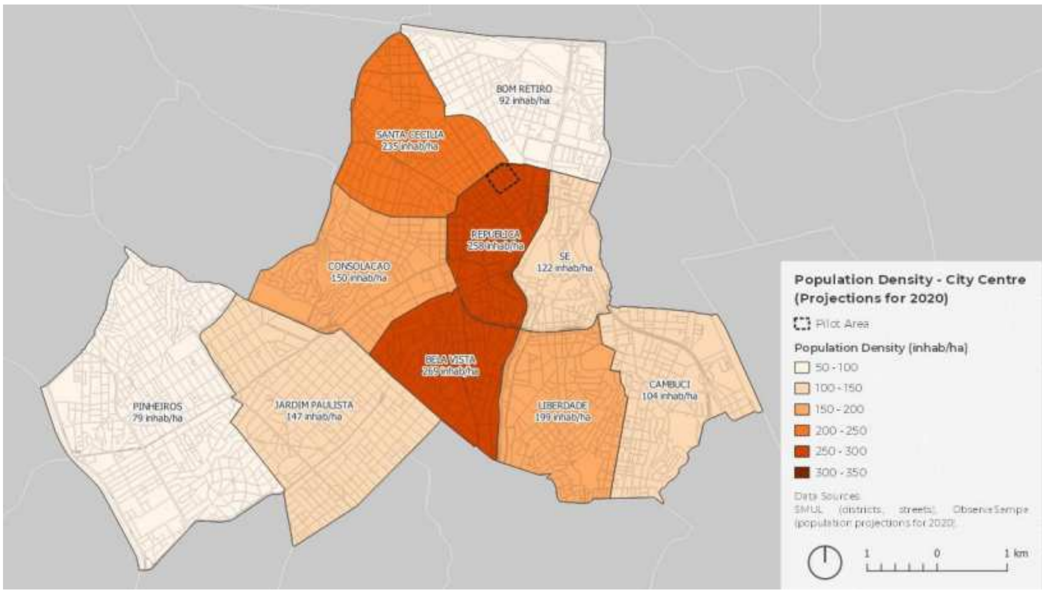


Figure 2. Population density for São Paulo's city centre[6].

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[2] IBGE: Brazilian Institute of Geography and Science

[3] Available at: https://www.qgis.org/pt_BR/site/forusers/download.html

[4] http://geosampa.prefeitura.sp.gov.br/PaginasPublicas/_SBC.aspx. Geosampa is an open and public digital database of Geographic Information System for the city of São Paulo.

[5] Public and open database provided by the São Paulo City Hall. Available at: http://observasampa.prefeitura.sp.gov.br/.

[6] SMUL: Municipal Department of Urbanism and Licensing. Observa Sampa: Observatory of Indicators from the City of São Paulo.

For the built density, the proportion between the total area of the buildings' projection and the district area were calculated (Equation 2). From this, it was possible to quantify the "site coverage[7]" (Figure 3). In this context, it is possible to observe that the districts of Bela Vista, República and Santa Cecília registered the highest values for population density, also a tendency in the built density map, in which these districts presented the highest results.

$$\text{Built density} = BP/DA \times 100 \quad (2)$$

Where: BP - buildings' projection
DA - district area

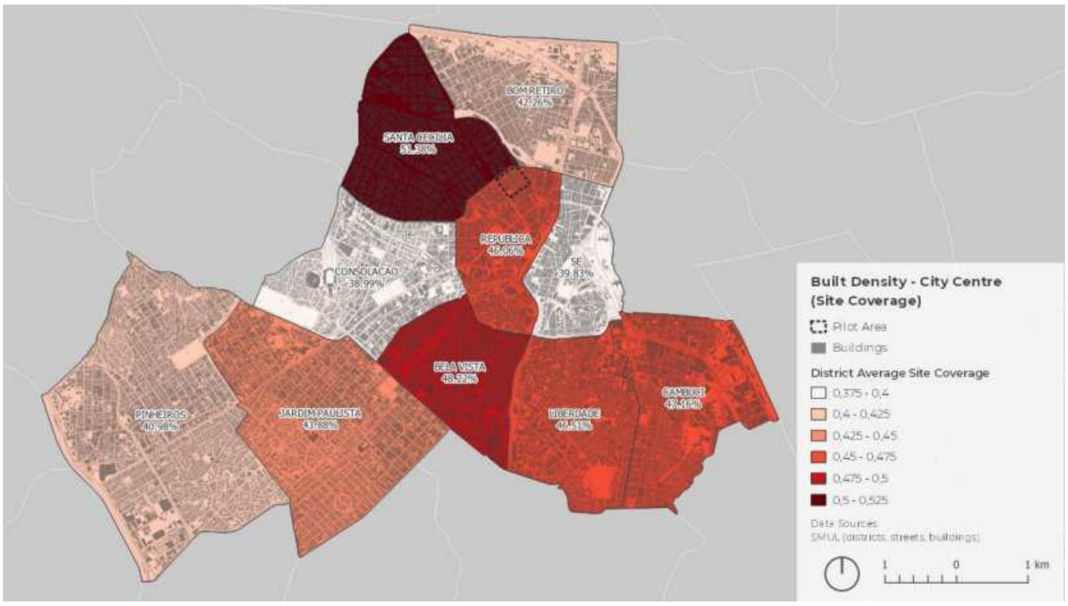



Figure 3. Built density (site coverage) for São Paulo's city centre.

For the NDVI[8] map, the entire process was also made on the software QGIS®, using images obtained from CBERS-4A satellite[9] (for 10 July 2021) and shapefiles from GEOSAMPA. This satellite was selected due to its spatial resolution of eight metres, which is important to the urban scale assessment, and for this, the multispectral and panchromatic - WPM - camera was used. The calculation for the NDVI was carried out on QGIS and is presented in Equation 3. It is possible to observe that the densest places – mainly in built area, but also in population – are the ones with the lowest green areas (Figure 4). For example, the República district has many areas with nearly no urban green at all, mainly where site coverage is the highest (and the amount of free space, the lowest).

[7] *Site coverage* is defined as the ratio between the area of a building's projection and the area of the site. In this context, it represents the percentage of the district's land occupied by buildings (its complement would be the percentage of open spaces in the district, including parks, parking lots, unbuilt areas on private sites etc.).

[8] NDVI is a vegetation index commonly used to measure the "greenness" of a certain pixel in a satellite image. It is calculated measuring the amount of radiation emitted by the pixel in certain regions of the electromagnetic spectrum, compared to what vegetation would typically emit, in a scale from -1 to 1 (the higher the value, the greener the area). It is not a direct measurement of green coverage, but poses as a standard indicator for it.

[9] CBERS-4A is an open and free source of imagens made available by Brazil in partnership with China. Available at: http://www2.dgi.inpe.br/catalogo/explore

NDVI = (ρNIR - ρR) / (ρNIR + ρR) (3)

Where: ρNIR - near infrared band;
ρR - red band.

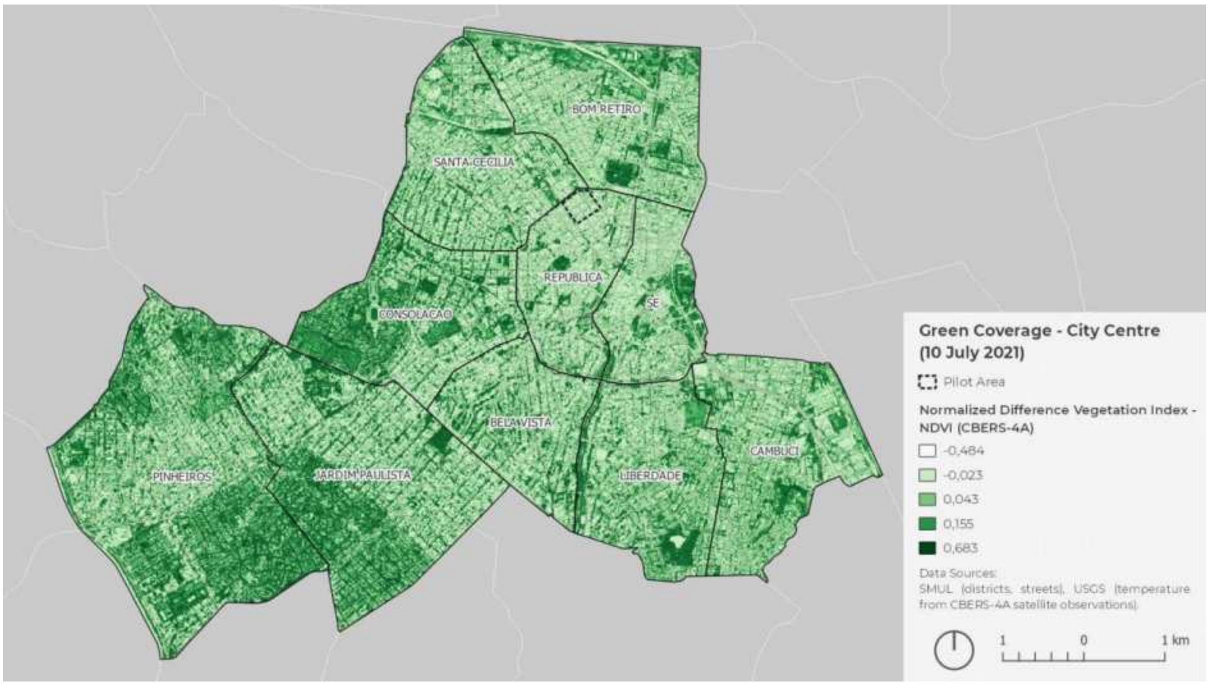



Figure 4. Normalized Difference Vegetation Index (NDVI) for São Paulo's city centre.

Finally, for the land surface temperature (LST), Landsat 8 OLI-TIRS C2 L2 and LANDSAT 9 OLI-TIRS C2 L2 images were used for August 22nd, 2021, and February 22$^{nd}$, 2022, respectively. The images were obtained at USGS official website[10]. On QGIS® software an adjustment was made to transform the standard temperature of the images (K) into Celsius (Equation 4). Furthermore, this lack of green has evident effects on the land surface temperatures observed by satellites throughout the year in this region. As shown in Figures 5 and 6, areas where urban green is more present and better distributed face significant reductions in surface temperature.

LST = (B10 x 0.00341802) + 149) - 273.15 (4)

Where: B10 - band 10 correspondent image.

[10] https://earthexplorer.usgs.gov/.

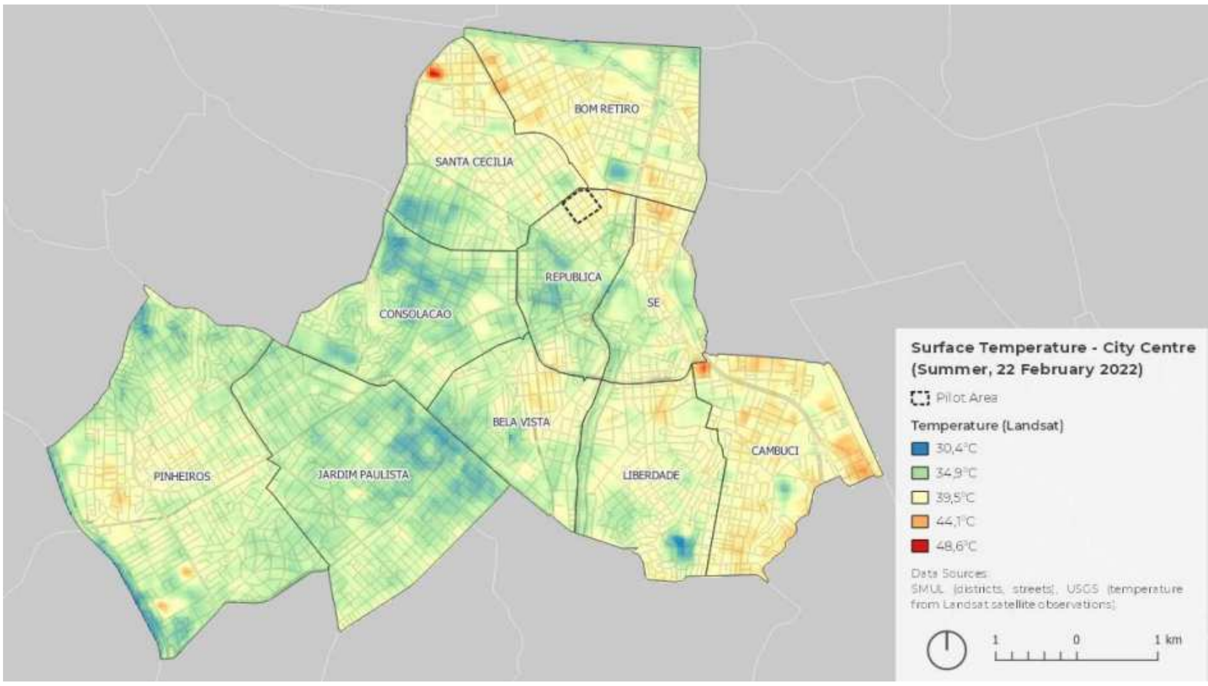



Figure 5. Land surface temperatures for São Paulo's city centre (summer morning).

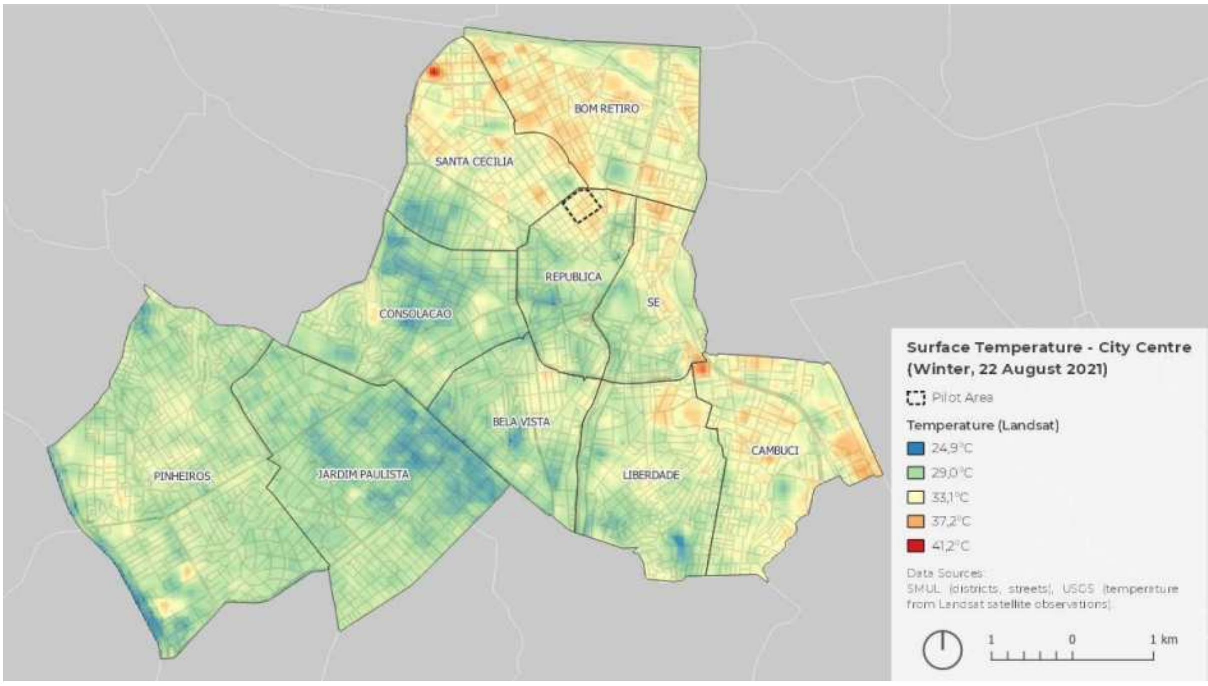



Figure 6. Land surface temperatures for São Paulo's city centre (winter morning).

Districts like Santa Cecília, República, Bom Retiro and Cambuci once more face the worst scenarios regarding environmental quality criteria. A particularly interesting spot in this regard is at the border between República and Santa Cecília, close to the Santa Ifigênia Street (as indicated on the maps above): warm, densely built and populated, and close to no green available. Thus, it was selected a pilot area for this work, located in the city centre, in Santa Ifigênia region, between the streets Andradas, Gusmões, Santa Ifigênia and General Osório, encompassing eight blocks (Figure 7). All shapefiles used in Figures 8 and 9 were also obtained from GEOSAMPA and modified by the authors.

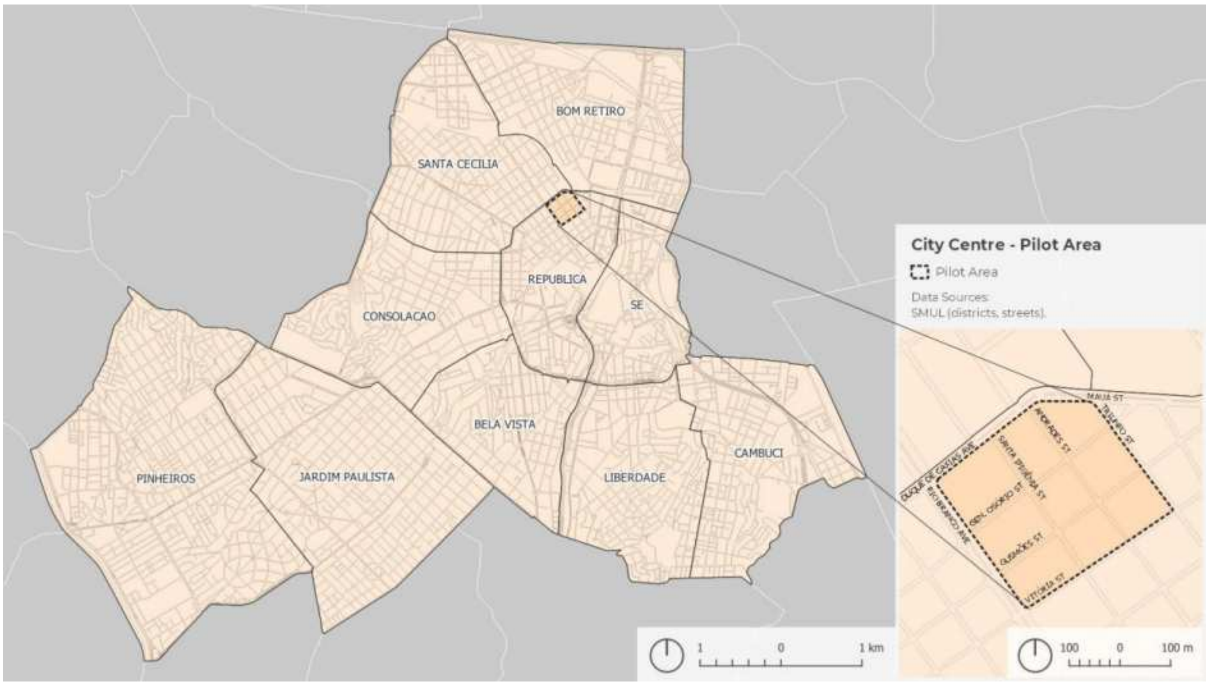



Figure 7. The pilot area.

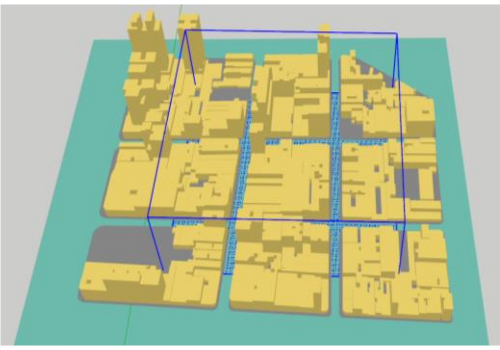
### 3.2. Urban redesign proposal

The urban redesigns were made for the selected area in order to qualify this urban space, increasing and implementing the presence of vegetation. Redesigns for streets, avenues, parking and idle areas were developed and followed the guideline available on Nacto (2018). Also, some proposals to improve mobility were included, such as bike lanes and pedestrian crossing in strategic places. The redesigns were made on Sketchup® and edited on Illustrator®. For this, green measures were implemented, such as bioswales, rain gardens, street trees and permeable surfaces everywhere it was possible.

To evaluate the benefits of vegetation implemented in the project, simulations were carried out using ENVI-met V5.0.3. It is a three-dimensional model to simulate surface-vegetation-atmosphere interactions for urban environments with resolutions of 0.5m to 10m in space and up to 10 seconds in time (Bruse, 1998). It considers not only the shading effect of the trees, but also the physiological process of photosynthesis and gas exchange of the stomata.

The 3D modelling area was designed using SketchUp (Figure 8a) and exported to ENVI-met by a specific plugging called ENVI-met INX. The area of study was formed by nine blocks with the pilot area in the centre. The size of grid cells was defined as 3m x 3m, with a horizontal domain size of 285m x 288m, and for the vertical grid, the height of the 3D model top was 108m. Two scenarios were considered for the simulations, one without and one with trees and retention gardens (Figure 8b). The characteristics of building materials (wall construction systems) and surfaces (asphalt, concrete) were considered from the studies of Gusson (2020).

For the vegetation, previous survey of typical vegetation characteristics such as canopy form, total height and crown diameter for the main existing tree typologies in Sao Paulo was based on the studies of Shinzato et al. (2019). The type of soil was sandy clay loam up to 4 meters deep, and a 10-meter-high tree was chosen with a LAD – Leaf Area Density of 0.8 $m^2/m3$. The climate data considered field measurements in April 2016 and the input data was already calibrated to the local microclimatic conditions of Sao Paulo. Simulation ran for 24 hours, starting at 4 AM on April 17th.


(a)

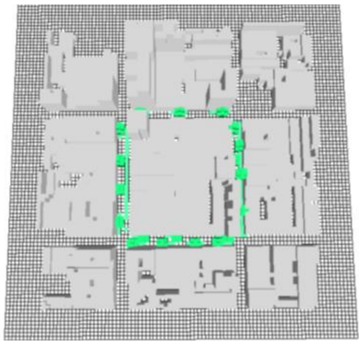

(b)

Figure 8: (a) The 3D modelling area built in SketchUP; (b) 3D modelling area exported to ENVI-met V5 with vegetation.

## 4. Results and Discussion

The selected area is located in the centre of the city of São Paulo, Santa Ifigênia area and, therefore, represents a consolidated region of the city and an important place for social life and commerce. It is important to highlight that this is a pilot area, and these redesigns can be replicated in the future for different areas of the city. The area has high pedestrian circulation during the entire year. The area also presents a massive lack of vegetation, high values of land surface temperature and a lack of space available to walk and to include vegetation. So, for the proposal, a reference block and its four surrounding streets (Gusmões, Andradas, Santa Ifigênia and General Osório) (Figure 9), besides other three special cases located in the surroundings (Figure 10) were selected. In this context, the proposals encompass: (i) the streets located in the surroundings of the reference block; (ii) a parking lot, that represents a private idle urban space; (iii) a public and idle urban space, located in the avenue and developed to organise and guide the urban traffic; (iv) redesigns for Duque de Caxias and Rio Branco Avenues.

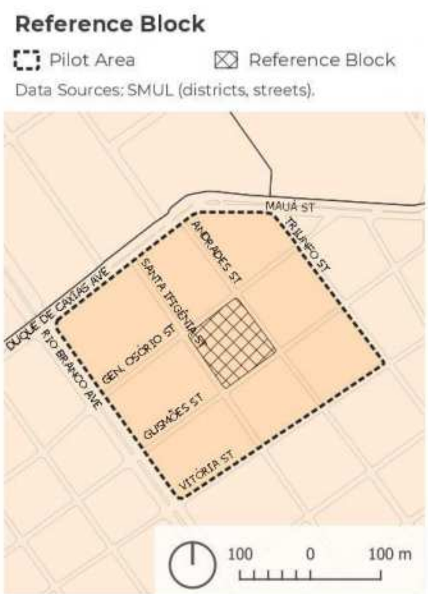



Figure 9. The pilot area and the reference block.

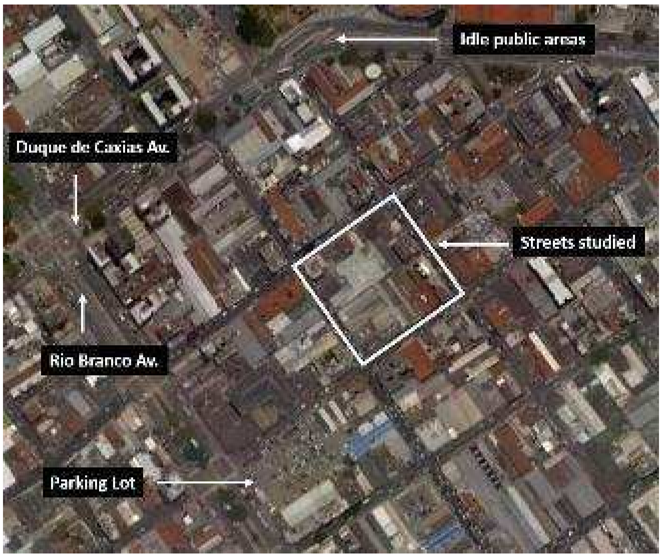


Figure 10. The spaces assessed for the proposals. Source: Image from Google (2022) and modified by the authors (2022).

### 4.1. Proposals for the streets

The four streets studied for the proposal show quite similar patterns: all of them are narrow, as well as its sidewalks, impervious and present a high flux of pedestrians and loading zones. In this context, it is important to say that the proposals intervened only on the transit lanes, since the sidewalks are already narrow for the current pedestrian circulation. Besides including vegetation to provide shading, the redesign focused on increasing permeable surfaces, in order to increase the rainwater infiltration, and on organising this urban space, to protect and to stimulate walking and cycling.

Santa Ifigênia Street presents medium sidewalks, around 2.50 metres on average, and the sum of the travel lanes totals 9 metres width. Among the four streets studied, this has the largest transit-only area, which gives more possibilities of interventions. This street shows a complete lack of urban vegetation and a dispute for space between cars, people and some street vendors (Figure 11). To do so, a bike lane was proposed, protected by a linear retention garden, on the right side of the street (Figure 12).

Currently, both sides of the street are available for parking, and, in the proposal, the bike lane was developed to occupy one of them. This bike lane would be integrated into an existing bicycle network, located on Duque de Caxias Avenue, which leads to Julio Prestes Station, an important transport hub for the city. On the left side, some areas used as parking spaces were suggested to be turned into larger retention gardens. On both sides street trees were suggested, to provide shading. Both street corners were extended and vegetated in order to protect the pedestrians and cyclists at the intersections.

Figure 11. The current situation of Santa Ifigêcia Street. Source: Image from Google (2022).

Figure 12. The proposal for Santa Ifigênia Street.

Andradas street presents sidewalks with 3 metres width and its car lanes totals 7.2 metres width. This street presents one of the largest sidewalks within the streets surrounding the reference block (Figure 13). Despite the car lane width, it is currently possible to circulate in two rows of cars, which leads to an extreme situation of insecurity and accident possibilities and, because of this, the proposal changed this to a one lane street. Due to the orientation and geometry of this street, most of the urban trees were implemented on its right side, where the buildings are lower and provide less shading. To the left side, on-street parking spaces were converted into retention gardens, in which trees were suggested too. This street doesn’t have bike lanes, but the street corners were also extended and vegetated to protect the pedestrians (Figure 14).

Figure 13. The current situation of Andradas Street. Source: Image from Google (2022).


Figure 14. The proposal for Andradas Street.

Gusmões Street presents a double car lane with an average of 7,8 metres width, while its sidewalks width varies. The left and right sides present 2,4 and 3,1 metres, respectively (Figure 15). In this case, the double travel lane was also converted into one as in Andradas street. Trees and retention gardens were proposed for both sides and, especially for the right one, parklets were implemented to expand the sidewalk space (Figure 16). Parklets are extension areas where people can enjoy the open urban spaces, day and night, socialize and, in some cases, are extensions of restaurants and commerce. Implementing this strategy might be a stimulus for the occupation of the street in different periods, especially at night, which would increase the sense of security in the area.

In the General Osório case, the street has the entire left side for parking, a characteristic that was kept the same in the proposal due to the changes developed on the other streets and in order to keep some parking spaces in the area. The street is completely gray and presents massive impervious surfaces (Figure 17). So, on the right side some retention gardens were suggested, resulting from the suppression of parking spaces. This enables shading by the street trees, which improve the thermal comfort and walkability, and also preserves some parking spaces, maintaining the car access to this important economic region (Figure 18).

Figure 15. The current situation of Gusmões Street. Source: Image from Google (2022).

Figure 16. The proposal for Gusmões Street.

Figure 17. The current situation of General Osório Street. Source: Image from Google (2022).

Figure 18. The proposal for General Osório Street.

The microclimate impact of these proposals for the four streets on land surface temperature was assessed in order to quantify its likely cooling effect. The Figure 19 shows the reduction of the surface temperature was up to 18.6K, comparing the scenarios with and without vegetation, and around 10oC, in relation to the areas not shaded by buildings.

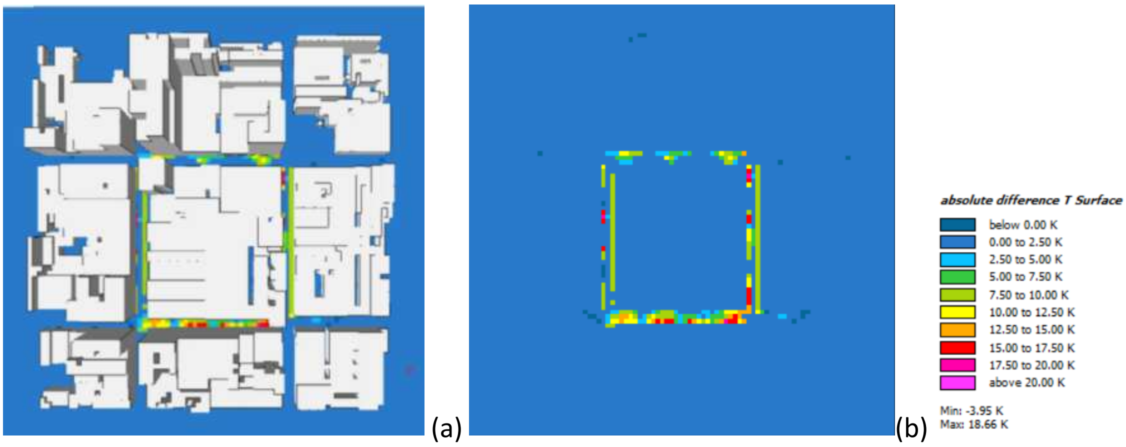



Figure 19: (a) Result of surface temperature comparing the scenarios with and without vegetation, using ENVI-met V5; (b) the same result without buildings.

## 4.2. Proposals for the idle spaces

In the area there are some private and public idle spaces. The former are basically areas that organize the transit, and the latter are large parking lots. Both presents lack vegetation and pervious surfaces (Figures 20 and 21), and retention gardens were suggested. For the public case, two retention gardens in the Mauá Avenue were designed, which are surrounded by two bike lanes. This increases the cyclist's thermal comfort and the possibility of managing the rainwater (Figure 22). This intervention is located in front of the Julio Prestes Cultural Complex, an important cultural and historical building and a point of tourism, that includes a very important concert hall, Sala São Paulo. For the parking lot case, retention gardens with trees were implemented between parking bays (Figure 23). These strategies also increase the shading potential and rainwater infiltration and management.


Figure 20. The dry and idle public space. Source: Image from Google (2022).


Figure 21. The parking lot. Source: Image from Google (2022).


Figure 22. The proposal for the dry and idle public space.

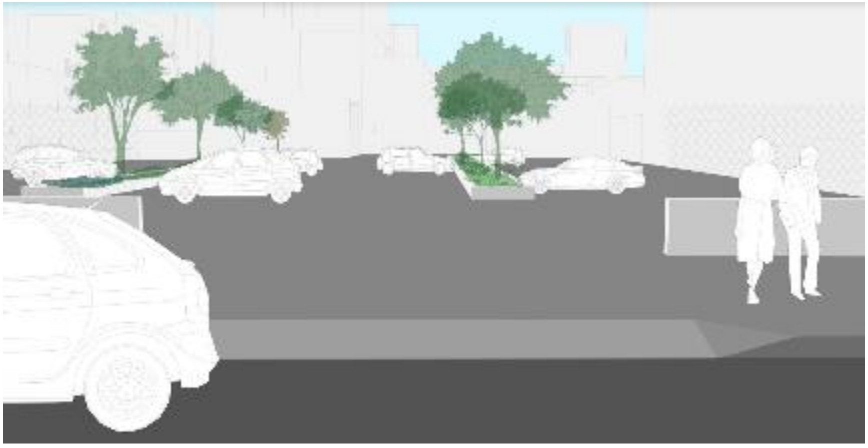


Figure 23. The parking lot proposal.

### 4.3. Proposals for the avenues

The avenues present quite similar structures: wide spaces surrounded by commerce and residential buildings, and densely occupied by pedestrians. Due to its width, it was possible to develop large vegetated and shaded areas and to qualify the existing mobility structures: bike lanes and a bus stop. The sidewalks of Duque de Caxias Ave. present 5.5 metres width on average, while its travel lane presents 8.50 m and and its bike lanes, 1.5 m. In this avenue there are some existing trees, located in its central area, that are surrounded by the two bike lanes (Figure 24).

The cyclists are not protected from the cars, and this was one of the focuses of the proposal. Another concern was about increasing the vegetation. Thus, linear gardens were developed between the bikes and car lanes, on the sidewalks and some parking spaces were converted into green surfaces (Figure 25). The shading potential was enabled, the pedestrian walkability and cycling were qualified and, hence, people were more protected.

Figure 24. The current situation of Duque de Caxias Ave. Source: Image from Google (2022).

Figure 25. The proposal for Duque de Caxias Ave.

For the Rio Branco Ave., the main concerns were to redesign the bus stop, previously completely exposed to the solar radiation, and to increase the vegetation. This avenue lacks vegetation, despite the space available on the sidewalks, 7.5 metres width on average, and being the largest sidewalks of the whole pilot area (Figure 26). Trees were suggested across the sidewalks, through retention gardens, and next to the bus stop, to provide shading to the users and improve walkability (Figure 27). These strategies could stimulate the use of these open areas by, for example, customers from stores, restaurants and cafes. These activities could occur on both day and night periods and increase the sense of security and the social life potential.

Figure 26. The current situation of Rio Branco Ave. Source: Image from Google (2022).

Figure 27. The proposal for Rio Branco Ave.

## 5. Conclusion

The presence of vegetation across the entire urban fabric is essential for adapting and mitigating climate change effects and its extreme events, even where, at a glance, this seems impossible. This implementation is essential to reduce land surface temperature and mitigate urban heating, to increase the rainwater infiltration and to create buffer areas between public and private spaces.

All types of open urban spaces must present urban greening, whether in the streets or within the blocks, especially in consolidated and densely populated and built areas of the city, like the centre of São Paulo. For this, innovative urban redesign proposals are essential for increasing the presence of vegetation and the environmental quality of these spaces, which means improving the walkability and the presence of shaded and pervious surfaces for both urban areas: streets and within the blocks. These actions increase the urban life both during day and at night, which improve the occupation of these urban spaces and increase the sense of security for the users.

Also, a pilot study was developed, which could be replicated for other areas across the city. It is important to highlight the importance of governance, public policies and of a suitable zoning law to make these proposals real. The time to change is now and, although these changes are not simple to be implemented, they are definitely feasible and important to make the cities more resilient and sustainable.

## 6. Acknowledgments

This research was supported by Fundação de Amparo à Pesquisa do Estado de São Paulo – FAPESP (process n. 2021/04751-7), by the National Council for Scientific and Technological Development - CNPq Foundation - for the Research Productivity Grant 312592/2021-3 and undergraduate scholarship PIBIC (process n. 149265/2021-2) and by the University of São Paulo - USP/PRP/PIPAE USP 2021.1.10424.1.9. Thanks to Daniel Yoshida for his collaboration during the simulations on ENVI-met.

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# Investigation: The Urban Heat Island phenomenon in the Holy City of Makkah, Saudi Arabia, and its impacts on energy consumption.

**Abdulaziz Alsharif[1], David HC Chow[2]**

[1]School of Architecture, University of Liverpool, United Kingdom, Abdulaziz@liverpool.ac.uk;
[2]School of Architecture, University of Liverpool, United Kingdom

**Abstract:** The rapid growth of the urban population is impacting and creating challenges for the surrounding environment. The most significant effect of urbanization is rising the temperature in the urban areas that is well known as Urban Heat Island (UHI) effect phenomenon. The UHI causes a serious thermal environmental problem including increasing temperature. This research implemented an on-field measurement to investigate the UHI effect in Makkah city. The aim of this project to study the UHI effect upon energy consumption based on dry-bulb air temperature and relative humidity measurements in the city.

I-button data loggers were used to monitor dry-bulb air temperatures at 36 selected locations to measure the air temperature and the effect of the UHI extension pattern all over the city during year 2019 – 2020. The Arafah site, 18 km from the city center, was selected as the reference station for this research during the experimental period. According to the observation, the monthly day time UHI averages as high as 2.9 C and the monthly night-time UHI average as high as 2.53 C.

Moreover, three main factors were studied (i.e., Sky View Factor, Distance from City centre and Albedo). Thus, an algorithms-based approach was carried out to generate equations for each month, day and hour. The generated algorithms link parameters such as Sky View Factor, Distance from City centre and Albedo to predict the UHI intensity for any site in the city comparing to the reference site.

In addition, a Design-Builder model was used to calculate the buildings' energy consumption. By modifying and applying generated equations to the weather file. the Design-Builder software results revealed the extent of UHI's contribution to increase in energy consumption.

**Keywords:** Cooling Energy, Urban Heat Island, Climate Change. Air Temperature.

## 1. Introduction

Research studies conducted in 2007 indicated that the percentage of the world's population that resided in urban areas was above 50 per cent, and it was expected that this number would increase to 70 % by 2050 (Dutta i et al 2020). As a result of the rising demand for convenience and an improved quality of life, there is likely to be a high pace of urbanization and industrial development in the years following the expansion of economies and human populations. To make more space available for further development in a region, the removal of ground vegetation and land cover is often carried out in conjunction with an increase in the metropolitan area's population. The replacement of natural ground cover with artificial surfaces will result in greater heat retention during the summer months as well as on days with high levels of solar radiation. The climate of metropolitan regions is undergoing significant change as a direct result of the rapid urbanization that is occurring. This phenomenon, which causes air temperature in typical metropolitan areas to be higher in comparison to the immediately bordering rural environment, is known as an Urban Heat Island (UHI) (Bernard j et al 2017). Researchers anticipated that the rise in temperature will be a slow progression from the outskirts of the city to the heart of the metropolitan region, which is predicted to experience maximum temperatures (Bahi h et al 2016). This difference in air temperature between the city and surrounding rural regions is referred to as urban heat island intensity (UHI), which is a term that is used to anticipate urban heat island intensity in an environment (Yang x et al 2020).

The UHI may be attributed to several different factors based on the findings of several research investigations (Yang x et al 2020). These factors have been grouped into four main categories as following: 1) climate of an environment; the geographical location, regional- and city-scale features, such as vegetation, land use, morphology, demography, and topography; 2) local characteristics affecting the temperature, including the structures, surfaces and building characteristics; and 3) anthropogenic activities (Stewart i. d. et al 2012) and meteorological factors such as solar radiation, rainfall, cloud cover and wind. Over the last few decades, the phenomenon of UHI has been studied extensively.

In recent years, relevent research studies have been conducted in various cities all over the world to investigate the effects of UHI. These cities include Manchester in the United Kingdom (Skelhorn c. p et al 2016), Shanghai in China (Zhou y et al 2017), and Riyadh in Saudi Arabia (Bakarman m. a. et al 2015).

Using a variety of approaches of measurement, several in-depth research have been conducted on the phenomen of UHI. On-site measurements (Abuhussain m. a et al 2018), modelling approaches (Bahi h et al 2020) and remote sensing techniques (Seto k. c et al 2013) are the three primary categories into which the methods that may be utilized to assess UHI have been categorized (Abuhussain m. a et al 2018).

It has been shown that this phenomenon is impacted not only by daylight but also by midnight hours. When comparing rural and urban regions during the daytime, the temperature measurements may be comparable; nevertheless, the microclimate profile during the evening hours has a greater air and surface temperature (Zhou et al, 2014). This difference in air or surface temperature may be attributed to heat gain, human heat or solar radiation that is stored in the surrounding thermal mass (Zhou et al, 2014). On a global scale, the relevance of the impacts of UHI may be seen in a powerful way by the performance of buildings. It has been calculated that the UHI effect raises the amount of energy required for cooling by 30 %in Rome and 11 %in Beijing (Guattari et al, 2018).

In addition, the increase in the demand for total energy consumption will range between 0.5 %and 8.5 %per degree of UHI (Santamouris et al, 2015). The Kingdom of Saudi Arabia (KSA), which is the location of the case study, experienced an increase in the amount of power generated during the summer of 2015, from 23 GW during the winter season, to a whopping 60 GW (Howarth N,2020). There is speculation that it will be necessary for an extra 1.18 GW of power to be generated for every one degree Celsius in the rise of air temperature (Krarti et al, 2020).

In 2018, in Saudi Arabia, the residential sector accounted for approximately half of the country's total power consumption, and more than two-thirds of that was used to meet cooling needs. Increasing human population, government policies and unsystematic development have all contributed to cities' structural growth, innovation, and complexity during the previous thirty years.

The experiment was carried out throughout the city, covering the city center as well as urban and rural regions. The collection of data was carried out based on recording hourly temperatures. This research aims to investigate the variation of air temperature between the various areas of the city by addressing the following questions:

1- what are the most important factors that contribute to UHI?
2- What is the impact of the UHI on the energy consumption of cooling residential buildings in the city of Makkah?

## 1.2. Literature Review

The holy city of Makkah, Saudi Arabia's Islamic capital, is a major pilgrimage destination for Muslims globally. Muslims from throughout the world travel to Saudi Arabia to fulfil the obligatory pilgrimage of Umrah and Hajj. The number of 'internal pilgrims', as measured by the Umrah Survey in 2019 was over 2.3 million. By 2030, the number of pilgrims is expected to rise over four million yearly.

The development of the urban area of Makkah city, which includes the Holy Mosque, has rapidly developed in the previous 44 years as a result of the growing number of visitors (AlqurashI et al, 2016). Figure 1 shows the urban development over a period of more than 40 years.

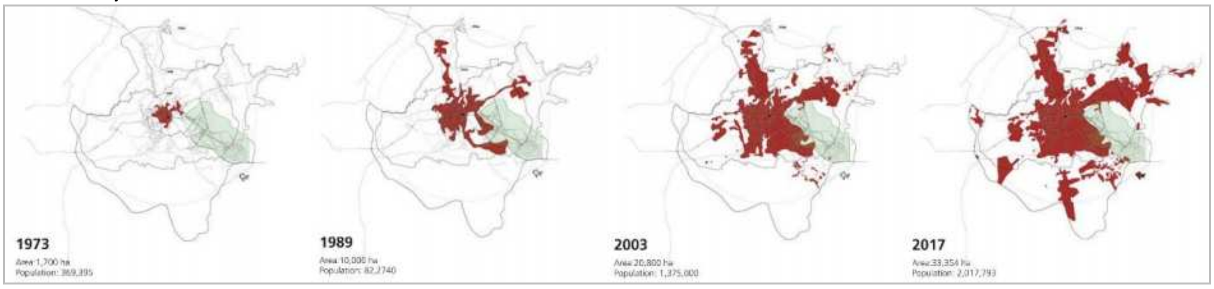


Figure 1 urban development of Makkah from 1973 to 2017.

Makkah is located about 70 kilometres east of the Red Sea. It is located in a geographically diverse territory, extending from longitudes of 39° 35' east to 40° 02' east and latitudes of 21° 09' north to 21° 37' north (Authority for Statistics, 2020); the city's height spans from 82 to 982 meters above sea level, with most development activity concentrated in the lower areas (Authority for Statistics, 2021).

According to the Köppen-Geiger system of climatic classification, the climate of the KSA is best characterized as a hot and arid desert. Makkah's climate is hot and dry, with very low levels of humidity (around 12 days of rainfall per year) (Obure, 2019).

The months of May to October are often the warmest in the city, with July regularly recording temperatures above 45 ℃ (Abdou, 2014). November to April are traditionally the months with the lowest average monthly temperatures, ranging between 23 and 27 ℃ (World Weather & Climate Information, 2021). Figure2 represents Makkah's average maximum, minimum and mean monthly dry-bulb temperatures, respectively.

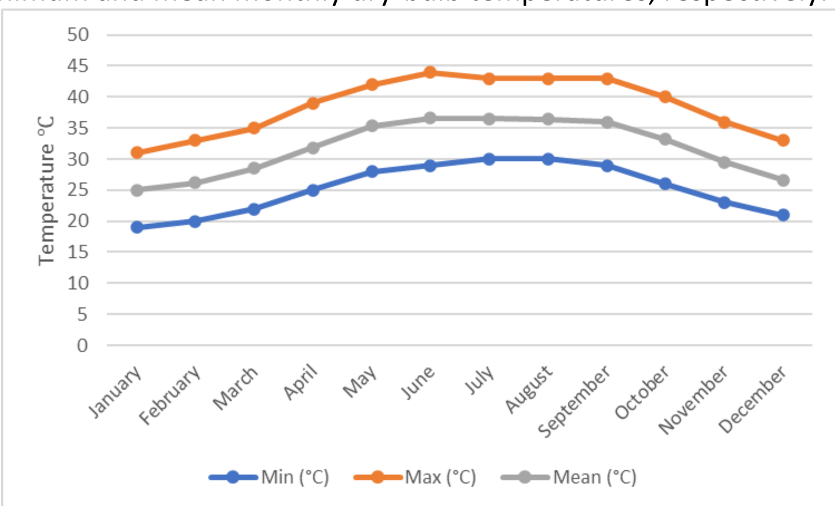


Figure 2. Average air temperature of Makkah

### 1.3. Energy Trend and Building Sector in the Context of Saudi Arabia

In recent years, there has been a significant rise in the amount of energy consumed per capita by the global population, especially in more developed countries of the world. The high pace of urbanization, which has an effect on environmental characteristics, is one of the factors contributing to the increase. According to information gathered from a number of different countries between the years 1970 and 2000, a one %increase in industrialization activities might result in approximately 11 %more emissions per capita. In accordance to Liu x., whose research found that industrialization may have both short-term and long-term effects on the environment, this finding was consistent with their conclusion. Saudi Arabia is rated to be in top position among nations that have levels of energy consumption higher than the world average (Liu and Bae, 2018). In 2012, the country utilized 129.7 million tons of oil and 92.5 million tons of natural gas, respectively. $CO_2$ emissions are a side effect of the exceptional production rate and consumption level of petroleum products and natural gases in the KSA. The country's total $CO_2$ emissions accounted for 2.8 % of the world's total emissions, which placed it tenth on the list of major emitters (Alshehry and Belloumi, 2015).In spite of Saudi Arabia's efforts to diversify its economy, the oil industry continues to dominate the country's financial landscape, accounting for approximately 45 % of the country's gross domestic product (GDP), 75 % of the country's budget revenues and 90 % of the country's earnings from exports (Alyousef and Abu-Ebi, 2012).

### 1.4. Observational Approaches to Study the UHI Phenomenon

Sensors are the most commonly used approaches to examine the UHI phenomenon and measure the air temperature of a particular region over a certain period of time. The air temperature in the urban area is compared to the surrounding rural area to determine the intensity of UHI (Ye et al, 2021). In recent years, the UHI has been the focus of a number of studies. Urban heat island intensity depends on a variety of factors such as rainfall, temperature and relative humidity fluctuations, surface energy fluxes and wind speed (Lee, 2021). The METROMEX project was initiated in the United States in the 1970s as a significant effort on the effects of UHI phnomanan. In 1818, Luke Howard made the first on-field measurements to study the UHI in London (Gartland, 2008). The UHI in Athens was also examined through twenty-three experimental locations in Athens' urban and suburban districts to monitor the ambient air temperature and humidity during 1997 and 1998 (Changnon, 1971).

In recent years, a large number of in-depth research studies have been conducted to investigate the effects of UHI in various parts of the world, including Manchester in the United Kingdom (Skelhorn c. p et al 2016), Shanghai in China (Zhou y et al 2017), and Riyadh in Saudi Arabia (Bakarman m. a. et al 2015). In a recent study on UHI in London, UK, researchers employed a variety of various measurement locations around the city of London. The values that were obtained in these areas were compared by the researcher to the values reported at the reference site, which was the London Heathrow Airport (Kolokotroni et al, 2007) see figure 3.

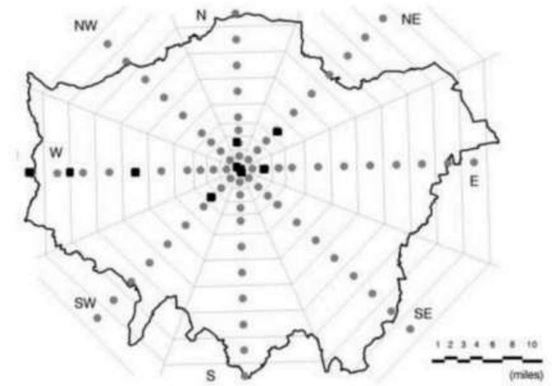


Figure 3. On-field measurement locations in Greater London

A different approach applied to observe UHI impact is via motorcars. This unique investigation of the local climate of Uppsala in Sweden was conducted by Sundborg in 1950 (Sundborg, 1951). The instrument used is shown in Figure 4 and was positioned on top of the vehicle.

Figure 4: The instrument on the automobile

**2. Research Methodology**

The most common method to investigate the UHI phenomena is to install sensors in an urban area to be studied and monitor the ambient air temperature and humidity for an extended period of time. The comparison of urban and rural air temperature fields is used to estimate the UHI level. In 1818, Howard first employed on-field measurements to explore the UHI of Greater London (Cheung, 2011). For this study, 36 experimental stations were set up across the city and suburbs of Makkah to monitor and record the hourly changes in ambient air temperature and humidity by using two types of iButton Data Loggers (DS1923-F5) and (DS1922L-F5). These sensors were situated on lampposts approximately four meters above ground level on streets. The Arafah station's location is mostly free from UHI, and the station was used as a reference station for this investigation in Makkah City, while the official data was not available. The measurement sites and the reference station are shown in Figure 4. Strategically, these locations were chosen based on factors such as sky view, distance from the city centre and space albedo in comparison to the on-field measurements used. According to Howard 2012, identified the UHI as the air temperature difference between the city core and its surrounding rural areas. It hypothesizes that the difference in air temperature ($\Delta T_{u-r}$) between urban and rural areas must rise from the city's suburb toward its core (Mills, 2008). In this research, the monthly average UHI was determined by subtracting the monthly average air temperature of each urban site from the monthly average air temperature of the reference station at the rural site. Moreover, three main factors were studied sky view factor (SVF), distance from the city center, and albedo. The SVF was calculated by a Photographic method by using fish-eye images (Offerle, et al, 2005). The albedo value of each measurement site was estimated by figuring out the average number of pixels of pictures in each direction by using Adobe Photoshop software. (Adobe Guide, 2022). This study applied a basic algorithm to link factors such as SVF, distance from city center, and albedo to predict the UHI for any location compared to the reference station.

### 2.1. Site Selection

The investigation endeavored to explore all urban and rural areas of Makkah city as illustrated in Figure 5, and different orientations all around the city, with the goal of regulating the geographical variances that existed between different locations within the city. The distance from the geographic center of the city is the most important factor considered in the classification of the areas. It has been determined that this is one of the primary factors that contribute to the UHI (Kolokotroni et al, 2007). Through the observation visit, locations were selected based on the chosen parameters (distance, Sky view factor and albedo). All 36 of the different sites were selected to represent all the various characteristics of the urban areas and the reference site to study the temperature variation in Makkah city.

In this study, the impact that population density has on the temperature of the surrounding environment in built-up areas (both urban and suburban) was analyzed. The urban area is distinguished by the presence of a mixed-use districts that include both residential and commercial structures, while the suburban design is an example of an urban area for residential use only. The layout of Makkah city consists of multi-story structures with narrow streets interspersed.

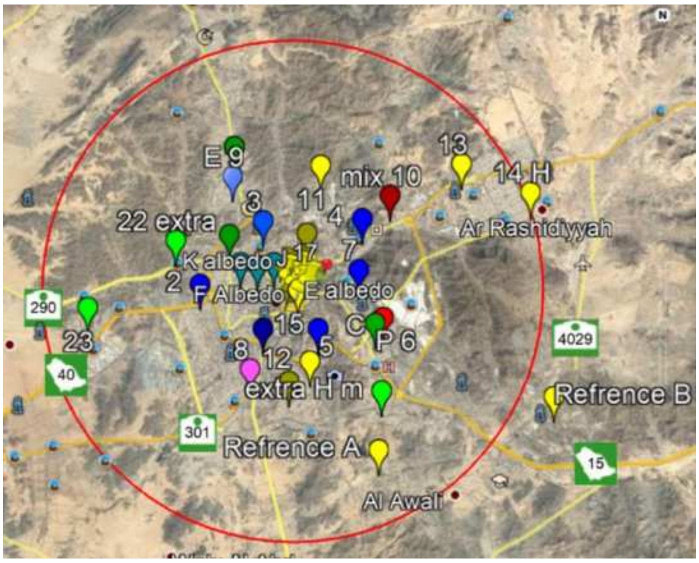

Figure 5. The network maps of sensors of Makkah

### 2.3. Equipment

The main instrument for the experiment in this study is a data logger, which is designed to monitor air temperature and relative humidity simultaneously. The measurement of data loggers should be configured at an interval of one hour. Only battery-powered devices are available for sensing and logging measurements in this case. The battery lifetime and the storage capacity of data loggers should guarantee that at least a whole year's data can be collected and stored safely. Data loggers should be small and lightweight, as they need to be attached and detached easily from the radiation shield for downloading data. The iButton DS1923, a compact battery-powered temperature and humidity data recorder, was chosen. In a secured memory area, a total of 8,192 8-bit measurements. (See Figure 6.)

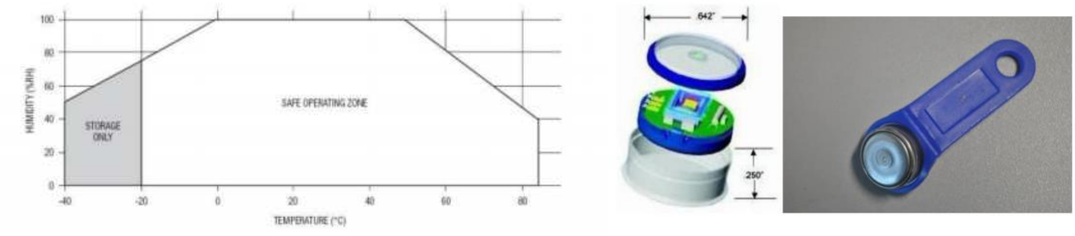

Figure 6. iButton loggers

## 2.4. Data Collection and Field Measurement

When it is necessary to determine the temperature of the air or the thermal environment in an urban setting, sensors are often positioned inside the atmospheric layer of the urban area or the urban border layer. In the study area, the combined effects of the various factors are evaluated using data collected from a variety of sensors and monitoring stations. According to United States Environmental Protection Agency, the UHI phenomena in a region may be measured from surface temperature or ambient air temperature readings. However, air temperature is affected indirectly by surface temperatures and by the density of buildings in an area. The data collection was set to be gathered within each period of three months (Table 1).

Table 1: Date of logger's installation and data collection

| Installation time | 1st data collection & replacement | 2nd data collection & replacement | 3rd data collection & replacement | 4th data collection & replacement |
|---|---|---|---|---|
| 1/5/2019 | 1/7/2019 | 2/9/2019 | 22/12/2019 | 6/6/2020 |

## 3. Data Analysis of On-Field Measurements

This part represents the data analysis collected from on-field measurements in Makkah city. The UHI was investigated by utilizing the data that were collected on air temperature as the dependent variable in the study. This included the average daytime and nighttime temperatures as well as the monthly average temperature to determine the difference between collected air temperature in urban areas and adjoining rural area in a particular period (Despini f. et al 2016). The research approach used in this investigation was one that was applied in different regions of the globe (Kolokotroni et al 2008). According to the observation, the cooling down from the great mosque is affecting the air temperature all over the city, especially in the city center. As shown in Figure 6, there is no clear relationship between the UHI and distance. Therefore, the city center has been investigated as a separate part from other urban areas in this study. (See Figure 7)

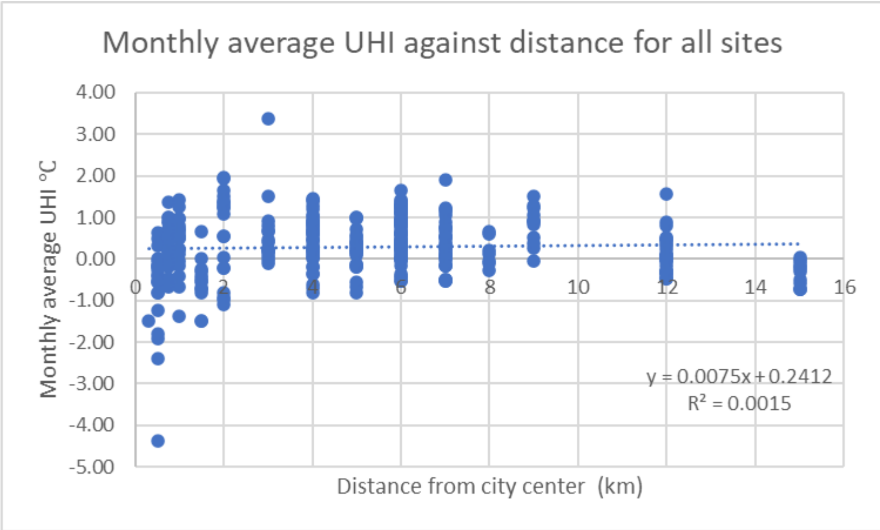


Figure 7. The monthly average UHI of all measured sites of Makkah city.

## 3.1. Daytime and Night-time Averages

### 3.1.1 Urban areas of Makkah city

The data loggers were set to record daytime air temperature per hour from 6 am until 6 pm during the experimental year from 1 May 2019 to 30 April 2020. According to the observation, the monthly daytime UHI average was as high as 2.94℃. For the night-time, the data loggers were also set to record night-time air temperature per hour from 7 pm until 5 am. The monthly night-time UHI average as hight as 2.53 C. At night, heat from nearby built-up areas is often released into the atmosphere, resulting in increased air temperatures, which is one of the primary causes of the UHI condition (Kardinal jusuf s 2007). In various studies, it has been shown that UHI has considerable impact on building performance and thermal comfort in the surrounding (Guattari et al, 2018). Furthermore, the UHI pattern for night-time over Makkah city is dominated by a strong linear and negative relationship between UHI and distance toward the city centre. It is shown in Figure 8 that UHI values gradually increase toward the city centre of Makkah.

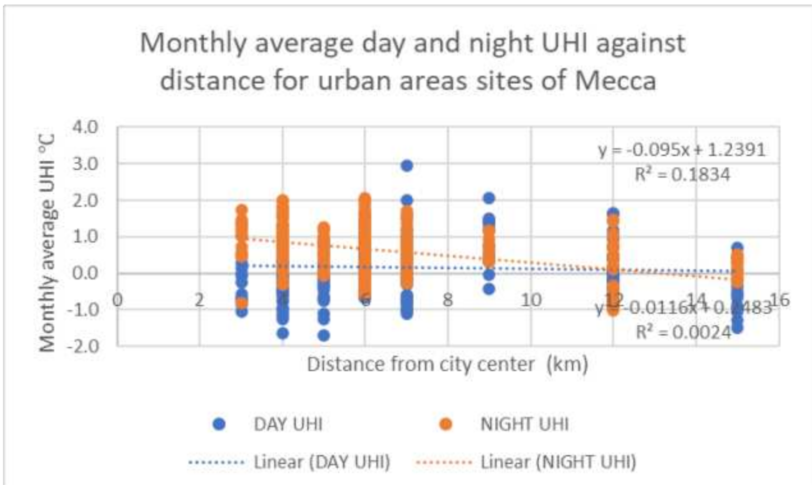


Figure 8. Day/Night-time UHI average of measured sites in urban areas against distance from city center.

#### 3.1.2 city center

The UHI pattern effect depends on the local urban morphology types and the distance from the city centre. The UHI effect is pronounced in the city centre where buildings are concentrated. In this case study, it was determined that Makkah's city centre has an especial situation than other parts of the city. The cooling from the Great Mosque has caused the city's central area to become much cooler than the rural site. This observation illustrates that there is a significant linear and positive relationship between UHI and the distance from the city centre, which is in contradiction with previous studies (See Figure 9).

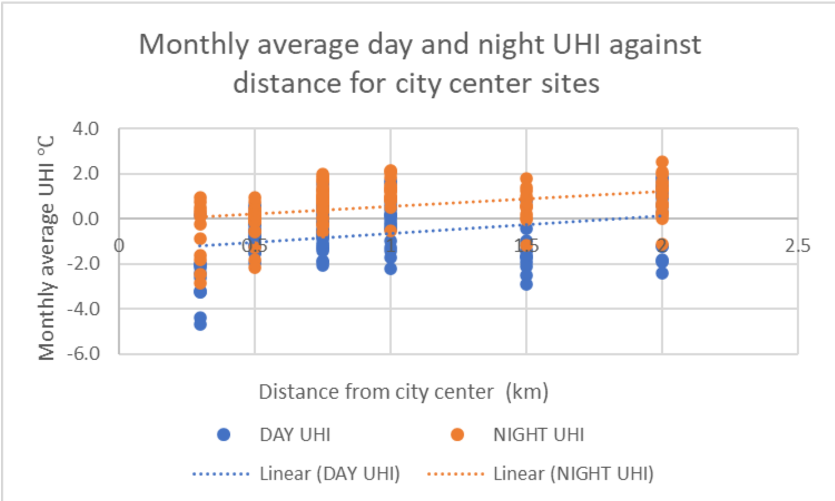

Figure 9: The decrement of UHI at city centre due to the cooling down from great mosque

### 4. Modelling and validation.

#### 4.1 Modelling.

In order to investigate the influence of UHI on residential building energy consumption in Makkah City, Saudi Arabia, a single-family house (villa) has been chosen to be the case study for this research. This building was considered a typical residential house in Makkah. The model was built based on the architectural drawings by DesignBuilder software, as shown in figure 10. This simulation tool was used to investigate the impact of the UHI effect on energy consumption performance. The building characteristics, including construction materials, cooling system types, lights, and equipment of the physical villa, were applied and modelled in DesignBuilder with occupancy and activity profiles as shown in table 1.
The building construction materials, types of cooling systems, lights, and equipment were used to model the building in DesignBuilder, along with the occupancy and activity profiles shown in table 2.

#### 4.2 Validation

The actual air temperature was obtained by recording the hourly air temperature at the rural site. An Ibutton datalogger (DS1923-F5# Hygrochron) was placed in a rural area to be free from the UHI effect. In addition, the Ibutton datalogger (DS1923-F5# Hygrochron) was installed on a lamppost within four metres of the ground and shielded from direct sunshine and precipitation. The process of on field measurements began in May 2019 and ended in April 2020. Figure 11 shows a comparison between monthly utility bill consumption and DesignBuilder results during the entire year. Based on the comparison, the researcher can consider the model valid as long as the monthly difference between simulated and measured results in terms of energy consumption is less than 15% (Ashrae. 2009). The calibration processes were primarily used to validate the DesignBuilder model's results. In order to conduct research on the impact of the climate change scenario simulations, it is necessary to bolster a level of confidence and certainty about the simulations.

Figure 10: case study

Table 2: Date of logger's installation and data collection

| | |
|---|---|
| **No. of floor** | 2 floors+ annex |
| **Total area of ground** | 364.25 m2 |
| **Building Height** | 9.6 m |
| **Orientation** | East |
| **External/ Internal walls** | 20 mm mortar (outer surface), 200 mm Concrete block, 20 mm mortar (inner surface) |
| **Internal floors** | 10 mm ceramic tiles (outer surface), 25 mm mortar, 300 mm Reinforced Concrete, 20 mm mortar (inner surface) |
| **Roof** | 25 mm Terrazzo Tiles (outer surface)<br>25 mm mortar, 07 mm concrete foam, 300 mm Reinforced Concrete, 20 mm mortar (inner surface) |
| **Window glazing** | 6 mm double clear glazing |
| **Infiltration rate** | 7 ac/h (estimated) |
| **HVAC system** | Split no fresh air |
| **Occupancy** | 0.0109 person/m2 |
| **Cooling set point temperature** | 25.5 ◦C (stated in the code) |

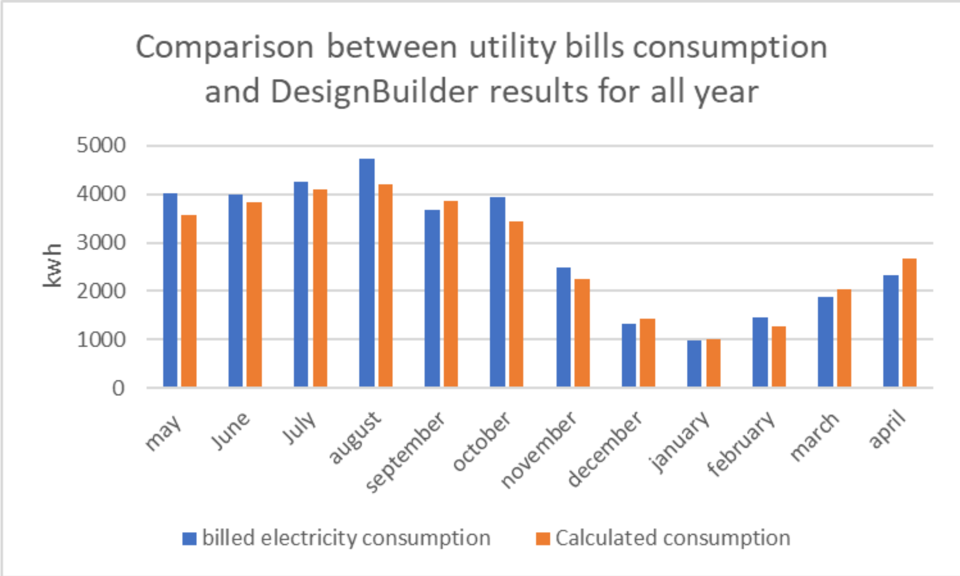


Figure 11: Comparison between utility bills consumption and DesignBuilder results for one year.

**5.Simulation Process.**

In order to generate weather files (TMY1: urban areas and TMY2: city center) based on the reference site weather file TMY, including the UHI for the city center and for all over the urban areas in Makkah, The TMY weather file for reference sites was changed by adding the UHI values, which are the difference in air temperature between the city center site and the reference site. For this study, the UHI values associated with three major factors (namely, sky view factor, distance from the city center, and albedo) were calculated to be used in DesignBuilder Software to examine the energy consumption. Thus, an algorithms-based approach was conducted to generate equations for each month over different periods of time. The generated algorithms were used to link parameters such as sky view factor, distance from the city center, and albedo to predict the UHI for any site in the city in comparison to the reference site. The monthly energy in DesignBuilder Software simulation results for the basic case of a typical residential house of Makkah is shown below in (Tables 2 and 3).

Table 3. Monthly cooling energy of the typical residential house of Makkah for a one-year period based on original and modified TMY weather data.

| Cooling energy(kWh) | MAY | JUN | JULY | AUG | SEP | OCT |
|---|---|---|---|---|---|---|
| **Reference sites TMY** | 10292.4 | 12277.17 | 12747.5 | 12061.33 | 12731.8 | 10104.77 |
| **Modified TMY 1** | 11172.99 | 12818.68 | 12796.64 | 12322.48 | 13098.2 | 10836.41 |
| **Modified TMY 2** | 10032.34 | 10492.42 | 11399.1 | 12071.93 | 11183 | 10101.27 |
| | | | | | | |
| **Percentage of increase** $\frac{T-T1}{T}$ | 9% | 4% | 0% | 2% | 3% | 7% |
| | | | | | | |
| **Percentage of increase** | -3% | -15% | -11% | 0% | -12% | 0% |

| | | | | | | |
|---|---|---|---|---|---|---|
| $\frac{T - T2}{T}$ | | | | | | |

Table 4. Monthly cooling energy of the typical residential house of Makkah for a one-year period based on original and modified TMY weather data.

| Cooling energy (kWh) | NOV | DEC | JAN | FEB | MARCH | APRIL |
|---|---|---|---|---|---|---|
| **Reference sites TMY** | 7814.232 | 5001.617 | 2727.1 | 3683.587 | 5964.785 | 7996.377 |
| **Modified TMY 1** | 8351.616 | 5174.937 | 2907.381 | 3686.416 | 6380.924 | 8289.675 |
| **Modified TMY 2** | 6699.956 | 4319.628 | 3058.822 | 3831.63 | 5882.182 | 7551.299 |
| | | | | | | |
| **Percentage of increase** $\frac{T - T1}{T}$ | 7% | 3% | 7% | 0% | 7% | 4% |
| | | | | | | |
| **Percentage of increase** $\frac{T - T2}{T}$ | -14% | -14% | 12% | 4% | -1% | -6% |

## 6. Discussion and Conclusion

This study investigated the UHI and its effect on energy consumption. Urbanization has been blamed for the rise in the incidence of the UHI phenomena. Due to an increase in human population, metropolitan areas often see a significant increase in infrastructure development.

The magnitude of the UHI impact varies with distance to the city center and local urban morphology types. Theoretically, the UHI effect is pronounced in the city center, where buildings are concentrated. Due to the cooling effect from the Great Mosque, the city center is closer to the rural areas in this case study. The urban areas of Makkah city are experiencing a higher temperature than the rural areas. The distance from the city center factor is associated with the UHI intensity and is pronounced during the nighttime.

The occurrence of the UHI phenomena has been linked to the expansion and development of urban areas. As a result, urban centres often have air temperatures that are higher than surrounding rural settlements, which are located within the same borders (Santamouris m et al 2014). In a review of previous research on the effect of UHI on energy consumption in buildings, it was indicated that UHI can lead to increasing the demand for cooling by up to 19 % (li x et al 2019).

When considering the microclimate of Makkah city, it was found that there is a significant difference in the air temperature between the city centre and other urban areas throughout the city. The urban area throughout Makkah except the city centre has the highest nighttime UHI of any other urban and suburban areas of Makkah.

DesignBuilder Software was used for this study as a simulation to calculate the cooling demand based on modified weather files that took the UHI into account. It is clear that the cooling effect from the Great Mosque has affected the UHI in the city centre, and the effect was clear during winter in January and February 2020 when the cooling down was turned off, energy consumption increased in these months by 12% and 4%, respectively.

Furthermore, the energy consumption for the urban areas throughout the city, excluding the city center, increased monthly and reached up to 9% in May 2019. Therefore, there is still an increase in cooling energy demand due to climate change.

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# The effect of environmental settings on walking comfort of older and younger adults in very hot weathers

**Zheng Tan[1], Georgios Christopoulos[2], and Adam C. Roberts[3]**

[1] The Hong Kong Polytechnic University, Hong Kong S.A.R. (China), tanya.tan@polyu.edu.hk
[2] Nanyang Technological University, Singapore
[3] Singapore-ETH Centre

**Abstract:** Walking effectively reduces age-related risks of chronic diseases and promotes active ageing among older adults. However, thermal discomfort experienced in hot weathers affects the willingness to walk. Thermal comfort in walking is a relatively less explored field, but it is essential to provide further understanding on outdoor comfort. This study investigated the interrelationship between microclimate conditions, environmental settings, and comfort sensation in walking. Older-adult and younger-adult participants were recruited to conduct a walking experiment in urban green spaces and densely built-up areas. On-site measurements were conducted to record microclimate variables in different environmental settings. Thermal sensation votes were obtained. The physiological equivalent temperature (PET) was estimated with microclimate variables, clothing index, and metabolic rates calculated with individual walking speed. The results indicate that after reaching thermal discomfort walking in unshaded areas, tree shade can effectively restore comfort in very hot weather. Building shade would change the thermal sensation from "hot" to "slightly warm", but not to the neutral level. Compared to younger adults, older adults tend to have a larger difference in thermal sensation when they walk in built-up areas and green space, and also a more noticeable difference in neutral PETs obtained in these two environmental settings. Based on this study, neutral PETs for older adults in walking were 31.6°C in green spaces and 33°C in built-up areas. Neutral PETs for younger adults in walking were 32°C and 32.6°C in green spaces and built-up areas, respectively.

**Keywords:** Walking Comfort; Very Hot Weather; Age-Friendly Environment

## 1. Introduction

Over the past two decades, there have been an increasing number of outdoor thermal comfort studies. All three aspects defining thermal comfort, i.e., the psychological aspect, the thermophysiological aspect, and the energy exchange with the environment, show different characteristics in the assessments of indoor and outdoor thermal comfort (Höppe 2002). In terms of psychological aspect, people tend to have different psychological expectations and a larger comfort zone outdoors than indoors (Nikolopoulou and Steemers 2003; Yan et al. 2016), as a result of more diverse weather conditions in the outdoor environments. In addition, compared to the fixed and static indoor settings, the outdoor spaces offer more stimulation. As for the thermophysiological aspect, the steady state models established under indoor conditions tend to overestimate discomfort in outdoor environments. As explained by Höppe (2002), steady state is seldom achieved in the outdoor spaces, due to the highly diverse environments and the relatively short period of stay.

In outdoor spaces, people are usually in movement. Human metabolic rate changes from resting to walking, which is an important parameter in the discussion of thermal comfort (Zhang et al. 2020). On the other hand, in outdoor settings, the complex urban morphologies create continuously varying microclimate conditions (cite). A person would experience varying thermal sensation when walking between those outdoor spaces in a temporal and spatial sequence (Vasilikou and Nikolopoulou 2020). When people are walking in the city, they spend a relatively short time in one microclimate condition and are subject to more diverse and contrasting environments than in indoor spaces. In addition, during a walking trip, one has access to continuous views, scenes, and stimulation from the urban environments (Labdaoui et al. 2021). How these factors play a role on the psychological aspects of comfort sensation remains unclear. In terms of pedestrian thermal comfort studies, comfort during walking is an emerging topic that is worth investigating.

Walking effectively reduces age-related risks of chronic diseases and promotes active ageing among older adults (Buehler and Pucher 2012). However, thermal discomfort experienced in hot and humid regions affects physical activities and the use of outdoor spaces (Lin et al. 2010), especially for the older user group (Huang et al. 2020). On the one hand, the elderly are particularly vulnerable to heat stress (Fouillet et al. 2006), on the other hand, a recent study found that elderly people have relatively low thermal sensitivity and require a more intense thermal stimulus to elicit the appropriate behavioral responses (Jiao et al. 2017). An earlier study done by Schellen et al. (2010) also noted that the elderly preferred a higher temperature than young adults. Therefore, older adults should be analyzed as a separate group in the studies of thermal comfort in walking.

In summary, thermal comfort in walking should be studied to provide further understanding on outdoor comfort. With a special focus on older adults, this study aims to investigate the interrelationship between microclimate conditions, urban settings, and physiological responses and comfort sensation in walking.

## 2. Method

### 2.1 Site information

The study was carried out in Hong Kong, a high-density city located in the subtropics. The hot-humid climate in the city causes thermal discomfort in the long summer (Wang et al. 2021). Hong Kong has one of the fastest ageing populations in Asia. The population aged 65 and above will reach 2.44 million (approximately 32% of the total population) in 2038 (Census and Statistics Department, 2016).

This study combines a real-site experiment with a longitudinal survey. Such a method is suitable to provide an understanding of thermal sensation during walking in varying urban settings, while allowing a relatively small number of participants to be sampled more than once without introducing too much individual bias (Chen et al., 2012). The experiment is conducted in a traditional neighbourhood in Sham Shui Po (Figure-1).

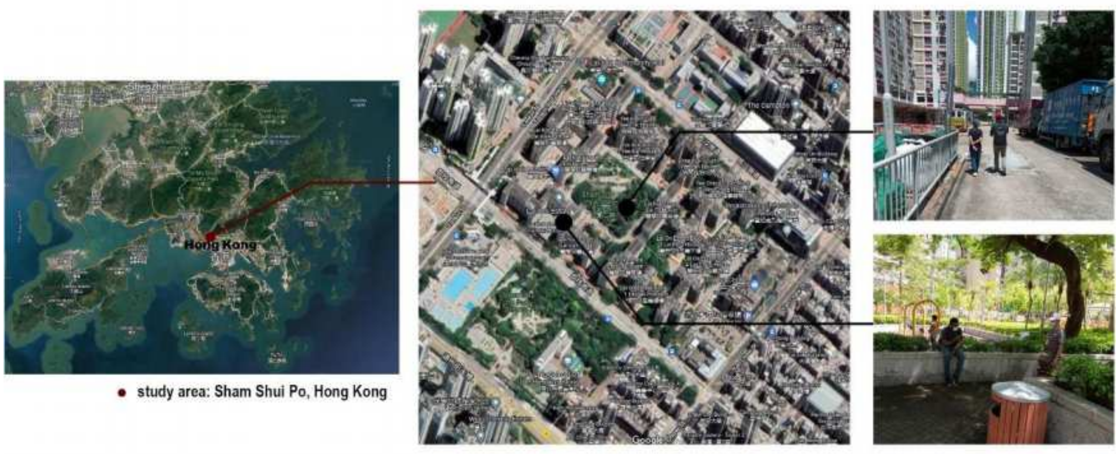


Figure 1. Sites for field experiment in Sham Shui Po district, Hong Kong.

2.2 Experiment setting

The experiments were conducted between 10:00 am and 12:00 pm, on very hot days in August and September of 2021, when the “very hot weather warning” was issued by the Hong Kong Observatory (according to Lee et al. (2016), the issuance of very hot weather warning considers the effect of air temperature, wind speed, and relative humidity on human, and the forecast regional dry bulb temperatures). In the experiment, each participant conducted a walk in the green space and the built-up area settings, respectively. In both settings, the participant walked alternately in shade and exposed to solar radiation with a “shaded” – “unshaded” – “shaded” sequence. Shading was provided by trees in the green space, and by buildings in the built-up area (see Figure-2). For one participant, the time for the whole experiment was controlled to be within 30 minutes, to minimize the fluctuation of the background weather.

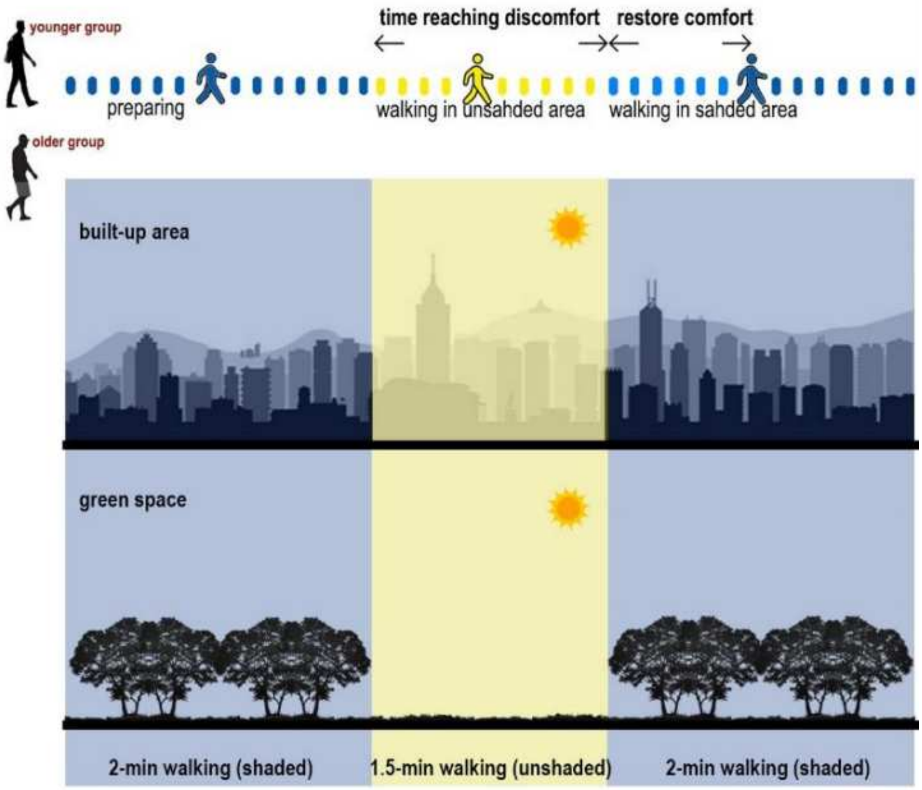


Figure 2. experiment design

2.3 participants

The study recruited 20 local residents on site to participate in the experiments. The sample can be categorized into two groups: an older adult group and a younger-adult group. Participants in the older-adult group were 65 to 83 years old, and those in the younger-group were 20 to 33 years old. All participants stayed in Hong Kong in the 6 months prior to the experiment. In 2020, male to female ratio for Hong Kong was 0.84 (Census and Statistics Department, 2021). In the sample, both groups consisted of six females and four males. All the participants were in good physical condition to conduct the experiment. During the recruitment, the participants were briefed about the procedures on site. They all self-affirmed that they were physically able to participate in the study and signed an informed consent form before the experiment.

2.4 Microclimate measurement

During the measurement period, the air temperatures recorded at Hong Kong Observatory station were between 30°C and 33°C. On both studied sites, microclimate conditions in the "shaded" and "unshaded" areas were assessed by mobile meteorological stations, respectively. With the TESTO 400 instrument, the mobile meteorological stations recorded data on wind speed (v), air temperature (Ta), relative humidity (RH) with a one-second sampling and logging interval. Globe temperature (Tg) was measured using a globe thermometer (150-mm diameter black ball probe with TC type K sensor inserted). All equipment set-ups were tested and calibrated before the survey. The mean radiant temperature Tmrt, an index summarizing all different radiation fluxes in the space and evaluating the radiant environment (Fröhlich et al. 2019), was calculated with the measurement data (Ta, RH, v, and Tg) adopting the ISO 7726 (1998) forced convection formula.

2.5 Physiological responses and thermal sensation vote

The physiological equivalent temperature (PET) is a comprehensive thermal comfort index, which was designed to integrate the complex effects of environmental parameters and human factors in outdoor comfort assessment (Höppe 1999). In this study, PET is computed using the RAYMAN model (Matzarakis & Ruiz 2010). The calculation is based on four climatic variables, Ta, RH, v, and $T_{mrt}$; and two human factors, clothing level and metabolic activity. Inputs of climatic variables were based on measurement data. The clothing levels of all participants during the experiment were typical light summer clothing, and a clothing value of 0.5 was assigned. The metabolic rates of the participants were estimated adopting the MET (Metabolic Equivalent of Task) index, which is an indicator for the absolute intensity and caloric expenditure of different physical activities (in this case, walking) (Glass et al. 2007). MET was individually assessed for all participants in each experimental phase based on the walking speeds recorded (Coelho-Ravagnani et al. 2013). Thermal sensation votes (TSV) were simultaneously obtained from the participant by asking them their comfort level every 15 seconds, using the ASHRAE seven-point sensation scale.

## 3. Results

3.1 Thermal sensation in walking

Figure-3 shows the thermal sensation votes placed in time sequence, which were obtained from the participants when they walked in the three phases. When being recruited on site, participants were at "neutral" to "slightly warm" status (TSV 0.6–1.1). After walking for 2 minutes in shade in green space, TSV of older-adult group slightly increased from 0.8 to 1.1 (slightly warm), and younger-adult group from 0.6 to 1.1 (slightly warm). Much more profound increase in TSV were observed in built-up area setting than green space setting. For example, TSV increased from 1.1 to 1.8 (warm) for the older-adult group in built-up area setting. It is worth to note that in both settings, the older-adult group and younger-adult group were at similar levels of thermal sensation at the beginning of the second phase (unshaded).

In the second phase, participants were walking in unshaded areas for 1.5 minutes. TSV increased rapidly and reached maximum values (TSV max) in the second phase. For older-adult group, TSV max = 3 (hot) when walking in unshaded built-up area setting, and TSV max = 2.3 (warm) when walking in unshaded green space setting. For younger-adult group, TSV max were 2.7 (warm–hot) and 2.5 (warm–hot) for unshaded built-up area setting and green space setting, respectively.

The participants entered the shaded areas after walking in unshaded areas, and the TSV began to descend in the third phase (shaded). Minimum TSV values in the third phase are defined as TSV min. When walking under tree shade in green spaces, TSV min of the older-adult group reduced to 0.2 (neutral), and TSV min of the younger-adult group were 0.6 (neutral–slightly warm). Meanwhile, TSV min was 0.8 (slightly warm) for younger-adult group and 1.3 (slightly warm) for older-adult group, when walking in the shaded built-up areas. For the overall sample, it took average 45 seconds walking in shaded green spaces to restore comfort (neutral), after walking in unshaded areas. when walking in shaded built-up areas, an average of 72 seconds would be needed to reach TSV min. A two-way ANOVA was performed to analyze the effect of age and environmental setting on time reaching TSV min. It revealed that the interaction effect was nonsignificant (F=1.860, p=0.181, n=20). Simple main effect analysis showed that environmental setting had a statistically significant effect (F=6.025, p=0.019) on time needed to reach TSV min, while the influence of age is nonsignificant (F=0.669, p=0.419).

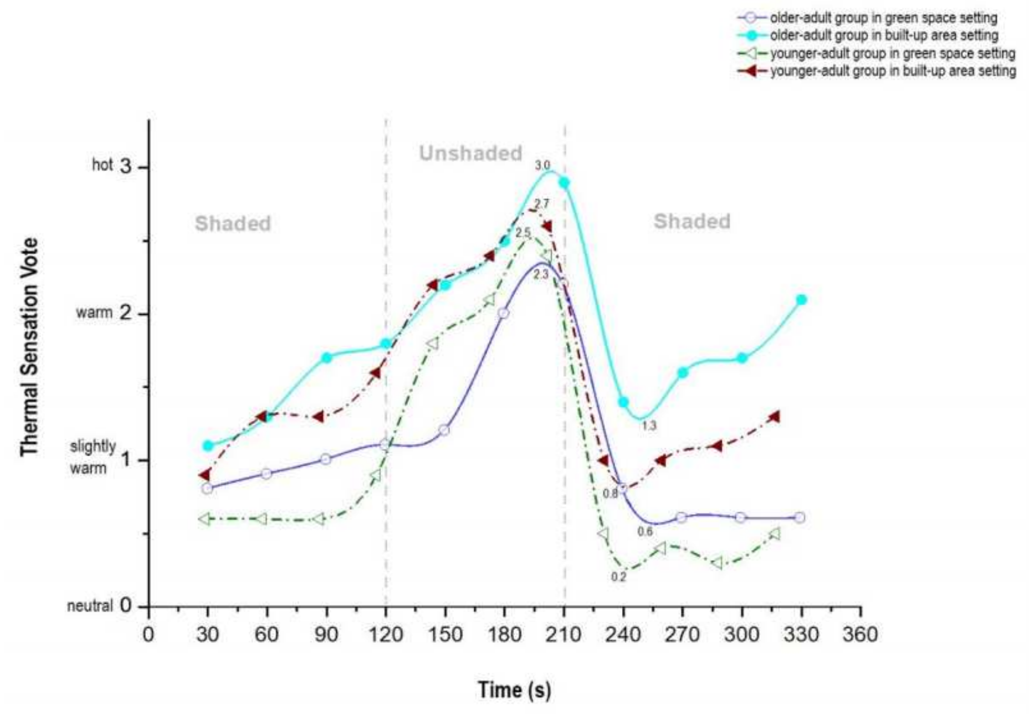


Figure 3. Average thermal sensation votes (TSV) while walking through the Shaded-Unshaded-Shaded sections in built up and green areas for both young and older adults.

3.2 PETs in walking

PET values during walking were computed with the measured microclimate variables and recorded walking speeds in each phase (shaded-exposed-shaded). PETs experienced when walking in built-up urban setting were 34.9°C–36.6°C in shaded areas, and 37.5°C–38.8°C in exposed areas. When walking in green spaces, PET values were 32.8°C–34.3°C in shaded areas, and 35.9°C–37.1°C in exposed areas. Figure-1 shows the correlations between the computed PET values and the thermal sensation vote obtained from the older-adult group and younger-adult group in different settings. According to the regression lines, the neutral PETs (TSV=0) obtained in green space setting are lower than that in built-up urban setting. Neutral PETs for walking in green spaces were 31.6°C and 32°C for older-adult group and younger-adult group, respectively. Neutral PETs for walking in built-up urban areas were 33°C for older-adult group and 32.6°C for younger-adult group.

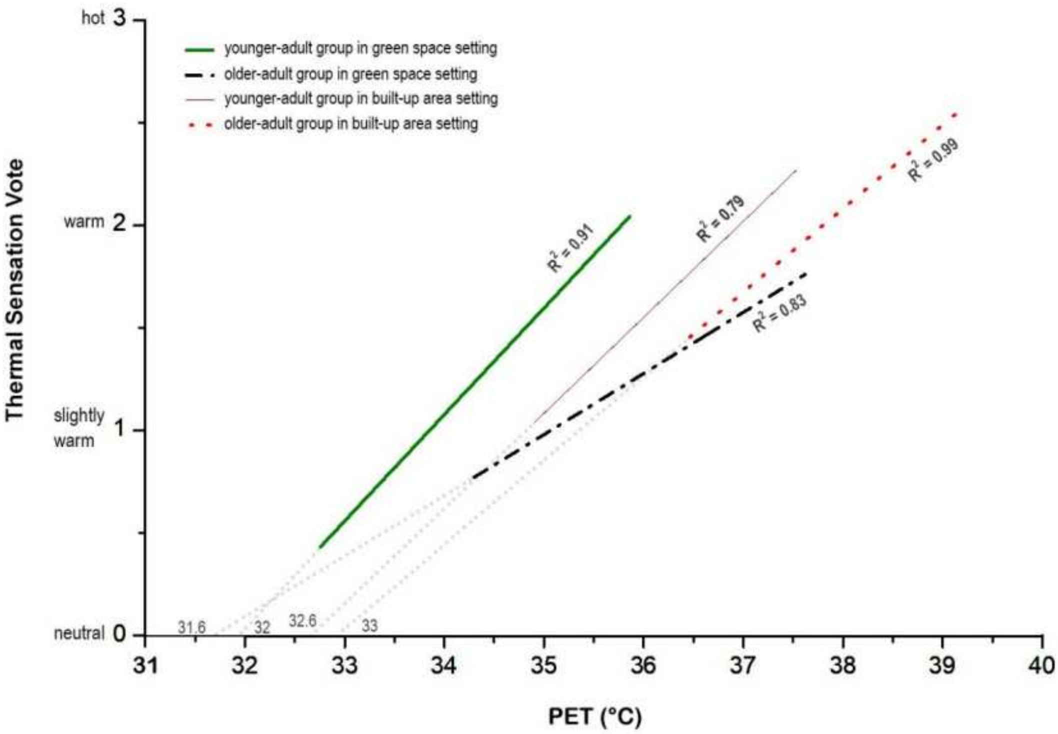


Figure 4. correlations between PET and TSV in different environmental settings for younger and older adults.

3.3 Effect of age and gender on thermal sensation in walking

The effects of age on thermal sensation in walking was analysed with two-tailed t-test between the older-adult group and the younger-adult group. A significant difference in TSV between the older-adult group and younger-adult group was detected in the third phrase, when walking in the shaded built-up areas. The average TSV for the older-adult group was 1.7, and for the younger-adult group it was 1.1 ($p = 0.049$).

For older-adult group, the average TSV was significantly higher ($p = 0.034$) when walking in the unshaded built-up areas (TSV = 2.5) than walking in the unshaded green spaces (TSV = 1.8). Both the older-adult group and younger-adult group had significantly higher TSVs when walking in the shaded built-up areas than walking in the shaded green spaces during the third phrase. For older-adult group, averaged TSVs obtained were 1.7 and 0.6 when walking in the shaded built-up areas and shaded green spaces, respectively ($p = 0.002$). For younger adult group, it was 1.1 for shaded built-up areas and 0.4 for shaded green spaces ($p = 0.016$).

The effects of gander on thermal sensation in walking was also explored. The only significant difference between male and female participants was detected in the first stage walking (shaded). However, such difference may be introduced by the various comfort status of the participants at the start of the experiment. Female participants showed significantly higher TSVs when walking in the built-up area setting than in the green space setting, during all phrases. For example, in the second phrase, average TSV for female participants walking in the unshaded built-up areas was 2.6, and it was 1.9 for unshaded green spaces ($p = 0.006$). In the third phrase, both male and female participants showed profound differences in TSVs when walking in difference environmental settings. The average of TSV were 1.6 and 0.6 for walking in shaded built-up areas and shaded green spaces, respectively, for female participants ($p<0.001$). For male participants, the averaged TSV was 1.2 when walking in the shaded built-up areas, and 0.4 when walking in the shaded green spaces ($p = 0.015$).

## 4. Discussion and conclusion

The results reveal that walking in shaded green spaces can effectively restore comfort in the third phrase, in both magnitude of comfort sensation and time course. 45-second walking in shaded green spaces would improve TSV from "warm-hot" to "neutral" or "neutral-slightly warm". Furthermore, the thermal sensation stayed in similar comfort level during the rest of the walk. On the contrary, walking in the shaded built-up areas would change the TSV from "hot" to "slightly warm", but not the neutral condition. It also takes a longer time (72 seconds) to reach the minimum TSV walking in shaded built-up areas. After reaching the minimum values, TSV slowly increased during the rest of the walk in shaded built-up areas.

The study revealed neutral PETs during walking in very hot weather. Neutral PETs for older adults in walking were 31.6°C in green spaces and 33°C in built-up areas. Neutral PETs for younger adults in walking were and 32°C and 32.6°C in green spaces and built-up areas, respectively. According to previous studies, neutral PET in stationary state in similar hot-humid climate context were 26°C - 30°C (Cheng et al. 2012; Lin et al. 2010).

The study points to the importance of green spaces in creating pleasant neighbourhood environments for senior residents. Scientific understanding on the planning and design of green spaces is essential for creating age-friendly urban areas to facilitate active ageing.

This study has several limitations. The sample size of the study is relatively small. This is due to difficulties recruiting local residents on site. Having said that, the study adopted a longitudinal experiment approach, in which a relatively small number of participants are followed and evaluated over different environmental settings. Such an approach can limit the bias introduced by individual differences in thermal perception in a large sample. Another limitation is that the experiments were conducted in different days and therefore, under slightly different background weathers. The control here is that all measurements were conducted during a period where a very hot weather warning was issued. In future studies, a more specific criteria on comparable background weathers should be set up to reduce related bias.

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# Gender effects on thermal perception: A controlled experiment

**Ricardo Forgiarini Rupp*, Natalia Giraldo Vasquez and Jørn Toftum**

International Centre for Indoor Environment and Energy, Department of Environmental and Resource Engineering, Technical University of Denmark, Nils Koppels Allé, Building 402, 2800 Kgs. Lyngby, Denmark, *rrifo@dtu.dk

**Abstract:** Gender is one of the main factors explored in earlier thermal comfort studies. The main objective of this work is to analyse potential gender effects on thermal perception under equivalent thermal conditions. The method is based on controlled experiments involving human subjects who were exposed to different thermal conditions in a climate chamber. During the experiments, participants were asked to answer questionnaires including background questions (e.g. physical characteristics) and thermal perception questions (thermal sensation, preference, comfort and acceptability). The criteria for the subject's participation took into account age, gender, body composition, health condition and thermal history. In total, 24 subjects participated in the experiments (50% females). Results showed that, in fact, gender had no significant effect on thermal perception under equivalent thermal conditions.

**Keywords:** Thermal comfort, Personal factors, Controlled experiments.

## 1. Introduction

Previous research has shown that contextual (e.g. ventilation type) and personal factors (e.g. gender) play a role in the perception of thermal comfort (Rupp et al., 2018; Wang et al., 2020). Gender is one of the main factors explored in earlier laboratory (Fanger, 1970) and field studies (Maykot et al., 2018; Indraganti and Humphreys, 2021), where an overall trend was that females were more dissatisfied in a specific thermal environment when compared to their male counterparts (Karjalainen, 2012). However, most studies have been performed in actual buildings, where confounding variables (e.g. body composition, age, clothing) could not be controlled or properly measured, which might be the reason for the differences in thermal perception. For instance, different clothing behaviours have been pointed out as one of the reasons for gender differences in thermal comfort in actual buildings (Indraganti et al., 2015; Wang et al. 2018). Thus, a well-controlled experiment is needed to assess if gender has a significant impact on thermal perception, including thermal sensation, preference, comfort and acceptability.

The main objective of this work is to analyse potential gender differences in thermal perception under equivalent thermal conditions.

## 2. Method

The method was developed using controlled experiments involving human participants who were exposed to various temperatures in a climate chamber equipped with laboratory quality instruments to measure the air and globe temperatures, relative humidity, and air velocity. The climate chamber provided a homogeneous thermal environment. The participants' activities during the experiments simulated office work. The participants were chosen based on their age, gender, body composition (body mass index - BMI), health status and thermal history. The experiments involved a total of 24 people (50 percent females) – Table 1.

The experimental protocol consisted in exposing each individual to three temperatures in a randomized order: 20°C, 25°C, and 30°C – Cool, Neutral, and Warm conditions. Subjects were exposed to the three temperatures on different days, always at the same time slot. All other environmental parameters were kept constant, e.g. air speed was kept below 0.1 m/s. Other possibly influential parameters were controlled (for example, clothing insulation was set to 0.61 clo and activity was restricted to reading and typing on a computer). Subjects wore a long-sleeve shirt, trousers, ankle high socks, shoes and underwear. Each experimental session lasted 120 minutes in total (first 30 minutes of acclimatization, followed by 90 minutes where subjects answered thermal perception questionnaires including thermal sensation, preference, comfort and acceptability).

Data analysis included descriptive statistics and linear mixed-effects modelling.

Table 1. Characteristics of the participants.

| Gender/Parameter | N | Age (years) | Height* (m) | Weight* (kg) | BMI (kg/m$^2$) | Body fat* (%) |
|---|---|---|---|---|---|---|
| Females | 12 | 25.6±2.2 | 1.67±0.06 | 60.6±8.4 | 21.6±2.0 | 29.2±4.8 |
| Males | 12 | 23.4±2.5 | 1.82±0.05 | 71.2±9.1 | 21.5±2.4 | 17.9±4.9 |

* indicates a significant difference ($p<0.05$) between gender, independent *t*-test.

## 3. Results

Table 2 presents a summary of statistics of thermal sensation votes (TSV) and Figure 1 the interaction between experimental condition and gender. Overall, we observed that females felt cooler thermal sensations than males, except in the warm experimental condition, where the responses were virtually the same between gender. However, differences were modest and not statistically significant, as described in detail as follows.

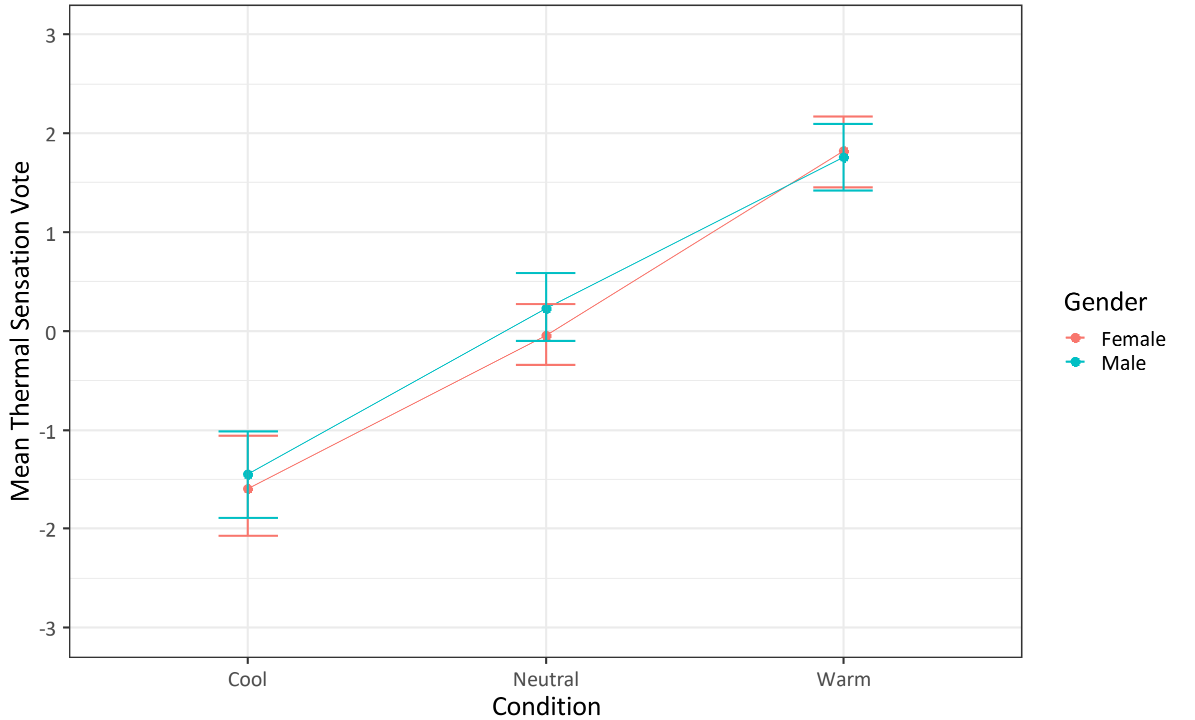


Figure 1. Line chart of the mean Thermal Sensation Vote with error bars (standard error of the mean) for each experimental condition and gender.

The results of our linear mixed-effects model showed that gender did not have a significant main effect on TSV, $\chi^2(1) = 0.36$, $p = .547$ and neither did the interaction between gender and the condition, $\chi^2(2) = 0.95$, $p = .621$. As expected, the experimental condition did have a significant overall effect on TSV, $\chi^2(2) = 114.75$, $p < .0001$, i.e. subjects felt warmer in the warm condition, near-neutral in the neutral condition, and cooler in the cool condition.

Table 2. Summary statistics of thermal sensation vote according to the experimental condition and gender.

| Condition | Gender | N | Mean | SE (mean) | SD |
|---|---|---|---|---|---|
| Cool | Females | 12 | -1.59 | 0.28 | 0.96 |
| | Males | 12 | -1.45 | 0.23 | 0.80 |
| Neutral | Females | 12 | -0.05 | 0.17 | 0.61 |
| | Males | 12 | 0.23 | 0.19 | 0.66 |
| Warm | Females | 12 | 1.82 | 0.19 | 0.66 |
| | Males | 12 | 1.76 | 0.19 | 0.65 |

A similar trend was observed for thermal preference, comfort and acceptability, i.e. overall, gender did not have a significant main effect on thermal perception.

## 4. Conclusions

The main conclusion of this work is that, when controlling for confounding variables, the thermal perception of both males and females was similar under equivalent thermal conditions. This appears to contradict recent studies reporting gender differences in thermal perception based mainly on field study data. This may be an indication that other factors than gender play a role in the perception of thermal comfort, such as gender differences in behaviour (e.g. dissimilarities in clothing insulation or apparent level of control over the thermal environment) and individual characteristics (e.g. body composition).

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## 6. Acknowledgement


The research leading to these results has received funding from the European Union's Horizon 2020 research and innovation program under the Marie Sklodowska-Curie grant agreement no. 713683 (COFUNDfellowsDTU) and from Aase and Ejnar Danielsens Fund (grant no. 20-30-0058).

# Analysis of a questionnaire for visual comfort assessments: Effects of question formats

**Natalia Giraldo Vasquez*, Ricardo Forgiarini Rupp, Jørn Toftum**

International Centre for Indoor Environment and Energy, Department of Environmental and Resource Engineering, Technical University of Denmark, Nils Koppels Allé, Building 402, 2800 Kgs. Lyngby, Denmark, *natgir@dtu.dk

**Abstract:** This study tests two sets of questionnaires to collect subjective lighting assessments. The questionnaires, one using semantic differentials and the other using Likert-type statements, were presented to 48 participants to compare the differences due to the question format. Experiments were performed in a climate chamber simulating an open-plan office. In a randomized order, participants were exposed to three temperatures (20 °C, 25 °C, and 30 °C) while the artificial lighting was constant (550 lux, 3200 K). Light perception, visual comfort, and acceptability were assessed through 13 items using 7-point scales. Overall, the statement format had higher internal consistency than the semantic differential format. Questions about visual comfort seemed to be reliable under both questionnaire formats, while further development of questions about perception is needed to increase their internal consistency. Although most of the answers were not different due to the questionnaire format ($n_{average}$= 61.5%), 38.5% of the answers were different, and the changes were small or moderate and statistically significant in eight items. Further analysis compared the effect of the temperature on lighting evaluations. Our results contribute to a better understanding of the implications of formulating questions on subjective responses and might help develop questionnaires for the field of visual comfort.

**Keywords:** visual comfort, visual perception, visual acceptability, questionnaire.

## 1. Introduction

Lighting surveys are powerful tools to collect data about occupants' perception, satisfaction, acceptability, and needs. For years, researchers in daylighting and lighting have been asking people in different ways with such purposes (Allan *et al.*, 2019). The assessment of glare has drawn the attention of many researchers and therefore, it is possible to find comprehensive literature about the development and adjustments of the glare scale to ensure a better understanding of the participants (Fotios, 2018; Fotios and Kent, 2021). Although a consensus about questions and scales, among other aspects, seems nonexistent, Fotios (2018) conducted a broad review of category rating scales and summarized some recommendations for the design of questionnaires for research in lighting.

This study tested two sets of questionnaires used to collect subjective assessments about perception, visual comfort, and acceptability of the visual environment.

## 2. Method

The data presented in this paper is part of a more extensive experiment. Forty-eight healthy subjects (50% females) participated in a series of controlled experiments performed in a climate chamber with no windows to the surrounding space (except a small porthole in the chamber door) or to the outside. The chamber set-up simulates an office environment with six workstations, including computers.

In a randomized order, each participant was exposed to three temperatures (Cool= 20 °C, Neutral= 25 °C, and Warm= 30 °C) while the artificial lighting was constant [550 lux (+-50 lux), 3200 K). The duration of each experimental session was 120 min. After the first 30 min (adaptation period), the participants remained seated until the end of the session (90 minutes more, Figure 1). Participants answered five rounds of digital questionnaires after regular intervals using their computers. Two sets of questionnaires were presented in two rounds under each condition.

| Adaptation | Exposure period | | | |
|---|---|---|---|---|
| | Round 1 | | Round 2 | |
| 30 min | 18 min | 54 min | 72 min | 90 min |
| 120 min | | | | |

Figure 1. Experimental session design.

## 2.1. Questionnaires

Two separate questionnaires, composed of 13 items using 7-point scales, presented two formats for asking the participants about their lighting perceptions (6 items), comfort (6 items), and acceptability (1 item). In one of the questionnaires, semantic differentials were used, while the other questionnaire asked for the degree of agreement to diverse statements, as Van Den Wymelenberg and Inanici (2014) implemented. Perception questions were based on Amorim *et al.* (2022), in which seven light descriptors were used to investigate participants' perceptions. The second section asked about visual comfort in terms of color, light level, distribution, glare, and an overall assessment of the visual environment. One last question asked about the acceptability of the visual environment. Figure 2 presents the two formats used for the questionnaires.

## 2.2. Data analysis

The internal consistency or reliability of the scales was assessed through Cronbach's Alpha (α) coefficient (Cronbach, 1951). To interpret the results, we followed the recommendations of George and Mallery (2003), presented in Table 1. The analyses were conducted separately for each temperature and questionnaires administration round.

Table 1. Interpretation of Cronbach's Alpha (α)

| **Internal consistency** | **Cronbach's α** | **Internal consistency** | **Cronbach's α** |
|---|---|---|---|
| Excellent | $0.9 \leq \alpha$ | Questionable | $0.6 \leq \alpha < 0.7$ |
| Good | $0.8 \leq \alpha < 0.9$ | Poor | $0.5 \leq \alpha < 0.6$ |
| Acceptable | $0.7 \leq \alpha < 0.8$ | Unacceptable | $\alpha < 0.5$ |

To examine the differences in participants' answers due to the question format (semantic differentials vs. agreement with the statements), we used non-parametric tests for repeated measures. Thus, Wilcoxon signed-rank tests were run to examine differences between each question. Furthermore, the effect of air temperature changes on lighting assessments was examined within each type of questionnaire using Friedman's ANOVA. Statistical analyses were conducted in R software (R Core Team, 2021).

**Semantic differentials**

**Perception**

**Q1 How do you perceive the color of the lighting in the room?**
*[Cold* O O O O O O O *Warm]*
1 2 3 4 5 6 7

**Q2 How do you perceive the color of the room surfaces?**
*[Distorted* O O O O O O O *Natural]*

**Q3 How do you perceive the room?**
*[Dark* O O O O O O O *Bright]*

**Q4 How do you perceive the light distribution in the room?**
*[Uneven* O O O O O O O *Uniform]*

**Q5 How do you perceive the glare, if any, caused by the lamps?**
*[Perceptible* O O O O O O O *Imperceptible]*

**Q6 Overall, how do you find the visual appearance of the room?**
*[Not pleasant at all* O O O O O O O *Very pleasant]*

**Comfort**

**Q7 How do you find the color of the lighting in the room?**
*[Very Uncomfortable* O O O O O O O *Very Comfortable]*

**Q8 How do you find the appearance of the surfaces' colors?**
*[Very Uncomfortable* O O O O O O O *Very Comfortable]*

**Q9 How do you find the lighting level/amount of light in the room?**
*[Very Uncomfortable* O O O O O O O *Very Comfortable]*

**Q10 How do you find the light distribution in the room?**
*[Very Uncomfortable* O O O O O O O *Very Comfortable]*

**Q11 How do you find the glare, if any, caused by the lamps?**
*[Very Uncomfortable* O O O O O O O *No glare]*

**Q12 Overall, how do you find the visual environment of the room?**
*[Very Uncomfortable* O O O O O O O *Very Comfortable]*

**Acceptability**

**Q13 At this moment, how do you judge the visual environment?**
*[Unacceptable* O O O O O O O *Acceptable]*

**Statements**

**Perception**

**Q1 The color of the lighting in the room is Warm**
*[Very strongly disagree* O O O O O O O *Very strongly agree]*
1 2 3 4 5 6 7

**Q2 The color of the surfaces seems natural, without distortion**
*[Very strongly disagree* O O O O O O O *Very strongly agree]*

**Q3 The room seems bright**
*[Very strongly disagree* O O O O O O O *Very strongly agree]*

**Q4 The light is distributed evenly in the room**
*[Very strongly disagree* O O O O O O O *Very strongly agree]*

**Q5 There is imperceptible glare in the room caused by the lamps**
*[Very strongly disagree* O O O O O O O *Very strongly agree]*

**Q6 Overall, the visual appearance of the room is very pleasant**
*[Very strongly disagree* O O O O O O O *Very strongly agree]*

**Comfort**

**Q7 The color of the lighting in the room is very comfortable**
*[Very strongly disagree* O O O O O O O *Very strongly agree]*

**Q8 The appearance of the surfaces' colors is very comfortable**
*[Very strongly disagree* O O O O O O O *Very strongly agree]*

**Q9 The amount of light in the room is very comfortable**
*[Very strongly disagree* O O O O O O O *Very strongly agree]*

**Q10 The light distribution in the room is very comfortable**
*[Very strongly disagree* O O O O O O O *Very strongly agree]*

**Q11 The lamps do not cause glare**
*[Very strongly disagree* O O O O O O O *Very strongly agree]*

**Q12 Overall, the visual environment of the room is very comfortable**
*[Very strongly disagree* O O O O O O O *Very strongly agree]*

**Acceptability**

**Q13 At this moment, the visual environment is acceptable**
*[Very strongly disagree* O O O O O O O *Very strongly agree]*

Figure 2. Questions using semantic differentials (left) and agreement with the statement (right). The numerical values of the scales were not presented to the participants.

## 3. Results

### 3.1. Internal consistency

We tested the internal consistency of the applied scales by considering the entire questionnaire (13 items or questions) and the Perception and Comfort sections independently (6 items each). The analyses were run separately for each condition and round of the administration of the questionnaires. Table 2 presents these results.

Both questionnaires showed good or excellent reliability ($\alpha > .8$). Items about comfort appear to have good or excellent reliability as well. Nevertheless, perception items had lower Cronbach's $\alpha$, indicating questionable or even poor internal consistency, especially for the Cool condition (20 °C). Thus, the items considered for the perception have little interrelatedness (Cortina, 1993). Overall, Cronbach's $\alpha$ was slightly higher when using the statements' format (shaded columns in Table 2).

Table 2. Internal consistency of the entire set of the questionnaire and Perception and Comfort sections.

| Condition and admin. round | | Entire questionnaire (13 items) | | Perception (6 items) | | Comfort (6 items) | |
|---|---|---|---|---|---|---|---|
| | | Semantic differentials Cronbach's α | Statements Cronbach's α | Semantic differentials Cronbach's α | Statements Cronbach's α | Semantic differentials Cronbach's α | Statements Cronbach's α |
| Warm | 1st | .89 | .91 | .60 | .69 | .90 | .91 |
| | 2nd | .90 | .90 | .68 | .69 | .88 | .89 |
| Neutral | 1st | .90 | .89 | .62 | .65 | .90 | .88 |
| | 2nd | .91 | .90 | .66 | .64 | .91 | .89 |
| Cool | 1st | .86 | .91 | .45 | .66 | .89 | .91 |
| | 2nd | .88 | .90 | .57 | .65 | .88 | .91 |

### 3.2. Differences between semantic differential questionnaires and statements agreement

The percentage of answers that were not changed and those that were different in each questionnaire are presented in Table 3. Changes were considered as an "increase" or "decrease" in the rating by subtracting the difference between the semantic differential and statements ratings. Thus, increases were when the answer's rating using statements was higher than the rating with semantic differentials. A decrease in the answer means a lower rating when using statements and higher ratings when using semantic differentials. Only when asked about the perception of the surfaces' colors (Q2), less than half of the answers (46.5%) were with the same rating in both questionnaires. Comparing the changes in the answers, items Q4, Q11 and Q13 (Figure 2) had more answers with a lower rating when statements were presented (light green in Table 3). For the remaining items of the questionnaires, there were more answers with higher ratings (increased) using the statement format.

Table 3. Participants (%) did not change the answers, and participants with different answers.

| | Q1 | Q2 | Q3 | Q4 | Q5 | Q6 | Q7 | Q8 | Q9 | Q10 | Q11 | Q12 | Q13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No change | 51.4% | 46.5% | 56.9% | 70.1% | 53.5% | 60.1% | 58.3% | 62.2% | 60.8% | 64.9% | 71.9% | 75.0% | 68.4% |
| Increased | 37.2% | 29.5% | 29.5% | 12.5% | 24.7% | 30.6% | 30.6% | 21.2% | 22.6% | 21.5% | 13.5% | 16.0% | 11.5% |
| Decreased | 11.5% | 24.0% | 13.5% | 17.4% | 21.9% | 9.4% | 11.1% | 16.7% | 16.7% | 13.5% | 14.6% | 9.0% | 20.1% |

Increase/Decrease = Semantic differential rating – Statement rating

Table 4. Differences between questionnaires: summary of statistics and p-value for Wilcoxon signed-rank tests

| Item | Semantic Differentials | | | | Statements | | | | *p-value* (effect size) |
|---|---|---|---|---|---|---|---|---|---|
| | Median | Mean | SD | IQR | Median | Mean | SD | IQR | |
| Q1 | 5 | 5.01 | 1.06 | 1 | 5 | 5.38 | 1.05 | 1 | .000 (r= - .39) |
| Q3 | 6 | 5.65 | 0.92 | 1 | 6 | 5.83 | 0.94 | 1.25 | .000 (r= - .23) |
| Q6 | 5 | 4.40 | 1.38 | 2.25 | 5 | 4.67 | 1.37 | 3 | .000 (r= - .32) |
| Q7 | 5 | 4.74 | 1.30 | 2 | 5 | 5.00 | 1.28 | 2 | .000 (r= - .28) |
| Q9 | 5 | 4.74 | 1.54 | 3 | 5 | 4.87 | 1.54 | 2 | .000 (r= - .12) |
| Q10 | 6 | 5.32 | 1.32 | 2 | 6 | 5.43 | 1.23 | 1 | .032 (r= - .13) |
| Q12 | 5 | 4.51 | 1.41 | 3 | 5 | 4.62 | 1.43 | 3 | .012 (r= - .15) |
| Q13 | 5.5 | 5.15 | 1.42 | 2 | 5 | 5.06 | 1.38 | 2 | .024 (r= - .13) |

For each of the 13 items, we tested whether participants' answers were different due to the question format (Table 4). Wilcoxon signed-rank tests showed significant differences in participants' answers to the items Q1- perception of light color, Q3- perception of light levels, Q6- visual pleasantness, Q7- comfort with the color of the light, Q9- comfort with light levels, Q10- comfort with the light distribution, Q12- comfort with overall visual environments, and Q13- acceptability. Although, even with significant differences, we found small differences, especially in comfort assessments (Q9, Q10, Q12 and Q13), due to the format of the questions. Except the comparison of Q13, even when the median values were equal in both groups, the tests reported significant differences, which can be explained by variations in the distribution, as shown in Figure 3.

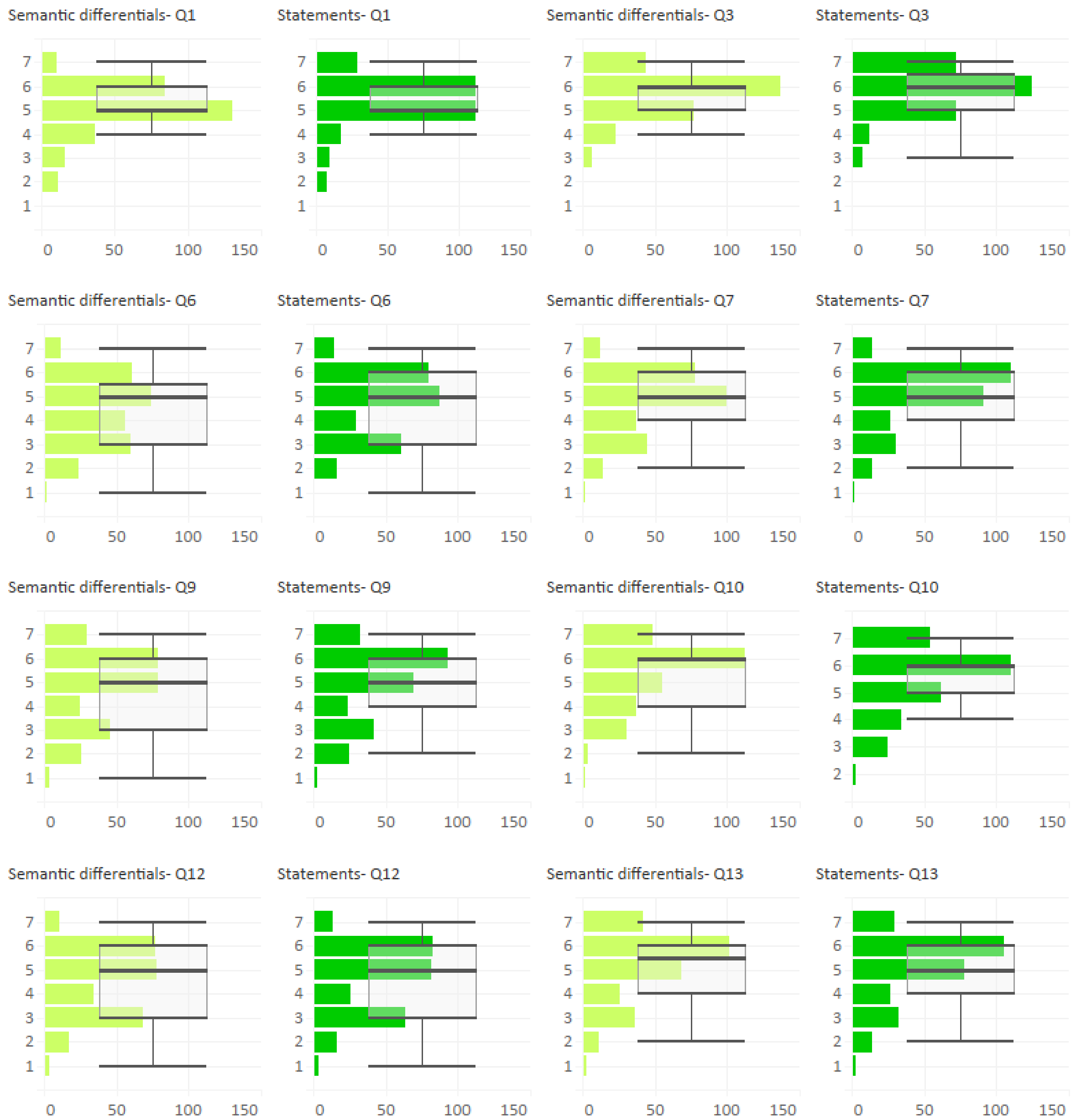


Figure 3. Differences due to the questionnaire format. Frequencies and boxplots of the items with significant differences.

### 3.3. Differences due to changes in air temperature

Some studies investigating the effect of temperature on visual assessments have shown an interaction between these two domains (te Kulve *et al.*, 2016; Toftum *et al.*, 2018; Brambilla *et al.*, 2020). With both questionnaires and under the specific lighting conditions, the perception of the color of the light (Q1) was significantly affected by the air temperature ($p < .0001$ for semantic differentials; $p < 0.01$ for statements). Using semantic differentials, the post hoc tests indicated that light was perceived as warmest under Neutral and Warm thermal condition [Cool vs. Neutral (Observed dif. = 35; Critical dif. = 33.17, $p < .05$) and Cool vs. Warm (Observed dif. = 35; Critical dif. = 33.17, $p < .05$)]. When using statements, the perception of the color of the light was significantly different only between Cool vs. Warm conditions (Observed dif. = 37; Critical dif. = 33.17, $p < .05$) (Figure 4). Although we found significant differences in items Q5, Q6, Q12, and Q13 of the statements questionnaire, post hoc tests did not confirm these.

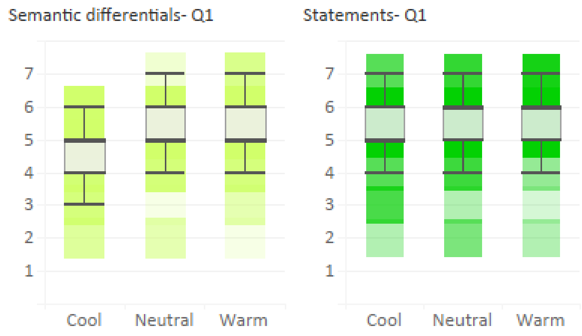


Figure 4. Differences in perception of the color of the light (Q1) under each thermal condition.

## 4. Conclusion

From this brief study, we reached three conclusions:

1. Overall, questionnaires using the statements format had a higher Cronbach's Alpha coefficient, indicating that this questioning format might have higher internal consistency than the semantic differential format. Questions about visual comfort seemed to be reliable with both questionnaire formats. However, perception items presented lower internal consistency. Therefore, further development of questions about perception is needed to increase their internal consistency and, consequently, the reliability of the results.
2. Although most of the answers were not different due to the questionnaire format ($n_{average}$= 61.5%), an average of 38.5% of the answers were different due to the questionnaire format, which represented an increase of the answer rating for most of the questions. Additionally, changes in the answers were small or moderate and statistically significant in eight items (Table 4).
3. Under the tested conditions, changes in air temperature significantly affected the perception of the color of the light. Differences in the perception of glare, the overall appearance of the room and comfort, and acceptability of the visual environment seemed to be significant; however, there was not enough evidence to confirm significant differences between the conditions when running the post hoc tests.

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## 6. Acknowledgement

The research leading to these results has received funding from the European Union's Horizon 2020 research and innovation program under the Marie Sklodowska-Curie grant agreement no. 713683 and from Aase and Ejnar Danielsens Fund (grant no 20-30-0058). This project has received funding from the European Union's Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant agreement No 101031380.

## All you need to know about the indoor environment, its occupants, interactions and effects

**Philomena M. Bluyssen**

Chair Indoor Environment, Faculty of Architecture and the Built Environment, University of Technology, Delft, the Netherlands; p.m.bluyssen@tudelft.nl

**Abstract:** Research has shown that, even though the conditions seem to comply with current standards for indoor environmental quality (IEQ), staying indoors is not good for our health. We are confronted with diseases and disorders related to IEQ such as mental illnesses, obesity and illnesses that take longer to manifest, among which cardiovascular and chronic respiratory diseases and cancer, and very recently, COVID-19, caused by mainly airborne transmission of SARS-CoV-2 indoors. Except for these health effects, the consequences for indoor environment of climate change, the effects of the retrofitting measures we take to reduce energy consumption on health and comfort indoors, is also an emerging concern. IEQ is still described with quantitative dose-related indicators, expressed in number and/or ranges of numbers for each of the factors (indoor air, lighting, acoustics and thermal aspects). Building and occupant-related indicators are overlooked. Interactions of stressors and effects at and between human and environment level are ignored. Individual differences in needs and preferences of occupants (over time) are not accounted for. Resilient new ways of creating and maintaining healthy and comfortable indoor spaces for different occupants in different situations, require better understanding of the indoor environment, its occupants, interactions, and effects.

**keywords:** indoor environmental quality, diseases and disorders, interactions, preferences and needs, stressors

### 1. Introduction

Most people are aware of the importance of the outdoor environment, especially in relation to climate change issues but also related more directly to our health. The effects of indoor environment quality are, however, not that common knowledge. We know that air pollution such as fine dust and noise pollution caused by airplanes, or too much sunlight can be very unhealthy. We, however, don't realize that people in the Western world in general spend 80-90% of their time indoors, of which more than 60% of their time at home (Bonnefoy, et al. 2004) and the rest of their time at their work, at school and/or commuting. Exposure 'indoors' is therefore much longer than outdoors. What most people also don't realize is that there are many diseases and disorders related to that indoor environment, such as mental illnesses, obesity, cardio-vascular and chronic respiratory diseases (think of asthma with children and Chronic Obstructive Pulmonary Disease (COPD) with adults), cancer (Bonnefoy et al., 2004; Fisk et al., 2007; Lewtas, 2007; Houtman et al., 2008), and more recent COVID-19 (Marowska, et al. 2020).

Worldwide, studies have shown that the relationships between indoor building conditions (thermal aspects, air quality, lighting, and noise) and wellbeing (health and comfort) of occupants of different buildings are complex and not easy to unravel (e.g. homes: Bonnefoy et al., 2004; offices: Kim and de Dear, 2012; schools: Bluyssen, 2017). Indoor building conditions may be associated with discomfort (annoyance), building-related symptoms (e.g. headaches, nose, eyes, and skin problems, fatigue etc.), building-related illnesses (e.g. legionnaires disease), productivity loss and decrease in learning ability

(Bluyssen, 20014a).There are many indoor environmental stressors: thermal factors (e.g. draught, temperature), lighting aspects (e.g. reflection, view, luminance ratios), air quality (e.g. odours, mould, chemical compounds, particulates) and acoustical aspects (e.g. noise and vibration). These stressors can cause their effects additively or through complex interactions (ASHRAE, 2016; Torresin et al., 2018), and depend/are influenced by psychological, physiological, personal, social and other environmental factors (Bluyssen, 2014a) (Figure 1).

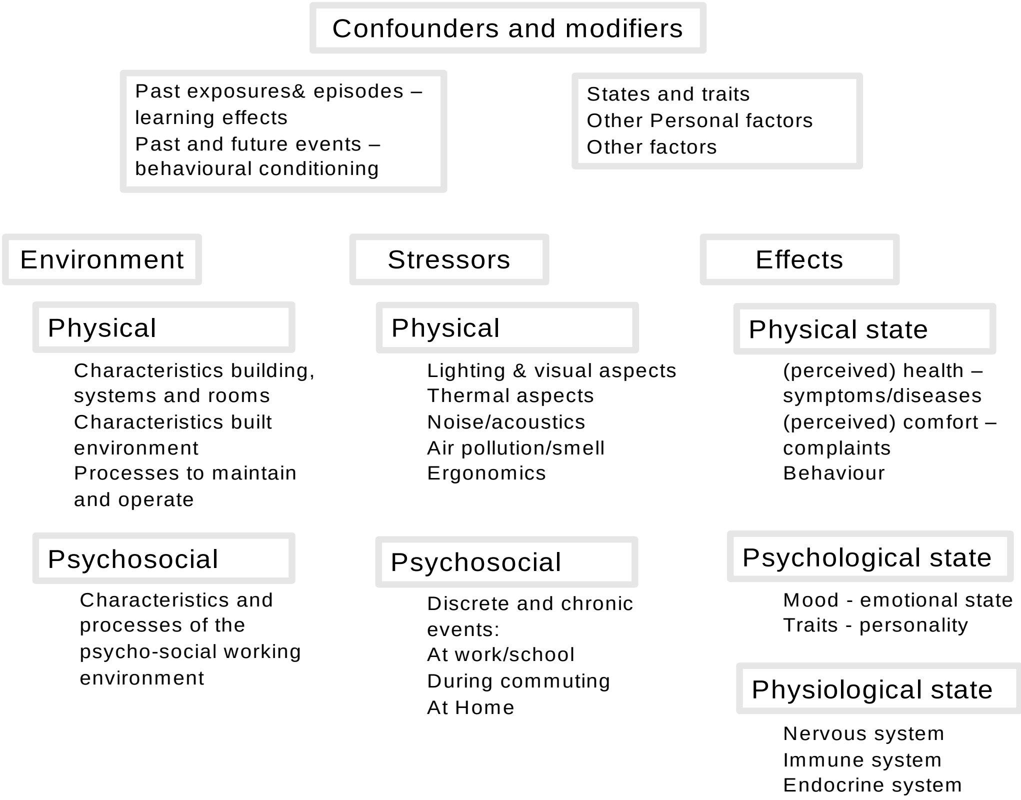



Figure 1. Stressors, factors, causes and effects (adapted from Bluyssen, 2014a).

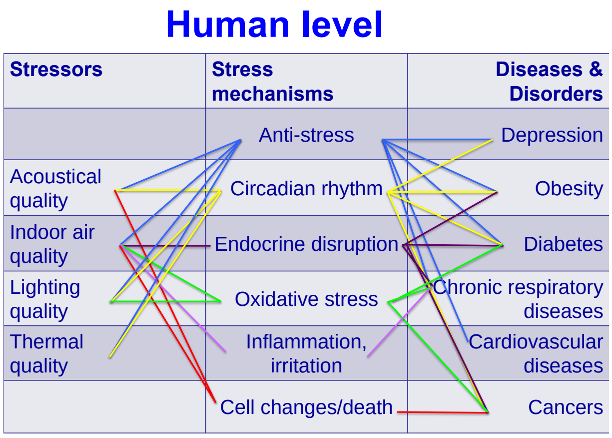



Figure 2. Possible interactions between stressors, mechanisms and diseases and disorders at human level (from Bluyssen, 2014a).

If you look at the scientific outcomes it seems that staying indoors is not good for our health, even though the conditions seem comfortable enough. Even when the conditions seem to comply with the current guidelines for indoor environmental quality (thermal, lighting, acoustical and air quality), people feel uncomfortable and get sick. This can partly be explained by the way our human bodies cope with the different stressors we are exposed to.

We have several stress mechanisms available for that and from research in different fields, it is clear that the relations between the stressors, those mechanisms that take place in the human body causing the diseases and disorders, are very complex (Bluyssen, 2014a) (Figure 2).

## 2. What is indoor environmental quality?

Indoor environment quality is determined by the quality of four factors: indoor air quality, thermal quality, acoustical quality and visual or lighting quality.

### 2.1 Thermal quality

Thermal quality or thermal comfort, the parameter we are probably the most familiar with., includes aspects such as feeling warm, cold, draught etc. In our daily conversations, in the Netherlands, we often use these to describe the weather, of yesterday, today or tomorrow. The big name most people know in this area is Prof. Fanger, who tested his thermo-physiological model in climate chambers in the 1970s using several subjects. His model has been and is still the basis for guidelines on thermal comfort. In the Netherlands, those guidelines comprise of ranges for the operative temperature (the average of the air and the radiant temperature), air velocity, draught risk (calculation based on air velocity, air temperature and turbulence), vertical temperature gradient and radiant asymmetry (CEN, 2019).

When people are dissatisfied with their thermal environment, thermal stress can occur. For example, when one is not able to regulate its thermal balance, or when one believes or perceives it isn't possible. The psychological effect of expectations and the perceived individual level of control seem important in this process. To deal with that, another model than the model of Fanger, begins to win ground: the adaptive comfort model, in which the context and preferences of the occupant are considered to be important (de Dear and Brager, 2002). Both of these models are focused on creating thermally neutral conditions. Recently it was found, however, that thermally neutral conditions do not have to be necessarily healthy. Studies indicate that increased exposure to thermally neutral conditions might be related to increased adiposity, an increase of fat tissue. This was first observed in experiments with rats and later with adult men (Marken Lichtenbelt et al., 2009). Actually, it means that when your body doesn't have to work to feel thermally comfortable, more fat is stored!

### 2.2 Lighting quality

The parameter visual or lighting quality comprises of aspects such as illuminance, luminance ratios and colours, but also aspects you would rather like to prevent, such as reflection on a floor or desk. Visual comfort is more that providing enough light to perform a task. View is also an important aspect to consider. The lighting quality of a space is determined by the interplay between the sources of light (indoors and outdoors), the distribution of light in that space, and the way light is received and interpreted by the receiver. Current guidelines for lighting quality are focussed on the provision of enough light to perform a task well, such as the horizontal illuminance on a desk, colour temperature of artificial light, and daylight factor, but also the minimalization of blinding caused by daylight and/or artificial light (CEN, 2019).

For visual perception, we have the light sensitive cells, located in the inner layer of the eye (the retina): the rods and the cones, of which the cones (three types) are sensitive to colours (the different wavelengths of light). Additionally, not so long ago, a third type of light-sensitive cell was found (Brainard et al., 2001). These cells are distributed between the rods and the cones, and play a role in the control of the size of the pupil opening and the biological clock (via the production of the hormone melatonin). Under influence of light during the day, the hypothalamus signals to the pineal body to produce melatonin, a hormone that makes us want to sleep. If exposed to light during night, however, for example during a night shift, the production of the anti-oxidant melatonin is immediately stopped, alertness and core body temperature is increased and sleep is distorted (Hinson, Raven & Chew, 2010). Moreover, the Dutch health council reported that people who are working night shifts are exposed to an increased risk for cardio-vascular disease and diabetes type 2 (Gezondheidsraad, 2017). This shows that also non-visual aspects of light are important to consider.

### 2.3 Acoustical quality

Acoustical quality of a space is determined by its sources of noise or sound indoors (for example quarrelling neighbours and flushing a toilet) and outdoors (such as traffic), the distribution of the sound in the space and the way the sound is received and interpreted. A sound enters the external auditory canal, setting the eardrum and the ossicles in motion. Then, these vibrations are transmitted to the fluid of the inner ear, where nerve impulses are transmitted via the eight cranial nerve to the brain. The inner ear also contains the equilibrium organ that acts independently of hearing. While the equilibrium sense is sensitive to low frequencies (vibrations), the auditory sense is more sensitive to higher frequencies (hearing). Current guidelines for sound comprise mainly of maximum allowed sound levels (e.g. CEN, 2019). Additionally, reverberation time and intelligibility are applied (Bluyssen, 2009).

Exposure to sound or noise has been associated with direct stress reactions, such as temporary or even permanent hearing loss. It is known that noise effects do not only occur at high sound levels, but also at relatively low environmental sound levels, when certain activities such as concentration, relaxation or sleep are disturbed (Babisch, 2008). Annoyance seems to play an important role in this mechanism. If we look into that anti-stress mechanism, we can see that in response to various stressors, the secretion of anti-stress hormones can increase. On the short-term adrenaline is produced and the body is prepared for action by producing noradrenaline. If the stressor is limited in time and perceived intensity, in due time the balance is restored. However, with prolonged stress (chronic stress), production of anti-stress hormones such as cortisol is increased and a chronic imbalance in the hormones released during stress can occur. It has been proven, although simplified because there are other hormones and reactions involved, that cortisol plays an important role in the health effects of this chronic imbalance (McClellan and Hamilton, 2010). High cortisol levels contribute to changes in carbohydrate and fat metabolism and can lead to anxiety, depression and heart disease. While a low cortisol production can lead to fatigue, allergies, asthma and increased weight.

### 2.4 Air quality

Indoor air quality is determined by its sources, the distribution of their pollutants in the space and how the receiver is exposed to these pollutants over time (Bluyssen, 2009). The pollutants that can be found in that indoor air comprise of gaseous pollutants, of which some of them you can smell, and others do not smell, plus several other components that influence the air quality such as water and particles.

We perceive air with our nose, which contains the senses with which you can perceive air quality yourself: one for smell - the olfactory sense in the olfactory epithelium, and one for irritation - the trigeminal nerve, which endings are located all over the nasal respiratory lining, forming the common chemical sense. On being stimulated by pollutants, the olfactory and trigeminal nerve endings send signals to the brain where the signals are integrated and interpreted. The result of this process is called perceived air quality (Bluyssen, 2014a).

When you breath in air through the nose or mouth, the air enters the trachea, a long tube, which branches into two bronchial tubes, or primary bronchi, that go to the lungs. In the lungs, the primary bronchi branch off into bronchioles, which end in the alveoli. In those alveolar sacs the gas exchange with blood takes place. Oxygen of the inhaled air passes through the walls of the alveoli and blood vessels and enters the blood stream. At the same time, carbon dioxide ($CO_2$) produced passes into the lungs and is exhaled. While larger particles are too heavy to stay suspended and will not be inhaled, of the sizes that can be inhaled and reach the lung cells, the ultra fine or nano particles can together with oxygen pass the membrane of the alveoli and in this way reach our organs via our blood, where they can cause so-called oxidative stress. Oxidative stress occurs when there is an excess of free radicals over antioxidants (Kelly, 2003). Oxidative stress can damage cells and can lead to systemic inflammation, and even cell death.

Air pollution is probably the most important cause for oxidative stress indoors, but air pollution is responsible for more mechanisms. Fine dust can cause inflammation, radon and asbestos fibres can cause lung cancer, SARS-CoV-2 can cause COVID-19, several VOCs can cause annoyance to toxic reactions, and several phthalates of certain plastics - these are the so-called endocrine disruptors, which can have an effect on hormone production and hormone balance - can cause a whole range of effects that are still hard to grasp. Specific chronic respiratory diseases and disorders caused by air pollution are for example COPD, asthma, allergic rhinitis and hay fever. Besides all those diseases and disorders, there are several building-related symptoms that have been related to exposure of air pollutants, such as symptoms of eyes and nose, the upper airway-related symptoms, tiredness and headaches (Bluyssen, 2009).

Guidelines for air quality comprise of: a) minimum ventilation rates in l/s/person or $l/s/m^2$ floor area to ventilate/dilute the emissions of persons and emissions of building- and furnishing materials; b) a limit value of the $CO_2$ concentration above the outdoor air concentration as indicator for emissions of persons, applied to determine the required amount of fresh (outdoor) air; c) limit values for maximum exposure to pollutants in indoor air, such as formaldehyde, carbon monoxide and radon (e.g. CEN, 2019).

## 3. Assessing the indoor environmental quality

### 3.1 Single dose response relationships

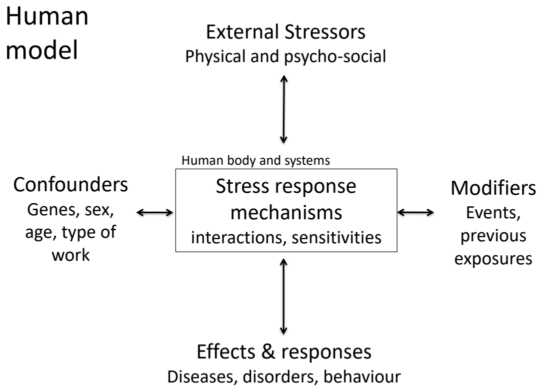
From section 2 follows, that although the built environment is a complex system, IEQ is still most of the time assessed with indicators using the dose or indoor environmental parameter, such as concentrations of certain pollutants, temperature, lighting level or ventilation rate (e.g. CEN, 2019). We assess IEQ on effect modelling: for each parameter or indicator its effect is determined separately. These dose-related indicators are based on linear single dose-response relationships for negative stressors, developed for the average occupant; ignoring that we are dealing with individuals in different scenarios and situations; neglecting other stressors and their integrated effects over time; and ignoring interactions between stressors at environmental level, and interactions between various body responses to exposure(s) at human level; forgetting that there are two other categories of indicators available (Bluyssen 2010; 2014b):

- The occupant-related indicators: focused on the occupant such as sick leave, productivity, and number of symptoms or complaints;

- The building-related indicators concerned with buildings and its components, such as certain measures or characteristics of a building and its components (for example the possibility of mould growth), or even labelling of buildings and its components.

Thus, according to the standards, a healthy building is a building that complies with the existing standards and guidelines for mainly the environmental or dose-related indicators. However, from the previous it is clear that in order to assess whether a building is healthy, more is needed. A good example is the minimum ventilation rate. Based on either $CO_2$, as an indicator for bioeffluents, or on certain emissions of building materials, minimum ventilation rates have been discussed and are still being discussed for almost two hundred years now. We still have no clue what to take. Even more now, as a result of the corona crisis.

A 'healthy' building is a building that has the means to support the physical, psychological, and physiological health and comfort of its occupants over time. A healthy building has the means to influence health and comfort of its occupants through the thermal, lighting, acoustical and indoor air quality of the indoor environment. It is clear that next to the dose-related indicators we need to also make use of the occupant-related indicators providing information on the effects of stress, and preferences and needs, preferable at individual level because people differ and situations change over time (Figure 3 The Human Model); and we need to make use of building-related indicators, providing information on the stressors, and the interactions that occur in the indoor environment over time (Figure 4 The Environment model) (Bluyssen, 2020).



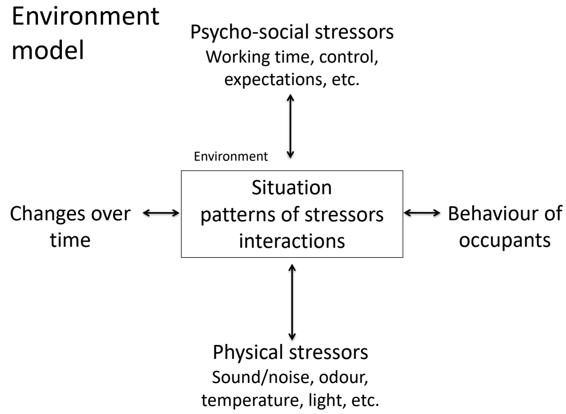




Figure 3. The Human model (Bluyssen, 2020). Figure 4. The Environment model (Bluyssen, 2020).

### 3.2 Human Model

The human body has a number of stress mechanisms available to cope with all the physical and chemical external stressors such as noise, indoor air pollutants, bad lighting or thermal discomfort, that is (Figure 2): the anti-stress mechanism, the mechanism to keep to our bio-rhythm, endocrine disruption, oxidative stress, infections, cell changes, and cell death. When the coping fails, or when the mechanisms make us overreact, diseases and disorders will occur. The relations between the stressors, the mechanisms that take place in the human body, and the effects that can occur (the diseases and disorders), are very complex. Each of the mechanisms has a relation with one or more diseases and disorders (see Figure 2). This can partly explain the difficulties we are having with identifying clear cause-effect relations for diseases or disorders reported by/diagnosed with occupants. Moreover, during perception with our senses interactions of different environmental stressors (smell, sight and hearing) at brain level (central nervous system) might occur (Bluyssen et al., 2019).

People differ in their preferences and needs, influenced by psychological, physiological, personal, social and environmental factors and stressors (Figure 3). We are exposed to a mix of stressors, that can change over time, and our responses (the coping and the effects) are influenced by genetics, previous exposures and interactions between those stressors (e.g. Bluyssen, 2014b).

### 3.3 Environment Model

Besides interactions at human level, we also have to deal with the interactions that occur in the indoor environment over time, which makes it even more complex (ASHRAE, 2016; Bluyssen, 2014b; Torresin et al., 2018). Interactions, such as chemical interactions between pollutants in the air and microbiological growth at indoor surfaces, and interactions between different indoor environmental factors:

- Light and thermal aspects, when sunlight heats up the interior surfaces.
- Thermal conditions and indoor air. Emission rates of most volatile organic compounds increase with increasing temperature.
- Acoustics and indoor air, via the introduction of ventilation air by mechanical ventilation systems, which can produce equipment as well airflow noise, or via natural ventilation through open windows, bringing the noise produced outdoors indoors.

Also, interactions occur as a result of human behaviour (actions). When certain actions are taken to improve one factor, other factors might be affected negatively (Table 1), improving the situations for one person, but creating problems for another (Zhang and Bluyssen, 2021).

Table 1. Actions and possible interactions in the indoor environment (Bluyssen, 2015).

| Factor | Action | Factor | Interaction-effect |
|---|---|---|---|
| Thermal quality | Increase temperature | Indoor air quality | Emissions of most volatile compounds increase |
| | Use of solar screens to prevent overheating | Visual quality | Possible reduction of daylight entrance |
| Visual quality | Use of internal walls made out of glass | Acoustical quality | Possible reflections of sound |
| | Increase of glass surface area in facade | Thermal quality | Possible overheating |
| Acoustical quality | Sound adsorption material in air supply ducts | Indoor air quality | Possible reduction in air quality |
| | Closing of windows | Indoor air quality | Possible reduction of ventilation |
| Indoor air quality | Increase of ventilation rate | Thermal quality | Possibly draught |
| | Opening of windows | Acoustical quality | Possibly noise from outdoors |
| | Increased relative humidity | Thermal quality | Influence on mould growth |
| | Removal of fleecy surfaces (such as curtains, carpet) | Acoustical quality | Possible reduction of sound adsorption |

### 3.4 A 'new' model

It is clear, therefore, that we are in need of a more complex model to assess IEQ. A model that accounts for all stressors, both positive and negative, interactions, and preferences and needs of the individual for different scenarios and situations (Bluyssen, 2014a). A first concept of a 'new' model was introduced in Bluyssen (2014b); an improved version in Bluyssen (2020) (Figure 5). The model takes account of the combined effects of stress factors in buildings on people (patterns) as well as the individual preferences and needs of the occupants (profiles) for different scenario's (such as homes, offices, schools), and different situations (for example sleeping/eating; meeting/concentrated work; getting lessons); and interactions at human and environmental level. This model features the stress factors caused by the (indoor) environment that a person is exposed to (represented by patterns of stressors and the

Environment model, Figure 4), and the individual differences in needs and preferences (profiles of people as shown in the Human model, Figure 3), depending on their situation (activity and time).

Together with this 'new' model, a methodology to determine profiles of occupants and patterns of stressors for different scenarios (office workers and their workplace; students and their homes; primary children and their classrooms; employees of outpatient areas in hospitals) was introduced and validated in several field studies (Bluyssen et al., 2015; Bluyssen et al., 2016; Kluizenaar et al., 2016; Bluyssen et al., 2018; Zhang, Ortiz and Bluyssen, 2019; Kim and Bluyssen, 2020; Eijkelenboom and Bluyssen, 2020; Bluyssen, Eijkelenboom, Ortiz and Bluyssen, 2021; Zhang and Ortiz, 2021; Ortiz and Bluyssen, 2022). For each scenario, occupant-related indicators and building-related indicators were collected through a questionnaire and checklist(s) to associate patterns of building-related stressors to occupant-related indicators (health: symptoms; comfort: complaints) based on multivariate regression analysis; and to determine clusters of occupants and their profiles based on TwoSteps cluster analysis (Bluyssen, 2022a).

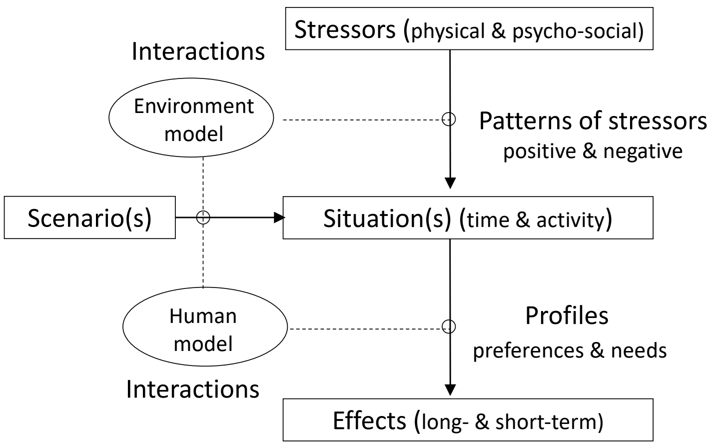



Figure 5. New model (Bluyssen, 2020).

## 4. Future directions

### 4.1 Risk-based guidelines

Most current standards and guidelines for IEQ are focused on dose-related indicators (such as temperature level and ventilation rate), while building-related indicators and occupant-related indicators have been rarely considered. Previous studies show, however, that building-related indicators such as building layout and the amount of space can influence occupants' overall satisfaction with IEQ (e.g. Kim and de Dear, 2012), building materials and furnishings can affect health (e.g. Bluyssen et al., 2016). Moreover, these comfort and health effects are related to preferences and needs of the occupants (occupant-related indicators), and therefore can differ (Bluyssen, 2010). Therefore, there seems to be a need to include both building-related and occupant-related indicators, additionally to the dose-related indicators listed in most standards and guidelines. Moreover, it is necessary to adopt risk-based, rather than absolute guidelines and standards.

A good example is the discussion on how to provide good IAQ. An important control strategy for IAQ is to reduce emissions of pollutions as much as possible, also named source control. If this is not possible, for example when you are cooking or the outdoor air is polluted, then you can choose to ventilate and/or clean/filter the air. How to ventilate 'properly' and how much ventilation is required depends on the pollutants and the situation. Nevertheless, our current standards and guidelines for IAQ are based on dose-response relationships only.

To decrease the risk of far-range airborne transmission of SARS-CoV-2, the use of 'proper' ventilation measures has been recommended (Morawska et al., 2020; ASHRAE, 2020; REHVA, 2021). 'Proper' ventilation means the supply of 'clean' air and exhaust of polluted ('infected') air from the breathing zones of each individual person, without passing through the breathing zones of other persons, and preferable without recirculation of air. In spaces in which the main pollution sources are people, the standards and guidelines are aimed at controlling odour and $CO_2$ exhaled by occupants, and base this control on limit values for $CO_2$. Also, during the COVID-19 pandemic, a number of organisations made recommendations to use $CO_2$ as an indicator of the risk of airborne infection transmission (e.g. REHVA, 2021). While $CO_2$ can be useful as an indicator of ventilation of a space under certain circumstances, indoor $CO_2$ concentrations do not necessarily correlate with other important indoor air pollutants (ASHRAE, 2022). Moreover, the outcome of these $CO_2$ measurements gives us information on how much should be ventilated at room level, and not on how and when to 'properly' ventilate: how is this fresh air ventilated and distributed through the space, in relation to the activities taking place and the occupancy over time (Bluyssen, 2022b). To be able to say something about the how and the when, thus to provide 'proper' ventilation, it is clear that both building-related and occupant-related indicators are required.

In Tables 2 and 3, respectively, a list of building-related and occupant-related indicators is presented that would be worthy to include and have been suggested in previous studies (overview in Bluyssen, 2022a). More research is required to better define the criteria/requirements for these indicators for different scenarios, occupants, activities and spaces.

Table 2. Suggested building-related indicators to be included in standards and guidelines for IEQ.

| **Component/topic** | **Building-related indicators** |
|---|---|
| Ventilation regime | ventilation type; (local) ventilation efficiency; airflow pattern |
| Natural ventilation | windows location and dimensions; passive grills |
| Mechanical ventilation | location of air supply and exhausts; grilles direction flow; maintenance schedule |
| Air cleaning | type of air filter; air cleaning devices |
| Floor | type of wall material; emission label; hard/fleecy material |
| Walls | type of ceiling material; emission label |
| Ceiling | type of ceiling material; emission label; height |
| Cleaning | cleaning schedule; cleaning products |
| Windows | window frame colour vs. wall colour; single/double/triple glazing |
| Lighting | type of lighting; natural or artificial; reflection on the surface |
| Sound absorption material | presence and location of sound absorption material |
| Heating and cooling system | type of heating system; location of radiators (if present); type of cooling system |

Table 3. Suggested occupant-related indicators to be included in standards and guidelines for IEQ.

| Component/topic | occupant-related indicator |
|---|---|
| Personal characteristics | number of occupants; age range; sex; duration of stay; activity level |
| IEQ and health | needs to deal with diseases and disorders, such as: allergies, asthma, diabetes, etc. |
| IEQ and comfort | preferences for IEQ to perform well, such as preferences for light (brighter/darker), background noise (non/a lot), temperature (warm/cold), draft/still air, etc. |

## 4.2 Climate change

Except for the health effects that we see today, the possible consequences for indoor environment of climate change, is also a topic to be mentioned (Aries and Bluyssen, 2009; Salthammer et al., 2022). The average outdoor air temperature is rising; variation in weather conditions is increasing: we experience more heatwaves, more heavy rainfalls, sudden wind speeds and storms (IPCC, 2021). We observe an increase in smog frequency in urban areas caused by temperature rise, resulting in an even more polluted outdoor air. As a consequence, we will stay even more indoors, due to the air quality (smog events) but also because of these sudden heavy rainfalls and wind speeds. The air outdoors will be hotter, more humid, and more polluted. Changes in heat and mass transfer between the inside and outside of buildings will have an increasing impact on indoor air quality and thermal quality (Salthammer et al., 2022). Consequently, the outdoor air will need to be cleaned before it can be used to ventilate indoors, depending on regional climate and concentrations of ambient air pollutants.

To combat climate change, a transition to less carbon emissions in the buildings and construction sector is needed (EU, 2018). This transition implies retrofitting the existing building stock as such that no (or less) fossil fuels (e.g. gas and coal) are used to heat and/or cool our buildings. Unfortunately, homes that already have been retrofitted to use less 'energy' (fossil fuels), seem to not use less energy in real life. Behaviour of people towards energy use and comfort has an important role in this discrepancy (Ortiz and Bluyssen, 2019). Moreover, more health problems seem to occur as a by-coming result of these retrofits. Energy-efficient retrofitting measures have shown to lead to complaints about mould growth, built-up of pollutants (including radon), lack of control, thermal comfort stress (people feel too cold, or too warm, draught), noise annoyance from heating and ventilation installations, and a whole range of health problems (Ortiz, Itard and Bluyssen, 2020). Clearly, resilient new ways of creating and maintaining healthy and comfortable indoor spaces for different occupants in different situations, require better understanding of the indoor environment, its occupants, interactions, and effects.

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# Acceptable temperatures for naturally ventilated buildings

**Susan Roaf[1] and Fergus Nicol[2]**

[1] Institute of Sustainable Buildings Design, Heriot Watt University, s.roaf@hw.ac.uk
[2] London Metropolitan University

**Abstract:** The main challenges in our changing climate are two-fold: The most urgent need is to reduce the build-up of greenhouse gases in the atmosphere. Secondly we must all adapt to live in a world that is changing so fast that only the use of existing, known, technologies can hope to keep abreast of the pace of those changes. This paper looks at the currently available comfort related risks and opportunities. It looks at the dangers signalled by the inappropriate understandings of comfort in buildings and suggests ways in which a better understanding of indoor comfort can be used by architects and other building professionals to minimise building impacts on the climate and improve comfort in them. The paper shows how only a proper understanding of the second challenge can be used to help solve the first.

**Keywords:** Comfort, Windows, Ventilation Climate Change, SARS CoV-2

## 1. Introduction

The scale of the global challenges facing humanity now require radical new thinking and action on how we design, build and operate buildings in order to:

### 1.1 Lower Green House Gas and Ozone emissions

This imperative is number one on the agenda for change. It is now certain that increases Carbon Dioxide and other greenhouse gases caused by Human activity is the underlying cause of climate change. Despite the apparent fervour of politicians and civil groups global greenhouse gas (GHG) emissions continue to rise steadily. With the global the increase in GHGs from the built environment is the highest of any sector. In 2019 they totalled 34% of all man-made emissions (IPCC, 2022).

Ozone emissions are often overlooked but are also a major driver of climate change as their role over each Pole is critical in ice melting processes. As air-conditioning use increases so do Ozone depleting emissions.

The reduction in energy use in buildings has many linked social and economic impacts including fuel poverty. As energy prices globally soar the need to use low or no-cost solutions to increase affordable comfort levels indoors eg. using more insulation, shading and natural ventilation also soars. Understanding thermal comfort issues is key to safely reducing usage.

### 1.2 Stop the Over-heating and Over-cooling of Buildings

A large proportion of these building emissions come from energy used to heat, cool and ventilate buildings. Much is wasted because of discredited thermal comfort standards that mandate the same temperatures everywhere in the world, regardless of local climates and customs. They apply inappropriate and unnecessarily narrow set temperatures for mechanical conditioning systems. The standards are based on limited laboratory experiments to formulate crude, steady state models that take little account of the responses of local people and typically compare poorly when measured against the real local comfort experiences, as pointed out by Olesen and Parsons (2002).

In the USA in 2012 the *over-cooling* of buildings wasted around 104,000 GWh of energy and produced some 57,000 kt $CO_{2e}$ of emissions at a huge cost of 10 billion USD (Derrible and Reeder, 2015). Many know this phenomenon through feeling cold in conference centers, offices or hotels, and from the thermal shock of going from say $40^0$C outside to indoors at $20^0$C. In the Gulf States, with their all glass skyscrapers it has been calculated that 15% energy can be saved simply by raising the thermostat by two degrees (Alnuaimi et al., 2022).

### 1.3 Improve Indoor Air Quality (IAQ) and Reduce Building Toxicity

The recent SARS CoV-2 pandemic has makes us question why highly serviced buildings with fixed windows lead to higher levels of Sick Building Syndrome, nosocomial (hospital-related) infections and SARS CoV-2 related infections and deaths than naturally ventilated buildings and spaces with opening windows do (Roaf, 2022a). The very high levels of nosocomial infections in hospitals have forced many to reassess the evidence on what actually constitutes good IAQ and begin to evolve designs that can actually improve the mental and physical health of staff and patients, not infect or kill them. We need buildings people can trust to keep them safe (Roaf 2022a and b). What is the role played by current building standards, regulations and assumptions based on outdated models in the poor health performance of many modern buildings (Roaf and Nicol, 2022c)?

### 1.4 Increase Resilience of Buildings against Failure during Extreme Weather Events

The growing frequency of record breaking weather events is causing power supplies to fail around the world on a regional and local scale. Extreme events also cause whole building systems to fail. On Tuesday 19th July 2022 one of the UK's biggest hospital Trusts declared a 'critical site incident' because their datacentres both failed in the heatwave when their air-conditioning failed. Guy's and St Thomas' hospitals had to cancel operations, postpone appointments and divert seriously ill patients to other hospitals in the capital (Guardian, 2022).

As temperatures rise in the heating world air-conditioning systems will increasingly fail because they are totally dependent on the installed HVAC systems and if the buildings windows cannot be opening then often whole buildings must be evacuated as was the case for most buildings in Lower Manhattan during the 2003 power outage, affecting the whole of the US Eastern Seaboard and 50 million people living there. In response to that event and also to those resulting from Hurricane Sandy the Urban Green Council for the city has recommended that all buildings should include openings windows to help to avoid building failures.

### 1.5 Design Good Bio-Climatic with Opening Windows

Over the last seventy years, buildings have become less well designed for their local climates, becoming ever more light-weight, unshaded, over-glazed, tight-skinned and mechanically air-conditioned and ventilated (ECON19, 1992). They increasingly lack thermal mass to absorb, release or store excess heat for zero-energy night-time heating or day-time cooling. Pitifully few have effective natural ventilation systems, either simple or advanced

(Roaf, 2012), and sensible opening windows. A fast way to dramatically reduce both energy use in and $CO_2$ emissions from, buildings is to mandate safe opening windows in all new buildings and refurbishments, to enable them to be run for as much of a day and a year as possible on free, local energy (Roaf and Nicol, 2018). Up to 80% of building energy running costs in ordinary homes can be achieved by this one step alone (Alders, 2018).

Despite huge investment in 'energy efficiency' programmes, the opposite is happening with regulations and standards promoting fixed window building and thus leading to higher energy buildings (Cass and Shove, 2018) not least because those regulations increasingly demanded fixed windows and genuinely 'energy sufficient' buildings (ECEEE, 2019) inevitably rely to a lesser or greater extent on free cooling and heating with natural ventilation.

Buildings in future will have to be capable of being naturally ventilated for as much of the year as possible, particularly during emergencies. Ideally only when absolutely necessary will they be heated and cooled. Ventilations is necessary for five different reasons:

- to provide air for breathing
- to remove pathogens from spaces for health reasons
- to purge harmful substances from indoors including everything from off gassing from the furniture, fabrics and finishes of buildings and their machines to human effluents
- To charge and discharge heat from building fabric for heating and cooling purposes
- for comfort cooling of occupants indoors. For this latter function designers need to understand what temperatures can be safely used for the comfort cooling and heating of people, how and when they can and cannot be used.

## 2. What is Comfort?

Is there such thing as a comfort temperature or a comfort zone that fits everyone? In the 20th century people largely assumed that the way people feel about their physical environment can be calculated from an index which brings together different factors such as clothing and work-rate as well as temperature, humidity, and the movement of the air.

The relationship between people and their surroundings is more complex than is assumed by theoretical indices such as PMV developed by Ole Fanger fifty years ago (Fanger, 1970). People do not interact with their thermal environment in a passive way. They respond dynamically to their surroundings and if they find themselves uncomfortable, or in a thermally dangerous situation, they naturally try to react in such a way as to make themselves more comfortable and safe. At the very least they act to avoid excessive thermal stress and their responses to the thermal conditions are not random, but are directed to this essential goal.

Each and every individual is thermally unique in terms of their physiology, psychology, behaviour, experience and how wealthy or healthy they are. Every building is unique in terms of its site and the physics of its inter-reactions with the indoor environment, its occupants and the climate outside. However, one major driving force in the thermal comfort of occupants is the relationship between indoor and outdoor temperatures.

To find out how good the building is at modifying the outdoor climate and weather Nicol suggested in 2019 that the physical relationship between them could be made visible by plotting the temperatures of the indoor environment against the outdoor environment at the same time in what he called *Temperature Clouds* (Nicol, 2019). Much comfort research strove to reduce data to norms in order that comfort could be reduced to singe figures that can be used to inform machine controls. For a real understanding of comfort as experienced by real people in real buildings it is indeed necessary to look at the data in detail, not just as a preliminary data mapping exercise but also to be a central part of the data analysis process.

Norms and mean values of data do not really help in understanding the landscape of comfort issues at play for populations and the buildings they occupy, nor do they help to map the vulnerability of those populations in a heating world who live at the thermal edges of societies. Clouds provide us with vital new insights into our understanding of comfort and adaptation in addition to the current understandings we can gain through the more traditional applications of the Adaptive Thermal Comfort Method to fieldwork analysis.

### 2.1 Comfort Clouds

Temperature clouds demonstrate that around the world people occupy an enormous range of indoor temperatures, driven by the climates around them. Historically, people innately evolved to adapt their behaviours and lifestyles to create the comfort cultures that enable them to maximise the benefits of the natural energy flows in and around their buildings, while avoiding their worst impacts. Traditionally comfort was achieved in different climates through the co-evolution of the buildings along with the comfort cultures of a region.

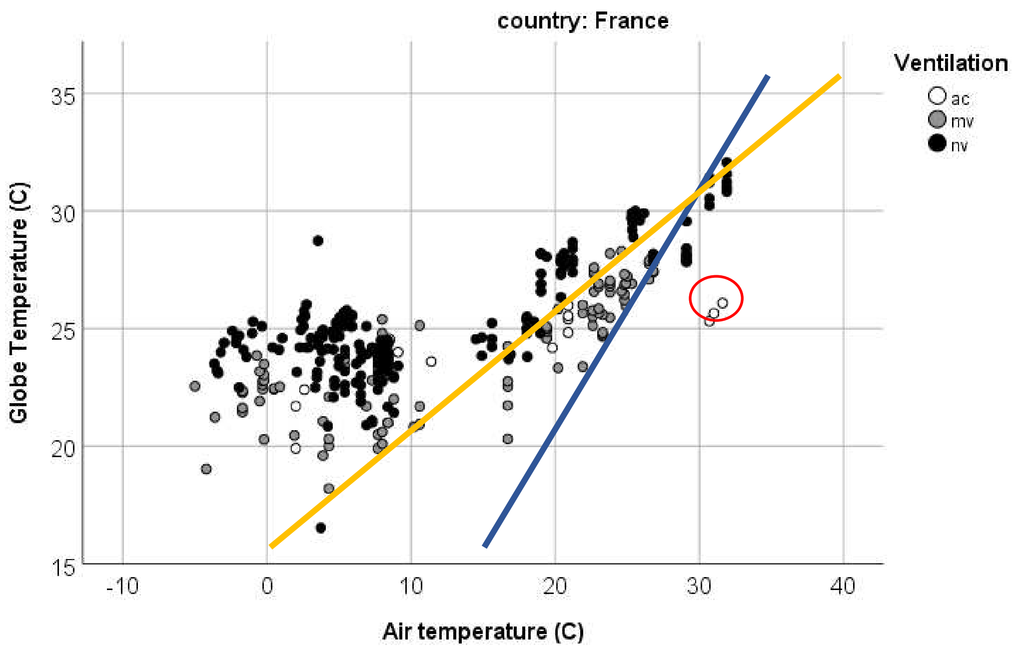


Figure 1. A comfort cloud for French data showing the change of indoor globe temperature with concurrent outdoor air temperature. The blue line shows where the indoor temperature is equal to that outdoors, the yellow line shows the approximate line of slope for the summer cloud. Shading indicates if the buildings is fully air-conditioned (ac), mechanically ventilated (mv) or naturally ventilated without mechanical ventilation (nv) (data from SCATS project in Nicol and McCartney 2001).

Figure 1. shows a comfort cloud of data collected in French offices collected for the European SCATS project (Nicol and McCartney, 2001). It shows that as outdoor temperatures increase above about 12°C in summer when many of the buildings are

naturally ventilated, and their indoor is a little warmer in the naturally ventilated buildings. The few air-conditioned buildings are cooler indoors than the mechanically ventilated ones and the general trend follows the typical line for naturally ventilated buildings where indoor temperatures follow outdoor temperatures as outdoor air is used for comfort cooling and ventilation.

In winter the buildings are heated and naturally or mechanically ventilated with the few AC buildings sharing similar temperature ranges. This does beg the question of why waste the money on energy needed to control temperatures in AC buildings when similar temperatures can be achieved naturally.

This cloud gives us a number of clear indications of what temperatures are comfortable in the region of the survey in France. First of all, it tells us that people in the region generally are happy occupying temperatures between 20$^0$C and 30$^0$C. If they were not, they would change their surroundings. It also shows where individuals, or the buildings they occupy are outliers in the local comfort cultures of the region.

Outliers can be mapped. Why is a temperature of 29$^0$C being occupied in winter? Is the building designed to over-heat? What can be done about that? Why are some naturally ventilated buildings so cool in summer? What can be learnt from them? Vulnerabilities and exceptions can be mapped and actions allocated to them as resilience across the stock is built. Indicators can be developed from them around what is considered too hot or cold in different seasons by the local populations. The data can be used to inform bottom-up action planning and implementation programmes to ensure the most cost-effective investments for the protection of population in a hotter future.

## 2.2 Climate and the Comfort of Nations

In the mid-20th century the ideas of climate determinists such as Ellsworth Huntington around the idea that white men were superior and that the growth of northern empires depended in them being able to occupy buildings even in the hotter regions of the world. The way to do this was to impose their comfort standards on nations around the world (Roaf and Nicol, 2022c).

The use of normalised and imposed steady state standards that did not recognise the close relationship between outdoor climate and indoor comfort was the tool by which such comfort imperialism was imposed. This is why buildings in the Gulf region are super-cooled to the low end of what is required by the American standards, to reflect the hyper-capitalism espouse by modern inhabitants of that region. The tie between climate, buildings and occupants was cut with such standards. In reality, the data from local comfort surveys shows clearly that every region has its own highly evolved thermal culture and experiences based on the links between those in the comfort reality of a place.

Figure 2 shows clear the very differences in the occupied temperatures from different comfort surveys of office workers. The comfort clouds for the different surveys show different typical cloud forms. The Swedish subjects are all using air conditioning set to an indoor temperature of between 20 - 25°C at all times of year despite a generally cool outdoor climate. These are the sort of temperatures seen as desirable in many European countries.

The cost in terms of energy used will be high but their employers can afford to think that this will make the workers more productive and the expense is consequently worth it. That was the case at least before energy prices began to soar in 2022. A useful narrative in the past to sell high energy premises was that the personnel costs of a commercial building far outweigh its energy costs, but that balance is now shifting.

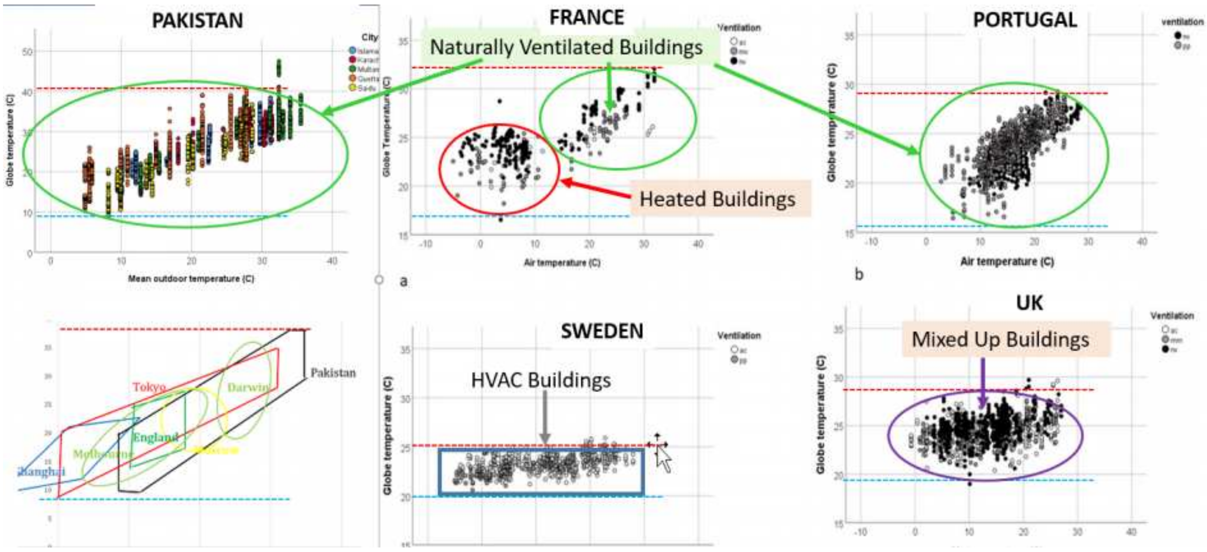


Figure 2. Composite image showing a range of different comfort clouds for cities and countries emphasising how different each city or country cloud can be depending largely on their climates and the extent to which they are naturally or mechanically cooled or heated but also as seen above, on close investigations providing insights into the geography, economy and societies they reflect. After Nicol 2019

The Portuguese in the warmer south appear quite happy in anywhere between 10-30$^0$C at different times of year in their naturally ventilated buildings. In poorer Pakistan the people occupy indoor temperatures ranging between 10-40$^0$C and use little power apart from the use of ceiling fans. Now a Scandinavian might assume that everyone in the world would like to occupy the temperatures they themselves do, and so that is what they legislate for, but such temperatures can actually be uncomfortable for people from warmer climates and are certainly not applicable to warm humid tropical climates. In many countries with hot climate would not be able to afford to do so. As temperatures and energy costs soar all of us will have to establish new norms for our own choice of the temperatures we afford to occupy.

### 2.3 What Temperatures should we Design for?

From now buildings must be designed to keep people safely and affordably comfortable, while using minimal fossil fuel energy, the burning of which for buildings creates around a quarter of all the emissions that are driving climate change. Energy guzzling and Ozone destroying AC systems should be used only when and where necessary. Data from global field studies highlighted in Figure 3 shows that people inside the buildings they normally occupy can be comfortable in a range of temperatures from 10$^0$C to 35$^0$C.

This does not mean that someone who is used to occupying 23$^0$C in summer can immediately adapt to being comfortable in 30$^0$C. It takes time to adapt and to learn how to use the controls at their disposal. If the Air conditioning was cut on a warm summer would the people in the building know how to shade the windows and get some cross-ventilation? Would the buildings allow them to? The comfort challenge in buildings has for too long been hijacked by engineers who have persuaded nations that the solution to keeping people safe in buildings in the current and future climates is having more efficient buildings.  Wrong answer.

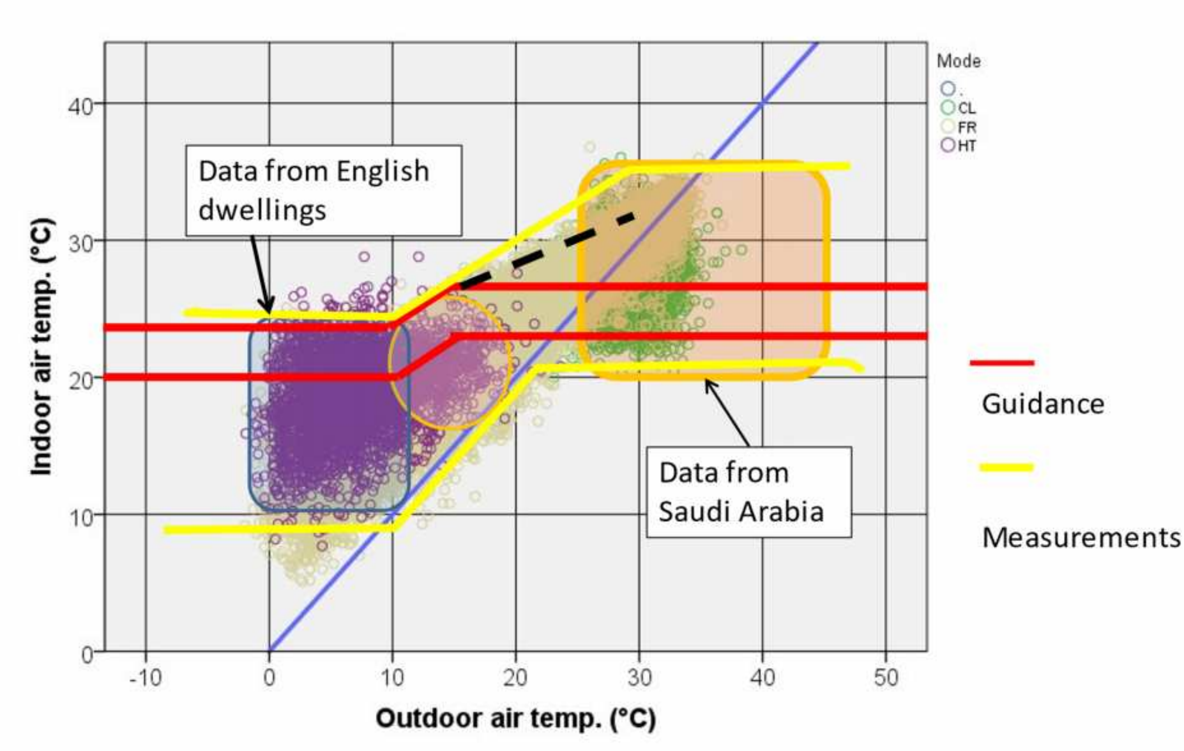


Figure 3. clouds of points from surveys in England, (purple) Japan (green) and Saudi Arabia (orange) show that the indoor temperatures from a range of climates can give rise to a liveable indoor climate ranging from 10-35°C outlined in yellow. The temperature ranges recommended in guidance by climate scientists and engineers are outlined in red and appear to simply reflect indoor temperatures in conditioned buildings. From Nicol 2019

The real solution is better bio-climatic buildings adapted to future climates. If whole populations lock themselves into narrow, backward looking, comfort zones, the hotter it gets and the more expensive grid energy becomes, the worse their economies will fare. Schools will sack teachers, hospital sack doctors and nurses and business and families bankrupt themselves to achieve retrograde ideas of what comfort temperatures they should provide for their families, employees and populations. Comfort regulations and Standards should in future set limits on what might be considered a safe and healthy temperature for local populations.  Figure 3. Shows that safe temperatures internationally exist between 10-35$^0$C. Where data shows households are falling outside those temperatures, action must be taken.

### 2.4 What Future Temperatures and Standards Should We Aim For?

For a start the word comfort should be eliminated from the building standards. There is no such thing as a comfortable temperature. In our rapidly heating world future standards should address what constitutes unsafe temperatures. Because of the inevitable relationship between the physiology of the human thermoregulatory response that is designed to keep the core temperature of humans in the region of 37$^0$C there are inevitably safe and unsafe temperatures. In the meta-analyses of comfort surveys undertaken across human populations in the last fifty years it is clear people can be comfortable at indoor temperatures between 10-35$^0$C and can often do so with little or no discomfort. Outliers to those findings represent the extremes.

Politicians are increasingly recognising the social, economic and planetary harm being inflicted by outdated and increasingly irrelevant international comfort standards as they increasingly disregard them. In the Netherlands, on April 2nd 2002, the temperature in government buildings was been set to a new maximum of 29$^0$C. In Italy, the air conditioning was required to be turned on above 25 °C -27 °C degrees since May and in winter you can only start heating when temperatures fall below 19-21$^0$C. In doing so, politicians no longer believe in the HVAC Industry's 'comfort zone', or the political benefits of sticking to a comfort mantra that is driving the over-heating and cooling of buildings, impacting the growth prospects of whole economies, and the quality of life of populations devastated by soaring energy prices.

Comfort surveys at an urban and regional level, undertaken on a regular basis, as are being done in Japan (Rijal, 2022) and India (Rawal et al., 2022). The reduction of their data to norms will obscure the detail of the exposure and vulnerability of buildings, individuals and local areas who may be either more exposed to, and/or more vulnerable to higher or lower temperatures. People should be liberated from the often punitive and limited comfort zone and to be able to choose what temperature they want to occupy in their own spaces within safe limits. What decision makers should now concentrate on is making sure that people who are falling outside those limits are caught in a supportive safety net. Using field surveys with data analyzed in clouds people and buildings of the outer limits of those safe limits can be identified and helped, not least during extreme weather events. Every municipality should have a reserve fund to draw on during severe weather and early warning systems possibly informed by data from comfort clouds.

### 2.5 Future Design Blue-Prints by Proxy

To help designers understand better designs solutions for a hotter climate Hacker et al. in a paper titled *Beating the Heat* (2005) suggested that designers learn from 'Proxy Climates'. Using models that showed by 2080 London will have a climate similar to that now found in Marseilles (Figure 4). They urged architects to explore the traditional solutions that have worked well in hotter climates for centuries to inform building design in London now. As modern buildings fail to prevent indoor overheating much can be learnt from vernacular wisdom.

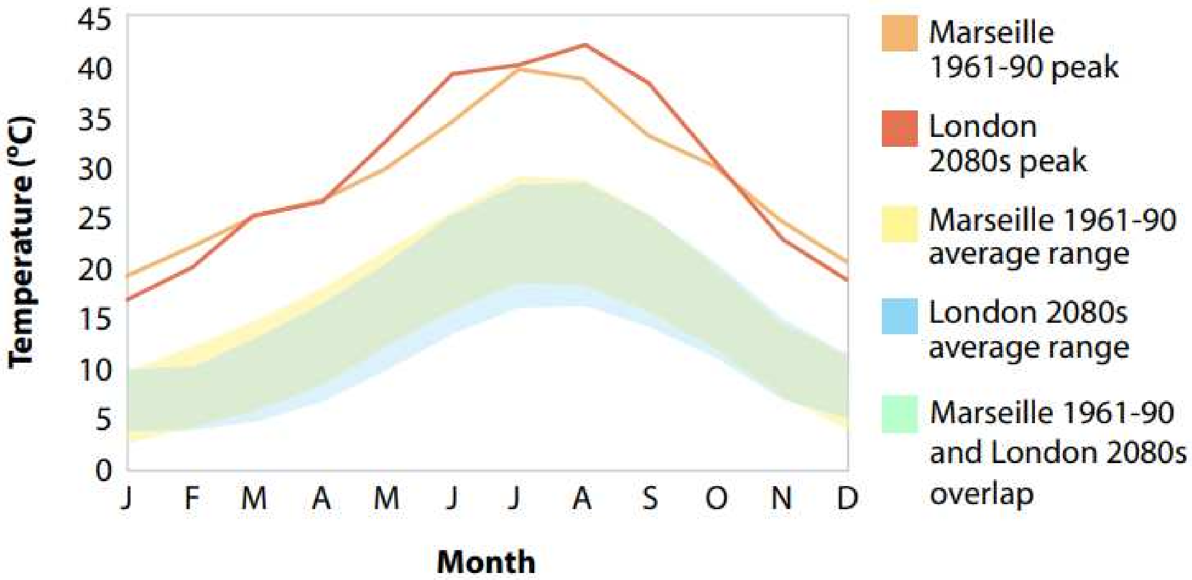


Figure 4. Temperatures for Marseille (1961-90) and London (2080s high emissions scenario) comparing the predicted average and maximum temperatures in London in the 2080s under the High emissions scenario with those in Marseille for 1961-90. (Hacker et al., 2005)

It is important to curtail the imposition of backward facing design products developed for colder climates onto societies in very different climates and buildings in a hotter future. For example, the Passive House movement tenets encompass a very limited palette of cool / cold climate options based simplistically on the use of more insulation, higher performance windows, no cold bridging or draughts along with mechanical heat recovery systems that are largely irrelevant in Mediterranean regions.

There are better solutions where high mass buildings, with well-shaded windows use natural ventilation to charge and discharge heat and coolth from thermal mass. Importantly mass enables the load shifting of heat to enable the movement of temperature peaks from day to night or vice versa, and the shaving or dampening down of temperature peaks that is critical to the de-stressing of the power supply grid at times of peak consumption, (and basically to keeping the lights on).

We can learn not just from the buildings but also the townscapes with shade trees on every major street, angled to catch the breeze, and cafes spreading to the pavements. This may well be the time to move the European Head Quarters from Brussels to Madrid or Rome where the experience of warmer climate would help to focus on realistic solutions for future hotter climates, and the shifting of the power of local lobby groups may inject a bit of urgent reality into the discussions on optimal ways forward for design in a rapidly heating world. A new broom is perhaps needed to sweep clean that Augean stable.

## 3. Conclusions

The world is heating far faster than the scientists predicted. At our CATE event on April 7th 2022 Alan Kennedy warned us that by 2050 somewhere in the UK temperatures above 40$^0$C would be recorded. Three months later this threshold was exceeded in three places in England on the 19th July. The infrastructure of the built environment could not cope. Blackouts were recorded. Two major hospitals HVAC systems failed taking down their data centres, threatening patient health and the ability of the medical staff to cope. The two messages of this paper relate to fundamental mechanisms of adaptation to runaway climate change.

1. *Mechanical systems will fail in the face of extreme weather events* and trends and to provide safe and affordable comfort the focus now must return to designing resilient buildings that can cope with extremes of heat and cold, even during the extremes. These safer buildings must include opening widows for purging spaces of toxins and pathogens, comfort cooling, passive cooling and heating of buildings and to provide free indoor comfort conditioning for as much of the year as possible.
2. *Thermal comfort standards and policies must be radically revised*, to avoid narrow, energy profligate and increasingly unaffordable temperature limits enforced in artificial comfort zones through regulations. Instead emphasis must be put on mapping and monitoring, supporting and alleviating the thermal distress of the most vulnerable and exposed people in their buildings, especially during extreme weather events. The tragedy is that many who suffer from the heat live in so called 'efficient' modern buildings.

The study of thermal comfort should from now on be incorporated into the curricula of all design courses for architects and engineers.

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# Overheating in Australia's new housing stock – a simulation study

**Dong Chen[1], Zhengen Ren[1], Mahsan Sadeghi[1], Zhi Tan[1] and Brad Lane[1]**

[1]Commonwealth Scientific and Industrial Research Organisation (CSIRO), Melbourne, Australia

**Abstract:** Overheating risks of the new housing stock in Australia were investigated by building simulation using over 320,000 recent residential building designs based on the overheating criteria in CIBSE TM59. Results show that 62.6% of the new dwellings are predicted to fail the overheating criteria. In Northern Territory (NT), South Australia (SA), Victoria (VIC) and Western Australia (WA), over 90% of these new dwellings are predicted to fail the overheating criteria. In general, overheating risk is reduced with increasing house energy efficiency. However, there is no guarantee that a high energy rated dwelling will perform better during naturally-ventilated operation with no air conditioning. This study shows that overheating in the Australian new housing stock is serious and significant efforts are needed to resolve this issue. It is recommended that a separate assessment similar to TM59 should be used in order to minimise the overheating risks in Australian homes.

**Keywords:** energy efficiency; house energy rating; overheating; new housing stock; building simulation

## 1. Introduction

Overheating in residential buildings can cause productivity reduction, increase in morbidity and mortality (Seppänen et al., 2003; Cadot et al., 2007; Herbst et al., 2014; ZCH, 2015). Considering global warming and that more people are working from home due to COVID pandemic, the impact of overheating in residential buildings could become more prominent in future.

During the last two to three decades, residential building energy efficiency standards have been gradually introduced in many countries in order to reduce energy use and minimize greenhouse gas emissions (World Energy Council, 2008; Iwaro and Mwasha, 2010, United Nations, 2015). These energy efficiency standards generally set energy targets to achieve indoor thermal comfort with the assumption that the house will be air conditioned whenever needed, while the thermal performance under naturally-ventilated (NV) operation without heating and cooling is not regulated, such as the National Construction Code (NCC) 2019 in Australia (ABCB, 2019). Modelling and monitoring studies in various climates in different countries have demonstrated that energy efficient houses may be more likely to be overheated if the thermal performance during NV operation is not properly considered (Mlakar and Strancar, 2011; Ren et al., 2014; Hatvani-Kovacs et al., 2018). Particularly, overheating has been frequently reported in heating dominated relatively mild climates in UK, Australia, and US. Designs in heating dominated climates generally emphasize on minimizing winter heat loss, which could potentially contribute to the overheating risks in summer (Lomas and Porritt , 2017; Ren et al., 2014; Willand et al., 2016; Mitchell and Natarajan, 2019).

Previous studies on overheating in residential buildings were generally carried out using a small number of sample houses at selected climates. Several studies have been carried out in Australia using monitoring and simulation methods (Ren et al, 2014; Berry et al, 2014; Hatvani-Kovacs, 2018; Willand et al. (2016), Sharifi et al, 2019). The largest scale study in Australia was the monitoring study in 107 houses in Melbourne as reported in Willand et al. (2016). Currently, the overall extent of overheating risks for the housing stock under NV operation is still not clear across the entire Australia which has climates from cold alpine to warm humid tropical. Considering that most of the new dwellings built in recent years will be in service for the next 50 years or even longer when many regions in Australia will be 1-2°C warmer, in this study, the overheating risk of the new housing stock in Australia was investigated. Building simulations were carried out using 322,504 residential building designs from 2020 to 2021 which represent over 75% of the dwellings approved for built for the same period in Australia (ABS, 20222). This is likely the first housing stock scale overheating risk study which utilizes such a large number of real dwelling designs. The objects of this study are: 1) to understand the extent of overheating risks in Australia's new housing stock; 2) to learn from the existing new housing stock for future energy efficient house designs in Australia. The methodologies used and the findings of this study could provide useful references for understanding the overheating issue in similar climates in other countries.

## 2. Methodology

### 2.1. Overheating criteria

In Australia, Nationwide House Energy Rating Scheme (NatHERS) accredited software (NatHERS, 2022) is used for house energy rating for National Construction Code (NCC) compliance (ABCB, 2019). NatHERS is a star rating system (out of ten) based on the dwelling design, orientation and local climate. It assigns a dwelling an energy star based on the calculated total annual heating and cooling energy requirement for maintaining indoor thermal comfort in a specified local climate zone. The more stars the dwelling, 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 states and territories require a minimum 6 star for new houses and a minimum 5 star for new apartments.

With the NatHERS scheme, energy efficiency is regulated under the assumption that the house is always heated or cooled whenever is need. However, the thermal performance and thus the overheating risk under naturally-ventilated (NV) operation is currently not regulated in Australia. Overheating risks in residential buildings have had relatively extensive investigations in European countries (Chen, 2019). In this study, we adopted the overheating criteria recommended by CIBSE TM59 (2017) for predominantly naturally-ventilated residential buildings. CIBSE TM59 (2017) specifies two overheating criteria:

1) For living rooms, kitchens and bedrooms: the number of hours during which $\Delta T$ is greater than or equal to one degree (K) during the period of May to September (equivalent to November to March in southern hemisphere) inclusive shall not be more than 3% of occupied hours.
2) For bedrooms only: the operative temperature in the bedroom from 10 pm to 7 am shall not exceed 26°C for more than 1% of annual hours.

Here $\Delta T$ is calculated based on Equations (1)-(3):

$$T_{max} = 0.33 T_{pma(out)} + 21.8 + T_{speed} \quad (1)$$

$$\Delta T = T_{op} - T_{max} \quad (2)$$

$$T_{speed} = 6(v - 0.2) - (v - 0.2)^2 \quad (3)$$

Where, $T_{max}$ (°C) is the thermal comfort upper limit temperature for Category II buildings (normal expectation for new buildings and renovations) operating in NV mode defined in the European standard BS EN 15251 (BSI, 2007). $T_{op}$ and $T_{pma(out)}$ (°C) are the indoor operative temperature and the prevailing mean ambient temperature respectively. $\Delta T_{speed}$ (°C) is the cooling effect of air movement based on Aynsley and Szokolay (1998). $v$ is the indoor air speed (m/s).

### 2.2. Building simulation software

Building simulations were carried out with naturally-ventilated operation mode using AccuRate Sustainability V2.4.3.21, which is the benchmark software for NatHERS star rating. Due to that AccuRate calculates an environment air temperature which combines the effect of both radiative and convective heat transfer, in this study, the indoor operative temperature, $T_{op}$, was approximated by the indoor environment air temperature. AccuRate also calculates the relative humidity by taking into account the indoor moisture sources as well as the moisture transfer due to infiltration and ventilation.

### 2.3. Weather files used in this study

AccuRate Sustainability V2.4.3.21 includes a total of 69 RMY (Refence Meteorological Year) weather files for the 69 NatHERS climate zones which cover the entire Australia. CIBSE TM59 requires the use of the local design summer year (DSY) weather file for overheating assessment, which is the year with the third highest average dry-bulb temperature from April to September during a twenty-year period. So, in this study, we selected the design summer year with the third highest average dry-bulb temperature from October to March during a twenty-year period from 1996 to 2015 for all the 69 climate zones.

### 2.4. Sample dwellings

A total of 322,504 residential building designs during year 2020 and year 2021, which were collected in the Australia Housing Data portal (https://ahd.csiro.au/), were selected for this study. These sample dwellings represent around 75% of the total 414,899 dwellings approved for built during the same period in Australia (ABS, 2022a). Table 1 shows the distributions of these dwellings in each state and territory. In Table 1, Class 1A buildings are detached houses or one of a group of attached dwellings, e.g. a town house, terrace house or the like. Class 2 buildings are apartments. These sample dwellings cover 68 climate zones (CZs) out of the 69 NatHERS CZs in Australia with no new dwelling being designed for CZ 51, Forrest, Western Australia (WA) in 2020 and 2021, since its population is zero according to the 2016 census (ABS, 2022b).

Table 1. Sample dwelling distributions in different states and territories

| State/Territory | Building Class 1A | Building Class 2 | Total |
|---|---|---|---|
| Australian Capital Territory (ACT) | 2286 | 909 | 3195 |
| New South Wales (NSW) | 30719 | 87719 | 118438 |
| Northern Territory (NT) | 831 | 156 | 987 |
| Queensland (QLD) | 16127 | 4356 | 20483 |
| South Australia (SA) | 9541 | 683 | 10224 |
| Tasmania (TAS) | 8726 | 261 | 8987 |
| Victoria (VIC) | 130739 | 19096 | 149835 |
| Western Australia (WA) | 9860 | 495 | 10355 |

### 2.5. Building simulation

Simulations were first carried out with the standard NatHERS protocol assuming heating and cooling were always available to obtain the rated heating and cooling energy requirement, and the energy efficiency star rating for each sample dwelling. Then, simulations were carried out with naturally-ventilated operation with no heating and cooling. Windows and doors were considered open for ventilation if ambient air temperature was cooler than the indoor air temperature. The temperatures in each room of the dwellings during NV operation mode were calculated and compared against the overheating criteria as described in Section 2.1. Due to the large number of sample dwellings, simulations were carried out in parallel using a total of around 100 treads over five workstations. One simulation of the 322,504 sample dwellings took approximately three days to complete.

For the NV operation mode simulations in this study, internal thermal masses were also included. The internal thermal mass was implemented as a within-zone internal wall and assumed to be a 50 mm thick timber per $m^2$ of floor area for each room. This within-zone internal wall represents an approximation of the internal thermal mass relating to furniture and other household contents in residential buildings (Johra and Heiselberg, 2017).

## 3. Results and discussions

### 3.1. The extent of overheating risks in the new housing stock

Figure 1 shows the percentage of dwellings which fails the overheating criteria recommended by CIBSE TM59. It was found that for the new housing stock in Australia, 62.6% of the dwellings fails the CIBSE TM59 overheating criteria. Except in Tasmania with a cold temperate climate, significant number of dwellings in all the other seven states and territories were predicted to fail the CIBSE TM59 overheating criteria. In Northern Territory (NT), South Australia (SA), Victoria (VIC) and Western Australia (WA), 90% of dwellings for both building classes 1A and 2 were predicted to fail the CIBSE TM59 overheating criteria. Although adopting the CIBSE TM59 criteria for Australian climate context probably was not the appropriate approach, the results appeared consistent with previous studies which reported that around 80% of the energy efficient houses investigated in Adelaide, South Australia had summer overheating issues (Berry et al, 2014; Sharifi et al, 2019). Considering that most of these new dwellings built in recent years will be in service for the next 50 years or even longer when many regions in Australia are anticipated to be 1 - 2°C warmer, overheating is serious in Australia's new housing stock.

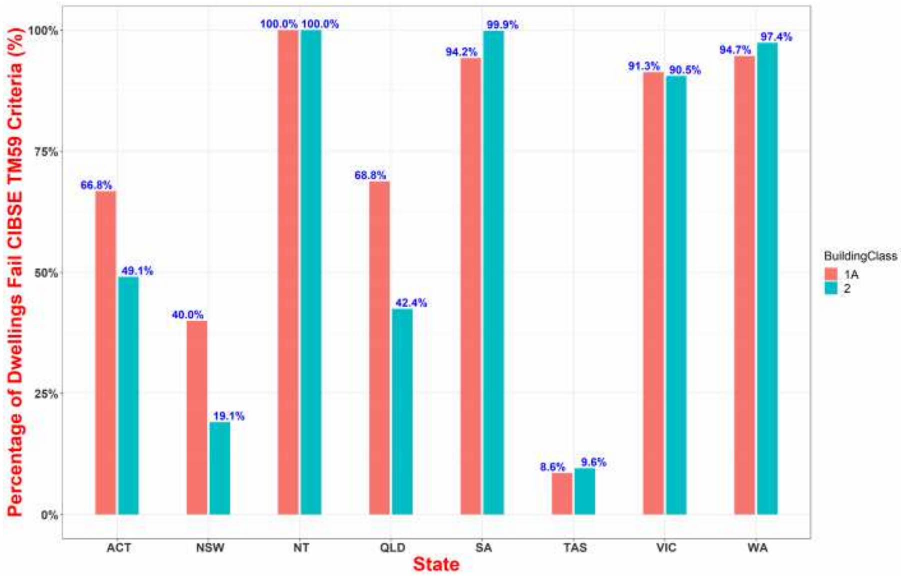

Figure 1. Percentage of dwellings fail the CIBSE TM59 overheating criteria in different states and territories

### 3.2. Energy efficiency and overheating risks

Overheating is caused by the trapping of internal and/or external heat gains. While it is not conclusive, modern energy efficient dwellings have been reported more likely to be overheated if without due consideration of overheating risk during design stage. This is because energy efficient dwelling tends to have reduced external surface areas, more airtight building envelopes, lower ceiling heights, increased thermal insulation levels etc which can potentially cause heat trapping during warm season (Ren et al. 2014; Psomas et al. 2016). Figure 2 shows the percentage of dwellings which are predicted to fail the CIBSE TM59 overheating criteria for different energy star rated dwellings in different climates in Australia. It is found that almost in all the 68 NatHERS climate zones investigated in this study, the percentage of dwellings which fail the CIBSE TM59 overheating criteria decreases with the increase in the energy star rating (more energy efficient). In other words, energy efficient modern dwellings should generally perform better in reducing overheating risks, at least across Australian climate zones .

To further understand this issue, Figures 3 and 4 show the hours overheated during daytime and night time (in bedroom) in the fastest growing region (with the highest dwelling number being designed in 2020 and 2021) in each state and territory. The corresponding NatHERS climate zone numbers for these fastest growing regions are shown in Figure 2. In Figures 3 and 4, each dot represents one dwelling and the red dashed line is the hour limit (i.e., 68 hours for daytime and 32 hours for night-time) for meeting the CIBSE TM59 overheating criteria. Figures 3 and 4 suggest that, in general, the more energy efficient the dwellings the less overheated hours during both daytime and night time. High energy efficient 9 and 10 star dwellings generally have much better performance in terms of minimising overheating risks. However, there is no guarantee that a given higher star rated or more energy efficient dwelling will perform better during NV operation mode in comparison with a lower star rated dwelling.

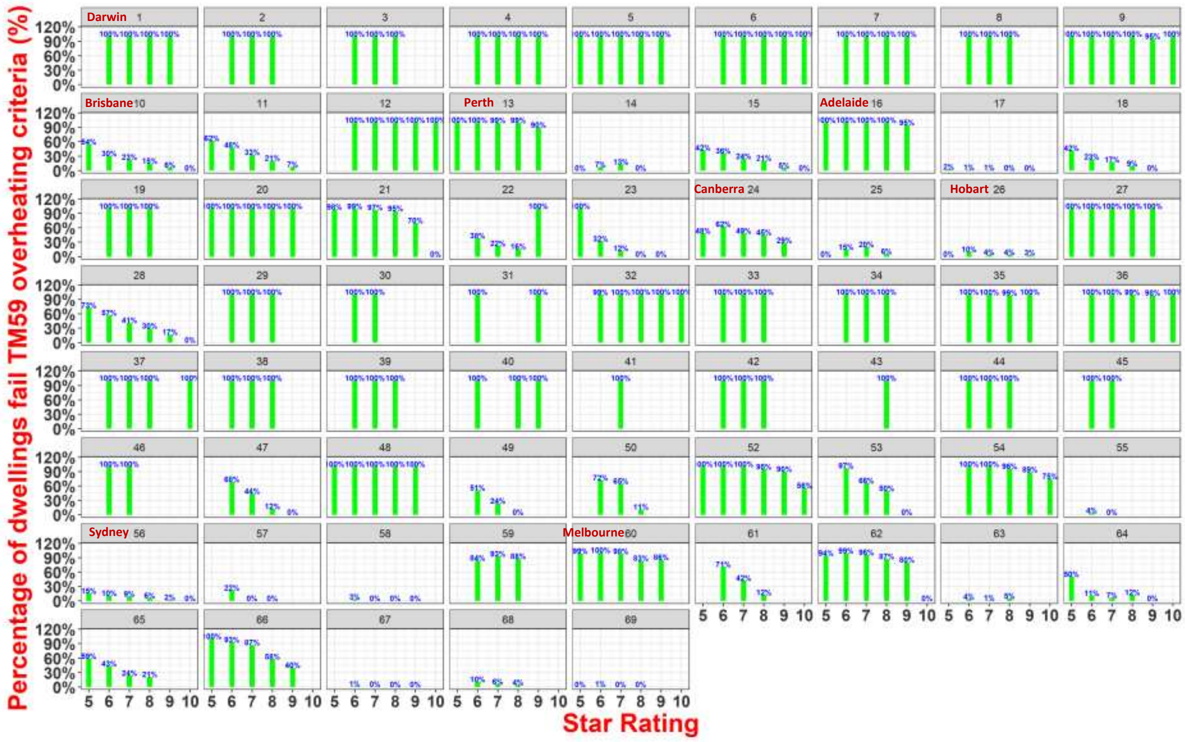


Figure 2. Percentage of dwellings fail the CIBSE TM59 overheating criteria for different energy star rated dwellings in different climates in Australia

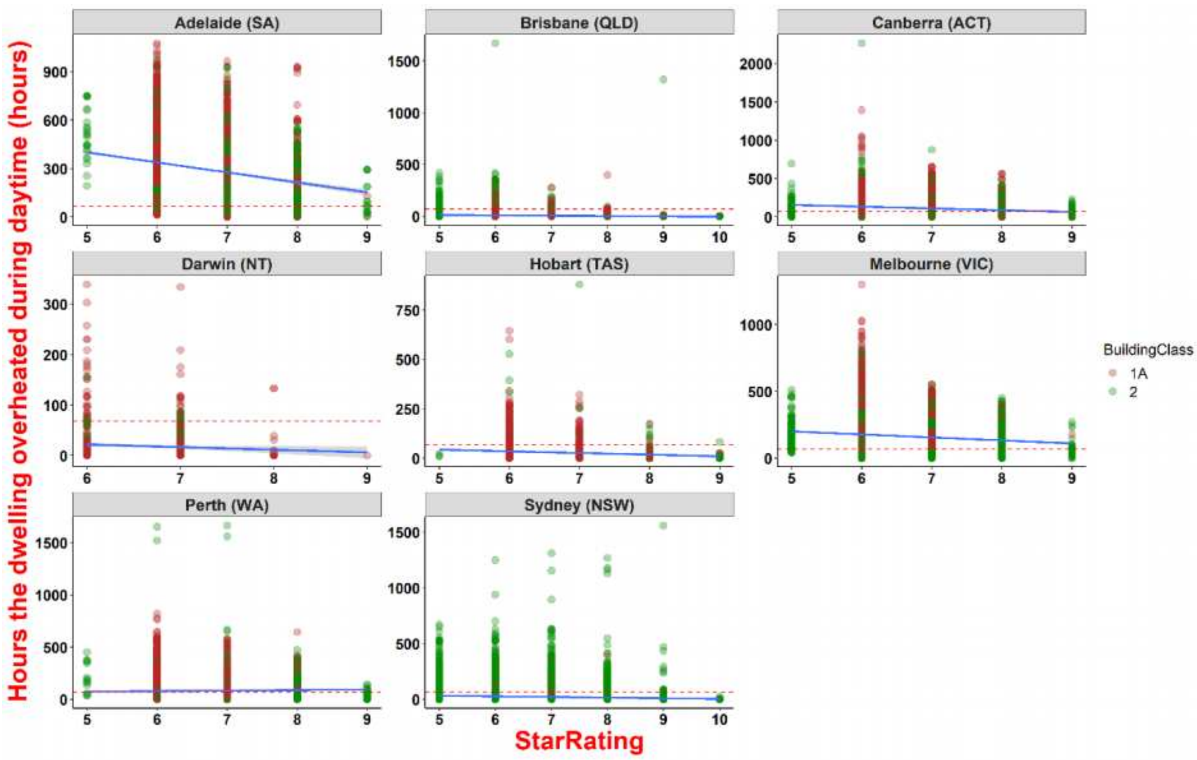


Figure 3. Hours overheated during daytime in the fastest growing region in each state and territory

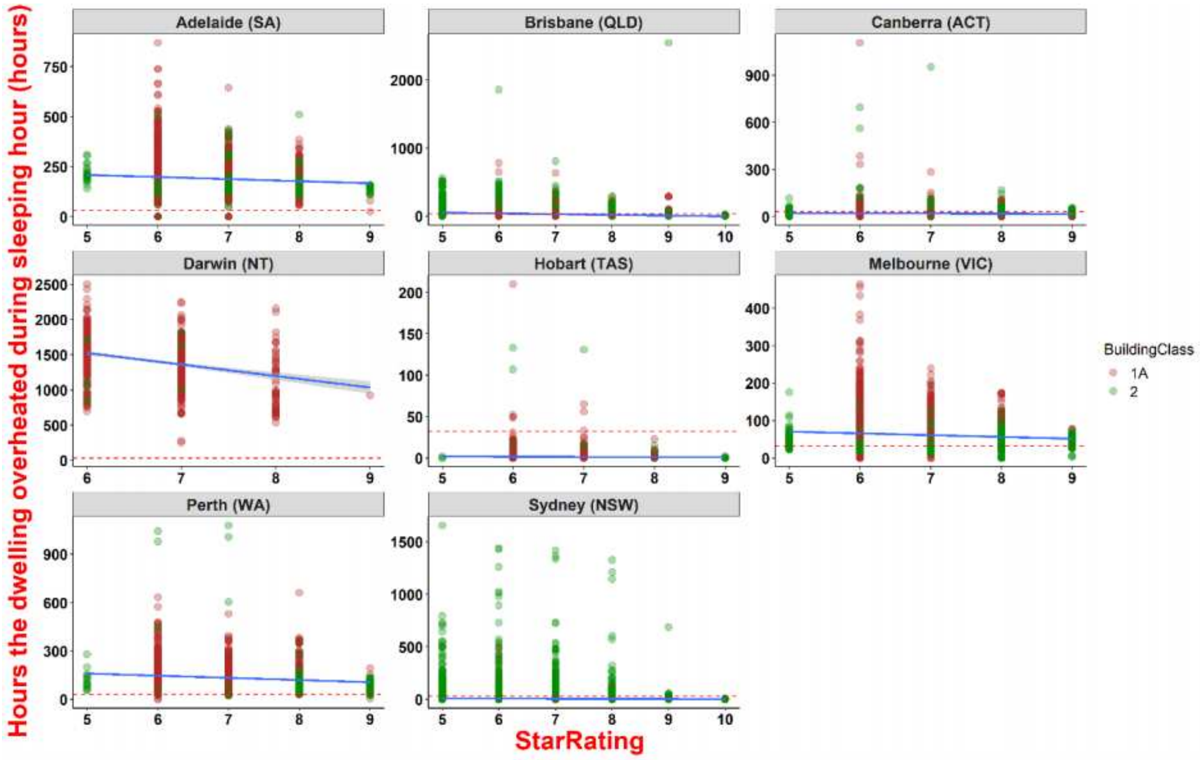


Figure 4. Hours overheated in the bedroom during sleeping hours in the fastest growing region in each state and territory

### 3.3. Cooling energy requirement and overheating risks

By investigating the thermal performance of one sample house and one sample apartment at different star ratings, Ren et al. (2014) pointed out that, in general, measures that can reduce space cooling energy requirement are effective in reducing occupant exposure to overheat risks during extreme weather conditions. Obviously, for 10 star dwellings with cooling energy requirement close to zero, occupants should generally not require cooling to maintain thermal comfort. This is confirmed by Figure 5, which shows the relationship between the overheating hours during daytime and their corresponding cooling energy requirements for the fastest growing region in each state and territory. The daytime overheating hours reduced with the reduction in the annual cooling energy requirement. However, there is no guarantee that dwellings with low annual cooling energy requirement will definitely perform better during NV operation in comparison with a dwelling with a high annual cooling energy requirement.

In should be noted that in order to reduce the overheating risks, in its last edition of the National Construction Code, i.e., NCC 2019 (ABCB, 2019) has introduced an upper cooling energy limit for each NatHERS climate zone. These cooling energy limits were enforced after May 2020. The vertical dotted green lines in Figure 5 show the corresponding NCC 2019 cooling energy limits for six star houses in Adelaide, Brisbane, Canberra Melbourne, and Perth. Figure 5 shows that the cooling energy limits may have some effect in reducing the overheating risks. However, its effectiveness is very limited and there are substantial number of dwellings, which satisfy the NCC 2019 cooling energy limits, are predicted to fail the TM59 overheating criteria. It is recommended that a separate assessment similar to TM59 should be used in order to minimise the overheating risks in Australian homes.

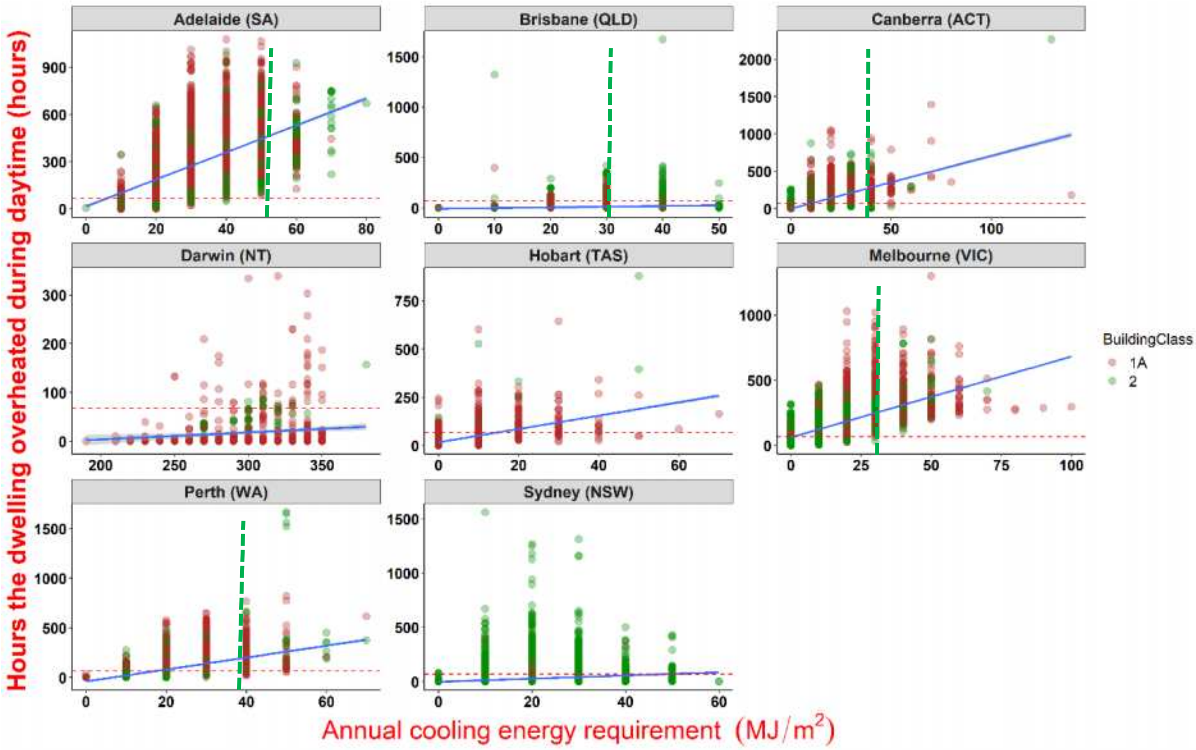


Figure 5. Relation between hours overheated during daytime and annual cooling energy requirement in the fastest growing region in each state and territory (vertical dotted green lines show the corresponding NCC 2019 cooling energy limits)

### 3.4. Learn from the sample dwelling designs

Although different designs may be needed for different climates, some general common building characteristics are observed among poor performing dwellings in terms of overheating risks among dwellings with different energy star rating and in different climates. These common building characteristics are high window to floor area ratios, limited ventilation opportunity, no ceiling fan and no shading available. Dwellings with low window to floor ratios can also sometimes cause overheating risks due to low cross ventilation opportunities. Although individual character may not necessarily cause overheating, the combination of these characters can have a high possibility resulting in overheating risks.

On the other hand, good performing dwellings generally have a medium level of window to floor area ratio, good ventilation opportunity, shading features and ceiling fans are available especially for warm and hot climate regions. It is also observed that in tropical and semi-tropical regions, e.g. Darwin and Brisbane, light weight constructions such as steel sheet or fibre cement sheet wall constructions generally perform poorly during daytime due to relatively small thermal mass. However, light weight constructions often perform better during night-time due to rapid cooling down by night-time ventilation.

Further detailed analysis is undergoing on individual sample dwelling with different thermal performance to gain more understanding for future housing designs in different Australian climates.

## 4. Conclusions

The overheating risks of the new housing stock in Australia were investigated by building simulation using 322,504 recent residential building designs based on the overheating criteria in CIBSE TM59. Results showed that 62.6% of the dwellings were predicted to fail the overheating criteria. In Northern Territory (NT), South Australia (SA), Victoria (VIC) and Western Australia (WA), over 90% of these new houses and apartments were predicted to fail the overheating criteria. The common building characteristics which combined could result in high overheating risks are high window to floor area ratio, limited ventilation opportunity, no ceiling fan and no shading available to the windows and walls. In general, overheating risks during naturally-ventilated operation are reduced with an increase in house energy efficiency and with a reduction in the rated cooling energy requirement. However, there is no guarantee that a high energy efficient dwelling with a low rated cooling energy requirement will perform well during naturally-ventilated operation.

This study has also demonstrated that the current cooling energy limits mandated in the Australia National Construction Code have very limited effect in reducing the overheating risks. This study shows that overheating in Australia's new housing stock is serious and significant efforts are needed to resolve this issue. It is recommended that a separate assessment similar to TM59 should be used in order to minimise the overheating risks in Australian homes.

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## Varying comfort: a different kind of challenge

**Gary J Raw, DPhil CPsychol AFBPsS**

GR People Solutions, Nailsworth, UK
*rawgj@hotmail.com*

**Abstract:** Subjective scales of thermal comfort emerged largely from research in contexts with little temporal variation in environmental conditions, clothing and activity. But many people live or work with marked variation in these things. This variation can become a particular kind of extreme. It is questionable how people in these circumstances would give a single comfort rating; I therefore tested an alternative approach. In a pilot study in a UK primary school, I asked staff to report the percentage of the time when it is (a) too cold and (b) too warm (separately for summer and winter, and on the day of the survey). Students reported whether they had felt too hot or too cold at any time during the day. Respondents could answer without difficulty and could state, for example, that a room had been too cold and too warm on the same day. Responses show a logical relationship with other subjective variables and with classroom thermal characteristics in different parts of the school. The survey allowed specific problems with the thermal environment to be identified and for mitigation to be suggested. The findings are discussed in relation to how thermal comfort is balanced with other requirements.

**Keywords:** Thermal comfort – Variation – Questionnaire – Diagnosis – Mitigation

### 1. Introduction

Many people live or work in thermal conditions that vary markedly over time, and where their physical activity and/or clothing vary too, sometimes within hours or minutes. A limited range of variation should not be problematic because people can adapt; in fact, it can reasonably be argued to be a positive thing (e.g. Parkinson & De Dear 2016). But there is the limit to the variation – especially rapid variation – that can be managed or tolerated; this is recognised in standards (e.g. CIBSE 2015). Even if good adaptation could be achieved to each individual set of conditions, at a point in time, the variation itself can represent a particular kind of extreme condition.

Addressing issues related to such variation may be hampered by the way in which comfort is commonly measured. Numerical scales for subjective evaluation of thermal comfort emerged largely from research in settings where environmental conditions, respondents' activities and clothing vary little over time (for example, in climate chambers or air-conditioned offices). In this context, a question in the general form "how do you feel" makes sense and lends itself to understanding how comfort is determined at a point in time or during a specified period. This is the main approach that has been adopted in national and international standards such as ASHRAE (2020) and ISO (2005).

It is questionable how people who are experiencing noticeable variation would give a meaningful single rating of the thermal conditions or their thermal sensation. It is also at odds with how design standards are often expressed: in terms of the percentage of the time that conditions fall outside a recommended range, not simply the conditions at a point in time (e.g. CIBSE 2017).

Schools in the UK (and elsewhere) can have significant variation in the indoor thermal conditions – not only between days or seasons but within a day. An invitation to investigate overheating in one such school presented an opportunity test an alternative questionnaire-based method.

The research had three main aims.

- To test whether respondents can answer the new questions without difficulty and give answers that are consistent with other subjective variables and classroom thermal characteristics.
- To test whether the survey was potentially a cost-effective way to (a) define indoor environmental quality (IEQ) problems more clearly and precisely, (b) suggest causes and mitigation of the problems, and (c) target and prioritise follow-up investigations to be most relevant and cost-effective.
- To identify ways to improve the questionnaire and survey method.

The survey also provided an opportunity to reflect on the dynamics of how thermal conditions were managed in the classrooms, and the potentially conflicting requirements. Achieving thermal comfort is not the only aim – not even the primary aim – of a school. Therefore, it is an aim that is pursued against a background of other requirements, while also recognising that achieving thermal comfort should support the primary aim of the school: to educate (in the broadest sense of that word, not merely academic achievement).

The questionnaire survey was combined with basic observations of the building. In addition, IEQ parameters (thermal, acoustic and indoor air quality – IAQ) were objectively measured during the day of the survey but findings are not reported because this paper focuses on what can be achieved with questionnaires alone, prior to any further investigation.

The findings should not be seen as a definitive evaluation of IEQ in the school. This was the first survey of its kind and there is, therefore, no basis for comparison with IEQ in other schools.

## 2. Materials and Methods

### 2.1. Context

The research was conducted in a recently constructed primary school (children aged 4-11) in the south-east of England. The school was selected because complaints had been made about overheating.

The survey was conducted on a warm day in September, very early in the school year. The staff survey covered all staff, throughout the building, but the student survey covered only the four oldest year groups, classified in England as "Key Stage 2" (KS2: ages 7-11). There were two classes in each KS2 year group, each of approximately 30 students (similar numbers of male and female). In each year group, one class was on the south side of the building and the other on the north, all on the upper floor of the two-storey building. The classrooms have large glazed areas along one façade, with manually operated internal shading by horizontal blinds. A corridor runs between north and south rooms. The south side faces over the school's outdoor sports and play areas, with a residential street beyond. The north side faces over a small outdoor area with housing beyond.

The classrooms have openable windows plus supply-only mechanical ventilation (MV). The MV delivers unconditioned outdoor air, horizontally from a single outlet near the front of the room, close to ceiling level. The supply air is directed towards the rear of the room, initially remaining close to the ceiling but then descending towards the rear wall (the rate of descent depending on temperature gradient and any turbulence created within the room). Large low-speed overhead fans had been installed in three of the eight classrooms, to evaluate whether they would be an effective remedy for overheating. One south-facing room had four fans; the other two rooms (one on the south, one on the north) each had two fans. Staff in the classrooms could switch the fans on and off.

**2.2. Questionnaire design**

Questionnaires were designed to investigate thermal conditions, IAQ, light and noise. There were two questionnaires for staff, the main one to report on conditions during the previous summer and winter, and a supplementary one to report on conditions on the day of the survey. Student questionnaires covered only conditions on the day of the survey. The aim was for the main questionnaire to be completed in 10-15 minutes, the supplementary questionnaire in up to five minutes and the student questionnaire in 10 minutes (including time for distribution and collection by the class teacher).

Prior to deployment, draft questionnaires were subjected to cognitive testing with volunteers from other schools (primary school teachers and students within the target age range). Modifications were then made to improve clarity, relevance and simplicity. Following the study, further improvements have been made but I report here the questionnaire designs as used. Space does not allow a complete account of the designs, and so I focus on parts that are most relevant to the reported findings. Enquiries regarding the full questionnaire designs should be directed to the author.

The main staff questionnaire asked, separately for summer and winter, about the following aspects of the environment.

- The percentage of time when it is (a) too cold and (b) too warm in the main space occupied by the respondent.
- Perceived control over temperature.
- Whether it is too cold or too warm in particular locations elsewhere in the school, or at particular times or during particular activities.
- Aspects of IAQ, all using seven-point scale ratings (*Too still -- too draughty / Too dry -- too humid / Fresh -- stuffy / Odourless -- smelly / Clean -- dirty/dusty / Good -- poor ventilation / Indoor air satisfactory -- unsatisfactory overall*).
- Frequency (*Never / Occasionally / Most weeks / Most days*), of problems with:
  - light and lighting (*Electric lighting too bright / Electric lighting not bright enough / Flickering light / Glare or reflections from electric lights / Needing electric lights on during the day / Glare or reflections from sunlight / Large variations in light within the room / Not dark enough / Problems with colour of light / Insufficient control over lighting / Difficulty teaching / Other lighting problem*);
  - noise from outside the building (*Distraction / Interruption of teaching / Having to close windows / Having to raise your voice / Other noise problem*);
  - noise from elsewhere within the building (*Distraction / Interruption of teaching / Having to raise your voice / Other noise problem*).

The main staff questionnaire also asked about:

- the available means to control the temperature, whether these means are easy to use, or actually used, and the training given about controlling the temperature;
- the respondent's role and location in the school, working hours, age and gender.

The supplementary staff questionnaire covered the same IEQ issues as the main questionnaire but asked only about conditions on the day of the survey. This questionnaire was intended primarily to link with the objective measurements made during the day; therefore, it is not the focus of this paper.

The student questionnaire asked an age-adapted version of seven-point thermal comfort scales: "How do you feel about the temperature in the room at the moment?" Response options were: *Much too warm -- A bit too warm -- Warm but comfortable -- Just right -- Cool but comfortable -- A bit too cool -- Much too cool*. For analysis, responses were coded +3 to -3. Students were then asked whether they remembered any of the following things happening during that day (yes or no): *Feeling too hot / Feeling too cold / Cold air blowing on you / Feeling that the air in the class is dry or dusty / Unpleasant smells / The electric lights being too bright / The electric lights not being bright enough / Flickering lights or reflections / Sunlight in your eyes / Being distracted by noise / Not hearing the teacher clearly because of noise*.

Student questionnaires were pre-coded to identify the classroom and the student's location within the room. Location was categorised in quarters of each room, according to whether the student was (a) nearer vs further away from the windows and (b) nearer the front of the class (nearer the teacher) vs nearer the rear of the class.

**2.3. Survey procedure**

A week before the survey, staff were sent a summary of what the survey would involve, its purpose, and assurances about confidentiality. Most staff were issued with paper questionnaires on the morning of the survey. Staff had the opportunity to ask the author questions at this time. Staff who were due to arrive later in the day were issued with questionnaires as soon as possible after arrival. The main staff questionnaire could be completed at any time that day, the other two questionnaires near the end of the school day. All staff were issued with the main questionnaire. Only teaching staff (teachers and teaching assistants) in the eight KS2 classes were issued with the supplementary questionnaire, plus a supply of questionnaires for their students.

KS2 teaching staff also received instructions for how to distribute and collect the student questionnaires in their class. The key elements of the instructions concerned giving out the questionnaires to the correct quarter of the classroom, giving a minimum of assistance to answer the questions, and asking students not to talk to each other while filling in the questionnaire.

Students were asked not to put their name on their questionnaires. Staff could give their names if they wished to do so, and most did. Once completed, staff were asked to place their own and their students' questionnaires in the envelope provided, and seal it. Questionnaires were either collected by a researcher or returned directly to a researcher or through a slot in a box in the staff room. All questionnaires were removed from the school at the end of the day and any personal identifiers stored separately from the rest of the questionnaire.

**2.4. Analysis**

Consistent with this being a pilot study, findings are presented mainly descriptively, to generate hypotheses rather than to test them. Sample sizes are too low for meaningful statistical comparison and the survey is, in any case, closer to a census than a sample survey. The reported findings are therefore based on the magnitude of differences, to focus on the largest effects rather than statistical significance. Comments focus on percentages that differ by at least 10% (with some reference to differences of 5% or more), and scale ratings that differ by at least 0.5.

Data from individual students were first averaged (arithmetic means) for each quarter of each room. These averages were then used for further analysis. The use of the averages means that each quarter of a room is equally represented (not distorted by the small variation in number of students in each quarter) and inter-respondent variations are smoothed out.

## 2. Results and Discussion

### 3.1. Classroom environment

Table 1 shows the mean percentage of time that staff report being too cold or too warm. The first observation is that overheating was confirmed and, as expected, more frequent on the south side (while also being experienced the majority of the time on the north side in summer). However, overheating is not the only issue: classrooms can also be too cold, particularly on the north side, and even in summer. In each season, it can be sometimes too warm and sometimes too cold in the same room.

Table 1. Mean percentage of time that staff report being too cold or too warm

| | Summer | | Winter | |
|---|---|---|---|---|
| | *Too warm* | *Too cold* | *Too warm* | *Too cold* |
| South side rooms | 77 | 0 | 25 | 24 |
| North side rooms | 61 | 21 | 15 | 77 |
| Both sides | 72 | 14 | 20 | 46 |

Responses to other questions show that, as expected, the variation in responses about temperature is due partly to (a) it being more likely be too cold during more static activities and (b) progression from being too cold to too warm in the course of a working day. The survey also identified the locations most likely to be too cold in winter (classrooms, gym and assembly hall) or too warm in summer (classrooms, gym, assembly hall, offices, staff room and library). Note that three kinds of space are in both categories.

Consistent with these findings, ratings of *Still -- Draughty* were higher (more draughty) in winter than in summer (3.4 vs 2.0) and higher on the north than the south (4.0 vs 3.3 in winter, 3.1 vs 1.3 in summer).

These issues with thermal conditions were present, even though staff did try to control the temperature in their rooms (mainly using thermostats, windows and blinds). And so, staff do not believe they have effective control of temperature in the room where they work. They report that little training about managing the temperature had been provided, and what had been provided was not useful. Some had brought in their own portable heaters or fans.

The temperature can affect pollutant emissions. In addition, perceived IAQ is affected by temperature, not only pollutant levels (e.g. Lan *et al*, 2011). It is therefore consistent with the thermal comfort findings that IAQ is perceived to be better in winter than in summer (even though there is probably a higher air change rate in summer, when windows are more likely to be open). In addition, staff on the south side report worse IAQ – in both seasons but more so in winter. The mean ratings are shown in Table 2.

Table 2. Mean IAQ ratings by staff

| | | *Dry -- Humid* | *Fresh -- Stuffy* | *Odourless -- Smelly* | *Clean -- Dirty* | *Good -- Poor ventilation* | *Satisfactory -- Unsatisfactory* |
|---|---|---|---|---|---|---|---|
| Summer | South side | 4.4 | 6.6 | 4.7 | 5.6 | 6.6 | 6.5 |
| | North side | 4.3 | 5.9 | 4.3 | 4.5 | 5.7 | 5.4 |
| Winter | South side | 3.6 | 5.7 | 4.3 | 4.9 | 5.7 | 5.3 |
| | North side | 3.4 | 3.5 | 2.8 | 4.1 | 4.0 | 3.9 |

Students' mean thermal sensation vote (TSV) was 0.6 on the seven-point scale, which is within the range *Warm but comfortable*. But this single vote does not represent conditions throughout the day: 44% report being too hot in their classroom at some point during the day and 17% too cold. As with staff, there is a clear difference between the two sides of the school, as shown in Table 3. The overall effect is that TSV in mid-afternoon was in the comfort range (middle three points) for 55% of students on the south side and 62% on the north side.

Table 3. Percentage of students reporting feeling too cold, too warm, or cold air movement

| | Student felt, at some point in the day: | | |
|---|---|---|---|
| | *Too warm* | *Too cold* | *Cold air movement* |
| South side rooms | 56 | 4 | 23 |
| North side rooms | 31 | 31 | 37 |

The staff and student surveys were thus useful in confirming or identifying thermal environment problems. The student survey provided additional value because it offered greater spatial analysis of the environment: conditions varied with location within rooms. These variations underpin how the effect of the ceiling fans can be understood (as described in Section 3.2). Regarding proximity to the front of the classroom:

- students nearer the front of the class are more likely to have felt too hot (53% vs 35%) but there is no difference in having felt too cold;
- more students nearer the front of the class report *Unpleasant smells* (24% vs 16%) and *Dry or dusty air* (30% vs 24%).

Regarding proximity to windows:

- students nearer the windows are more likely to have felt too hot (49% vs 39%) but also, on the north side only, more likely to have felt too cold (40% vs 22%);
- on the south side, more students nearer the windows report *Unpleasant smells* (32% vs 21%) but fewer report *Dry or dusty air* (21% vs 29%);
- on the north side, any effect on IAQ is small but consistent, perceptions being slightly less negative nearer the windows (15% vs 12% *Unpleasant smells* and 31% vs 28% *Dry or dusty air*).

Overall, more students on the south side than on the north side report *Unpleasant smells* (26% vs 14%) but fewer report *Dry or dusty air* (25% vs 30%).

### 3.2. The effect of ceiling fans

There were too few staff in the relevant rooms to draw quantitative conclusions about the effect of the ceiling fans although, informally, staff opinions were positive. The student survey was again more useful. Comparisons are made here between rooms with and without fans. Findings from the south side classrooms are more robust because (a) there were two rooms with fans and two without and (b) the rooms with fans were in the middle of the age range and the middle of the corridor. Findings from the north side are included for completeness but should be treated with greater caution because only one room out of four had fans. Comparing four fans with two was not considered to be useful because there is only one class with each arrangement on the same façade and they are in different year groups.

On the south side, students in rooms with fans are overall less likely to have felt too hot but the effect is not large (52% vs 60%). This effect is consistent between the front and rear of classrooms but other effects vary with location (see Table 4). An overall effect of fans on perceived cold air movement is due solely to students at the front of the class (37% with fans vs 18% without). This is reflected only weakly in reports of feeling too cold, suggesting that the air movement is mostly beneficial. In addition, students at the rear of the class have a higher (warmer) TSV with fans present (1.4 vs 0.9) but there is no difference at the front of the class (1.2 with or without fans).

On the north side, the pattern is different. At the front of rooms, the one with fans had fewer reports of feeling too hot, too cold and – in particular – cold air movement. At the rear of rooms, the one with fans again had fewer reports of feeling too cold, but more reports of feeling too hot and cold air movement. The net effect on the north side was that fans reduced the difference between the front and rear of rooms.

Table 4. Percentage of students reporting feeling too cold, too warm, or cold air movement

| | | South side | | North side | |
|---|---|---|---|---|---|
| | | Fans | No fans | Fans | No fans |
| Too hot | *Front of classroom* | 59 | 66 | 39 | 45 |
| | *Rear of classroom* | 46 | 54 | 25 | 15 |
| Too cold | *Front of classroom* | 8 | 3 | 22 | 31 |
| | *Rear of classroom* | 4 | 3 | 25 | 37 |
| Cold air movement | *Front of classroom* | 37 | 18 | 28 | 50 |
| | *Rear of classroom* | 20 | 19 | 33 | 25 |

Other IEQ parameters provided further evidence on the effect of the fans. Table 5 shows IAQ findings for students on the south side. Improvement due to the fans is observed at the front of rooms. At the rear of rooms, improvement is less for *Dry or dusty air* and the opposite effect is seen for *Unpleasant smells*. In addition, IAQ is perceived more negatively at the front of rooms where there are no fans; in contrast, IAQ is perceived more negatively at the rear of rooms where there are fans. On the north side, in the room with fans, *Unpleasant smells* are reported less frequently than in other rooms (10% vs 17%) but *Dry or dusty air* is reported more frequently (44% vs 26%); location within the room has little effect.

Table 5. Percentage of students on the south side reporting dry/dusty air or unpleasant smells

| | *Dry or dusty air* | | *Unpleasant smells* | |
|---|---|---|---|---|
| | Fans | No fans | Fans | No fans |
| Front of class | 9 | 49 | 18 | 46 |
| Rear of class | 16 | 27 | 23 | 19 |

The intention of the fans was to increase air speed and turbulence. The thermal environment and IAQ responses suggest that a second factor is at work. On the south side, there was an overall improvement in perceptions nearer to the front of classrooms with fans, partly balanced by some worsening of perceptions at the rear of classrooms. This could be due to fans displacing MV supply air downward to a greater extent nearer to the front of the room. The implication is that fans might result in greater experience of cooling for staff than for students, because staff spend more time at the front of the room and/or a location that they choose, and because they are taller and more often standing, therefore closer to the fans.

On the north side, the fans should similarly displace the MV supply air but the impact is different in ways that could be accounted for by (a) there being a lesser need for cooling on the north side and (b) the MV supply air possibly having a warming effect.

There were distinct patterns in the findings for the two student ratings of IAQ, *Unpleasant smells* and *Dry or dusty air*. To account for this, two further hypotheses can be made: (a) higher temperatures on the south side, especially near the windows, increase odours; and (b) MV supply air dilutes odorous pollutants but is perceived as more dry or dusty.

Students' responses about light and lighting add further insight. The most frequently reported problem was *Sunlight in your eyes* (39% overall). There were differences between the south and north sides, the front and rear of classrooms, and rooms with and without fans (see Table 6). The overall effect is complex but one observation is that the percentages are generally higher at the rear of the room, particularly on the south side and in rooms with fans.

Table 6. Mean percentage of students reporting sunlight in their eyes

| Location in room | With fans | | Without fans | | Overall |
|---|---|---|---|---|---|
| | Front | Rear | Front | Rear | |
| South side rooms | 37 | 58 | 42 | 37 | 44 |
| North side rooms | 17 | 25 | 36 | 42 | 34 |

There is suggestive evidence here of possible changes in occupant behaviour, consequent to the installation of ceiling fans: the fans appear to have done more than simply change air movement. If teachers feel cooler in rooms with fans, they could be less inclined to lower window blinds, thus increasing students' exposure to direct sunlight, especially at the rear of rooms. On the north side, the blinds would be less necessary, even without fans, so the impact of fans would be less. A similar consequential reduction in window-opening can also be hypothesised. Such changes in behaviour could partly account for why the fans have only a moderate effect on students' reports of being too hot.

The hypothesis regarding use of blinds would easily be tested by further observations but it is supported by findings about electric lighting. In rooms without fans, students were more likely to report lights being too bright nearer the front of the class than at the rear (40% vs 13%). This could be due to the ceiling height being reduced at the front of classrooms, hence lights being more in students' field of view. In rooms with fans, reports of lights being too bright are reduced to 6% in both halves of the room. This would be explained by blinds being raised, thus reducing the need for electric lighting.

A prior concern was that the fans might cause flickering from overhead lights or in reflections in desk surfaces. Overall, 20% of students reported *Flickering lights or reflections*. There was no effect of fan installation on the south side. On the north side, 29% reported flickering or reflections in the one classroom with fans compared with 14% in the other three. This might be accounted for by greater reliance on electric lighting on the north side.

Another concern was that fan noise might affect teaching, although staff did not feel that it was intrusive except when the fans were starting up. The student survey did not indicate a problem with fan noise: in classrooms with fans, there were fewer reports of distraction (60% vs 70% on the south side, 39% vs 49% on the north side) and not being able to hear the teacher clearly (35% vs 42% on the south side, 31% vs 43% on the north side). Any impact of fan noise might have been offset by a reduced need to open windows (hence less noise from outside) and/or a masking effect of the constant low-level noise from the fans.

### 3.3. Comfort in competition

The findings can be interpreted in relation to how comfort can be seen as competing with other factors that influence how heating and cooling are managed. Raw *et al* (2017) identified five "OCHRE" factors that influence how heat energy is managed in the home.

- ***O**ther people* represents a concern for other people – their comfort and how they perceive you – including being productive.
- ***C**omfort* has broader connotations than thermal comfort, including also feeling in control, and being able to rest and relax. It is similar to the Danish concept of hygge.
- ***H**ygiene* represents hygiene in both the specific modern sense of cleanliness and the broader (original) sense of healthiness, including safety and security.
- ***R**esource* is defined by four motivations: energy costs, avoiding wasting energy, the value or cost of the home, and concern for the environment.
- ***E**ase* represents convenience and simplicity, adopting (perceived) norms and familiar behaviours that make life easier by reducing the need to make or repeat decisions.

My interpretation of what is happening in the classrooms can be examined in relation to these factors. It is not necessary to accept that my interpretation is correct – only that it is plausible. In this way, some possible restrictions on achieving thermal comfort can be explored.

For a teacher in a classroom, *Other people* means students and possibly a teaching assistant. There is a clear challenge to meeting the needs of around 30 individuals, spread around a room. Teachers might try, and probably meet with only partial success, probably biased by their own perceptions of the environment. Or they might take the simpler approach and aim for their own comfort, on the assumption that (a) this will maximise the comfort of others and (b) their own comfort and productivity is to the benefit of the students. Either approach could be moderated by any complaints or signs of obvious discomfort from others in the room. Nevertheless, teachers might over-estimate the benefit of the fans for students, with the possible consequence of changing how they use blinds and windows, as discussed above.

And so the *Ease* factor also potentially comes into play – in relation both to taking a simple approach to anticipating the needs of others and to the mitigation actions taken. Operating windows and blinds is more instinctive and immediate than operating heating controls. This then links to the "being in control" element of *Comfort*.

Opening windows, raising blinds and turning off electric lights can be related to *Hygiene* as a motive. "Fresh" air and natural light are generally perceived as good for health. Some staff spontaneously reported adverse health effects that they attributed to the artificial lighting.

And what of *Resource*? The was no specific evidence that staff were strongly motivated by minimising costs or energy consumption, although this could be because they had little practical control over these parameters. Some had brought in their own heaters or fans. But the design of the school and building services appears to have been subject to high expectations of low energy demand. The result might be an indoor environment that falls short of reasonable expectations.

## 3. Conclusions

The study succeeded according to its main aims.

- Respondents willingly completed the questionnaires and were able to answer the questions without reporting substantial difficulty in doing so.
- The subjective responses give a picture of the indoor environment and the impact of the ceiling fans that is coherent in itself and consistent with classroom characteristics.
- The suspected overheating problem was confirmed in a cost-effective way and described in greater spatial and temporal detail, while also identifying additional problems and evaluating mitigation.
- The findings suggest a logic to how teachers sought to manage thermal conditions, consistent with the OCHRE framework of motives.
- The findings indicate what follow-up should be carried out to confirm conclusions, using objective measurements in various locations within rooms, not in a single central location. There should also be further observations and discussion with staff to clarify their behaviour and the reasons for it (e.g. use of openable windows and blinds).
- Although not detailed here because of space limitations, the survey suggested ways in which the questionnaires could be shortened and simplified.

The method piloted is thus a valuable triage tool when evaluating the indoor environment. It is not intended to replace seven-point scale ratings of thermal comfort, particularly if the mechanisms of comfort response are being researched. It is a supplementary method, applicable particularly to IEQ investigations where conditions could vary over time. With further methodological development, and creation of a database of findings from multiple schools (and other environments), the method could become even more powerful.

Regarding the recommendations that can be made from this survey, ceiling fans were shown to have a useful role in mitigation of overheating and improving some aspects of IAQ – particularly on the south side of the school. Any further action should give attention to consequential changes in use of openable windows and shading, and the balance of natural and electric lighting. This could include, for example, replacing the horizontal blinds with vertical blinds. The causes of rooms being too cold should also be investigated, focusing on the heating and how it is controlled. Checks should be made to ensure that air delivered to rooms by the MV is adequately filtered and not excessively dehumidified.

As noted above, the findings should be seen primarily as hypotheses to be tested rather than final conclusions. Some specific limitations should also be noted.

- The data are comparative rather than absolute: it should not be assumed that staff accurately report the exact percentage of time when they experience discomfort or that students accurately recall every IEQ experience from the day. This is why it is important to develop a reference database of multiple environments, using exactly the same method.
- The survey was conducted on one warm autumn day, and therefore should not be taken as fully representative of conditions throughout the year.
- The overall pattern of findings is a good basis for defining next steps as outlined above: in relation to the specific school (further data collection) and the survey method (wider application to develop a reference database). However, each individual finding should be treated with caution because of small sample sizes and the large number of variables measured – probably a few of the observed effects are random.

## 4. Acknowledgements

This work was funded by CETEC Foray Ltd, with support and advice from Paul Ajiboye (CETEC UK) and Richard Daniels (UK Department for Education). Questionnaire distribution and collection was assisted by Andrew Bellamy and Jamie Liang of CETEC. The kind cooperation of the staff and students of the school is gratefully acknowledged.

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# The effect and influence of personalised ceiling fans on occupants' comfort and physiological response

**Romina Rissetto[1], Isabel Mino-Rodriguez[1] and Andreas Wagner[1]**

[1] Building Science Group, Karlsruhe Institute of Technology, Karlsruhe, Germany

**Abstract:** Personal environmental control systems (PECS), such as fans, have been widely implemented as an effective strategy to increase energy efficiency and occupants' satisfaction with indoor environmental conditions. This paper explores significant differences between thermal sensation votes and participants' physiological responses when using personal ceiling fans. In an experimental study in summer of 2018, 45 participants were exposed to two thermal conditions (28°C and 31°C) and different airflow speeds and directions in a climate chamber that simulates a typical office environment. Indoor environmental, psychological and physiological responses (skin temperature and heart rate) were recorded during the entire session. We tested differences in physiological responses between different demographic, contextual groups and airspeed levels. Results showed that at 31°C, participants had a significantly higher distal skin temperature and that airspeed helped reduce proximal skin temperature. Overweight participants showed a significantly lower proximal skin temperature than average weight participants. Heart rate results yielded statistically significant differences between age groups. Besides, findings suggest that skin temperature follows indoor temperature changes. By increased airspeed, physiological adaptations can be stimulated to restore comfort. Overall, personal ceiling fans are an effective cooling solution that can target occupants' body parts and individual characteristics to increase their comfort.

**Keywords:** skin temperature; heart rate; personal comfort system; thermoregulation; thermal comfort

## 1. Introduction

The study of personal environmental control systems (PECS) has gained relevance in recent years, as they can improve occupants' satisfaction with the indoor environment and potentially increase energy savings in buildings. PECS targets occupants' proximity by conditioning only the occupied zone of the building space; hence, there might be less energy consumption than systems that condition the entire building volume, such as air conditioning systems. As a type of PECS, the use of fans has been widely implemented, as the cooling effect of the air movement increases occupants' thermal comfort and acceptability range in moderately warm thermal conditions. Furthermore, localised convective cooling of transitional spaces and work areas by ceiling or desk fans represents a way to enhance comfort recovery (Zhai et al., 2019).

The study of PECS is sustained in the paradigm that shifting thermal comfort toward a wider temperature range might stimulate the thermoregulatory system and not only achieve comfort but improve occupant's health (Ivanova et al., 2021; Luo et al., 2022). For instance, mild cold exposure can increase the human body's daily energy expenditure, contributing to maintaining a healthy weight and improving glucose metabolism. On the other hand, heat exposure can improve cardiovascular functioning after hot water immersion, decrease systolic blood pressure, and improve glucose metabolism (Ivanova et al., 2021). On the contrary, maintaining a stable indoor climate design could decrease the body's thermal resilience, in other words, the ability of the body to adjust to non-neutral conditions (Luo et al., 2022).

The human thermoregulation system responds to various indoor climate conditions through skin temperature adjustments and other physiological responses to keep the body core temperature within narrow temperature limits (Rawal et al., 2020). Skin temperature acts as one and an important sensor of the human body's thermoregulatory system (ASHRAE, 2017). Local skin temperature results from the complex balance between metabolic heat production, heat dissipation to the environment and tissue temperature (Binek et al., 2021). Differences in skin temperature could arise from body composition, health status, metabolic rate, circadian rhythm and ambient temperature (Neves et al., 2017). The underlying adaptive mechanisms to restore comfort are (a) behavioural, (b) physiological and (c) psychological adaptation. While minimising the availability of behavioural adaptation, physiological responses may occur. For instance, PECS can minimise thermal discomfort of targeted body parts which may activate thermoregulation. Very few studies have investigated the human body's physiological response to an increased airspeed due to the use of ceiling fans.

Luo et al. (2022) studied 18 participants between 18 and 40 years old in a climate chamber in autumn and winter. They tested two main scenarios (PECS and no PECS) and the indoor air temperature ranging from 17°C to 25°C. Results showed that skin temperature follows the same increasing pattern as the indoor air temperature. Distal and head skin temperature were significantly affected when using PECS, but this was not the case with torso skin and underarm-finger temperature gradient. Significant differences in lower limb temperature between 10 male and six female highly trained subjects were observed by Binek et al. (2021) under resting conditions but not during exercise. Regarding heart rate, Luo et al. (2022) reported no apparent relation with the indoor environment temperature ramp from 17°C to 25°C. However, there was a small but significant increase in hand skin blood flow and a significant increase in the average heart rate by 2.2 BMP ($p < 0.001$).

Finally, some researchers look into the ability to include physiological parameters to estimate thermal comfort responses better. Kingma et al. (2017) looked into the physiological thermoneutral zone (TZN) as a proxy to understand the thermal sensation. Some authors (Chaudhuri et al., 2018; Wu et al., 2017; Zhang and Lin, 2020) found a relationship between overall thermal sensation and mean skin temperature and proposed that the latter could predict thermal votes.

Existing research highlights the impact of physiological responses in thermal comfort studies; however, little is known about the cooling effect of the air movement due to ceiling fans in warm conditions. The study hypothesises that human thermoregulation can be moderately stimulated while providing comfort using personal comfort systems and investigates differences between demographics and contextual differences in human physiology.

## 2. Objective (Hypothesis)

The study focuses on the evaluation of the effect of personal ceiling fans on skin temperature and heart rate differences due to personal (sex, age, BMI), contextual characteristics (daytime, air temperature), and psychological responses (thermal sensation votes) for the given indoor environmental conditions. The main research questions are as follows:

- RQ1: Is there any significant difference in skin temperature (distal and proximal) and heart rate when subjects are exposed to increased airspeed from personal ceiling fans?

- RQ2: Is there any significant difference in skin temperature (distal and proximal) and heart rate when subjects are exposed to different levels of airspeed?
- RQ3: Is there any significant difference in skin temperature (distal and proximal) and heart rate when subjects felt comfortable or uncomfortable based on reported thermal sensation for different levels of airspeed?

## 3. Methodology

To investigate the above-mentioned research questions, we conducted a 3-weeks experimental study in the test facility LOBSTER in Karlsruhe, Germany (Schweiker et al., 2014) during the summer of 2018.

### 3.1. Facility and experimental procedure

The facility consists of two office rooms equipped with a personal ceiling fan, which is integrated into an acoustical ceiling panel. Participants took part in a three h 30 minutes sessions in one of the two rooms of the climate chamber, either in a slot between 9:00 and 12:30 (morning) or 13:30 and 17:00 (afternoon). During the first 30 minutes, the participants acclimatised to the given conditions in the room (acclimation phase). After this period, they experienced six different workstation configurations in a randomised order for 20 minutes concerning the ceiling fan position. For each configuration, participants were exposed to a constant fan speed for 10 minutes ('fixed' condition) and afterwards were given the possibility to adjust the fan speed level for the following 10 minutes ('adjustable' condition). They performed office tasks during the whole session, such as reading or working with the computer. The rooms were set with a room temperature of 28°C (50% RH), and a selected number of participants (N = 11) repeated the session another day with a room temperature of 31°C (50% RH). A detailed description of the study and the ceiling fan is explained in Rissetto et al. (2021).

### 3.2. Participants

Forty-five participants between 18 and 34 (Adult) and 50–70 year (Elderly) (age young 30.67 ± 4.04, age elderly 65.48 ± 6.45; BMI 24.7 ± 3.72 kg/m2) took part of the study. They were asked to wear long trousers, a t-shirt, and closed shoes (M = 0.44 clo-value; SD = 0.12). Table 1 shows the distribution of participants according to their age group, age, body mass index (BMI < 25 kg/m2 = normal and BMI > 25 kg/m2 = overweight) and sex.

Table 1. Participants' distribution according to personal characteristics (age, sex, BMI).

| | | Age | | Subtotal |
|---|---|---|---|---|
| **Sex** | **BMI** | **Adult** | **Elderly** | |
| Male | Normal | 8 | 7 | 15 |
| | Overweight | 3 | 8 | 11 |
| | Subtotal | 11 | 15 | 26 |
| Female | Normal | 7 | 2 | 9 |
| | Overweight | 1 | 9 | 10 |
| | Subtotal | 8 | 11 | 19 |
| | Total | 19 | 26 | 45 |

### 3.3. Materials and data collection

*Physiological data.* We measured the skin temperature of the single participants in four points with temperature loggers (iButton model = DS1921H; r = 0.125°C; a = +/- 1°C). The proximal skin temperature was measured at the back of the neck and the right shoulder, and the distal skin temperature was measured at the back of the left hand and the right shin. Their heart rate was measured with chest strap sensors (Model: EcgMove 4; r = 12 bit; Input range CM = 560 mV, DM = +/-5 mV). All data was recorded in a 1-minute interval.

*Temperature and airspeed.* We also collected with AHLBORN comfort meters located at 1.1 m height and 0.25 m away from the participant's head the following parameters: air temperature (r = 0.01 °C; a = ±0.2 K), globe temperature (r = 0.01 °C; a = ±(0.30 K + 0.005 × T)), relative humidity (r = 0.1%, a = ±2.0%) and air velocity (r = 0.001 m/s; a = ±(3% measured value + 0.01)). Participants' interactions with the ceiling fan during the adjustable condition were collected using a remote controller with a reference level from 0 to 100%. The device was connected to the building management system (BMS), and the fan speeds could be derived from the recorded levels.

*Psychological data*. Participants completed several questionnaires at different times during the session, including thermal sensation (7-point; *cold ←→ hot*), comfort (5-point; *comfortable ←→ extremely uncomfortable*), preference (7-point; *much cooler ←→ much warmer*), acceptability votes (4-point; *clearly acceptable ←→ clearly not acceptable*), perception of air quality and airspeed, among others.

**3.4. Data analysis**

Data preparation and analysis were conducted with the software environment R Version 4.1.3. Both physiological parameters (heart rate and skin temperature) and airspeed are measured on interval level and therefore assessed using parametric tests. Data normality was tested using Shapiro-Wilk's test, distal skin temperature is normally distributed (W = 0.988, p = 0.071), and proximal skin temperature (W = 0.985, p = 0.025) and heart rate (W = 0.969, p = 0.000) are non-normally distributed. An independent t-test was conducted to test differences between demographics and contextual factors when the studied variables had two groups when data was normally distributed. Furthermore, an ANOVA (F) test was used when the studied variables had more than two groups. Whenever data follows a non-normal distribution, comparisons between two levels were tested using the Mann-Whitney and Kruskal-Wallis (H) for three levels of analysis. Moreover, a paired t-test was conducted to test the significant difference between distal and proximal temperatures. All t-tests were calculated with a significance level of 0.05. Finally, effect sizes are interpreted as small (d = 0.10), medium (d = 0.30), and large (d = 0.50), based on Cohen's suggestions (Cohen, 1988). Table A 1 shows the mean and standard deviation for each analysed group's distal and proximal skin temperature and hear rate scores.

To evaluate the effect of an increased airspeed due to the use of personal ceiling fans in physiological responses, data corresponding to the acclimation period and airspeed below 0.05m/s was discarded from the analysis. To evaluate significant differences in physiological responses between participants' personal (sex, age, BMI) and contextual characteristics (daytime, air temperature) (*RQ1*), we conducted a series of independent-samples t-tests and Mann-Whitney tests to compare the average values of skin temperatures and the average heart rate during the whole session. The effect of different air velocities in participants' physiological responses (*RQ2*) was analysed at three levels of air velocity: Low = airspeed < 0.4m/s, Medium = airspeed between 0.4m/s and 0.8 m/s, High = airspeed > 0.8 m/s. To evaluate significant differences in skin temperature and heart rate between participants who reported thermal sensation for different airspeed levels (*RQ3*), thermal sensation votes (TSV) were classified into two groups: neutral (TSV $\geq 3 \leq 5$) and non-neutral (TSV < 3 and > 5). A correlation between physiological and psychological was performed using Kendall's rank correlation coefficient Tau.

## 4. Results and discussion

### 4.1. Differences between personal and contextual characteristics

Error: Reference source not found shows the results of the t-tests conducted for skin temperature and heart rate to identify differences between personal characteristics (age, sex, and BMI) and between contextual characteristics (daytime and temperature). All groups showed homogeneity of variance for the analysed variables (Table A 2Error: Reference source not found), except for the BMI groups for heart rate scores, which showed inequality of variance across samples. Additionally, we found a significant difference between proximal skin temperature (M = 34.07, SD = 0.89) and distal skin temperature (M = 33.26, SD = 0.68, t (44) = -5.80, p < .001, r = .66, N = 90).

Table 2. Central tendency comparison for skin temperature (distal and proximal) and heart rate measurements between independent groups (sex, age, BMI, time of day and temperature).

| | Sex | Age | BMI | Time of day | Temperature |
|---|---|---|---|---|---|
| **Skin t° distal** | t (37.34) = 1.50<br>p = 0.141<br>M = 33.08 (f); 33.39 (m) | t (31.41) = -0.52<br>p = 0.608<br>M = 33.32 (y); 33.21 (e) | t (39.89) = 1.81<br>p = 0.08<br>M = 33.42 (n); 33.07 (o) | t (42.96) = -0.56<br>p = 0.578<br>M = 33.31 (m); 33.20 (a) | t (15.43) = -5.02<br>**p < 0.01****<br>M = 33.05 (1); 34.00 (2) |
| **Skin t° proximal** | W = 185<br>p = 0.159<br>M = 34.43 (f); 33.88 (m) | W = 196<br>p = 0.249<br>M = 34.30 (y); 33.88 (e) | W = 373<br>**p < 0.01****<br>M = 34.38 (n); 33.57 (o) | W = 284<br>p = 0.492<br>M = 33.96 (m); 34.35 (a) | W = 137<br>p = 0.198<br>M = 33.92 (1); 34.42 (2) |
| **Heart rate** | W = 278<br>p = 0.487<br>Mdn = 73.19 (f); 75.11 (m) | W = 157<br>**p = 0.039***<br>Mdn = 77.78 (y); 72.79 (e) | W = 227<br>p = 0.581<br>Mdn = 72.97 (n); 75.59 (o) | W = 215<br>p = 0.398<br>Mdn = 77.00 (m); 73.82 (a) | W = 168<br>p = 0.861<br>Mdn = 73.86 (1); 74.46 (2) |

Note: The following abbreviations correspond for each group: Sex = f: female, m: male; Age = y: young, e = elderly; BMI = n: normal, o: overweight; Time of day = m: morning, a: afternoon; Temperature = 1: 28°C; 2: 31°C.

Results showed that heart rate values were significantly higher for younger participants than for the elderly group, with a medium effect size (d = -.31). At the same time, no differences were found in the skin temperature between groups. Reported psychological responses of the participants were previously analysed (Rissetto et al., 2021), and results showed that younger participants evaluated the temperature as significantly less comfortable, expressed a preference for a cooler temperature and found the temperature less acceptable than older participants. Besides, participants with normal weight showed higher proximal skin temperature than participants with overweight during the session, with a large effect size (d = -.42). However, there were no differences between heart rate scores and comfort votes between BMI groups.

Although Rissetto et al. (2021) showed that female participants perceived the temperature as significantly hotter and less comfortable, we found no statistically significant differences in skin temperature or heart rate values between female and male participants. Differences in skin temperature between women and men have been previously assessed, as in Wu et al. (2017), who found no statistically significant difference between groups in the hand skin temperature for warm thermal sensation votes at an average air velocity of 0,2 m/s and 26°C indoor temperature. We analysed differences in the average air speed between sex groups, and no significant difference was observed (t (40.71) = -0.84, p = 0.408).

We found statistically significant differences in distal skin temperature between the temperature sessions (d = .79), showing higher levels of distal skin temperature when participants experienced the warmer temperature condition (31°C). At 31°C, participants reported the temperature conditions as significantly warmer and less comfortable. Even though studies showed that temperature changes could induce changes in the heart rate (Lan et al., 2011), we found no differences between thermal conditions. Differences in results could be explained as the mentioned study compared neutral to warm changes, while participants experienced only warm indoor conditions in our study. Besides, Rissetto et al. (2021) showed that afternoon participants perceived the temperature as higher, evaluated the temperature and air velocity as less comfortable and chose a higher selected level of fan speed; in the present study, physiological responses did not significantly differ between daytime sessions.

### 4.2. Effect of airspeed levels for different thermal sensation votes and temperature settings

Table 3 summarised the differences in physiological responses between air speed levels. RQ2 needs to be rejected in this analysis. In this first analysis, the level of airspeed seemed not to influence physiological adaptations, as no significant differences were found for skin temperature, neither proximal nor distal, and heart rate between the different levels of airspeed.

Table 3. Central tendency comparison for skin temperature (distal and proximal) and heart rate between air speed groups.

| | Normality | Central tendency | Test | p-value | Effect size |
|---|---|---|---|---|---|
| **Skin t° distal** | W = 0.988, p = 0.303 | M = 33.3 (l), 33.3 (m), 33.2 (h) | F (2, 203) = 0.178 | 0.774 | 0.18 |
| **Skin t° proximal** | W = 0.982, p = 0.303 | M = 34.1 (l), 34.1 (m), 34.0 (h) | F (2, 124) = 0.147 | 0.048 | 0.05 |
| **Heart rate** | W = 0.969, p = 0.303 | Mdn = 73.8 (l), 75.8 (m), 74.6 (h) | H (2) = 0.570 | 0.752 | -0.03 |

Note: The following abbreviations correspond for air speed groups = l: low, m: medium, h: high.

Results of a correlation showed that the expressed sensation votes during the session were significantly related to the distal skin temperature (τ = 0.16, p < .01) and the proximal skin temperature (τ = 0.22, p < .001). These results align with previous studies that found a linear relationship between overall thermal sensation and upper extremity skin temperature (Wu et al., 2017). Assuming a relationship between thermal sensation and skin temperature, we analysed the effect of different levels of airspeed on skin temperature for different thermal sensation groups and temperature configurations. Error: Reference source not found shows the results of the performed t-test.

Table 4. Central tendency comparison for skin temperature (distal and proximal) measurements between thermal sensation groups and thermal conditions for different air speed levels.

| | Level | Airspeed and sensation | Airspeed and temperature |
|---|---|---|---|
| **Skin t° distal** | Low | t (25.3) = -2.29, **p = 0.030***, d = .41<br>C = 61 (n), 19 (nn); M = 33.2 (n), 33.7 (nn) | t (15.6) = -4.65, **p = 0.000***, d = .762<br>C = 35 (1), 10 (2); M = 33.1 (1), 34.0 (2) |
| | Med | t (8.22) = -1.46, p = 0.181, d = .454<br>C = 29 (n), 8 (nn); M = 33.2 (n), 33.7 (nn) | t (12.4) = -4.63, **p = 0.000***, d = .796<br>C = 28 (1), 9 (2); M = 33.1 (1), 34.1 (2) |
| | High | t (5.44) = -1.96, p = 0.103, d = .643<br>C = 52 (n), 6 (nn); M = 33.1 (n), 34.0 (nn) | t (16.2) = -5.12, **p = 0.000***, d = .787<br>C = 35 (1), 10 (2); M = 33.0 (1), 34.0 (2) |

| | | | |
|---|---|---|---|
| **Skin t° proximal** | Low | t (31.7) = -2.29, **p = 0.029***, d = 0.376<br>C = 61 (n), 19 (nn); M = 34.0 (n), 34.5 (nn) | t (19.1) = -1.35, p = 0.193, d = .295<br>C = 35 (1), 10 (2); M = 34.0 (1), 34.4 (2) |
| | Med | t (9.60) = 0.103, p = 0.920, d = .033<br>C = 29 (n), 8 (nn); M = 34.1 (n), 34.1 (nn) | t (18.4) = -1.75, p = 0.096, d = .379<br>C = 28 (1), 9 (2); M = 33.9 (1), 34.5 (2) |
| | High | t (7.21) = 3.160, **p = 0.015*,** d = .762<br>C = 52 (n), 6 (nn); M 34.0 (n), 34.9 (nn) | t (18.9) = -1.06, p = 0.301, d = .237<br>C = 35 (1), 10 (2); M = 34.1 (1), 34.3 (2) |

Note: The following abbreviations correspond for each group: Thermal sensation = nn: non-neutral, n: neutral; Temperature = 1: 28°C, 2: 31°C.

RQ3 is partially supported. Regarding thermal sensation votes, participants who voted neutral thermal conditions showed statistically significant lower distal and proximal skin temperature (0.5°C difference), when the air speed was below 0.4m/s, compared to participants voting feeling warmer (non-neutral). On the other hand, a 0.9°C difference between participants voting neutral and non-neutral is not significantly different when the airspeed is above 0.8m/s for distal skin temperature. This could be interpreted as at low fan speed values, the cooling effect of the airflow was not sufficient to restore comfort, slightly increasing participants' skin temperature, consequently reporting warmer thermal conditions. Although thermal conditions were perceived differently at elevated fan speeds (medium and high), it seems that participants did not require to thermoregulate their bodies, as the cooling effect provided by the fan airflow was higher. However, at airspeeds higher than 0.8 m/s, participants who voted neutral showed lower proximal skin temperature than participants who voted non-neutral thermal conditions. A possible explanation could be the direct cooling effect of the airspeed on the skin temperature in the upper body parts (shoulder and neck), which allowed a higher reduction of the skin temperature in some participants (neutral group), consequently leading them to perceive the indoor conditions as neutral. Although the effect sizes for the different tests are either medium or large, the sample size of the non-neutral group is relatively small, which could lead to different results.

In terms of thermal conditions, participants showed significantly higher values of distal skin temperature when the indoor temperature was 31°C, regardless of the airspeed level. Contrarily no significant difference in proximal skin temperature values was found between thermal conditions. This could be interpreted as a reduction of the skin temperature at warmer thermal conditions was achieved by the cooling effect of the air movement in the proximity of the participant's body, generating no difference in skin temperature between the two temperature conditions. In the case of the distal body parts, an increase in temperature resulted in an increase in skin temperature, in which no skin temperature reduction was possible as no direct airflow was directed to those body parts.

## 5. Conclusions

This study aims to understand the relationships between human physiology and perceptions of the indoor environment quality when using a personal ceiling fan. The effects of airspeed from and personal control over the fan and personal and contextual characteristics of participants were investigated. The main conclusions ~~are as follows~~in this study could be described as physical differences due only to demographics or physical characteristics, and differences due to environmental conditions (airspeed and air temperature).~~:~~

Regarding physical differences among participants, it was observed that o~~O~~**verweight participants showed a significantly lower proximal skin temperature than participants with average weight, while a higher mean heart value was measured for young**

**participants, showing that body composition and** ageing **can affect physiological responses under the same indoor environmental conditions.** Studies on women subjects have reported non-significant differences in core temperatures between normal and obese body mass (Chudecka 2014.) However, the mean body surface temperature decreases with an increasing percentage of body fat in the abdominal area, while the opposite relation was observed for the hand area, opposite to what was reported in this study. Furthermore, as it has been previously reported, younger adults are usually metabolically more active, and heart rate decreases with age (Kumral 2019). Thus, the observed differences in body composition and heart rate cannot be only attributed to the differences in the indoor environment. Further studies are required to better understand the main physiological variables involved in adapting, acclimating and resilience to more extreme indoor environmental conditions.

On the other hand, the main conclusions regarding sking temperature due to differences in the indoor environmental conditionsl could be summarised as fowllows:

The Sskin **temperature corresponds to changes in indoor temperatures** and consenquently with participants' perception of the indoor environment**. At increasing moderately warm indoor temperatures, participants had a significantly higher distal skin temperature and rated the thermal condition significantly warmer and less comfortable.**

- Participants selected a significantly higher air velocity for the warmer condition to restore thermal comfort. When the airspeed was insufficient to achieve thermal neutrality, it could be assume that a thermoregulation process took place in body extremities, increasing the distal skin temperature.
- The effect of the air movement in the proximity of the human body affected the skin temperature of the participants and, consequently, their thermal perception of the environment.

Despite results on physical results are not conclusive, different levels of airspeed provide insightful results to inform the definition of the thermoneutral zone. For instance, at medium or high airspeed, the thermal sensation does not directly affect the distal skin temperature as it does the air temperature. Furthermore, a difference in the range of 0.5 to 0.9 degrees in proximal skin temperature could be conclusive in terms of perceiving a neutral or non-neutral thermal sensation regardless of the air temperature in the assessed environment.

Findings in this study suggest that personal environmental control systems can improve thermal comfort by stimulating human thermoregulation processes targeting specific body parts. Moreover, these systems allow multiple configurations to target individuals' body composition to achieve individual comfort.

**Abbreviations**

r resolution
a accuracy

**Acknowledgement**

The analysis and data collection were conducted within the project ID: 03ET1563A. The data analysis and manuscript preparation work by Mino-Rodriguez was supported by the project

ID: 03EN1002A. Both funded by the German Federal Ministry of Economic Affairs and Climate Action (BMWK).

## Appendix

Table A 1. Count, mean and standard deviation (sd) for distal and proximal skin temperature and heart rate scores for each analysed group.

| Group | Levels | | Distal temp. (°C) | | Proximal temp. (°C) | | Heart rate (bpm) | |
|---|---|---|---|---|---|---|---|---|
| | | Count | mean | sd | mean | sd | mean | sd |
| Age | Young | 19 | 33.3 | 0.8 | 34.2 | 0.9 | 79.9 | 11.6 |
| | Adult | 26 | 33.2 | 0.6 | 33.9 | 0.9 | 72.8 | 8.2 |
| BMI | Normal | 24 | 33.5 | 0.8 | 34.5 | 0.8 | 75.9 | 13.1 |
| | Overweight | 21 | 33.1 | 0.5 | 33.6 | 0.8 | 75.8 | 6.5 |
| Sex | Male | 26 | 33.4 | 0.6 | 33.9 | 0.8 | 76.0 | 8.6 |
| | Female | 19 | 33.1 | 0.7 | 34.3 | 1.0 | 75.6 | 12.5 |
| Temperature | 28°C | 35 | 33.1 | 0.6 | 34.0 | 1.0 | 75.7 | 11.3 |
| | 31°C | 10 | 34.0 | 0.5 | 34.3 | 0.7 | 76.2 | 6.7 |
| Time day | Morning | 23 | 33.4 | 0.7 | 34.2 | 1.0 | 77.5 | 10.1 |
| | Afternoon | 22 | 33.2 | 0.7 | 33.9 | 0.8 | 74.3 | 10.5 |

Table A 2. Levene's test for equality of variance.

| | Sex | Age | BMI | Time of day | Control | Temperature |
|---|---|---|---|---|---|---|
| **Skin t° distal** | F = 0.01<br>p = 0.961 | F = 2.78<br>p = 0.103 | F = 3.93<br>p = 0.054 | F = 0.02<br>p = 0.896 | F = 0.11<br>p = 0.736 | F = 0.03<br>p = 0.874 |
| **Skin t° proximal** | F = 1.19<br>p = 0.282 | F = 0.02<br>p = 0.894 | F = 0.27<br>p = 0.607 | F = 3.36<br>p = 0.078 | F = 0.05<br>p = 0.820 | F = 1.46<br>p = 0.233 |
| **Heart rate** | F = 1.36<br>p = 0.249 | F = 2.57<br>p = 0.116 | F = 5.72<br>**p = 0.021*** | F = 0.17<br>p = 0.685 | F = 0.03<br>p = 0.867 | F = 1.50<br>p = 0.228 |

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# Natural ventilation: a comparative profile of the opening/closing frequency of windows in Spanish homes before and during COVID-19

**M. A. Navas-Martín[1] and T. Cuerdo-Vilches[2,*]**

[1]Escuela Nacional de Sanidad, Instituto de Salud Carlos III (ENS, ISCIII)
[2]Instituto de ciencias de la construcción Eduardo Torroja, Consejo Superior de Investigaciones Científicas (IETcc-CSIC)

**Abstract:** Almost all Spanish homes were built before the Technical Building Code (2006), which firstly adopted aspects on Indoor Air Quality (IEQ). Ventilation of occupied housing depends on the will and the culture of their users. In this questionnaire, prepared during the confinement of the first wave of COVID-19, the compared frequency of opening/closing windows before and during the COVID-19 pandemic was analysed, participating 1,763 households. The explanatory variables were sought to characterize the household profile according to ventilation frequency. The results yielded interesting insights: firstly, people staying at home were more likely to ventilate frequently, both before and during the pandemic. In contrast, people with a caregiver role declared lower ventilation rates, even before the pandemic. For cooking, liquefied fuels, coal or biomass, were related to poor ventilation. Ventilation was inversely proportional with thermal comfort. Likewise, adaptive preferences showed to be related to ventilation frequency. Therefore, this analysis of homes' profile from its use frequency of windows allows to understand the phenomenon from a cultural, occupational and behavioural perspective, as well as possible energy saving criteria to achieve thermal comfort or personal awareness. This can help establish multi-scale strategies on natural ventilation, in building renovation, promoting mechanical or hybrid systems.

**Keywords:** social research, adaptation, SARS-CoV-2, household, ventilation frequency Introduction

## 1. Introduction

The WHO declared a health emergency by the new coronavirus, so most countries established social isolation (Amer et al., 2021). Spain was one of the most affected countries in Europe by COVID-19 (Pollán et al., 2020). On March 14, a State of Alarm was declared in Spain, including measures to protect citizens against SARS-CoV-2 (Gobierno de España, 2020).

Quarantine was mandatory or voluntary depending on the country or region (Odusanya et al., 2020). In Spain, a severe lockdown was determined at the same time that the first wave of the COVID-19 pandemic spread across the territory. Spanish people had to adapt their lives, altering their habits in their houses (Navas-Martín et al., 2021).

It took time for WHO to reach a consensus with scholars about the transmission way of the virus by air (Read, 2020). 239 researchers from 32 countries published an open letter to this organization asking for adequately warning of the risks of aerosol contagion (Morawska y Milton, 2020).

In April 2021, the WHO released a series of recommendations on the importance of ventilating indoor spaces to improve air quality and avoid the transmission of COVID-19 (World Health Organization, 2021).

In Spain, the Ministry of Health, promoted measures during the first wave, such as physical distancing, hand washing, use of disposable handkerchiefs and coughing or sneezing over the elbow (Gobierno de España, 2020). During the third wave, through the 6M information campaign, the recommendations also added more ventilation, encouraging to go out when possible for activities and the opening of windows (Gobierno de España, 2021).

The indoor natural ventilation is the most ancient and common way of avoiding indoor pathogens, in these habitats, including viruses (Hobday y Cason, 2009). Before developing mechanical or hybrid mechanical systems, old buildings, including housing, depended on the layout design, windows and envelope gaps distribution and opening, and the meteorological events, such as winds and difference of outdoor-indoor temperature, to maintain the indoor air quality (Krarti, 2018; Roaf, 2022). In fact, inappropriate ventilation may increase indoor pathogen agents, since there is not enough fresh outdoor air to dilute them from indoor environment, and not getting them out of the dwelling (Environmental Protection Agency, 2021).

Entering external air, the internal one is replaced (Dimitroulopoulou, 2012). Indoor air pollution by pathogens generates non-comunicable diseases, compromises the state of health of respiratory and cardiovascular systems, causes irritation and allergic reactions, such as asthma, among others (Organización Mundial de la Salud, 2018). The origin of those pathogen agents is diverse: biological, chemical, radiations, or moisture, for instance. An over-exposition to high concentrations of these pathogen agents can provoke not only health diseases in users, but also low concentration or productivity, and absenteeism (Environmental Protection Agency, 2021). Besides, ventilation adjusts relative humidity that can be condensed in zones with a high internal load or where vapour is released (Wolkoff, 2018). This can also cause severe pathologies, by existence of fungi, lichens or moss, affecting persons through respiratory problems. Thus, indoor ventilation and public health are closely related (World Health Organization Regional Office for Europe, 2015).

Ventilation can be specified as natural (directly by envelope gaps to the outside, and by simple or merged action of temperature or pressure changes between outside and inside), mechanical (using inlet and/or outlet fans, which move the air by ducts, formerly going through filters and other elements for its adaptation), or hybrid, as a combination of the two preceding ones, according to internal and external conditions. The last two are usually controlled, and often integrated into the Heating, Ventilating and Air Conditioned (HVAC) system for non-residential buildings.

In Spain, the Technical Building Code (CTE), refers basic and compulsory aspects of ventilation to reach indoor air quality within its Basic Document HS3 (Gobierno de España, 2019), both in habitable spaces and in waste warehouses, storage rooms, garages, and parking lots. Also, the national Regulation of Thermal Installations of Buildings (RITE) refers to tertiary buildings (Gobierno de España, 2007), with a more effective application since 2006, when indoor air quality began to be present, since previously the regulations were not so strict, even less for homes. However, Spanish residential stock wasbuilt almost entirely before this regulation was created, and thus, these systems were not implemented (España, 2020).

So, to reach natural ventilation in the homes, it (at least partially) depends on the user's criteria (Fernández-Agüera et al., 2019), according to the window opening/closing frequency, as well as the time that they are kept opened, intensity and density of use indoors, the gap dimensions (Aflaki et al., 2015) and the volume of indoor areas, and climatic conditions, such as outdoor temperature, pressure and wind, for instance (Lei et al., 2017; Spengler y Chen, 2000).

Although the relation between housing and occupants' health is widely known (Ahmad et al., 2020; Culqui et al., 2022; Qian et al., 2021), some studies during the COVID-19 pandemic have deepened into the relevance of the domestic habitability aspects in this time, and more precisely during the quarantine, not only for physical, but also in mental health and well-being (Zarrabi et al., 2021).

However, few studies were able to establish in situ measurements in homes during this period, since only previous studies had the resources to carry out the needed monitoring. These studies sought social behaviour and explanatory relations by crossing with different variables, obtaining interesting but disparate outcomes, due to the heterogeneity of households, as well as of the quality of housing design and construction, among others (de Frutos et al., 2021; Domínguez-amarillo et al., 2020). Also, this studies had to be contextualized in their reality, according to all of the referred circumstances and features, and the adaptation to the quarantine that would be adopted in each case.

The analysis presented, as far as we know, is the only one at national level (and of the few internationally developed) that tried to answer to the general behaviour of the Spanish households in quarantine, related to domestic spaces and their environmental characteristics, with no other aim except to establish and describe this relation and the way in which housing has covered their needs and expectations under such extreme circumstances. The research questions for this analysis were: 1) what was the social profile of households, and the housing characteristics, of those that properly ventilated naturally (by means of opening windows) before the COVID-19 crisis, and 2) what circumstances drove those who ventilated poorly before quarantine, to increase the frequency of window opening during lockdowns, to adequately ventilating.

## 2. Materials and methods

An exploratory cross-sectional analysis was performed in Spanish households during the COVID-19 first wave of the pandemic. The data-gathering happened between April 30 and June 22, whilst the State of Alarm was decreed by authorities, and population, confined in their homes.

SurveyMonkey® was the online platform chosen to collect, through a questionnaire, the responses to 58 questions distributed into 18 topics, about households, housing features and use habits and behaviours related to domestic space.

Through different distribution ways (the official website, emails, social networks and the media), the participant recruitment was made, through the whole territory.

To participate, the required criterion was to be over 18 years and only one survey by home. An informed consent was attached, also with information on the aim of the study. It was approved by Ethics Committee from the Spanish National Research Council (CSIC, in Spanish).

A descriptive study is presented. Bivariate relations define significant potential explanatory relationships on ventilation habits prior to the COVID-19 quarantine, and also the positive ventilation habit-change, during the first wave of SARS-CoV-2. To develop this analysis, the statistical program SPSS, version 28 was used.

### 2.1. Chosen variables

To analyse ventilation as a routine, the recurrence of opening/closing windows was chosen as dependent variable, in two stages, "before" and "during" quarantine. Original responses were classified according to a Likert-type scale with five categories: from "continually closed", "sometimes a week", "once a day", "several times a day", and "continually open". They were codified so that they left only two: the first three into “poor ventilation”, and the last two, as “adequate ventilation”.

The selected independent or explanatory variables, twenty-eight, were categorized into six general groups. These are listed in the table 1.

Table 1. Selection of independent variables for the analysis on compared residential natural ventilation frequency (before/during quarantine)

| Category | Variables |
|---|---|
| **Household’s features** | Age, Gender, completed level of studies, current job situation, number of cohabitants, living with minors, living with elders (+65) |
| **Housing descriptors** | Housing type, tenure regime, usable floor area, own external space, dwelling orientation, perceived indoor air quality, perceived lighting quality, perceived noise insulation |
| **Thermal comfort perception and habits according to use domestic energy use** | Habitual clothing in the home, thermal sensation indoors (comfort), thermal preference indoors, thermal acclimatization measures, type of heating system, energy source of domestic hot water, Comparative use of household appliances and devices |
| **Telecommuting spaces (only for "during quarantine")** | Type of teleworking space, qualities of the teleworking space perceived as adequate |
| **Other tasks during quarantine (only for “during quarantine”)** | Alteration of habits at home |
| **home improving expectations (only for “during quarantine”)** | Desire to improve aspects of the home; desire for changes in housing (grouping of aspects); Satisfaction with the home (in essential aspects, or those related to design and construction). |

Due to the extension and depth in contents from the original questionnaire, to avoid participant dropout, and its own length (with 58 questions), the questions contained qualitative or categorical answers.

## 3. Results

In this analysis, 1,502 valid responses were included, regarding the window-opening recurrence in the home, before and during the COVID-19 quarantine (more specifically, during the first pandemic wave).

The frequency distributions were given to acquire a general picture on opening and closing windows, to facilitate natural ventilation.

### 3.1. Descriptive analysis: ventilation frequency before/during quarantine

Figure 1a represents the distribution of households that ventilated deficiently and those that did properly, both before and during lockdown. Besides, figure 1b shows detailed frequencies in lockdown, including the compared frequencies between those changing their routines during lockdown for the worse, and those for the better, improving ventilation. “Poor ventilation” implied window-opening frequencies originally collected in the survey through the following Likert-scale responses: "continually closed", "sometimes a week", and "once a day"; “Adequate ventilation” refers to window-opening frequencies related to "several times a day", and "continually open".

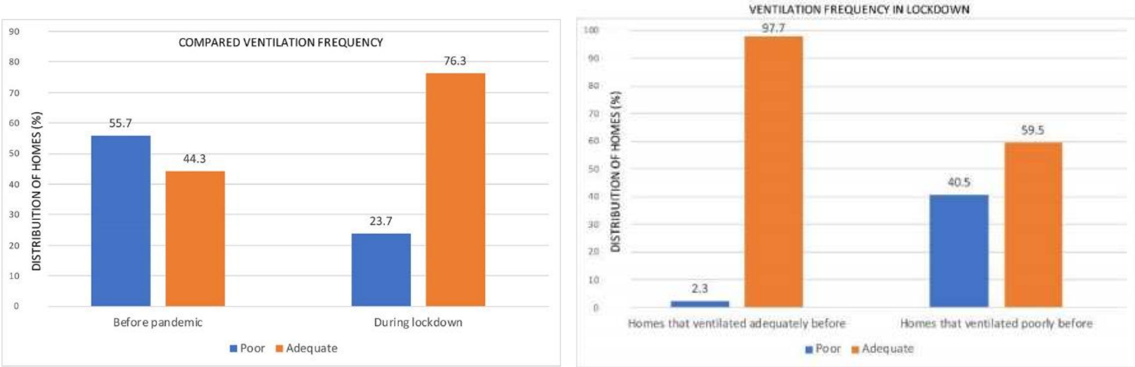


Figure 1.a. ventilation frequency before and during lockdown, and figure 1.b. ventilation frequency in lockdown for homes that ventilated adequately and poorly before.

After observing the compared dependent variables, a decision on the bivariate analysis and the way to compare the ventilation habits (before and during quarantine) was made, to show, as far as possible, the most significant behaviour changes between those two steps, and find some reasons on the potential causes that could origin them.

As shown in figures 1a and 1b, the households in "before" stage (1502), 55.7% experienced a deficient frequency (836), while 44.3 % ventilated properly (666). However, when resorting to the answers collected about “during”, the households modified their habits, since they declared deficient ventilation for 23.7%, while proper ventilation increased to 76.3%.

To further analyse the changing habits of households, the frequencies change was observed (positive or negative). Among those who on the basis ventilated properly (666), only 2.3% ventilated worse during lockdown, while of 97.7% kept their frequency. However, the greatest change happened where ventilation was poor, of which 59.5% changed their routines towards a proper frequency, while 40.5% kept their bad habits.

### 3.2. Bivariate relations with the ventilation frequency before pandemic

The significant bivariate relations with the dependent variable "ventilation frequency before COVID-19 pandemic" are presented below, in Figure 2. Also, the percentages shown in the bar graph consist of the description of homes’ distribution for each category of independent variable.

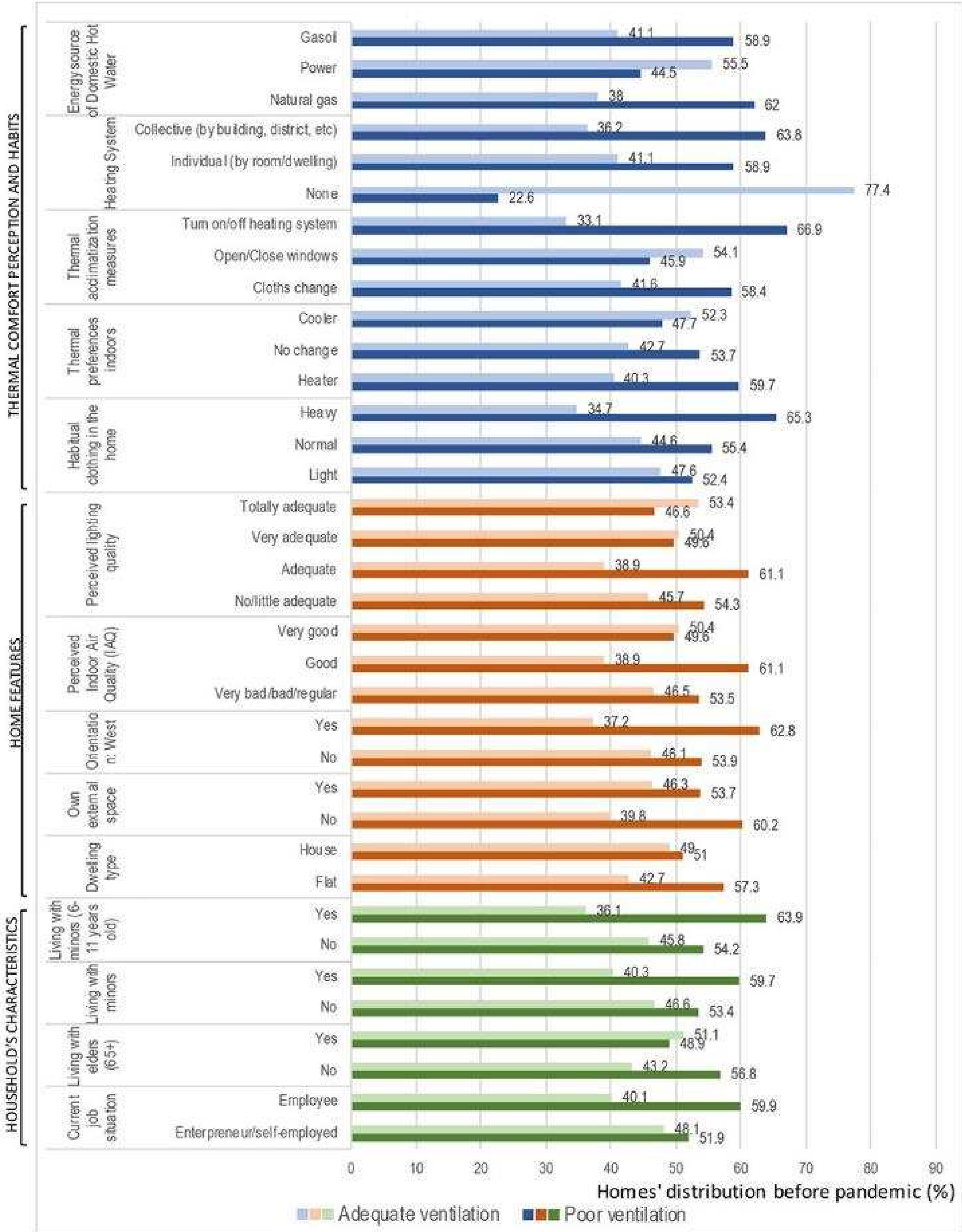


Figure 2. Homes' ventilation distribution (percentages) before pandemic. All the independent variables on the left showed significant relationships with the ventilation frequency before COVID-19 pandemic.

As shown in Figure 2, the general window-opening frequency variable (before) significantly show relationship with the current work situation, certain configurations of households, such as the presence of elders, and minors, and within them, between 6 and 11 years, the current employment situation, being the self-employed and businessmen the ones who ventilated more frequently on a regular basis.

Living with elderly people was related to proper ventilation (51.1% vs 48.9%), while living with minors, to deficient one (59.9% vs 40.3%).

On the characteristics of the home, a good frequency of ventilation on a regular basis was related to single-family homes (49.0% vs 51.0%), having their own patios or similar (46.3% vs 53.7%), and not having a west orientation (62.8% vs 37.2%), with polarized perceptions of indoor air quality lighting, being either poor/inadequate, or very good/very adequate.

On the perception of thermal comfort and the routines linked to domestic energy use, adequate ventilation was associated with lightweight (47.6%) or regular garments (44.6%), with the desire to have a cooler environment in the house (52.3%), the lack of a heating system (77.4%), and power energy sources to heat domestic water (55.5%), compared to fuel sources such as gasoil or natural gas.

### 3.3. Bivariate relations with the ventilation frequency during quarantine

To establish the "during" stage, the ventilation frequency variable during quarantine was created, especially seeking those dwellings that ventilated before deficiently. This variable was built in order to notice the positive habit-change performed by homes, just in this lockdown period, and the explanatory variables potentially associated with such change. The relations are presented in Figure 3 for independent variables on households' and housing features, comfort and use of energy, and in Figure 4, for activities, alteration of habits, and expectations of housing improvement, all in a context of COVID-19 confinement.

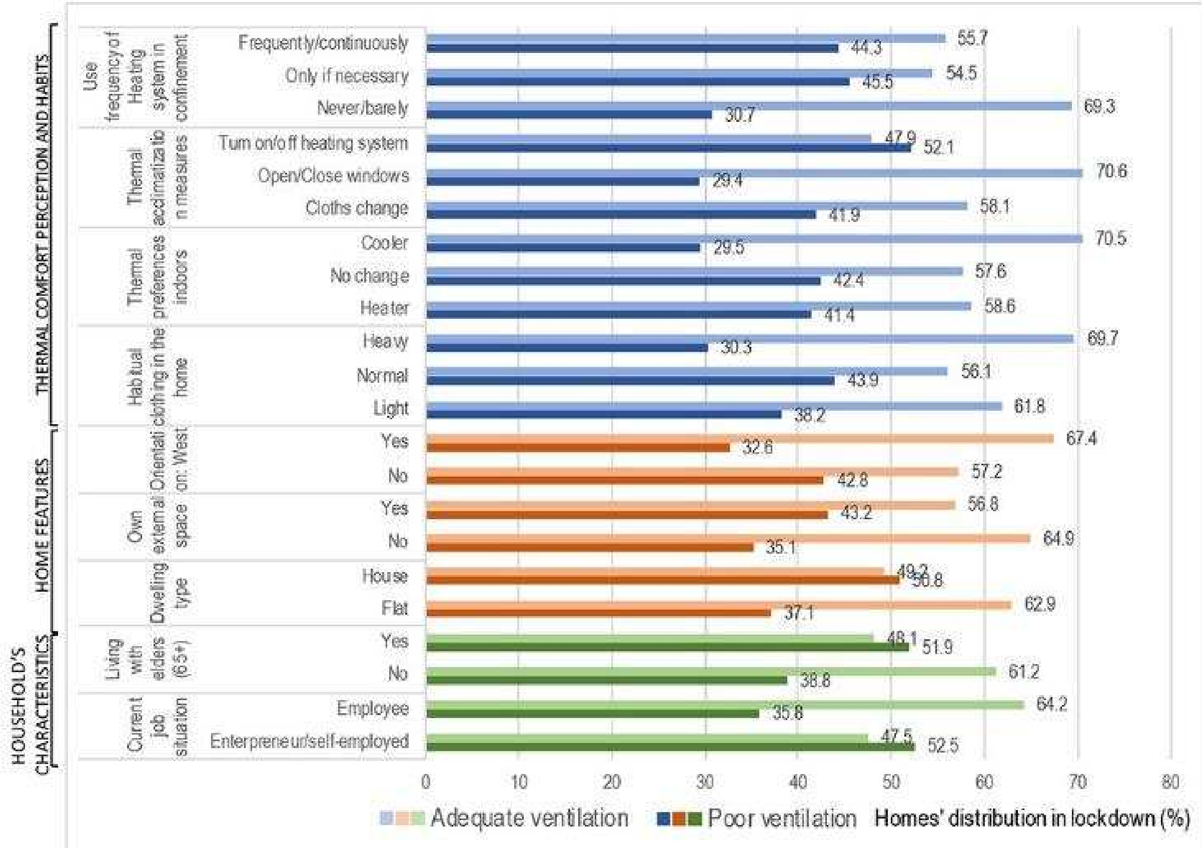


Figure 3. Homes' ventilation distribution (percentages) during lockdown (after a usual poor ventilation). All the independent variables on the left showed significant relationships with the ventilation frequency in quarantine.

The improvement towards a better frequency of natural ventilation was associated, with being an employee (64.2% vs 35.8%), and not living with elderly people (61.2 % vs. 38.8%).

Regarding the housing features, a better ventilation frequency reflected significant relationships with the type of housing (62.9% vs 37.1%), to not having outdoor space (64.9% vs 35.1%), and with west orientation (67.4% vs. 32.6%).

About thermal comfort and energy-use routines, the improvement of ventilation frequency was associated with cooler garments (61.8% vs 38.2%) or warmer than usual (69.7 % vs 30.3%), in a polarized way. It was also related to having a thermal preference of wanting a slightly cooler environment (70.5% vs 29.5%). Regarding the first adapting measures when households feeling uncomfortable, improved ventilation was associated with using the opening of windows to regulate indoor thermal comfort (70.6% vs 29.4%). Lastly, regarding the frequency of use of the heating system in quarantine, those who changed their habit declared a vague or null use of the system (69.3% vs 30.7%).

Figure 4 details the independent explanatory variables that showed a significant relationship with those who habitually ventilated poorly, changing during quarantine (or not) their related behavior patterns.

According the activities developed in the housing, the upgrading of natural ventilation routines was associated with teleworking in non-exclusive spaces, but itinerant or circumstantially shared (66.8% vs 33.3%), as well as with well-sized teleworking spaces (63.6% vs. 36.4%), and with good surface finishes (64.7% vs. 35.3%). Also, the increased use of stoves (65.3% vs 34.7%), ovens (66.5% vs 33.5%), and food processors (67.6% vs 32.4%), was also related to an augmentation in the frequency of natural ventilation.

Following the domestic routine changes, those homes that increased their ventilation routines were significantly related to having declared alterations during confinement, such as work habits (61.5% vs 38.5%), cleaning the home (64.8% vs. 35.2%), do other household chores (64.5% vs. 35.5%), get dressed (65.0% vs. 35.0%), play sports (64.0% vs. 36.0%), and enjoy outdoor space (65.2% vs. 34.8%).

Finally, about the expectations to home enhancement, the increase in opening windows was associated with the desire to improve insulation in general (64.2% vs 35.8%), with the desire for changes in the home (at least 5) (61.6% vs 38.4%), and with the lack of satisfaction in the home, in relation to non-modifiable design and construction characteristics (62.0% vs 38.0%).

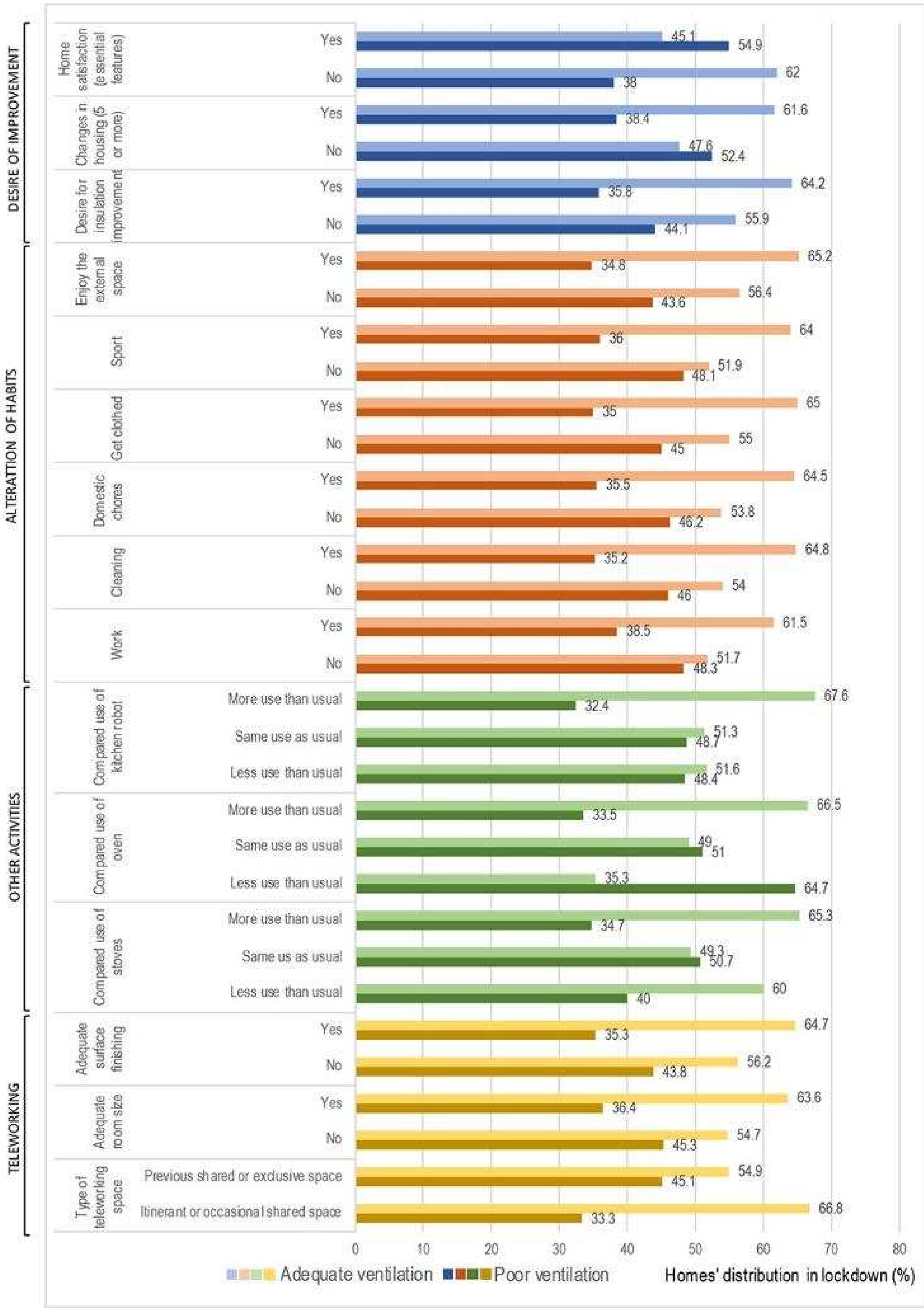


Figure 4. Homes' ventilation distribution (percentages) during lockdown (after a usual poor ventilation). All the independent variables (activities and expectations) on the left showed significant relationships with the ventilation frequency in quarantine.

### 4. Discussion

Observing the bivariate relationships, those workers who could stay at home longer in the house, presented proper window opening (Instituto Nacional de Estadística, 2020). Regarding the households, cohabiting with elders encouraged a greater frequency of ventilation. It could be due to a rural culture, and in general, of opening windows more frequently (Cuerdo-Vilches et al., 2020; Jiao et al., 2017; Levie et al., 2014). Meanwhile, the presence of minors was linked to poor ventilation, probably to avoid accidents (Dolgun et al., 2017).

The most frequent opening of windows was related to single-family homes; flats were related to poor ventilation. Potential reasons were the height at which they are, which has to do with child safety itself (Freyne et al., 2014). The availability of open spaces surrounding houses may be another reason to keep windows opened for much time in safety conditions.

On the other hand, among all the possible housing orientations, those with a west component tended to ventilate less regularly. Taking into account the Spanish latitude, it could be presumed that there is a component of a certain bias in this response due to the data collection period. In fact, at the beginning of spring, a house with a west component is usually not sunny until afternoon, so it is cold, and therefore, requires more heating than others (Olgyay, 1962). Therefore, if there was a higher demand for heating, opening windows could be avoided to be more energy efficient.

Regarding the perception of air quality, this showed a polarized relationship, which can be explained by a cause-effect duality. Among homes that ventilated the best, there were those with the greatest need to ventilate (due to humidity or charged environment, for example). Also, there were others that already considered their indoor air to be of high quality, perhaps as an effect of their own habit of often opening windows (Wang y Norbäck, 2022). Similarly, the relationship with the quality of perceived general lighting (both natural and artificial) was related in a polarized way with the frequency of natural ventilation. This may be due to cultural habits to illuminate properly, or the lack of lighting (Muñoz-González et al., 2021). For the latter case, they took advantage of opening them widely, to ventilate and perceive more lighting (and, when possible, enjoy the views) (Cuerdo-Vilches y Navas-Martín, 2021; Dzhambov et al., 2020; Meesters et al., 2020).

Frequent pre-pandemic ventilation and variables of perception of thermal comfort and habits on energy use, showed significant relationships. So, several reflections were also observed. In the first place, those who habitually ventilated the most tended to dress lightly or normally, compared to those who dressed warmly at home. This may be related to the hypothesis of bias due to the pre-pandemic winter period, which, together with colder dwellings. Reasons could be orientation, lack of sunlight due to the building's own or remote obstacles, or for other reasons. Also, due to a greater need for heating, they bundled up, avoiding opening windows, so as not to have greater thermal demands. Similarly, only those who wanted to feel cooler compensated for excess heat by opening windows more frequently, before the pandemic. This, however, is nuanced by the following variable, which associates the higher frequency of natural ventilation with the non-existence of a heating system, as an outstanding proportion. Therefore, it can be deduced that households that lack heating regulate themselves by opening windows (Nicol et al., 2012). Lastly, dwellings with better natural ventilation frequencies did not use fossil energy (combustion) to heat hot water. Instead, they used electrical energy. It can be explained by the intention of not interfering with unwanted air drafts in this combustion (Barnes, 2004).

Observing the ventilation frequency response in confinement of those who habitually ventilated poorly, the reason could be the disruptive change in habits entailed (Navas-Martín et al., 2021). As an example, in this period of confinement those who ventilated the best, were employees. The literature on workplace and COVID-19 pandemic explains it through the most stable households. They had inf fact, better work conditions, even being civil servants. Those who usually worked outside, by staying at home teleworking, did ventilate more, as highlighted relevant international organizations such as International Labor Organization (ILO) (International Labour Organization, 2020).

Other altered relation with ventilation frequency was the presence of people over 65 at home, related to less ventilation. The fear of contagion among the elderly, by COVID-19 or other viruses, could lead to close the windows. Also, the elderly could not leave the house and have less capacity for thermoregulation (Folkerts et al., 2020), as well as for a security issue (in case of cognitive deficit with diseases such as Alzheimer's (Alzheimer's Society, 2020), for example). They could be compelling reasons to close the windows more than usual, despite the fact that, in the case of Alzheimer, that adequate ventilation has been shown to be related to better cognitive processes (Wang et al., 2022).

While usual adequate ventilation was associated with single-family homes, during confinement the most ventilated homes were flats. This could be explained by the need for a greater relationship with the outside (Abellán García et al., 2021). Indeed, dwellings with no outdoor space ventilated more adequately during confinement. The reasons were the need of outside contact and the concentration of activity in the domestic space (Cuerdo Vilches et al., 2020).

According to thermal comfort and habits related to the use of energy, usual clothing in confinement for households was polarized. Those with lighter or warmer clothes ventilated more frequently. Only those who were in thermal comfort were related to poor ventilation. This can be explained by the use of heating. It can be seen in the variable of frequency of heating use, those who used heating the most ventilated poorly. However, the relationship of ventilating frequently was maintained between those who chose it as a priority acclimatization measure (open windows), and those who preferred to be cooler.

In relation to activities during confinement, the largest opening of windows occurred in teleworking spaces shared circumstantially or itinerant. This could be explained by a greater presence of cohabitants (because of care, above all), occupying wider spaces with access to façade more practicable, and more frequently open (Seo et al., 2014). However, those persons accustomed to teleworking, or using exclusive spaces in the home for these tasks, did not ventilated properly if they did not ventilate well beforehand.

These hypotheses about the most open and largest spaces, with greater presence of cohabitants, most satisfied with the size of the teleworking space, ventilated the best. Similarly, those with better surface finishes, also ventilated better. It could also be related to this type of space, traditionally more social, more cared for, and therefore more pleasant to stay working, as were the halls and living rooms, mainly (Cuerdo-Vilches et al., 2021a; Jaimes Torres et al., 2021).

On other activities during confinement, increased culinary activity in lockdown (Cuerdo-Vilches et al., 2021b), was related to a higher frequency of ventilation during confinement. It could be due to the need to exchange air with the outside, by the effect of the heat produced, mainly from the oven, or due to the odors generated (Wargocki, 2021).

The alteration of domestic tasks, including cleaning, denoted a change of presence in the home. Also, ventilate to release possible chemical products. Other activities, as sports, generated a high thermal load due to the greater latent heat produced by greater metabolic activity (which in this period also happened in the domestic space).

Regarding the desire for improvement, those who wanted greater insulation in the home, ventilated more frequently. In the same way, those who wanted 5 or more aspects to change in the dwelling, ventilated more frequently. This could be related to urban environments, with smaller flats, where families lived in a higher proportion of rent (Navas-Martín et al., 2022), and therefore presented less capacity for change in design and construction aspects, such as thermal- acoustic insulation, among others (Cuerdo-Vilches et al., 2021a), since flats were the ones that most frequently ventilated in confinement.

**5. Conclusions**

Opening the windows is a simple action, but one that obeys a complex reflection, based on multiple potential reasons, just like the fact of not opening them. It is not just a behavioral or cultural issue. There are other factors, of a very diverse nature, and which in turn can be either circumstantial or permanent (constituting the habit).

Beyond the need to ventilate to exchange the air with the outside, potentially stale for multiple reasons (stuffed, stale air, with bad smells, very humid or very hot), it can also be due to a relationship with the need to take advantage of sunlight. Another reason could be found in the sources of energy to carry out daily life, such as heating food, water for domestic use, or achieving thermal comfort, that is, in those systems that require energy of combustion, which traditionally could tend to avoid unwanted air drafts.

Other reasons may be the need to exchange air with the outside, either due to excessive daylighting (which in some cases can even lead to overheating of the spaces (Domínguez-Amarillo et al., 2020)), or to counteract the continued effect of the use of heating services, sometimes not well dimensioned or regulated and controlled.

These reasons can be partially nuanced in the face of a disruptive event such as home confinement due to COVID-19. With this, the criteria of ventilation, lighting, energy conservation, and others such as safety, both in terms of health and physical protection, were conditioned by this presence of people, as well as by the deprivation of contact with the environment. The very presence of people also led to opening the windows to compensate the greater exchange of interior air with the exterior, also due to the concentration of activities in this interior, when many of them they require a higher level of concentration or they generate a greater thermal load.

One of the most underlying issues is how natural ventilation is subject to criteria for the use of thermal energy, and to the perception of comfort and how each home uses the acclimatization (and adaptive comfort) options. These issues would be solved, at least to a large extent, if hybrid or mechanical ventilation systems could be integrated into hot/cold air conditioning systems in homes, as has already been introduced in the most recent building regulations. However, this is not reflected in the existing residential stock, almost entirely prior to these regulations, and thus, naturally ventilated.

The current home renovation policies that Europe is financing and that Spain is already beginning to implement cannot base their interventions in these existing homes solely on energy efficiency and decarbonisation, since the quality of indoor air has been shown to remain often compromised with very isolated dwellings, due to the significant increase in domestic airtightness.

But, beyond design and constructive architectural assessments, people obey multiple factors that influence us in the way we act and create habits. And in this, authors have seen how issues such as home security, the very presence of members in the house, the increase in activity, the perception of air quality, and many other issues, both learned and perceived or by necessity in each moment, it can alter the way we behave.

Meanwhile, proposals for new passive constructive solutions (even innovative ones based on the envelope improvement) (Cuerdo-Vilches et al., 2014a), and active ones when comfort is not reached by the building (Cuerdo-Vilches et al., 2014b), such as hybrid or mechanical ventilation, must not only be effectively included in the renovations of the building stock. It must also be encouraged to be properly sized and balanced with the effect of energy use, in such a way that the quality of indoor air does not reduce energy comfort (and vice versa), or increase consumption and expenses associated with a need generated as a result of the rehabilitation, or on the contrary, lead to the generation or aggravation of cases of energy poverty, due to not being able to afford these (new) domestic expenses.

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# Thermal comfort provision in naturally ventilated buildings: a comparison between Brazil and North American standards.

**Juliana da Silva Oliveira[1], Júlia Perassolli de Lázari[2], Joyce Kim[3] and Érico Masiero[1]**

[1] Federal University of São Carlos, São Carlos, Brazil, juliana.oliveira@estudante.ufscar.br;
[2] State University of Campinas, Campinas, Brazil, j200298@unicamp.dac.br;
[3] University of Waterloo, Waterloo, Canada, joyce.kim@uwaterloo.ca.

**Abstract:** As temperatures increase due to climate change, the need for cooling to satisfy occupant comfort in the built environment has also increased. In North America, mechanical systems are often adopted as a main cooling strategy to provide thermal comfort. However, in Brazil – a predominantly warm and humid climate – occupants rely mostly on natural ventilation. Yet, Brazilian thermal comfort standards do not have clear guidance on how to provide comfort in naturally ventilated spaces. In this paper, we reviewed Brazilian thermal comfort standards – ABNT NBR 15220, 16401, and 15575 – and compared them to ASHRAE 55. Despite natural ventilation being recommended in seven out of the eight bioclimate zones, Brazilian standard only specifies acceptable thermal conditions based on ASHRAE 55's Predicted Mean Vote (PMV), which is known to underestimate thermal sensations in naturally ventilated buildings. ASHRAE 55 also has specific provisions for naturally ventilated buildings using an adaptive model that accounts for adjusted comfort expectations of occupants with operable windows. To evaluate the applicability of ASHRAE's adaptive model in Brazilian climate, we analysed the weather data from 192 Brazilian cities. We concluded that the adaptive model can be applied to the Brazilian context as a significant area of the country is within the model's applicability limits.

**Keywords:** Thermal Comfort, Climate Change, Adaptive Model, Standards, Brazil.

## 1. Introduction

Global warming is likely to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate (IPCC, 2018). Climate change has adversely affected people's physical and mental health as hot extremes such as heatwaves have intensified in cities. This has led to some irreversible impacts as natural and human systems are pushed beyond their ability to adapt (IPCC, 2022).

While the projected temperatures increase energy demands for cooling on a global scale, North America relies mostly on air conditioning to ensure thermal comfort for its building occupants. In Brazil, however, the usage of this type of device is still relatively low, as only 17% of Brazilian residences have air conditioning (Eletrobrás, 2019).

In addition, with the concern to minimize environmental impacts by reducing energy and natural resource consumption, energy-efficient cooling strategies such as natural ventilation and fans become more relevant, especially in hot or subtropical climates such as Brazil. Research also shows that these alternatives help improve thermal comfort and indoor air quality in buildings due to air movement and air exchange (Millet et. al., 2021; de Oliveira, Rupp, and Ghisi, 2021).

To ensure occupant comfort amidst increasing temperatures, many countries are developing their public policies such as technical standards, codes, and regulations as a way of ensuring and measuring energy efficiency and thermal comfort, seeking to improve the built environment (Eli et al., 2021).

In North America, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) is responsible for the Standard 55 - Thermal Environmental Conditions for Human Occupancy. This standard specifies the combinations of indoor thermal environmental factors and personal factors that will produce thermal environmental conditions acceptable to most of the occupants within the space (ASHRAE/ANSI, 2020).

The Brazilian Association of Technical Standards (ABNT) is the National Forum for Standardization in Brazil. For the analysis of acceptable thermal conditions, three ABNT standards approach the subject more deeply: ABNT NBR 16401 – "Central and unitary air conditioning systems", ABNT NBR 15220 – "Thermal performance in buildings" and ABNT NBR 15575 - "Residential buildings — Performance".

ABNT NBR 15220 presents bioclimatic design strategies for eight climate zones based on the weather data from 330 cities across Brazil, where natural ventilation is recommended in seven out of the eight climate zones (ABNT, 2005). ABNT NBR 15575 provides the requirements and performance criteria that can be applied to residential buildings as a whole or for one or more specific systems (ABNT, 2013). ABNT NBR 16401 specifies acceptable thermal conditions for air-conditioned spaces and is heavily influenced by ASHRAE 55's analytical method, the PMV (Predicted Mean Vote) index (ABNT, 2008).

As the PMV method is known to underestimate thermal sensations in naturally ventilated buildings (Fanger and Toftum, 2002; van Hoof, 2008), ASHRAE 55 introduces a separate adaptive model that accounts for adjusted comfort expectations of occupants with operable windows. In this adaptive model, based on field studies in 160 office buildings located in nine countries on four continents (data from Brazil are not included), the comfort zone on a given day is dependent on a running mean of previous outdoor air temperatures, to which people continuously adapt over time (de Dear and Brager, 1997). The adaptive model can be used when the prevailing mean outdoor temperature is higher than 10°C and less than 33.5°C.

Despite being influenced by ASHRAE 55, the Brazilian standards do not describe an evaluation method to ensure thermal comfort in naturally ventilated buildings. Natural ventilation is recommended by Brazilian standards and is a primary cooling strategy in 83.31% of the residences in the country (Eletrobrás, 2019).

Therefore, there is a need to evaluate the applicability of ASHRAE's adaptive models for naturally ventilated buildings in Brazil. However, ASHRAE's adaptive model did not consider and was not tested for Brazilian data.

Thus, the objective of this paper is 1) to compare the ASHRAE and ABNT standards for thermal comfort for naturally ventilated buildings and 2) to analyse the temperature profile of 192 cities in Brazil to assess if ASHRAE 55's adaptive model is applicable to Brazilian context.

## 2. Method

### 2.1. Standards review

To identify the comfort provisions for naturally ventilated buildings in Brazil, keywords such as "thermal", "comfort", "building" and "performance" were searched in the Brazilian Association of Technical Standards' online catalog. From this search, it was identified that ABNT NBR 16401, ABNT NBR 15220 and ABNT NBR 15575 are the most fundamental standards when it comes to Brazilian thermal comfort provisions. To compare Brazilian and North American standards, ASHRAE 55 was also examined in this paper.

After a systematic review of all four standards, focusing on the provisions and methods to determine an acceptable thermal environment in naturally-ventilated spaces, it was possible to identify the similarities and differences between Brazilian and North American thermal comfort standards.

**2.2 Data analysis**

To study the Brazilian climate, data from 192 meteorological stations distributed in the country, out of the 330 cities presented in ABNT NBR 15220-3, was considered. The data was obtained in the Meteorological Database of the National Institute of Meteorology (2022) website. It consists of daily measures of minimum, mean, and maximum dry-bulb outdoor air temperature for the past three years (2019-2021). Air speed was not considered, as this data was not available in the database for the selected cities. The extracted data was then grouped into the 8 bioclimatic zones as described in ABNT NBR 15220-3. Null values were disregarded.

We computed an exponentially weighted running mean using a period of 7 days of the mean temperature using the pythermalcomfort library (Tartarini and Schiavon, 2020). An alpha of 0.8 was used, characterizing a slow response running mean, as recommended on the ASHRAE 55 for humid tropics. Based on that, we analysed the percentage of time the running mean temperature was within, above, and below the 10ºC-33.5ºC limits for each of the zones, considering data from all the cities.

The allowable indoor operative temperatures of each zone were also determined using the 80% acceptability limits. For this, we aggregated the temperatures for each zone and considered the mean of the running mean of all cities in the zone. The limits are defined as:

$$\mathrm{upper}_{80\%} = 0.31 \,.\left\{\overline{\mathrm{t}_{\mathrm{pma(out)}}}\right\} + 21.3$$
$$\mathrm{lower}_{80\%} = 0.31 \,.\left\{\overline{\mathrm{t}_{\mathrm{pma(out)}}}\right\} + 14.3$$

with $\left\{\overline{t_{pma(out)}}\right\}$ representing the running mean of the outdoor temperatures.

We then compared these limits with the ones defined on the ABNT NBT 15575-1, for each of the bioclimatic zones. The lower and upper limits for minimum comfort (M) are defined as:

$$\mathrm{lower}_{\mathrm{zones1to5}} = \mathrm{Te}_{\mathrm{min}} + 3$$
$$\mathrm{lower}_{\mathrm{zones6to8}} = \text{not applicable}$$
$$\mathrm{upper}_{\mathrm{zones1to8}} = \mathrm{Te}_{\mathrm{max}}$$

with $Te_{min}$ and $Te_{max}$ being the minimum and the maximum outdoor temperature.

This data analysis is available in a GitHub repository (Lázari, 2022).

## 3. Results and Discussion

### 3.1. Standards review

#### 3.1.1. ASHRAE 55

ASHRAE Standard 55 specifies conditions for acceptable thermal environments and is intended for use in the design, operation, and commissioning of buildings and other occupied spaces. The analytical method, the PMV (Predicted Mean Vote) index, based on Fanger (1970), calculates thermal sensation as a function of activity, clothing, air temperature, mean radiant temperature, air velocity, and humidity.

This heat-balance comfort model predicts the mean value of the thermal sensation votes (self-reported perceptions) of a large group of persons on a sensation scale expressed from –3 to +3 corresponding to the categories “cold,” “cool,” “slightly cool,” “neutral,” “slightly warm,” “warm,” and “hot.” For doing so, it requires the user to have knowledge of the indoor environment immediately surrounding the building occupant, as well as the occupants’ clothing insulation and metabolic rates, which are often difficult to estimate in the field.

The Standard 55 also has provisions for increased temperature acceptance due to air movement, by combining the PMV and the Standard Effective Temperature (SET) models. The PMV+SET model can be applied when the occupants have activity levels that result in average metabolic rates between 1.0 and 2.0 met, clothing insulation between 0.0 and 1.5 clo, and average air speeds greater than 0.20 m/s (40 fpm). In that case, if occupants do not have control over the local air speed and the operative temperatures are above 25.5°C (77.9°F), the upper limit to average air speed shall be 0.8 m/s (160 fpm).

Despite of the widespread adoption of the PMV models in building standards, field experiments have shown that in naturally conditioned spaces where occupants have control of operable windows, the subjective notion of comfort is different because of different thermal experiences and availability of control, resulting in shifts in occupant expectations, especially in warmer climates (Brager and de Dear, 1998).

As a result, the 2004 edition of ANSI/ASHRAE Standard 55 also includes a separate adaptive model for determining acceptable thermal conditions in occupant-controlled naturally conditioned spaces, in which acceptable indoor temperatures are linked to the mean outdoor temperatures.

The adaptive model was proposed by de Dear and Brager in 1997, based on RP-884 database. It includes measurements of environmental parameters, estimates of occupant-related parameters, and occupant’s subjective evaluations as thermal sensation, acceptability, and preference in each of them, resulting in 21,000 sets of raw data observed in 160 mostly office buildings across five continents, data from Brazil not included (de Dear and Brager, 1997).

As it determines acceptable thermal conditions in naturally conditioned spaces, this model can only be applied when there is no mechanical system in operation. The standard also specifies that the prevailing mean outdoor temperature must be between 10°C (50°F) and 33.5°C (92.3°F) and that occupants must be engaged in near-sedentary physical activities with metabolic rates ranging from 1.0 to 1.3 met and are free to adapt their clothing to the indoor and/or outdoor thermal conditions in an acceptable range of 0.5 to 1.0 clo.

When these conditions are met, it is possible to determine the allowable indoor operative temperatures with two sets of operative temperature (t0) limits, one for 80% acceptability and one for 90% acceptability. The 80% acceptability limits, described in the methods section of this paper, are for typical applications. The 90% acceptability limits are acceptable when a higher standard of thermal comfort is desired.

Also, when naturally conditioned spaces where air speeds within the occupied zone exceed 0.3 m/s, the upper acceptability temperature limits in the adaptive model can be increased by: 1.2°C (2.2°F) when air speed is within 0.3 m/s (59 fpm) to 0.6 m/s (118 fpm); 1.8°C (2.2°F) when air speed is within 0.6 m/s (59 fpm) to 0.9 m/s (118 fpm); and 2.2°C (2.2°F) when air speed is within 0.9 m/s (59 fpm) to 1.2 m/s (118 fpm). These adjustments to the upper acceptability temperature limits apply only at t0 > 25°C (77°F).

### 3.1.2. ABNT NBR 15220

ABNT NBR 15220 - "Thermal performance in buildings" first version was published in 2004 and presents design recommendations to guarantee thermal performance in single-family homes of social interest. Its main contribution is proposing to divide the Brazilian territory into eight homogeneous zones in terms of climate and, for each of these zones, a set of technical-constructive recommendations was given to optimizing the thermal performance of buildings, through their better climatic adaptation (ABNT, 2005).

The standard is divided into five parts and describes concepts related to thermal performance, the calculation and measurement of thermal properties of materials, and the division of the Brazilian territory into eight bioclimatic zones. ABNT NBR 15502-3 - "Brazilian bioclimatic zones and building guidelines for low-cost houses" presents the eight homogenous bioclimatic zones, based on the work of Roriz, Lamberts, and Ghisi (1999). The division was made based on similar characteristics such as maximum temperatures, minimum temperatures, and relative air humidity, as well as the geographic position of 330 cities. Based on these characteristics, constructive strategies for natural ventilation, solar shading, and the thermal properties of materials used to form the envelope are defined for residential buildings located in each of these zones.

The constructive strategies for each zoning were adapted from the Building Bioclimatic Chart by Givoni (1992), considering that the upper limits of accepted temperature and humidity would be higher for developing countries and acclimatized to hot humid conditions (Humphreys, 1978). As a result, the boundaries of the comfort zone and the different design strategies and natural cooling systems for ensuring indoor comfort are based on the expected indoor temperatures in buildings without mechanical air-conditioning, considering the actual acclimatization and comfort expectations of the inhabitants and the role of higher airspeeds in enhancing comfort at high humidity.

The adapted bioclimatic climate chart (Figure 1) specifies 9 possible strategies to maximize indoor comfort: artificial heating, solar heating, heating thermal mass, dehumidification (air renewal), evaporative cooling, cooling thermal mass, ventilation, artificial cooling, and air humidification.

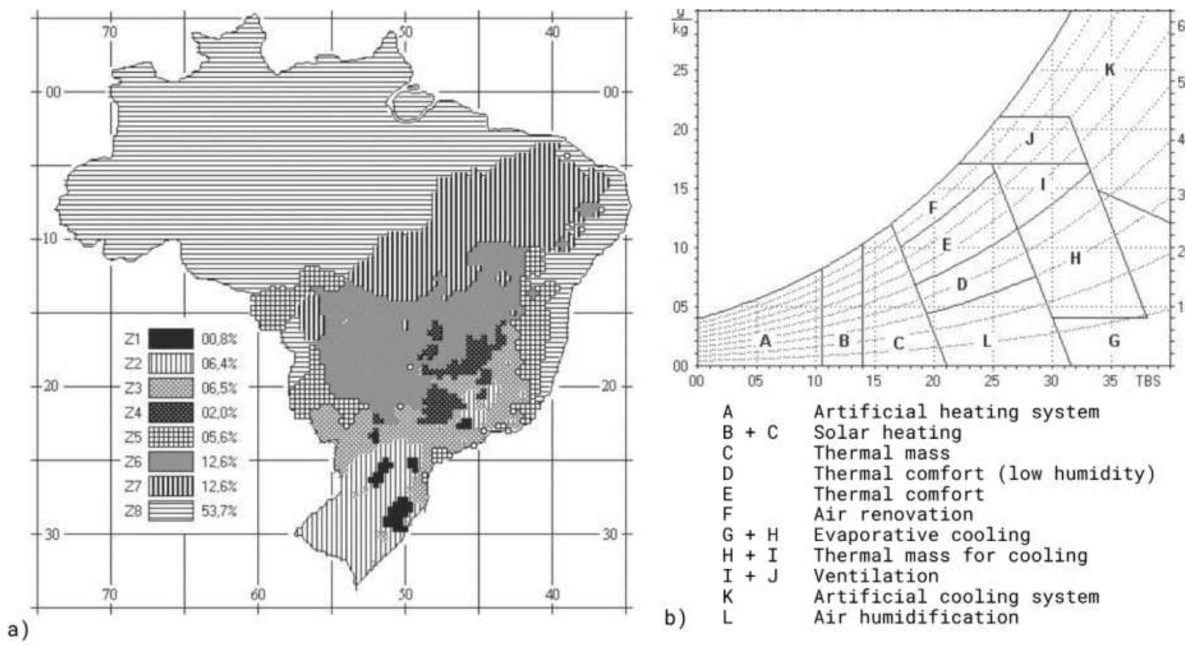


Figure 1. a) Bioclimatic zones and b) Bioclimatic chart (ABNT, 2005).

Considering that people in developing hot countries are acclimatized to higher temperatures and/or humidity and live mostly in unconditioned buildings (Givoni, 1992), ABNT NBR 15220-3 brings strong concern about airflow distribution in indoor environments, recommending ventilation patterns as a passive cooling strategy in 7 out of the 8 bioclimatic zones (all except zone 1, that represents a colder climate) and suggesting design strategies related to opening areas.

But several studies have pointed out the limitations of bioclimatic zoning and its constructive strategies. Bogo (2008) points out how it does not consider some constructive guidelines and passive thermal conditioning strategies for cities with subtropical climates, mostly located in the south region of the country. Bogo (2016) also points out solar control is not a part of the Building Bioclimatic Chart by Givoni (1992), but shading the openings is a strategy recommended for zones 4, 5, 6, 7, and 8. Another questionable definition is aggregating cities with very distinct altitudes in the same bioclimatic zone, like Camboriú, with 8 meters of altitude, and Chapecó, with 679 meters, both part of zone 3 (Bogo, 2016).

The classification of cities with different altitudes and thermal disparity in the same bioclimatic zone is partly due to the lack of refinement of the bioclimatic zoning caused by the lack of climatological data, as less than 4% of the 5500 cities of Brazil have their climatic data monitored, analyzed and/or published (Roriz, Lamberts and Ghisi, 1999). This also presents a problem to the use of monthly averages, especially in regions that present significant annual and seasonal amplitudes, such as the climatic region of the Brazilian semi-arid region, as the aggregation into one zone can produce distortions and prevents greater precision in the interpolation results (Martins, Bittencourt and Krause, 2012).

As these recent studies have been pointing out the limitations to the current version of the standard, ABNT NBR 15220-1 - “Terminology, symbols and units” and ABNT NBR 15220-3 - “Brazilian bioclimatic zones and building guidelines for low-cost houses” are currently under revision, with predicted publication dates for July and March 2023, respectively. ABNT NBR 15220-2 - “Calculation methods of thermal transmittance, thermal capacity, thermal delay and solar heat factor of elements and components of buildings” was updated and published in February 2022.

#### 3.1.3. ABNT NBR 16401

ABNT NBR 16401 - “Central and unitary air conditioning systems” was first published in 1980, the most recent version being published in 2008. It specifies the basic conditions and minimum requirements for the design of central and unitary air conditioning systems, as well as conditions of the internal environment for thermal comfort in air-conditioned spaces (ABNT, 2008).

The standard is divided into three parts and describes central and unitary air-conditioning design requirements, internal environment thermal comfort conditions for air-conditioned spaces, and indoor air quality. ABNT NBR 16401-2 - “Thermal Comfort” presents the indoor environment conditions that provide thermal comfort (temperature, humidity, airspeed, and radiant effects), and it supplies a method to determine thermal conditions that a considerable proportion of the occupants will find acceptable at a certain metabolic rate and clothing level, based mostly on the PMV method from ASHRAE’s Handbook of Fundamentals from 2005.

Another nod to the ASHRAE-55 is how thermal comfort is defined by environmental (airspeed, humidity, and operative temperature) and personal conditions (clothing insulation and metabolic rate) in this Brazilian standard. The value of said personal conditions are related to the type of clothing and the activity of the occupant, and it is defined by ASHRAE-55. ABNT NBR 16401-2, presents the definitions of these parameters, but does not define its values, referencing Table 4 and Table 8 of ASHRAE-2005's Handbook of Fundamentals Chapter 8 instead.

The document also defines indoor operative temperatures as varying between 22.5 to 25.5 °C at 65% humidity, and 23 to 26 °C with humidity of 35%, assuming a clo value of 0.5 during the summer. In that case, airspeed should be below 0.2 m/s for normal air distribution systems and below 0.25m/s for displacement ventilation. For winter, operative temperature should vary between 21 to 23.5 °C at a 60% humidity level and from 21.5 to 24 °C if humidity is set at 30% considering a clo value of 0.9. Airspeed should be below 0.15 m/s for normal air distribution systems and below 0.2 m/s for displacement ventilation.

Based on the PMV model, these limits can be increased by 1.4K per met for indoor environments with people developing activities with higher metabolic rates than sedentary. Changes in clo also result in 0.6K per 0.1 clo, and air velocities can also be used to offset an increase of 3K for air speeds up to 0.8 m/s if local control is made available to building occupants.

Currently, the PMV model presented in ABNT NBR 16401-2 is the only method to evaluate and ensure thermal comfort in buildings described in Brazilian standards. After initial ideas to update this current standard and establish a Brazilian Standard on Thermal Comfort were presented at the 2010 Windsor conference (Cândido et al., 2010) and later expanded into a paper for Building Research & Information (Cândido et al., 2011), the proposed text was sent to the Brazilian Committee on Refrigeration, Air Conditioning, Ventilation, and Heating (ABNT/CB-055) edited and incorporated into part 2 of NBR 16401. At the present time, the updated text is still not valid, as it awaits the opening for public consultation and subsequent publication after the closing of the reviews relating to the other parts.

#### 3.1.4. ABNT NBR 15575

ABNT NBR 15575 - "Residential buildings — Performance" was first published in 2013, the most recent version being published in 2021. It provides criteria for evaluating the performance of different systems in an existing residential building (ABNT, 2013).

The standard is divided into six parts: general requirements, requirements for structural systems, requirements for floor systems, requirements for internal and external wall systems; requirements for roofing systems, and requirements for hydrosanitary systems. Among these building performance requirements, methods to evaluate thermal performance are established, which aim to guarantee the user adequate thermal conditions for the development of their activities.

The thermal performance evaluation can be carried out through two methods: simplified (Part 4 - Requirements for internal and external wall systems and Part 5 - Requirements for roofing systems) or computer simulation (Part 1 – General Requirements). The simplified procedure evaluates the building by comparing its characteristics with reference values established by NBR 15220 for each zone. If the assessment is not in conformity with the standard, the designer must analyse the building through a simulation process. This simulation procedure adds different data related to the building in a program that simulates its thermo-energy behavior over time.

ABNT NBR 15575-1 defines for the simulation model the lower and upper limits for minimum (M), intermediate (I) and a superior (S) thermal comfort for each of the zones, determining the ideal indoor temperature (Ti) based on the external temperature (Te), as shown in Table 1. The lower and upper limits are based on minimum and maximum outdoor temperature of the day.

Table 1. Thermal performance evaluation criteria for summer and winter conditions.

| | **Lower Temperature Limits** | | **Upper Temperature Limits** | |
|---|---|---|---|---|
| **Comfort Level** | **Zones 1 to 5** | **Zones 6, 7 and 8** | **Zones 1 to 7** | **Zone 8** |
| **M** | $Ti_{min} \geq Te_{min}$ + 3ºC | Not applicable | $Ti_{max} \leq Te_{max}$ | $Ti_{max} \leq Te_{max}$ |
| **I** | $Ti_{min} \geq Te_{min}$ + 5ºC | | $Ti_{max} \leq Te_{max}$ - 2ºC | $Ti_{max} \leq Te_{max}$ - 1ºC |
| **S** | $Ti_{min} \geq Te_{min}$ + 7ºC | | $Ti_{max} \leq Te_{max}$ - 4ºC | $Ti_{max} \leq Te_{max}$ - 2ºC |

### 3.2. Data Analysis

The available data from the 192 stations were aggregated in each of the bioclimatic zones defined by ABNT 15220-3. Figure 2 illustrates the zones and the location of the selected weather stations, and the temperature profiles for each of the zones, as well as the verification if the running mean temperatures are within the 10ºC and 33.5ºC limits are shown in Figure 3.

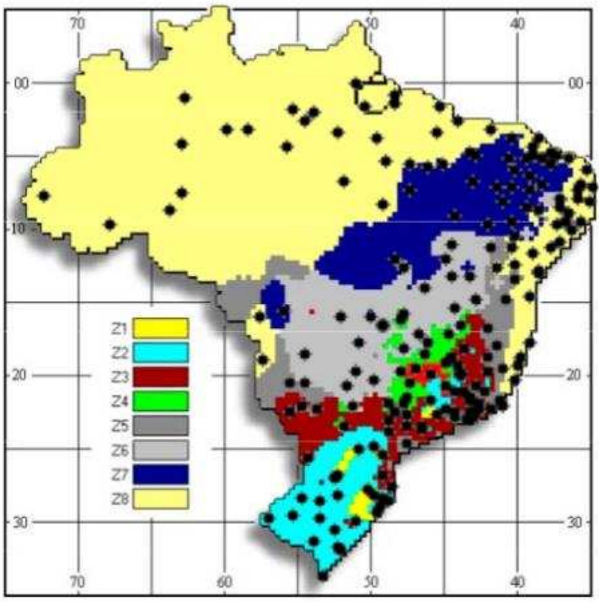


Figure 2. Bioclimatic zones and weather stations in Brazil (black dots).

Stations located in subtropical climates are known for their strongly marked thermal amplitude, presenting a broader temperature range throughout the year, as is the case of most of the cities in zones 1 and 2. In this case, the minimum and maximum running mean temperature was 4.7ºC and 23.5ºC for zone 1, and 9.4ºC and 25.8ºC for zone 2.

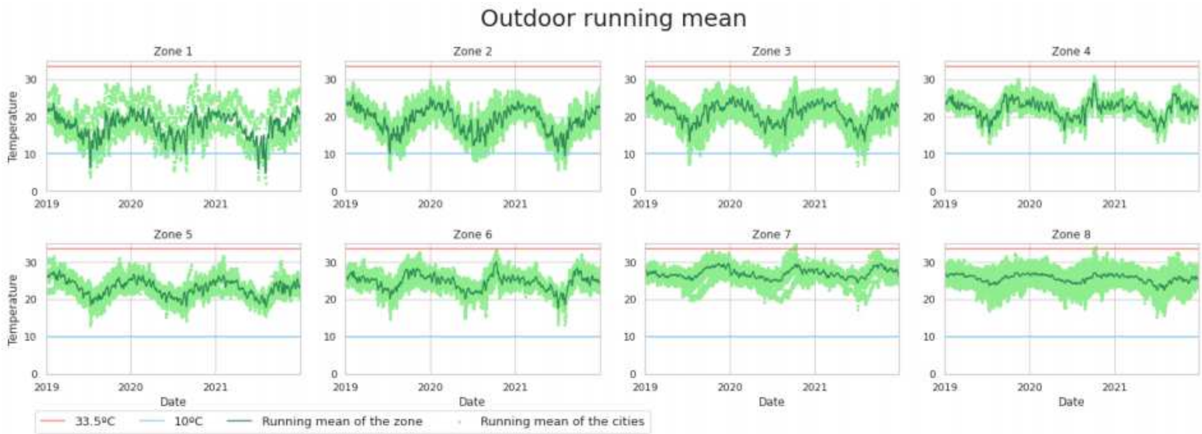

Figure 3. Outdoor running mean temperatures of each bioclimatic zone. The light green dots indicate the running mean for each city and the dark green line the running mean of the zone. Blue and red lines indicate the ASHARE-55 applicability limits of 10ºC and 33.5ºC.

However, tropical and equatorial climates, to which a great portion of zones 7 and 8 belong to, present a small temperature range, maintaining a constant thermal profile all year round. For this climate, the minimum running mean temperature was 24.3ºC for zone 7 and 22.4ºC for zone 8, and the maximum was 29.6º for zone 7 and 27.1ºC for zone 8.

Considering the running mean for each city individually, instead of doing the mean of the zone, the temperature range becomes broader in all cases, which reiterates the discussion of how similar the climate within the zones defined by ABNT NBR 15220-3 actually is.

As a result of the oscillating temperatures throughout the year in zones 1 and 2, they present the most significant percentage of days in which the running mean temperature is outside of the applicability limits of ASHRAE-55's adaptive model, as seen in Table 2. For zone 1, 2.79% of exceeding days happen during winter, while for zone 2 is 1.20%. For zones 7 and 8, which present a warmer climate, the results are the opposite, as the exceeding days happen during summer. As a result, some cities in zones 1 and 2 might need heating systems, while some in zones 7 and 8 might need artificial cooling, as it was stated in ABNT NBR 15220-3.

Still, as the aggregation of results for each zone flatten the running mean curve, the percentage of temperatures above 33.5ºC or below 10ºC is not prominent in this case, and the adaptive model can be applied to all zones throughout most of the year.

Table 2. Percentage of days in which the running mean temperature is in each of the intervals. The upper and lower indoor temperature limits are based on 80% acceptability calculated by the ASHRAE's adaptive model. All cities of the zone were included for this analysis.

| | **Outdoor Temperature** | | | **Indoor Temperature** | |
|---|---|---|---|---|---|
| **Bioclimatic zone** | **Between 10°C and 33.5°C (%)** | **Below 10°C (%)** | **Above 33.5°C (%)** | **Mean lower limit (°C)** | **Mean upper limit (°C)** |
| **1** | 96.75 | 3.25 | 0.00 | 19.72 | 26.72 |
| **2** | 98.79 | 1.21 | 0.00 | 20.23 | 27.23 |
| **3** | 99.86 | 0.14 | 0.00 | 20.84 | 27.84 |
| **4** | 100.00 | 0.00 | 0.00 | 21.15 | 29.15 |
| **5** | 100.00 | 0.00 | 0.00 | 21.43 | 28.43 |
| **6** | 100.00 | 0.00 | 0.00 | 21.92 | 28.92 |
| **7** | 99.97 | 0.00 | 0.03 | 22.64 | 29.64 |
| **8** | 99.99 | 0.00 | 0.01 | 22.23 | 29.23 |

Once the running mean was calculated, the allowable indoor operative temperatures of each zone was also determined using the 80% acceptability limits by ASHRAE-55, as seen in Figure 4.

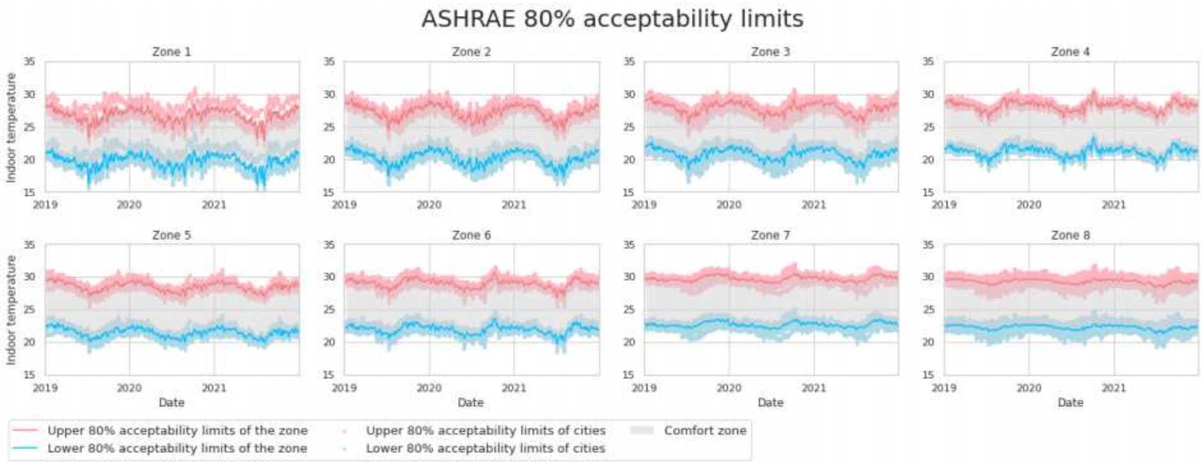


Figure 4. Indoor temperature limits for each bioclimatic zone based on 80% acceptability by ASHRAE-55's adaptive model. The dots indicate the limits for each city and the lines the limits of the zone. The shadowed grey area indicate the comfort zone.

As the operative temperatures are based on the running mean, zones 1 and 2 present the most heterogeneous temperature profile throughout the year, while zones 7 and 8 present a more constant temperature profile. Also, as ASHRAE uses the running mean to determine both the upper and the lower limits, the comfort zone will always be within a 7°C interval.

However, in ABNT NBR 15575 simulation method to analyse thermal performance, the upper and the lower temperature limits are based on the maximum and minimum temperature of the day. In that case, as ABNT is based on peak values and not the daily or the running mean, its comfort zones present more variability, as seen in Figure 5. Furthermore, the Brazilian standard does not determine a lower limit for zones 6, 7, and 8, known to have a warmer climate.

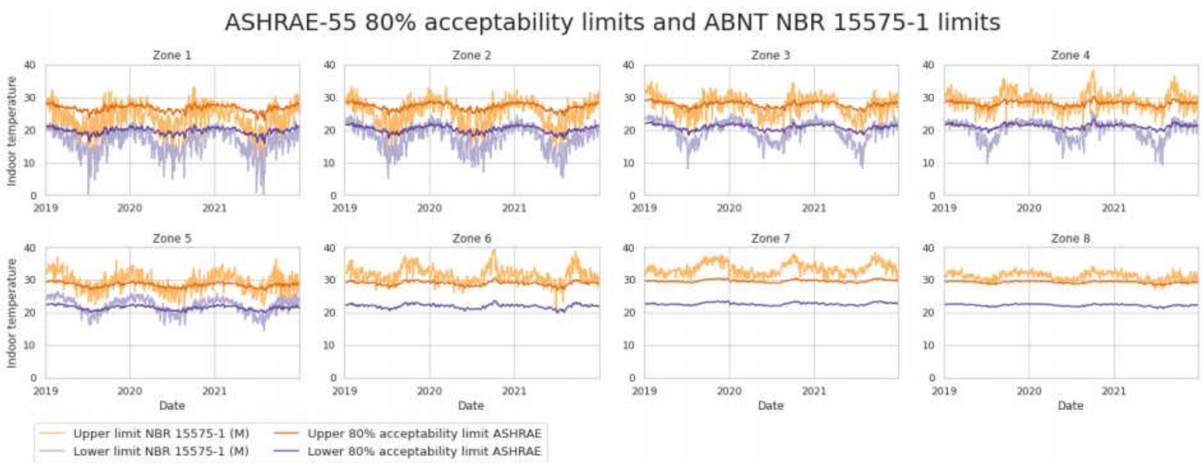


Figure 5. Comparison between ASHRAE-55 80% acceptability limits and ABNT NBR 15575-1 limits for thermal comfort.

## 4. Conclusion

This paper presents, discusses and applies methods to evaluate and ensure thermal comfort in naturally ventilated buildings in Brazil.

The systematic review showed that even though Brazilian standards often adopt the same parameters and methods as described by ASHRAE 55, it is not as thorough and updated as the North American standard. However, the bioclimatic zoning and its construction strategies to ensure thermal comfort are an advantage on top of the North American standard, as it relies mostly on natural and passive strategies, presenting less energy consumption than the traditional HVAC systems.

The lack of one unique thermal comfort standard also presents a difficulty to ensure thermal comfort in the Brazilian context. While ABNT NBR 15220 brings out recommendations and does not have a normative character, ABNT NBR 15575 does, and references values established by NBR 15220 to analyse building performance. It also defines a simulation method to evaluate thermal performance that can be used only if the values and criteria defined by NBR 15220 are not met.

Furthermore, even though NBR 15220 mostly recommends passive cooling strategies like natural ventilation for the most significant part of the country, the method of evaluating thermal comfort present in current standards is the PMV index described in ABNT NBR 16401, which is recommended mostly for air-conditioned buildings, as it is known to profile naturally ventilated buildings in hot and humid climates as uncomfortable.

Regarding the use of ASHRAE-55's adaptive model in Brazil, analysing current available data – ABNT NBR 15220-3's bioclimatic division and the mean temperature from the selected stations, the results show that the model can be applied to the Brazilian context, as a significant area of the country is within its applicability limits. However, thermal disparities within the bioclimatic zones, such as the case of the Brazilian semi-arid region, can distort the running mean and compromise the accuracy of the analysis, as well as the lack of thermal perception data to validate the applicability of adaptive models and identify the acceptability limits.

If Brazilian standards continue to follow ASHRAE's guidelines and decide to adopt the adaptive model to ensure thermal comfort in naturally ventilated buildings in the future, it would be important to test the model against field data collected from actual buildings.

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# Automation system for setpoint temperatures based on adaptive comfort: an in-depth guide of ACCIS capabilities running with EnergyPlus.

**Daniel Sánchez-García[1*], Jorge Martínez-Crespo[1], Ulpiano Ruiz-Rivas Hernando[1] and Carmen Alonso[2]**

[1] Appropriate Technology for Sustainable Development Group, University Carlos III of Madrid, Spain;

[*] email: dsgarcia@ing.uc3m.es;

[2] Department of construction. Eduardo Torroja Institute for Construction Science. CSIC.

**Abstract:** The possibility for energy savings from implementing setpoint temperatures based on adaptive comfort has recently been investigated. This can be achieved by using the recently proposed Adaptive-Comfort-Control-Implementation Script (ACCIS), that is a computational approach which extends the air-conditioning usage to adaptive comfort. According to both an Input Data File (IDF) and the setup supplied by the user, ACCIS turns PMV-based into adaptive setpoint building EnergyPlus models. Originally, ACCIS was an EnergyManagementSystem (EMS) script, but its capabilities have been expanded, and it has been nested in the Adaptive Comfort Control Implemented Model ("accim") Python package. This study focuses on the development of ACCIS, and provides a deeper view of the operation of the computational approach based on the relationship between the objects that compose it. As a result, ACCIS brings up new possibilities for conducting energy simulations on a global scale rather than merely on a national or continental size, since all weather file quantity limits have been tackled and now studies can be developed based on millions of simulations. Also, ACCIS could be applied to energy management, or coupled with artificial intelligence to develop smart thermostats.

**Keywords:** Adaptive thermal comfort, Energy efficiency, Heating and cooling setpoint temperatures, Computational approach

## 1. Introduction

Climate change has been a major issue for years. Climate change is worsening year after year as a result of human actions made without regard for the environment (World Wildlife Fund, 2014). Temperature rises might range from 2.5°C in 2050 to 4.5°C in 2100, 7.5°C in 2200, and 8°C in 2300 (Meinshausen *et al.*, 2011), using the preindustrial mean surface temperature as a baseline. The building industry is mandated to cut greenhouse gas emissions by 90% by 2050 (European Commission, 2011) in order to limit both pollutant gas emissions and resource depletion.

Therefore, the main purpose of buildings, which is offering shelter from the environment, is crucial in a climate change context. The human is capable to adapt physiologically and psychologically to changes in weather to a certain extent, and thus is expected to adapt the increasing temperatures. There are currently 2 main approaches to thermal comfort: adaptive thermal comfort and Predicted Mean Vote (PMV) index. Adaptive thermal comfort has been studied by means of field work mainly in buildings without active heating or cooling systems alternatively to the PMV index, which was developed by Fanger in climate chambers inspired on air-conditioned offices, where occupants were not free to take actions to adapt to the indoor environment, such as choosing the clothes they wore. Therefore, given the present and future scenarios, the research of adaptive thermal comfort is of great importance, since it leads to the Integration of users' climate adaptability into the low energy consumption.

To keep the indoor temperature within acceptable levels, air conditioning systems are sometimes utilized. However, using these systems, which often have highly limited setpoint temperatures that are quite pleasant for the human body, may reduce people's physiological, psychological, and behavioral capacity to adjust to ambient temperature fluctuations (Humphreys, 1996), in addition to consuming a significant amount of energy. Many researches have recently been focused on reducing this problem by expanding the use of air conditioning to adaptive comfort, that is, by adopting adaptive setpoint temperatures (AST). These ASTs are setpoint temperatures calculated using adaptive thermal comfort methods, and their values correspond to upper and lower comfort limits. Strictly, the use of adaptive comfort models is only applicable when no active heating and cooling systems are used. However, a recent study provided evidences that people apparently adapt to a much broader range of indoor temperatures, regardless of the technology delivering the indoor climate (Parkinson *et al.*, 2020). As a result, because the use of AST indicates that the operating temperature fluctuates within the adaptive thermal comfort zone, it is envisaged that energy consumption will be reduced due to the use of less-restricted setpoint temperatures while maintaining adequate thermal human thermal sensation: (i) R.P. Kramer et al. (Kramer *et al.*, 2015) investigated energy conservation at an Amsterdam museum by employing a variety of setpoint temperatures and adaptive thermal comfort levels. The lower comfort limit was allocated to the heating setpoint temperature, and HVAC systems were only operated during museum opening hours, resulting in a 74 percent energy savings; (ii) Sánchez-Guevara Sánchez et al. (Sánchez-Guevara Sánchez *et al.*, 2017) used setpoint temperatures in three residential structures in Spain, based on the comfort limitations of the simplified model from the ASHRAE Standard 55-2013 (ANSI/ASHRAE, 2013), which vary monthly. In both heating and cooling, energy consumption was lowered by 20% and 80%, respectively. As a result, adaptive comfort procedures are important for the inhabitants of all buildings, including air-conditioned ones. Table 1 summarizes some of the research publications that are important to this computational technique. Given the significant energy savings potential of this energy conservation technique, it has the potential to assist many buildings, particularly offices (Gangolells *et al.*, 2020), in reducing their energy usage (Gangolells *et al.*, 2019).

Table 1. Relevant research articles related to ACCIS.

| Authors | Citation | Setpoints | Energy Saving (%) | Level of automation |
|---|---|---|---|---|
| R.P. Kramer et al. | (Kramer *et al.*, 2015) | Adaptive set-points (based on Adaptive Thermal Guideline) | 74 | Not specified |
| Sánchez-Guevara Sánchez et al. | (Sánchez-Guevara Sánchez *et al.*, 2017) | Adaptive setpoints (ASH-RAE Standard 55-2013) | 80 (Cooling); 20 (Heating) | Low (based on several monthly simulations and following merge) |
| Sánchez-García et al. | (Sánchez-García, Bienvenido-Huertas, *et al.*, 2019) | Adaptive set-points (EN 15251:2007) | between 23 and 46 | Medium (based on Schedule:Compact objects) |
| Sánchez-García et al. | (Sánchez-García *et al.*, 2020) | Adaptive set-points (EN 15251:2007) | between 31 and 70 | Medium (based on Schedule:Compact objects) |
| Sánchez-García et al. | (Sánchez-García, Rubio-Bellido, *et al.*, 2019) | Adaptive set-points (EN 15251:2007) | between 40 and 62 | Medium (based on Schedule:Compact objects) |
| Sánchez-García et al. | (Sánchez-García *et al.*, 2021) | Adaptive set-points (EN 16798-1:2021) | 82.8 | High (by means of accim) |

Building energy simulations (BES) were primarily used to develop preliminary studies with DesignBuilder (DesignBuilder Software Ltd, 2021), which employs the simulation engine EnergyPlus (Crawley *et al.*, 2001). Furthermore, mainly 2 methods were used to determine the setpoint temperatures before the development of accim: on the one hand, very basic methods like changing setpoint temperatures monthly and then summing the results of the 12 simulations, and on the other hand, more effective methods like using Schedule:Compact objects, which are EnergyPlus objects that can define setpoint temperatures and operation schedules in detail. However, a lengthy, difficult, and time-consuming process was carried out manually, making it error-prone. Setpoint temperatures, for example, were previously computed with an Excel spreadsheet, and then copied and pasted into Schedule:Compact objects, the relevant EPW file was then allocated, and finally the combination of setpoint temperature and climatic zone was simulated. Other file management activities were also necessary.

The ACCIS is a computational technique for extending air-conditioning usage to adaptive thermal comfort (Sánchez-García *et al.*, 2021). ACCIS was developed within the scope of various research studies, known as the Adaptive-Comfort-Control-Implemented Model (ACCIM). Some parameters, which make up the input arguments for Comfort Mode (Sánchez-García, Bienvenido-Huertas, *et al.*, 2019), Category (Sánchez-García *et al.*, 2020), and HVAC mode (Sánchez-García, Rubio-Bellido, *et al.*, 2019), have been investigated. Furthermore, prior versions of ACCIS were employed, allowing for investigations based on a large number of simulations in various locations and ASTs, such as 780 (Bienvenido-Huertas *et al.*, 2020) or 48,786 (Bienvenido-Huertas *et al.*, 2021) distinct location-AST combinations. The program or process described in this paper is currently the only one available. Other approaches get similar outcomes, but they are manual and hence time-consuming, tiresome, and error-prone.

The Python package accim and the EMS script ACCIS have already been studied in a previous research (Sánchez-García *et al.*, 2021). However, that research provided a general definition of both, but did not explain the details of these. This study provides an in-depth insight into ACCIS, considering the use of the different objects in the EnergyPlus and EnergyManagementSystem environments, their role and function, as well as the operation and relationship between the different variables. Section 2 provides the previous considerations, including a brief presentation of the software on which ACCIS depends, the different objects used in the EnergyManagementSystem environment, and the limitations of ACCIS. Section 3 provides of the operation of ACCIS, broken down into the different objects that constitute it. Section 4 provides the discussion, and lastly Section 5 provides the conclusions.

## 2. Previous considerations

### 2.1. EnergyPlus and EnergyManagementSystem

EnergyPlus, the ACCIS simulation engine, is an open-source BES program developed by the US Department of Energy. Engineers, architects, and academics use it to simulate energy and water use in structures. This application is a console-based program that receives data from the user and writes it to text files. It was initially created in the FORTRAN programming language, but with version 8.2.0, it has been rewritten in C++. Because this software and its programming language are hard to understand, graphical user interfaces such as DesignBuilder or OpenStudio [33] have been created to help those who have no background in programming.

EnergyPlus is a strong software with few customization options. Nonetheless, there is an integrated component called EnergyManagementSystem (EMS) that compensates for this flaw. This is a strong tool for creating bespoke control and modelling routines as well as providing supervisory control over specific areas of EnergyPlus modelling. It is, however, difficult to utilize since it necessitates the creation of computer programs in the EnergyPlus Runtime Language (ERL), which is used to explain the control algorithms. When the simulation is conducted, EnergyPlus understands and runs the ERL program.

### 2.2. EnergyManagementSystem objects

In order to fully understand the operation of ACCIS, some EnergyManagementSystem typical objects need to be explained: *EnergyManagementSystem:Sensor* (hereinafter, sensor) objects are used to collect data from elements of the model that might change over time inside a single run period for use in control calculations. *EnergyManagementSystem:Actuator* (hereinafter, actuator) objects are used to actuate selected features inside EnergyPlus. Rather of adding a new set of EMS-aware controls and component models, they usually override existing functionalities. *EnergyManagementSystem:Program* are the objects which contain the overridden behaviour applied to the simulation run, by means of different statements, such as set-statements, to assign variables, if-blocks, to change behaviour based on conditions, or while-blocks, to iterate as long as some condition is met. *EnergyManagementSystem:ProgramCallingManager* (hereinafter, program calling manager) objects are used to describe the timing for when the ERL programs are run, at some specific EMS Calling Points. These EMS Calling Points are locations inside the EnergyPlus program where and when the EMS can be summoned to assist.

*EnergyManagementSystem:GlobalVariable* (hereinafter, global variable) objects are used to declare variables with a user-defined name and global scope. Global variables can be used to store intermediate results that span across ERL programs. *EnergyManagementSystem:OutputVariable* (hereinafter, output variable) objects are used to creates a custom output variable that is mapped to an EMS variable. The custom output variable can then be reported to the output file using the standard EnergyPlus output mechanisms such as with the Output:Variable object.

### 2.3. Limitations

In order to simplify the script, the building for what the script has been prepared has only one zone (named *Block1:Zone1*) and one window (named Block1_Zone1_Wall_4_0_0_0_0_0_Win). Therefore, for buildings with multiple zones and/or windows, the EMS sensors, actuators, program calling managers, programs, output variables and global variables related to any specific zone or window must be added for all of them. All these objects include the name of the room or window in its name.

Also, so that mixed-mode can be applied, the HVAC system indoor units must be monitored. For this purpose, a VRF system for each zone must be separately modelled, where the Outdoor units are named following the pattern "VRF Outdoor Unit_BlockX_ZoneY". The code to consider other HVAC systems is under development, but it will be included in future releases.

Further to the above, ACCIS requires the following points for the correct operation:

- "People" objects include "AdaptiveASH55" and "AdaptiveCEN15251" in the "Thermal Comfort Model 1 Type and 2 Type" fields, otherwise the PMOT and RMOT would not be computed by EnergyPlus.
- "Schedule:Compact" objects following the name pattern "FORSCRIPT_AHST_BLOCKX_ZONEY" must exist in the IDF file, and these must be assigned to the related "BLOCKX_ZONEY" by means of the corresponding "ThermostatSetpoint:DualSetpoint" object.
- So that mixed-mode can operate, the ventilation method must be "Calculated", natural ventilation must be available for all zones, and windows must be open always. ACCIS will close the windows if environmental conditions are not favourable.

Therefore, to apply setpoint temperatures by either copying and pasting ACCIS in the IDF or in the DesignBuilder Scripting module, these conditions must be met. Thus, the recommended and easiest method is to use accim, since it automatically checks if the IDF file comply with all limitations previously stated, and if not, automatically amends the IDF so that the operation is correct.

## 3. Script operation

The ACCIS code is included in the Appendix A, and it is available in open-source at the Python Package Index. It has been published in (Sánchez-García *et al.*, 2021), and a how-to-use guide can be consulted at the documentation (Sánchez-García, 2021). ACCIS can be broken down into 4 main stages: (i) Stage 1, when some user-defined data is stored at some global variables, and sensors, actuators and global variables are added; (ii) Stage 2, when some programs are executed to apply the user-defined input data to set up the customised outputs; (iii) Stage 3, when data to be reported is computed and actuators override the values of the components; and (iv) Stage 4, when the output variables are added to indicate which variables need to be reported. The operation at all stages is explained below, and it is recommended to follow the script included in Appendix A as this section is read as well as the flowcharts (Figures 1 and 2). Comments and clarification in the code are marked with "!" sign, in grey color; highlighted syntax has been preserved.

### 3.1. Stage 1

(i) Firstly, a ProgramCallingManager and Program objects are added, named SetInputData. As the name states, its function is to store the input data by means of set-statements to customise the simulation run afterwards. The input data is stored in the following variables: *AdapStand*, *CAT*, *ComfMod*, *HVACmode*, *VentCtrl*, *VSToffset*, *MinOToffset*, *MaxWindSpeed*, *ACSTtol*, and *AHSTtol*. These different parameters are explained in detail in the documentation website (Sánchez-García, 2021). Some input data variables treat the input values as categorical data, used in later in conditional statements. These are:

- *AdapStand* (if 0 is stored, then all computations will be performed later considering the Spanish Building Technical Code; if 1, EN16798-1 adaptive model; if 2, ASHRAE 55 adaptive model; if 3, a Japanese local adaptive model, hereinafter JPN);
- *CAT* (if 1, 2 or 3 is stored, then EN 16798-1's Category I, II or III will be applied; if 80 or 90, then ASHRAE 55 80% or 90% acceptability levels)
- *ComfMod* (if 0 is stored, then the setpoint temperatures will be based on the static model, based on the previous input data; if 1, 2 or 3, adaptive comfort model previously inputted will be applied when RMOT or PMOT is within applicability limits; the remaining time, static setpoint temperatures are applied).
- *HVACmode* (if 0 is stored, then the full air-conditioning mode is applied and natural ventilation is not allowed; if 1, free-running mode is applied, and natural ventilation is allowed; if 2, mixed-mode is applied, therefore natural ventilation is prioritised, otherwise windows are closed and HVAC system starts to work).
- *VentCtrl* (if 0 is stored, then the ventilation setpoint temperature is assigned to the comfort temperature; if 1, it is assigned to the upper comfort limit).

All other input data variables are treated as numbers. This program was initially located at the beginning of the script to separate it from the non-editable code, since before accim was developed, the method to apply this script was by adding it to the IDF file, and therefore the user had to customise the simulation by editing these values.

(ii) A global variable object is added to declare all the different variables that are used in ACCIS. Some of these are related to some specific zone, while others are not. Further details for each global variable can be found in the Appendix.

(iii) Then, a number of sensors, which will be used to get data from certain components, are added (Table 2). Therefore, these will allow to know the values at each timestep of the Running Mean Outdoor Temperature (RMOT), Prevailing Mean Outdoor Temperature (PMOT), and for both each thermal zone and window, the zone operative temperature, the cooling rate, the heating rate, the outdoor air wind speed and the outdoor air dry-bulb temperature. These last five components, in case of the zones, refer to the zones itself or the VRF indoor units located in these zones, and in case of the windows, these refer to the zones where the windows are located, or the VRF indoor units of the zones where the windows are located.

Table 2. List of sensors.

| Name | Output:Variable or Output:Meter Index Key Name | Output:Variable or Output:Meter Name |
|---|---|---|
| RMOT | People Block1:Zone1 | Zone Thermal Comfort CEN 15251 Adaptive Model Running Average Outdoor Air Temperature |
| PMOT | People Block1:Zone1 | Zone Thermal Comfort ASHRAE 55 Adaptive Model Running Average Outdoor Air Temperature |
| Block1_Zone1_OpT | Block1:Zone1 | Zone Operative Temperature |
| Block1_Zone1_CoolCoil | Block1:Zone1 VRF Indoor Unit DX Cooling Coil | Cooling Coil Total Cooling Rate |
| Block1_Zone1_HeatCoil | Block1:Zone1 VRF Indoor Unit DX Heating Coil | Heating Coil Heating Rate |
| Block1_Zone1_WindSpeed | Block1:Zone1 | Zone Outdoor Air Wind Speed |
| Block1_Zone1_OutT | Block1:Zone1 | Zone Outdoor Air Drybulb Temperature |
| Block1_Zone1_Wall_4_0_0_0_0_0_Win_OpT | Block1:Zone1 | Zone Operative Temperature |
| Block1_Zone1_Wall_4_0_0_0_0_0_Win_CoolCoil | Block1:Zone1 VRF Indoor Unit DX Cooling Coil | Cooling Coil Total Cooling Rate |
| Block1_Zone1_Wall_4_0_0_0_0_0_Win_HeatCoil | Block1:Zone1 VRF Indoor Unit DX Heating Coil | Heating Coil Heating Rate |
| Block1_Zone1_Wall_4_0_0_0_0_0_Win_WindSpeed | Block1:Zone1 | Zone Outdoor Air Wind Speed |
| Block1_Zone1_Wall_4_0_0_0_0_0_Win_OutT | Block1:Zone1 | Zone Outdoor Air Drybulb Temperature |
| OutT | Environment | Site Outdoor Air Drybulb Temperature |

(vi) Also, a number of actuators are added (Table 3). These will allow to override the values of the schedules assigned to the heating and cooling setpoint temperatures for the existing zone (*FORSCRIPT_ACST_Sch_Block1_Zone1* and *FORSCRIPT_AHST_Sch_Block1_Zone1* respectively, where ACST and AHST stands for Adaptive Cooling / Heating Setpoint Temperatures), as well as open or closed status of the existing window.

Table 3. List of actuators.

| Name | Actuated Component Unique Name | Actuated Component Type | Actuated Component Control Type |
|---|---|---|---|
| FORSCRIPT_ACST_Sch_Block1_Zone1 | FORSCRIPT_ACST_Block1_Zone1 | Schedule:Compact | Schedule Value |
| FORSCRIPT_AHST_Sch_Block1_Zone1 | FORSCRIPT_AHST_Block1_Zone1 | Schedule:Compact | Schedule Value |
| Block1_Zone1_Wall_4_0_0_0_0_0_Win_VentOpenFact | Block1:Zone1_Wall_4_0_0_0_0_0_Win | AirFlow Network Window/Door Opening | Venting Opening Factor |

### 3.2. Stage 2

Once the global variables, sensors and actuators have been added, the next objects are the programs, which will determine the relationship between the previously added sensors and actuators, and will define the different global variables declared. Also, the program calling managers are added, which will determine at which stage should the programs be called.

First, the programs used to determine the settings of the adaptive setpoint temperatures are added. These will compute and store the corresponding values to some global variables based on the input data specified at the *SetInputData* program.

*SetComfTemp* is used to store the comfort temperature at each timestep in the global variable *ComfTemp*. It depends on the value assigned to *AdapStand* at the *SetInputData* program: if 1, then *ComfTemp* will store the comfort temperature for EN16798-1; if 2, ASHRAE 55; if 3, JPN. In case of 1, the *RMOT* sensor is used to compute the comfort temperature, while in case of 2 or 3, *PMOT* sensor is used instead.

*SetAppLimits* is used to store the values of the applicability limits in the global variables added for that purpose (*AHSTaul*, *AHSTall*, *ACSTaul* and *ACSTall*). Depending on the value assigned to *AdapStand* as well, the applicability limits will be set for the corresponding comfort model. If the stored value is not any of the previously stated, then applicability limits are set to 50 (which means the model will not be applicable).

*ApplyCAT* is used to store the values of the offset for the heating and cooling setpoint temperatures from comfort temperature in the global variables added for that purpose (*AHSToffset* and *ACSToffset*). These also depends on the values previously stored in *AdapStand* and *CAT*.

*SetAST* is used to compute and store the values for the setpoint temperatures in the global variables *AHST* and *ACST*. It depends on the values previously store for *AdapStand* and *ComfMod*, as well as other sensors and global variables. This is the longest and one of the most important programs, since it consists of 25 if-blocks which contains the following set-statements patterns to compute and store the value for the setpoints:

set ACST = RMOT*m+n+ACSToffset+ACSTtol (1)

set AHST = RMOT*m+n+AHSToffset+AHSTtol (2)

where "*set*" is the command for ERL to store the value; *ACST* and *AHST* are respectively the global variables for the adaptive cooling and heating setpoint temperatures; *RMOT* is the sensor for the running mean outdoor temperature, which would be *PMOT* in case of ASHRAE 55 or JPN; "m" and "n" are coefficients of the comfort model regression equation (for example, 0.33+18.8 in case of EN 16798-1 adaptive model); *ACSToffset* and *AHSToffset* are global variables for the offset from comfort temperature previously stored in *ApplyCAT*; and *ACSTtol* and *AHSTtol* are global variables added to allow for certain tolerances, stored in *SetInputData*. Since sometimes, the simulated operative temperature might be some decimals of degree exceeding the setpoint temperatures, these tolerances, whose typical values could be ±0.1°C, are meant to be used to ensure that temperature in all timesteps falls within the comfort zone.

*SetASTnoTol* is used to compute and store the setpoint temperatures without tolerances (*AHSTnoTol* and *ACSTnoTol*), which are, indeed, the same value as the adaptive comfort limits. The value stored at *ACSTnoTol* must be negative, while the value stored at *AHSTnoTol* must be positive.

*SetVST* is used to compute and store the minimum outdoor temperature to apply the mixed-mode and the ventilation setpoint temperature at global variables *MinOutTemp* and *VST*. The value for *MinOutTemp* is computed by subtracting the global variable *MinOToffset* (stored at *SetInputData*) to the *AHST*, while *VST* is computed by adding the global variable *VSToffset* (also stored at *SetInputData*), when the adaptive model is applicable; otherwise, it is stored as the mean of both setpoint temperatures.

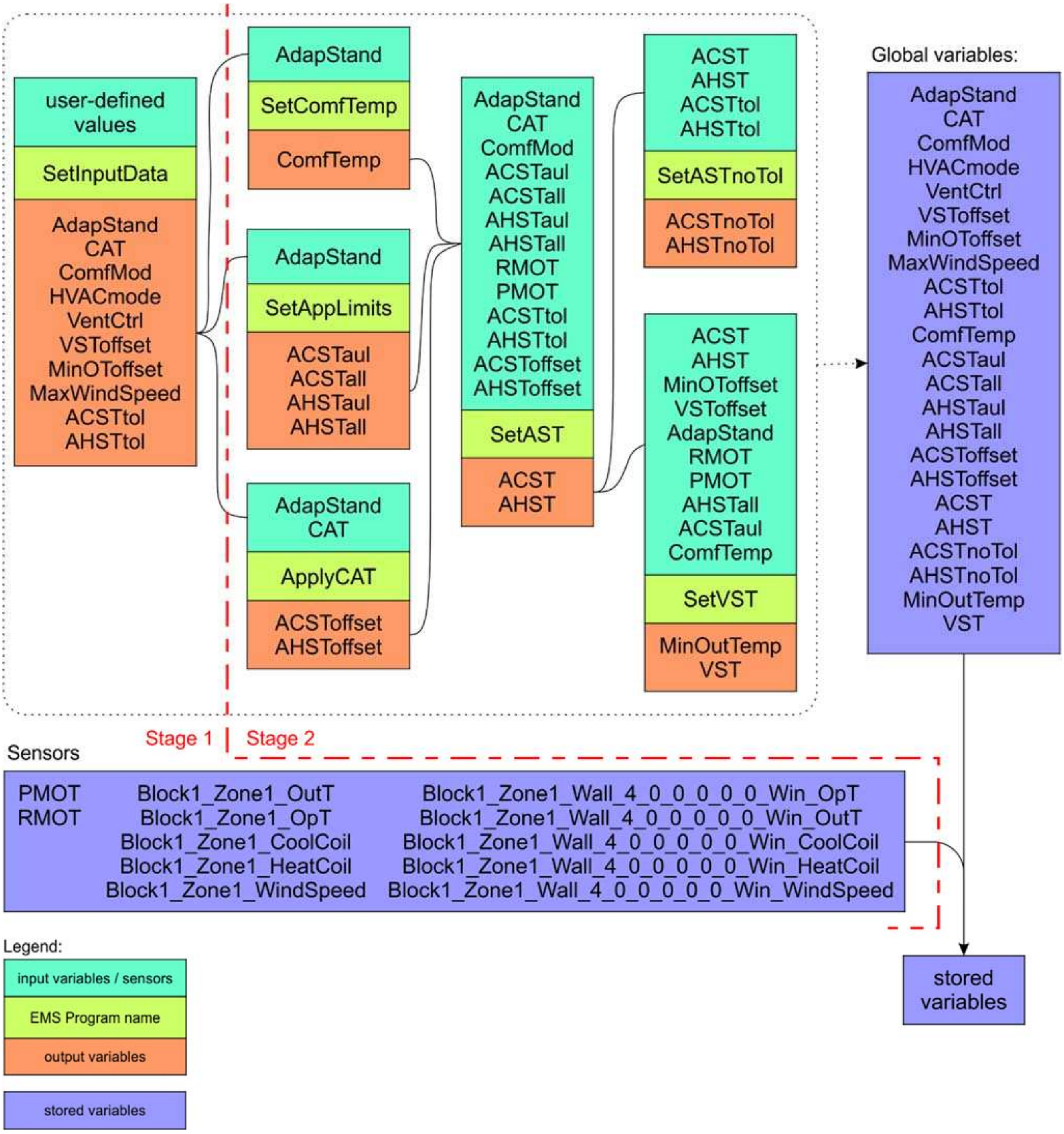


Figure 1. Stages 1 and 2 of ACCIS.

### 3.3. Stage 3

Up to now, all programs have been used to determine the settings of the setpoint temperatures. Therefore, all the following programs are used to perform calculations or override the setpoint temperatures schedule object and the open-or-close state of the window.

*CountHours_Block1_Zone1* is used to compute the time when the related zone's operative temperature (i) is within thermal comfort limits, when it is not because of heat (ii) or cold (iii) although still being applicable, and when it is not applicable because of heat (vi) or cold (v) and finally store it in the global variables (i) *ComfHours_Block1_Zone1*, (ii) *DiscomfAppHotHours_Block1_Zone1*, (iii) *DiscomfAppColdHours_Block1_Zone1*, (vi) *DiscomfNonAppHotHours_Block1_Zone1* and (v) *DiscomfNonAppColdHours_Block1_Zone1* respectively added for that purpose. At this point, all other variables are either sensors or global variables which has been previously stored.

*CountHoursNoApp_Block1_Zone1* is similar to the previous program, however this does not consider the applicability limits, that is, only evaluates if operative temperature is within comfort limits (stored at the global variables *ACSTnoTol* and *AHSTnoTol*), and if it is, stores the time at the global variable *ComfHoursNoApp_Block1_Zone1*.

*ApplyAST_Block1_Zone1* is composed by 3 if-blocks with several if-blocks nested. The first one is used to evaluate if environmental conditions are acceptable to ventilate in mixed-mode, and if so, 1 is stored as a boolean at the local variable *Ventilates_HVACmode2_Block1_Zone1* for later use at the third if-block. The second if-block is used to evaluate also if environmental conditions are acceptable to ventilate, but in free-running mode, and it depends on the global variable *VentCtrl* stored at *SetInputData*. If conditions are acceptable, 1 is stored as well as a boolean, but in a different local variable named *Ventilates_HVACmode1_Block1_Zone1*. Lastly, the third if-block overrides the values of the schedules named *FORSCRIPT_ACST_Block1_Zone1* and *FORSCRIPT_AHST_Block1_Zone1* depending on the value of the global variable *HVACmode* stored at *SetInputData*. If *HVACmode* is 0, the value of *ACST* and *AHST* is respectively assigned to the actuators *FORSCRIPT_ACST_Sch_Block1_Zone1* and *FORSCRIPT_AHST_Sch_Block1_Zone1*; if *HVACmode* is 1, 100 and -100 are respectively assigned to the cooling and heating setpoint actuators, so that EnergyPlus understands the HVAC system will not be allowed to work; finally, if *HVACmode* is 2 and the environmental conditions previously evaluated are not acceptable, *ACST* and *AHST* are assigned as well to the cooling and heating actuators. Also, the time when ventilation is allowed is stored at the global variable *VentHours_Block1_Zone1*. The local variable *VentHours_Block1_Zone1* has not been declared since its scope is limited to this program. This program works at zone level, therefore all sensors are related to thermal zones (all sensors include the zone name as a prefix or suffix).

*SetWindowOperation_Block1_Zone1_Wall_4_0_0_0_0_0_Win* is very similar to the previous program *ApplyAST_Block1_Zone1* in that the structure and purposes are the same, with the exception that the overridden component are the open-or-close status of the windows, controlled by the actuator *Block1_Zone1_Wall_4_0_0_0_0_0_Win_VentOpenFact* (1 is open, 0 is closed). In this case, this program works at window level, therefore all sensors are related to the window, and include the window name as a prefix or suffix.

### 3.4. Stage 4

Finally, the output variables for the global variables that have been declared are added. These objects are used to provide information to EnergyPlus of the EMS-related global variables that need to be reported at the simulation results. Table 4 shows the full list of output variables objects, where field "EMS Variable Name" is the name of the global variable, and "Name" and "Units" are the name and units under which these are reported.

It must be noted that "Output:Variable" objects are different to "EnergyManagementSystem:OutputVariables" objects. "Output:Variable" objects are used at a wider scope than EMS, and these indicates the variables that need to be reported, related and not related to EMS.

Table 4. List of EMS output variables.

| Name | EMS Variable Name | Units |
|---|---|---|
| Comfort Temperature | ComfTemp | C |
| Adaptive Cooling Setpoint Temperature | ACST | C |
| Adaptive Heating Setpoint Temperature | AHST | C |
| Adaptive Cooling Setpoint Temperature_No Tolerance | ACSTnoTol | C |
| Adaptive Heating Setpoint Temperature_No Tolerance | AHSTnoTol | C |
| Ventilation Setpoint Temperature | VST | C |
| Minimum Outdoor Temperature for mixed mode ventilation | MinOutTemp | C |
| Comfortable Hours_No Applicability_Block1_Zone1 (summed) | ComfHoursNoApp_Block1_Zone1 | h |
| Comfortable Hours_Block1_Zone1 (summed) | ComfHours_Block1_Zone1 | h |
| Discomfortable Applicable Hot Hours_Block1_Zone1 (summed) | DiscomfAppHotHours_Block1_Zone1 | h |
| Discomfortable Applicable Cold Hours_Block1_Zone1 (summed) | DiscomfAppColdHours_Block1_Zone1 | h |
| Discomfortable Non Applicable Hot Hours_Block1_Zone1 (summed) | DiscomfNonAppHotHours_Block1_Zone1 | h |
| Discomfortable Non Applicable Cold Hours_Block1_Zone1 (summed) | DiscomfNonAppColdHours_Block1_Zone1 | h |
| Ventilation Hours_Block1_Zone1 (summed) | VentHours_Block1_Zone1 | h |

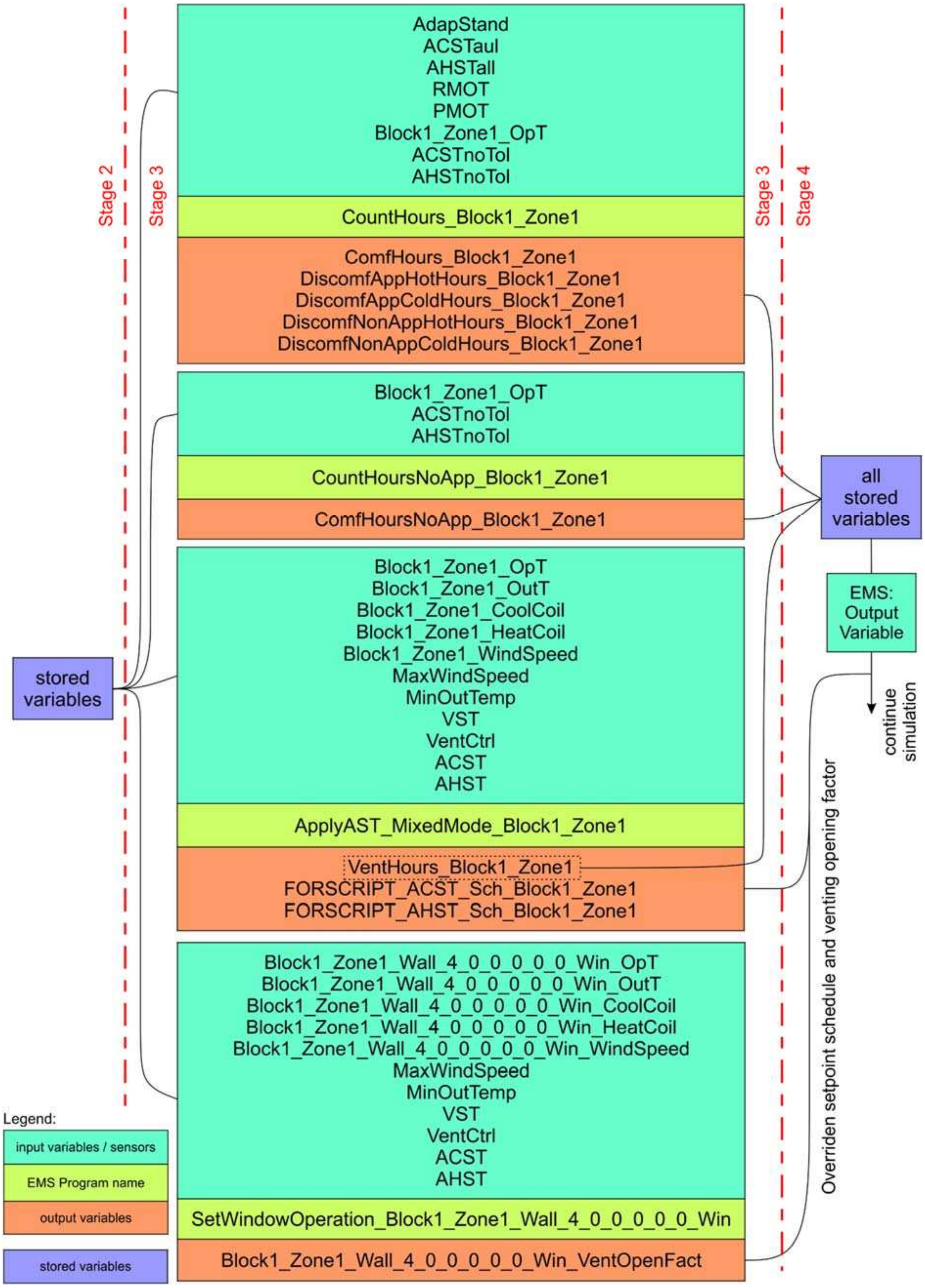


Figure 2. Stages 3 and 4 of ACCIS

## 4. Discussion

One of the most important features of ACCIS is that adaptive setpoint temperatures are not previously calculated for some specific climate and then pasted in the corresponding Schedule:Compact object which controls the thermostat of the thermal zones (in this code, *FORSCRIPT_ACST_Block1_Zone1* and *FORSCRIPT_AHST_Block1_Zone1*), but instead, these are calculated by EnergyPlus as the simulation runs and stored at the *RMOT* and *PMOT* sensors, and therefore this code is valid for the simulation with any climate file. Therefore, the proper operation of ACCIS relies on the availability of these sensors.

As a result, all possible setpoint temperatures are listed in Table 5, depending on the user-defined parameters *AdapStand*, *CAT* and *ComfMod*. All these setpoint temperatures make what could be understood as 'hybrid' comfort models, since when the adaptive model is applicable, adaptive setpoint temperatures are used, otherwise if it is not applicable, static setpoint temperatures are used instead (except when *ComfMod* is 0, which is entirely static).

The energy-saving potential of ACCIS, as well as the extensive simulation runs it allows, open up new avenues for performing energy simulations on a worldwide scale, rather than just on a nation or continent level. As a result, this tool opens up new opportunities for extending the scope of various adaptive comfort research investigations, such as climate change mitigation measures or energy poverty studies. Namely, this approach will be used in the Energy Poverty Intelligence Unit (EPIU) to estimate the energy consumption of different representative buildings of Getafe, in Madrid (Spain). To the best of the authors' knowledge, the suggested computational strategy is the first to do so, and it also permits additional standard adaptive-setpoint simulations to be completed in less time than any previous method. Furthermore, this technique has been automated and built for ease-of-use, whereas other systems require performing file management activities for dozens or hundreds of EPW files, and IDF files with adaptive setpoints must be simulated precisely with the relevant EPW file.

Table 5. List of all available setpoint temperatures based on the different input data.

| AdapStand | CAT | ComfMod | Cooling setpoint temperature (°C) | | | Heating setpoint temperature (°C) | | |
|---|---|---|---|---|---|---|---|---|
| | | | WMOT < ACSTall | ACSTall < WMOT < ACSTaul | ACSTaul < WMOT | WMOT < AHSTall | AHSTall < WMOT < AHSTaul | AHSTaul < WMOT |
| 0 | NA | NA | | 23:00-08:00h: 27 / 08:00-23:00h: 25 | | | 23:00-08:00h: 17 / 08:00-23:00h: 20 | |
| 1 | 1 | 0 | | 25.5 (25 in WS) | | | 21 (23.5 in SS) | |
| | | 1 | 27-25 | RMOT*0.33+18.8+2 | 27-25 | 17-20 | RMOT*0.33+18.8-3 | 17-20 |
| | | 2 | 25 | RMOT*0.33+18.8+2 | 25.5 | 21 | RMOT*0.33+18.8-3 | 23.5 |
| | | 3 | 10*0.33+18.8+2 | RMOT*0.33+18.8+2 | 30*0.33+18.8+2 | 10*0.33+18.8-3 | RMOT*0.33+18.8-3 | 30*0.33+18.8-3 |
| | 2 | 0 | | 26 (25 in WS) | | | 20 (23 in SS) | |
| | | 1 | 27-25 | RMOT*0.33+18.8+3 | 27-25 | 17-20 | RMOT*0.33+18.8-4 | 17-20 |
| | | 2 | 25 | RMOT*0.33+18.8+3 | 26 | 20 | RMOT*0.33+18.8-4 | 23 |
| | | 3 | 10*0.33+18.8+3 | RMOT*0.33+18.8+3 | 30*0.33+18.8+3 | 10*0.33+18.8-4 | RMOT*0.33+18.8-4 | 30*0.33+18.8-4 |
| | 3 | 0 | | 27 (25 in WS) | | | 18 (22 in SS) | |
| | | 1 | 27-25 | RMOT*0.33+18.8+4 | 27-25 | 17-20 | RMOT*0.33+18.8-5 | 17-20 |
| | | 2 | 25 | RMOT*0.33+18.8+4 | 27 | 18 | RMOT*0.33+18.8-5 | 22 |
| | | 3 | 10*0.33+18.8+4 | RMOT*0.33+18.8+4 | 30*0.33+18.8+4 | 10*0.33+18.8-5 | RMOT*0.33+18.8-5 | 30*0.33+18.8-5 |
| 2 | 80 | 0 | | 28.35 (26.35 in WS) | | | 20.1 (23.78 in SS) | |
| | | 1 | 27-25 | PMOT*0.31+17.8+3.5 | 27-25 | 17-20 | PMOT*0.31+17.8-3.5 | 17-20 |
| | | 2 | 26.35 | PMOT*0.31+17.8+3.5 | 28.35 | 20.1 | PMOT*0.31+17.8-3.5 | 23.78 |
| | | 3 | 10*0.31+17.8+3.5 | PMOT*0.31+17.8+3.5 | 33.5*0.31+17.8+3.5 | 10*0.31+17.8-3.5 | PMOT*0.31+17.8-3.5 | 33.5*0.31+17.8-3.5 |
| | 90 | 0 | | 27.42 (25.09 in WS) | | | 21.44 (24.74 in SS) | |
| | | 1 | 27-25 | PMOT*0.31+17.8+2.5 | 27-25 | 17-20 | PMOT*0.31+17.8-2.5 | 17-20 |
| | | 2 | 25.09 | PMOT*0.31+17.8+2.5 | 27.42 | 21.44 | PMOT*0.31+17.8-2.5 | 24.74 |
| | | 3 | 10*0.31+17.8+2.5 | PMOT*0.31+17.8+2.5 | 33.5*0.31+17.8+2.5 | 10*0.31+17.8-2.5 | PMOT*0.31+17.8-2.5 | 33.5*0.31+17.8-2.5 |
| 3 | 80 | 0 | | 28 | | | 18 | |
| | | 1 | 28 | PMOT*0.48+14.4+3.5 | 28 | 18 | PMOT*0.48+14.4-3.5 | 18 |
| | | 2 | 26.35 | PMOT*0.48+14.4+3.5 | 28.35 | 20.1 | PMOT*0.48+14.4-3.5 | 23.78 |
| | | 3 | 5*0.48+14.4+3.5 | PMOT*0.48+14.4+3.5 | 30*0.48+14.4+3.5 | 5*0.48+14.4-3.5 | PMOT*0.48+14.4-3.5 | 30*0.48+14.4-3.5 |
| | 90 | 0 | | 27 | | | 19 | |
| | | 1 | 27 | PMOT*0.48+14.4+2.5 | 27 | 19 | PMOT*0.48+14.4-2.5 | 19 |
| | | 2 | 25.09 | PMOT*0.48+14.4+2.5 | 27.42 | 21.44 | PMOT*0.48+14.4-2.5 | 24.74 |
| | | 3 | 5*0.48+14.4+2.5 | PMOT*0.48+14.4+2.5 | 30*0.48+14.4+2.5 | 5*0.48+14.4-2.5 | PMOT*0.48+14.4-2.5 | 30*0.48+14.4-2.5 |

PMOT: Prevailing mean outdoor temperature; RMOT: Running mean outdoor temperature; WS: Winter season; SS: Summer season; NA: Not applicable;
ACSTall: Adaptive Cooling Setpoint Temperature applicability lower limit; ACSTaul: Adaptive Cooling Setpoint Temperature applicability upper limit;
AHSTall: Adaptive Heating Setpoint Temperature applicability lower limit; AHSTaul: Adaptive Heating Setpoint Temperature applicability upper limit;
WMOT: Weighted Mean Outdoor Temperature (can be either RMOT or PMOT)

## 5. Conclusions

Adaptive setpoint temperatures are a possible way to improve the energy efficiency of a building. It has been widely demonstrated that it has a significant energy-saving potential. However, because the majority of the operations were completed manually, the approach used to reach these findings was time-consuming and error-prone. A computational strategy known as ACCIS was recently presented to address this issue, and there is presently no other way capable of automating the process of applying adaptive setpoint temperatures. However, ACCIS had some limitations in that a number of requirements must be complied with so that the operation was correct. Therefore, ACCIS has been nested in a Python library called accim, which allows to automate all these tasks. As a result, according to an IDF and the setup supplied by the user, ACCIS turns PMV-based into adaptive setpoint building energy models.

Once stated some previous considerations, this study provides an in-depth insight of ACCIS, breaking down the code into 4 stages:

- Stage 1, where the user specifies the input data for the customisation of the adaptive setpoint simulation settings, and all needed EMS objects are added;
- Stage 2, where EMS programs to apply the user-defined input data and compute and store the global variables to define the framework of the customised adaptive setpoint simulation
- Stage 3, where the setpoint schedule and open-or-close state of the windows are overridden based on the global variables previously computed in Stage 2
- Stage 4, when the variables that are going to be reported are specified.

The energy-saving potential of ACCIS, as well as the long simulation runs it permits, bring up new possibilities for conducting energy simulations on a global scale rather than merely on a national or continental size. As a result, this instrument expands the scope of many adaptive comfort research studies, such as climate change mitigation or energy poverty study.

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```
!APPENDIX A. ADAPTIVE-COMFORT-CONTROL-IMPLEMENTATION SCRIPT CODE.
!User-editable data

!STAGE 1_____________________________________________________________________________________________
EnergyManagementSystem:ProgramCallingManager,
SetInputData,
BeginTimestepBeforePredictor,
SetInputData;

EnergyManagementSystem:Program,
SetInputData,
!Values as categorical data
!Comfort standard to be used: 0=CTE; 1 = EN16798-1; 2 = ASHRAE 55; 3 = JPN
set AdapStand = 3,
!Category or acceptability to be used: 1 = CAT I; 2 = CAT II; 3 = CAT III; 80 = 80% ACCEPT; 90 = 90% ACCEPT
set CAT = 3,
!Comfort mode to be used: 0 = Static; 1 = OUT-CTE; 2 = OUT-SENXXXXX/SASHRAE55; 3 = OUT-AENXXXXX/AASHRAE55
set ComfMod = 3,
!HVAC mode to be used: 0 = Fully Air-conditioned; 1 = Naturally ventilated; 2 = Mixed mode
set HVACmode = 2,
!Natural ventilation control to be used: 0 = Ventilates above comfort temperature; 1 = Ventilates above upper comfort limit
set VentCtrl = 0,
!Values as numerical data
!This values will be summed to the ventilation setpoint. Only used when VentCtrl = 0
set VSToffset = 0,
!AHST - MinOToffset will be the minimum outdoor temperature for ventilation, therefore it must be positive. Only used if HVACmode = 2.
set MinOToffset = 15,
!Maximum wind speed for ventilation.
set MaxWindSpeed = 6,
!This value will be summed to the cooling setpoint. It must be negative or 0.
set ACSTtol = -0.25,
!This value will be summed to the heating setpoint. It must be positive or 0.
set AHSTtol = 0.25;


!Not to be modified from here on.

!Declaration of global variables
EnergyManagementSystem:GlobalVariable,
!Adaptive Cooling Setpoint Temperature
ACST,
!Adaptive Heating Setpoint Temperature
AHST,
!Adaptive Cooling Setpoint Temperature without tolerance (i.e upper comfort limit)
ACSTnoTol,
!Adaptive Heating Setpoint Temperature without tolerance (i.e lower comfort limit)
AHSTnoTol,
!Comfort standard used
AdapStand,
!Adaptive Cooling Setpoint Temperature applicability upper limit
ACSTaul,
!Adaptive Cooling Setpoint Temperature applicability lower limit
ACSTall,
!Adaptive Heating Setpoint Temperature applicability upper limit
AHSTaul,
!Adaptive Heating Setpoint Temperature applicability lower limit
AHSTall,
!Category or acceptability level used
CAT,
!Offset of ACST from comfort temperature
ACSToffset,
!Offset of AHST from comfort temperature
AHSToffset,
!Comfort mode used
ComfMod,
!Comfort or neutral temperature
ComfTemp,
!ACST tolerance
ACSTtol,
!AHST tolerance
AHSTtol,
```

```
!Comfort hour
ComfHours_Block1_Zone1,
!Applicable but discomfortable hour by heat
DiscomfAppHotHours_Block1_Zone1,
!Applicable but discomfortable hour by cold
DiscomfAppColdHours_Block1_Zone1,
!Not applicable hour by heat
DiscomfNonAppHotHours_Block1_Zone1,
!Not applicable hour by cold
DiscomfNonAppColdHours_Block1_Zone1,
!Comfort hour (no applicability considered)
ComfHoursNoApp_Block1_Zone1,
!Ventilation hour
VentHours_Block1_Zone1,
!Ventilation setpoint temperature
VST,
!Offset for the VST
VSToffset,
!Maximum wind speed for ventilation
MaxWindSpeed,
!Natural ventilation control mode
VentCtrl,
!HVAC mode operation
HVACmode,
!Minimum outdoor temperature for natural ventilation
MinOutTemp,
!Offset for the MinOutTemp
MinOToffset;

!Sensors
!Running Mean Outdoor Temperature
EnergyManagementSystem:Sensor,
RMOT,
People Block1:Zone1,
Zone Thermal Comfort CEN 15251 Adaptive Model Running Average Outdoor Air Temperature;

!Prevailing Mean Outdoor Temperature
EnergyManagementSystem:Sensor,
PMOT,
People Block1:Zone1,
Zone Thermal Comfort ASHRAE 55 Adaptive Model Running Average Outdoor Air Temperature;

!Zone-related sensors: Block1:Zone1
!Operative temperature
EnergyManagementSystem:Sensor,
Block1_Zone1_OpT,
Block1:Zone1,
Zone Operative Temperature;

!Cooling rate
EnergyManagementSystem:Sensor,
Block1_Zone1_CoolCoil,
Block1:Zone1 VRF Indoor Unit DX Cooling Coil,
Cooling Coil Total Cooling Rate;

!Heating rate
EnergyManagementSystem:Sensor,
Block1_Zone1_HeatCoil,
Block1:Zone1 VRF Indoor Unit DX Heating Coil,
Heating Coil Heating Rate;

!Wind speed
EnergyManagementSystem:Sensor,
Block1_Zone1_WindSpeed,
Block1:Zone1,
Zone Outdoor Air Wind Speed;

!Outdoor temperature
EnergyManagementSystem:Sensor,
Block1_Zone1_OutT,
Block1:Zone1,
```

```
Zone Outdoor Air Drybulb Temperature;

!Windows-related sensors: Block1_Zone1_Wall_4_0_0_0_0_0_Win
!Operative temperature
EnergyManagementSystem:Sensor,
Block1_Zone1_Wall_4_0_0_0_0_0_Win_OpT,
Block1:Zone1,
Zone Operative Temperature;

!Cooling rate
EnergyManagementSystem:Sensor,
Block1_Zone1_Wall_4_0_0_0_0_0_Win_CoolCoil,
Block1:Zone1 VRF Indoor Unit DX Cooling Coil,
Cooling Coil Total Cooling Rate;

!Heating rate
EnergyManagementSystem:Sensor,
Block1_Zone1_Wall_4_0_0_0_0_0_Win_HeatCoil,
Block1:Zone1 VRF Indoor Unit DX Heating Coil,
Heating Coil Heating Rate;

!Wind speed
EnergyManagementSystem:Sensor,
Block1_Zone1_Wall_4_0_0_0_0_0_Win_WindSpeed,
Block1:Zone1,
Zone Outdoor Air Wind Speed;

!Outdoor temperature
EnergyManagementSystem:Sensor,
Block1_Zone1_Wall_4_0_0_0_0_0_Win_OutT,
Block1:Zone1,
Zone Outdoor Air Drybulb Temperature;


!Actuators
EnergyManagementSystem:Actuator,
!Actuator name
FORSCRIPT_ACST_Sch_Block1_Zone1,
!Schedule actuated: Cooling setpoint schedule
FORSCRIPT_ACST_Block1_Zone1,
Schedule:Compact,
Schedule Value;

EnergyManagementSystem:Actuator,
!Actuator name
FORSCRIPT_AHST_Sch_Block1_Zone1,
!Schedule actuated: Heating setpoint schedule
FORSCRIPT_AHST_Block1_Zone1,
Schedule:Compact,
Schedule Value;

EnergyManagementSystem:Actuator,
!Actuator name
Block1_Zone1_Wall_4_0_0_0_0_0_Win_VentOpenFact,
!Window actuated
Block1:Zone1_Wall_4_0_0_0_0_0_Win,
AirFlow Network Window/Door Opening,
!Field actuated of the window
Venting Opening Factor;

!STAGE 2_____________________________________________________________________________________________

EnergyManagementSystem:ProgramCallingManager,
SetComfTemp,
BeginTimestepBeforePredictor,
SetComfTemp;

EnergyManagementSystem:Program,
SetComfTemp,
if AdapStand == 1,
  set ComfTemp = RMOT*0.33+18.8,
```

```
elseif AdapStand == 2,
 set ComfTemp = PMOT*0.31+17.8,
elseif AdapStand == 3,
 set ComfTemp = PMOT*0.48+14.4,
endif;

EnergyManagementSystem:ProgramCallingManager,
SetAppLimits,
BeginTimestepBeforePredictor,
SetAppLimits;

EnergyManagementSystem:Program,
SetAppLimits,
!Values to be updated in case of new standard revisions
If AdapStand == 1,
        set ACSTaul = 30,
        set ACSTall = 10,
        set AHSTaul = 30,
        set AHSTall = 10,
elseif AdapStand == 2,
        set ACSTaul = 33.5,
        set ACSTall = 10,
        set AHSTaul = 33.5,
        set AHSTall = 10,
elseif AdapStand == 3,
        set ACSTaul = 30,
        set ACSTall = 5,
        set AHSTaul = 30,
        set AHSTall = 5,
else,
        set ACSTaul = 50,
        set ACSTall = 50,
        set AHSTaul = 50,
        set AHSTall = 50,
endif;

EnergyManagementSystem:ProgramCallingManager,
ApplyCAT,
BeginTimestepBeforePredictor,
ApplyCAT;

EnergyManagementSystem:Program,
ApplyCAT,
if (AdapStand == 1 ),
        if (CAT == 1),
                set ACSToffset = 2,
                set AHSToffset = -3,
        elseif (CAT == 2),
                set ACSToffset = 3,
                set AHSToffset = -4,
        elseif (CAT == 3),
                set ACSToffset = 4,
                set AHSToffset = -5,
        endif,
elseif (AdapStand == 2 ) || (AdapStand == 3),
        if (CAT == 90),
                set ACSToffset = 2.5,
                set AHSToffset = -2.5,
        elseif (CAT == 80),
                set ACSToffset = 3.5,
                set AHSToffset = -3.5,
        endif,
endif;

EnergyManagementSystem:ProgramCallingManager,
SetAST,
BeginTimestepBeforePredictor,
SetAST;

EnergyManagementSystem:Program,
SetAST,
```

```
if (AdapStand == 0) && (CurrentTime < 7),
		set ACST = 27+ACSTtol,
		set AHST = 17+AHSTtol,
elseif (AdapStand == 0) && (CurrentTime < 15),
		set ACST = 25,
		set AHST = 20+AHSTtol,
elseif (AdapStand == 0) && (CurrentTime < 23),
		set ACST = 25+ACSTtol,
		set AHST = 20+AHSTtol,
elseif (AdapStand == 0) && (CurrentTime < 24),
		set ACST = 27+ACSTtol,
		set AHST = 17+AHSTtol,
endif,

if (AdapStand == 1) && (ComfMod == 0),
		if (DayOfYear >= 121) && (DayOfYear < 274),
				if (CAT==1),
						set ACST = 25.5+ACSTtol,
				elseif (CAT==2),
						set ACST = 26+ACSTtol,
				elseif (CAT==3),
						set ACST = 27+ACSTtol,
				endif,
		else,
				if (CAT==1),
						set ACST = 25+ACSTtol,
				elseif (CAT==2),
						set ACST = 25+ACSTtol,
				elseif (CAT==3),
						set ACST = 25+ACSTtol,
				endif,
		endif,
endif,

if (AdapStand == 1) && (ComfMod == 0),
		if (DayOfYear >= 121) && (DayOfYear < 274),
				if (CAT==1),
						set AHST = 23.5+AHSTtol,
				elseif (CAT==2),
						set AHST = 23+AHSTtol,
				elseif (CAT==3),
						set AHST = 22+AHSTtol,
				endif,
		else,
				if (CAT==1),
						set AHST = 21+AHSTtol,
				elseif (CAT==2),
						set AHST = 20+AHSTtol,
				elseif (CAT==3),
						set AHST = 18+AHSTtol,
				endif,
		endif,
endif,

if (AdapStand == 1) && (ComfMod == 1) && (RMOT >= ACSTall) && (RMOT <= ACSTaul),
		set ACST = RMOT*0.33+18.8+ACSToffset+ACSTtol,
elseif (AdapStand == 1) && (ComfMod == 1) && (CurrentTime < 7),
		set ACST = 27+ACSTtol,
elseif (AdapStand == 1) && (ComfMod == 1) && (CurrentTime < 15),
		set ACST = 50,
elseif (AdapStand == 1) && (ComfMod == 1) && (CurrentTime < 23),
		set ACST = 25+ACSTtol,
elseif (AdapStand == 1) && (ComfMod == 1) && (CurrentTime < 24),
		set ACST = 27+ACSTtol,
endif,

if (AdapStand == 1) && (ComfMod == 1) && (RMOT >= AHSTall) && (RMOT <= AHSTaul),
		set AHST = RMOT*0.33+18.8+AHSToffset+AHSTtol,
elseif (AdapStand == 1) && (ComfMod == 1) && (CurrentTime < 7),
		set AHST = 17+AHSTtol,
elseif (AdapStand == 1) && (ComfMod == 1) && (CurrentTime < 23),
```

```
        set AHST = 20+AHSTtol,
elseif (AdapStand == 1) && (ComfMod == 1) && (CurrentTime < 24),
        set AHST = 17+AHSTtol,
endif,

if (AdapStand == 1) && (ComfMod == 2) && (RMOT >= ACSTall) && (RMOT <= ACSTaul),
        set ACST = RMOT*0.33+18.8+ACSToffset+ACSTtol,
elseif (AdapStand == 1) && (ComfMod == 2) && (RMOT < ACSTall) && (CAT==1),
        set ACST = 25+ACSTtol,
elseif (AdapStand == 1) && (ComfMod == 2) && (RMOT > ACSTaul) && (CAT==1),
        set ACST = 25.5+ACSTtol,
elseif (AdapStand == 1) && (ComfMod == 2) && (RMOT < ACSTall) && (CAT==2),
        set ACST = 25+ACSTtol,
elseif (AdapStand == 1) && (ComfMod == 2) && (RMOT > ACSTaul) && (CAT==2),
        set ACST = 26+ACSTtol,
elseif (AdapStand == 1) && (ComfMod == 2) && (RMOT < ACSTall) && (CAT==3),
        set ACST = 25+ACSTtol,
elseif (AdapStand == 1) && (ComfMod == 2) && (RMOT > ACSTaul) && (CAT==3),
        set ACST = 27+ACSTtol,
endif,

if (AdapStand == 1) && (ComfMod == 2) && (RMOT >= AHSTall) && (RMOT <= AHSTaul),
        set AHST = RMOT*0.33+18.8+AHSToffset+AHSTtol,
elseif (AdapStand == 1) && (ComfMod == 2) && (RMOT < AHSTall) && (CAT==1),
        set AHST = 21+AHSTtol,
elseif (AdapStand == 1) && (ComfMod == 2) && (RMOT > AHSTaul) && (CAT==1),
        set AHST = 23.5+AHSTtol,
elseif (AdapStand == 1) && (ComfMod == 2) && (RMOT < AHSTall) && (CAT==2),
        set AHST = 20+AHSTtol,
elseif (AdapStand == 1) && (ComfMod == 2) && (RMOT > AHSTaul) && (CAT==2),
 set AHST = 23+AHSTtol,
elseif (AdapStand == 1) && (ComfMod == 2) && (RMOT < AHSTall) && (CAT==3),
        set AHST = 18+AHSTtol,
elseif (AdapStand == 1) && (ComfMod == 2) && (RMOT > AHSTaul) && (CAT==3),
        set AHST = 22+AHSTtol,
endif,

if (AdapStand == 1) && (ComfMod == 3) && (RMOT >= ACSTall) && (RMOT <= ACSTaul),
        set ACST = RMOT*0.33+18.8+ACSToffset+ACSTtol,
elseif (AdapStand == 1) && (ComfMod == 3) && (RMOT < ACSTall),
        set ACST = ACSTall*0.33+18.8+ACSToffset+ACSTtol,
elseif (AdapStand == 1) && (ComfMod == 3) && (RMOT > ACSTaul),
        set ACST = ACSTaul*0.33+18.8+ACSToffset+ACSTtol,
endif,

if (AdapStand == 1) && (ComfMod == 3) && (RMOT >= AHSTall) && (RMOT <= AHSTaul),
        set AHST = RMOT*0.33+18.8+AHSToffset+AHSTtol,
elseif (AdapStand == 1) && (ComfMod == 3) && (RMOT < AHSTall),
        set AHST = AHSTall*0.33+18.8+AHSToffset+AHSTtol,
elseif (AdapStand == 1) && (ComfMod == 3) && (RMOT > AHSTaul),
        set AHST = AHSTaul*0.33+18.8+AHSToffset+AHSTtol,
endif,

if (AdapStand == 2) && (ComfMod == 0),
        if (DayOfYear >= 121) && (DayOfYear < 274),
                if (CAT==80),
                        set ACST = 28.35+ACSTtol,
                elseif (CAT==90),
                        set ACST = 27.42+ACSTtol,
                endif,
        else,
                if (CAT==80),
                        set ACST = 26.35+ACSTtol,
                elseif (CAT==90),
                        set ACST = 25.09+ACSTtol,
                endif,
        endif,
endif,

if (AdapStand == 2) && (ComfMod == 0),
        if (DayOfYear >= 121) && (DayOfYear < 274),
```

```
                        if (CAT==80),
                                set AHST = 23.78+AHSTtol,
                        elseif (CAT==90),
                                set AHST = 24.74+AHSTtol,
                        endif,
                else,
                        if (CAT==80),
                                set AHST = 20.1+AHSTtol,
                        elseif (CAT==90),
                                set AHST = 21.44+AHSTtol,
                        endif,
                endif,
endif,

if (AdapStand == 2) && (ComfMod == 1) && (PMOT >= ACSTall) && (PMOT <= ACSTaul),
                set ACST = PMOT*0.31+17.8+ACSToffset+ACSTtol,
elseif (AdapStand == 2) && (ComfMod == 1) && (CurrentTime < 7),
                set ACST = 27+ACSTtol,
elseif (AdapStand == 2) && (ComfMod == 1) && (CurrentTime < 15),
                set ACST = 50,
elseif (AdapStand == 2) && (ComfMod == 1) && (CurrentTime < 23),
                set ACST = 25+ACSTtol,
elseif (AdapStand == 2) && (ComfMod == 1) && (CurrentTime < 24),
                set ACST = 27+ACSTtol,
endif,

if (AdapStand == 2) && (ComfMod == 1) && (PMOT >= AHSTall) && (PMOT <= AHSTaul),
                set AHST = PMOT*0.31+17.8+AHSToffset+AHSTtol,
elseif (AdapStand == 2) && (ComfMod == 1) && (CurrentTime < 7),
                set AHST = 17+AHSTtol,
elseif (AdapStand == 2) && (ComfMod == 1) && (CurrentTime < 23),
                set AHST = 20+AHSTtol,
elseif (AdapStand == 2) && (ComfMod == 1) && (CurrentTime < 24),
                set AHST = 17+AHSTtol,
endif,

if (AdapStand == 2) && (ComfMod == 2),
                if (PMOT >= ACSTall) && (PMOT <= ACSTaul),
                        set ACST = PMOT*0.31+17.8+ACSToffset+ACSTtol,
                elseif CAT==80,
                        if PMOT < ACSTall,
                                set ACST = 26.35+ACSTtol,
                        elseif PMOT > ACSTaul,
                                set ACST = 28.35+ACSTtol,
                        endif,
                elseif CAT==90,
                        if PMOT < ACSTall,
                                set ACST = 25.09+ACSTtol,
                        elseif PMOT > ACSTaul,
                                set ACST = 27.42+ACSTtol,
                        endif,
                endif,
endif,

if (AdapStand == 2) && (ComfMod == 2),
                if (PMOT >= AHSTall) && (PMOT <= AHSTaul),
                        set AHST = PMOT*0.31+17.8+AHSToffset+AHSTtol,
                elseif CAT==80,
                        if PMOT < AHSTall,
                                set AHST = 20.1+AHSTtol,
                        elseif PMOT > AHSTaul,
                                set AHST = 23.78+AHSTtol,
                        endif,
                elseif CAT==90,
                        if PMOT < AHSTall,
                                set AHST = 21.44+AHSTtol,
                        elseif PMOT > AHSTaul,
                                set AHST = 24.74+AHSTtol,
                        endif,
                endif,
endif,
```

```
if (AdapStand == 2) && (ComfMod == 3) && (PMOT >= ACSTall) && (PMOT <= ACSTaul),
		set ACST = PMOT*0.31+17.8+ACSToffset+ACSTtol,
elseif (AdapStand == 2) && (ComfMod == 3) && (PMOT < ACSTall),
		set ACST = ACSTall*0.31+17.8+ACSToffset+ACSTtol,
elseif (AdapStand == 2) && (ComfMod == 3) && (PMOT > ACSTaul),
		set ACST = ACSTaul*0.31+17.8+ACSToffset+ACSTtol,
endif,

if (AdapStand == 2) && (ComfMod == 3) && (PMOT >= AHSTall) && (PMOT <= AHSTaul),
		set AHST = PMOT*0.31+17.8+AHSToffset+AHSTtol,
elseif (AdapStand == 2) && (ComfMod == 3) && (PMOT < AHSTall),
		set AHST = AHSTall*0.31+17.8+AHSToffset+AHSTtol,
elseif (AdapStand == 2) && (ComfMod == 3) && (PMOT > AHSTaul),
		set AHST = AHSTaul*0.31+17.8+AHSToffset+AHSTtol,
endif,

if (AdapStand == 3) && (ComfMod == 0),
		if (CAT==80),
				set ACST = 28+ACSTtol,
		elseif (CAT==90),
				set ACST = 27+ACSTtol,
		endif,
endif,

if (AdapStand == 3) && (ComfMod == 0),
		if (CAT==80),
				set AHST = 18+AHSTtol,
		elseif (CAT==90),
				set AHST = 19+AHSTtol,
		endif,
endif,

if (AdapStand == 3) && (ComfMod == 1),
		if (PMOT >= ACSTall) && (PMOT <= ACSTaul),
				set ACST = PMOT*0.48+14.4+ACSToffset+ACSTtol,
		elseif CAT==80,
				if PMOT < ACSTall,
						set ACST = 28+ACSTtol,
				elseif PMOT > ACSTaul,
						set ACST = 28+ACSTtol,
				endif,
		elseif CAT==90,
				if PMOT < ACSTall,
						set ACST = 27+ACSTtol,
				elseif PMOT > ACSTaul,
						set ACST = 27+ACSTtol,
				endif,
		endif,
endif,

if (AdapStand == 3) && (ComfMod == 1),
		if (PMOT >= AHSTall) && (PMOT <= AHSTaul),
				set AHST = PMOT*0.48+14.4+AHSToffset+AHSTtol,
		elseif CAT==80,
				if PMOT < AHSTall,
						set AHST = 18+AHSTtol,
				elseif PMOT > AHSTaul,
						set AHST = 18+AHSTtol,
				endif,
		elseif CAT==90,
				if PMOT < AHSTall,
						set AHST = 19+AHSTtol,
				elseif PMOT > AHSTaul,
						set AHST = 19+AHSTtol,
				endif,
		endif,
endif,

if (AdapStand == 3) && (ComfMod == 2),
		if (PMOT >= ACSTall) && (PMOT <= ACSTaul),
```

```
                        set ACST = PMOT*0.48+14.4+ACSToffset+ACSTtol,
            elseif CAT==80,
                        if PMOT < ACSTall,
                                    set ACST = 26.35+ACSTtol,
                        elseif PMOT > ACSTaul,
                                    set ACST = 28.35+ACSTtol,
                        endif,
            elseif CAT==90,
                        if PMOT < ACSTall,
                                    set ACST = 25.09+ACSTtol,
                        elseif PMOT > ACSTaul,
                                    set ACST = 27.42+ACSTtol,
                        endif,
            endif,
endif,

if (AdapStand == 3) && (ComfMod == 2),
            if (PMOT >= AHSTall) && (PMOT <= AHSTaul),
                        set AHST = PMOT*0.48+14.4+AHSToffset+AHSTtol,
            elseif CAT==80,
                        if PMOT < AHSTall,
                                    set AHST = 20.1+AHSTtol,
                        elseif PMOT > AHSTaul,
                                    set AHST = 23.78+AHSTtol,
                        endif,
            elseif CAT==90,
                        if PMOT < AHSTall,
                                    set AHST = 21.44+AHSTtol,
                        elseif PMOT > AHSTaul,
                                    set AHST = 24.74+AHSTtol,
                        endif,
            endif,
endif,

if (AdapStand == 3) && (ComfMod == 3) && (PMOT >= ACSTall) && (PMOT <= ACSTaul),
            set ACST = PMOT*0.48+14.4+ACSToffset+ACSTtol,
elseif (AdapStand == 3) && (ComfMod == 3) && (PMOT < ACSTall),
            set ACST = ACSTall*0.48+14.4+ACSToffset+ACSTtol,
elseif (AdapStand == 3) && (ComfMod == 3) && (PMOT > ACSTaul),
            set ACST = ACSTaul*0.48+14.4+ACSToffset+ACSTtol,
endif,

if (AdapStand == 3) && (ComfMod == 3) && (PMOT >= AHSTall) && (PMOT <= AHSTaul),
            set AHST = PMOT*0.48+14.4+AHSToffset+AHSTtol,
elseif (AdapStand == 3) && (ComfMod == 3) && (PMOT < AHSTall),
            set AHST = AHSTall*0.48+14.4+AHSToffset+AHSTtol,
elseif (AdapStand == 3) && (ComfMod == 3) && (PMOT > AHSTaul),
            set AHST = AHSTaul*0.48+14.4+AHSToffset+AHSTtol,
endif;

EnergyManagementSystem:ProgramCallingManager,
SetASTnoTol,
BeginTimestepBeforePredictor,
SetASTnoTol;

EnergyManagementSystem:Program,
SetASTnoTol,
set ACSTnoTol = ACST-ACSTtol,
set AHSTnoTol = AHST-AHSTtol;

EnergyManagementSystem:ProgramCallingManager,
SetVST,
BeginTimestepBeforePredictor,
SetVST;

EnergyManagementSystem:Program,
SetVST,
set MinOutTemp = AHST - MinOToffset,
if AdapStand == 0,
            if (CurrentTime < 7),
                        set VST = (ACST+AHST)/2+VSToffset,
```

```
		elseif (CurrentTime < 15),
				set VST = 22.5+VSToffset,
		elseif (CurrentTime < 23),
				set VST = (ACST+AHST)/2+VSToffset,
		elseif (CurrentTime < 24),
				set VST = (ACST+AHST)/2+VSToffset,
		endif,
elseif AdapStand == 1,
		if (RMOT >= AHSTall) && (RMOT <= ACSTaul),
				set VST = ComfTemp+VSToffset,
		else,
				set VST = (ACST+AHST)/2+VSToffset,
		endif,
elseif AdapStand == 2 || AdapStand == 3,
		if (PMOT >= AHSTall) && (PMOT <= ACSTaul),
				set VST = ComfTemp+VSToffset,
		else,
				set VST = (ACST+AHST)/2+VSToffset,
		endif,
endif;

!STAGE 3___________________________________________________________________________________________

EnergyManagementSystem:ProgramCallingManager,
CountHours_Block1_Zone1,
BeginTimestepBeforePredictor,
CountHours_Block1_Zone1;

EnergyManagementSystem:Program,
CountHours_Block1_Zone1,
if (AdapStand == 1 ),
 if (RMOT >= AHSTall) && (RMOT <= ACSTaul),
		if (Block1_Zone1_OpT <= ACSTnoTol),
						if (Block1_Zone1_OpT >= AHSTnoTol),
						set ComfHours_Block1_Zone1 = 1*ZoneTimeStep,
						 set DiscomfAppHotHours_Block1_Zone1 = 0,
						 set DiscomfAppColdHours_Block1_Zone1 = 0,
						 set DiscomfNonAppHotHours_Block1_Zone1 = 0,
						 set DiscomfNonAppColdHours_Block1_Zone1 = 0,
						endif,
		elseif (Block1_Zone1_OpT > ACSTnoTol),
				set ComfHours_Block1_Zone1 = 0,
				set DiscomfAppHotHours_Block1_Zone1 = 1*ZoneTimeStep,
				set DiscomfAppColdHours_Block1_Zone1 = 0,
				set DiscomfNonAppHotHours_Block1_Zone1 = 0,
				set DiscomfNonAppColdHours_Block1_Zone1 = 0,
		elseif (Block1_Zone1_OpT < AHSTnoTol),
				set ComfHours_Block1_Zone1 = 0,
				set DiscomfAppHotHours_Block1_Zone1 = 0,
				set DiscomfAppColdHours_Block1_Zone1 = 1*ZoneTimeStep,
				set DiscomfNonAppHotHours_Block1_Zone1 = 0,
				set DiscomfNonAppColdHours_Block1_Zone1 = 0,
		endif,
 elseif (RMOT > ACSTaul),
		set ComfHours_Block1_Zone1 = 0,
		set DiscomfAppHotHours_Block1_Zone1 = 0,
		set DiscomfAppColdHours_Block1_Zone1 = 0,
		set DiscomfNonAppHotHours_Block1_Zone1 = 1*ZoneTimeStep,
		set DiscomfNonAppColdHours_Block1_Zone1 = 0,
 elseif (RMOT < AHSTall),
		set ComfHours_Block1_Zone1 = 0,
		set DiscomfAppHotHours_Block1_Zone1 = 0,
		set DiscomfAppColdHours_Block1_Zone1 = 0,
		set DiscomfNonAppHotHours_Block1_Zone1 = 0,
		set DiscomfNonAppColdHours_Block1_Zone1 = 1*ZoneTimeStep,
		endif,
elseif (AdapStand == 2 )|| (AdapStand == 3),
 if (PMOT >= AHSTall) && (PMOT <= ACSTaul),
		if (Block1_Zone1_OpT <= ACSTnoTol),
						if (Block1_Zone1_OpT >= AHSTnoTol),
						 set ComfHours_Block1_Zone1 = 1*ZoneTimeStep,
```

```
                                        set DiscomfAppHotHours_Block1_Zone1 = 0,
                                        set DiscomfAppColdHours_Block1_Zone1 = 0,
                                        set DiscomfNonAppHotHours_Block1_Zone1 = 0,
                                        set DiscomfNonAppColdHours_Block1_Zone1 = 0,
                                       endif,
                elseif (Block1_Zone1_OpT > ACSTnoTol),
                            set ComfHours_Block1_Zone1 = 0,
                            set DiscomfAppHotHours_Block1_Zone1 = 1*ZoneTimeStep,
                            set DiscomfAppColdHours_Block1_Zone1 = 0,
                            set DiscomfNonAppHotHours_Block1_Zone1 = 0,
                            set DiscomfNonAppColdHours_Block1_Zone1 = 0,
                elseif (Block1_Zone1_OpT < AHSTnoTol),
                            set ComfHours_Block1_Zone1 = 0,
                            set DiscomfAppHotHours_Block1_Zone1 = 0,
                            set DiscomfAppColdHours_Block1_Zone1 = 1*ZoneTimeStep,
                            set DiscomfNonAppHotHours_Block1_Zone1 = 0,
                            set DiscomfNonAppColdHours_Block1_Zone1 = 0,
                endif,
 elseif (PMOT > ACSTaul),
                set ComfHours_Block1_Zone1 = 0,
                set DiscomfAppHotHours_Block1_Zone1 = 0,
                set DiscomfAppColdHours_Block1_Zone1 = 0,
                set DiscomfNonAppHotHours_Block1_Zone1 = 1*ZoneTimeStep,
                set DiscomfNonAppColdHours_Block1_Zone1 = 0,
 elseif (PMOT < AHSTall),
                set ComfHours_Block1_Zone1 = 0,
                set DiscomfAppHotHours_Block1_Zone1 = 0,
                set DiscomfAppColdHours_Block1_Zone1 = 0,
                set DiscomfNonAppHotHours_Block1_Zone1 = 0,
                set DiscomfNonAppColdHours_Block1_Zone1 = 1*ZoneTimeStep,
 endif,
endif;


EnergyManagementSystem:ProgramCallingManager,
CountHoursNoApp_Block1_Zone1,
BeginTimestepBeforePredictor,
CountHoursNoApp_Block1_Zone1;

EnergyManagementSystem:Program,
CountHoursNoApp_Block1_Zone1,
if (Block1_Zone1_OpT <= ACSTnoTol),
            if (Block1_Zone1_OpT >= AHSTnoTol),
                        set ComfHoursNoApp_Block1_Zone1  = 1*ZoneTimeStep,
            else,
                        set ComfHoursNoApp_Block1_Zone1 = 0,
            endif,
else,
            set ComfHoursNoApp_Block1_Zone1 = 0,
endif;



EnergyManagementSystem:ProgramCallingManager,
ApplyAST_Block1_Zone1,
BeginTimestepBeforePredictor,
ApplyAST_Block1_Zone1;

EnergyManagementSystem:Program,
ApplyAST_Block1_Zone1,

!First if-block
if (Block1_Zone1_OpT>VST)&&(Block1_Zone1_OutT < VST),
            if Block1_Zone1_CoolCoil==0,
                        if Block1_Zone1_HeatCoil==0,
                                    if (Block1_Zone1_OpT<ACST)&&(Block1_Zone1_OutT>MinOutTemp),
                                                if Block1_Zone1_WindSpeed <= MaxWindSpeed,
                                                            set Ventilates_HVACmode2_Block1_Zone1 = 1,
                                                else,
                                                            set Ventilates_HVACmode2_Block1_Zone1 = 0,
                                                endif,
```

```
                        else,
                                set Ventilates_HVACmode2_Block1_Zone1 = 0,
                        endif,
                else,
                        set Ventilates_HVACmode2_Block1_Zone1 = 0,
                endif,
        else,
                set Ventilates_HVACmode2_Block1_Zone1 = 0,
        endif,
else,
        set Ventilates_HVACmode2_Block1_Zone1 = 0,
endif,
!Second if-block
        if Block1_Zone1_OutT < Block1_Zone1_OpT,
                if Block1_Zone1_OutT>MinOutTemp,
                        if Block1_Zone1_OpT > VST,
                                if Block1_Zone1_WindSpeed <= MaxWindSpeed,
                                        set Ventilates_HVACmode1_Block1_Zone1 = 1,
                                else,
                                        set Ventilates_HVACmode1_Block1_Zone1 = 0,
                                endif,
                        else,
                                set Ventilates_HVACmode1_Block1_Zone1 = 0,
                        endif,
                else,
                        set Ventilates_HVACmode1_Block1_Zone1 = 0,
                endif,
        else,
                set Ventilates_HVACmode1_Block1_Zone1 = 0,
        endif,
elseif VentCtrl == 1,
        if Block1_Zone1_OutT<Block1_Zone1_OpT,
                if Block1_Zone1_OutT>MinOutTemp,
                        if Block1_Zone1_OpT > ACSTnoTol,
                                if Block1_Zone1_WindSpeed <= MaxWindSpeed,
                                        set Ventilates_HVACmode1_Block1_Zone1 = 1,
                                else,
                                        set Ventilates_HVACmode1_Block1_Zone1 = 0,
                                endif,
                        else,
                                set Ventilates_HVACmode1_Block1_Zone1 = 0,
                        endif,
                else,
                        set Ventilates_HVACmode1_Block1_Zone1 = 0,
                endif,
        else,
                set Ventilates_HVACmode1_Block1_Zone1 = 0,
        endif,
endif,
!Third if-block
if HVACmode == 0,
        set FORSCRIPT_ACST_Sch_Block1_Zone1 = ACST,
        set FORSCRIPT_AHST_Sch_Block1_Zone1 = AHST,
elseif HVACmode == 1,
        Set FORSCRIPT_ACST_Sch_Block1_Zone1 = 100,
        Set FORSCRIPT_AHST_Sch_Block1_Zone1 = -100,
        if Ventilates_HVACmode1_Block1_Zone1 == 1,
                set VentHours_Block1_Zone1 = 1,
        else,
                set VentHours_Block1_Zone1 = 0,
        endif,
elseif HVACmode == 2,
        if Ventilates_HVACmode2_Block1_Zone1 == 1,
                set VentHours_Block1_Zone1 = 1,
        elseif Ventilates_HVACmode2_Block1_Zone1 == 0,
                set VentHours_Block1_Zone1 = 0,
                set FORSCRIPT_ACST_Sch_Block1_Zone1 = ACST,
                set FORSCRIPT_AHST_Sch_Block1_Zone1 = AHST,
        endif,
endif;
```

```
EnergyManagementSystem:ProgramCallingManager,
SetWindowOperation_Block1_Zone1_Wall_4_0_0_0_0_0_Win,
BeginTimestepBeforePredictor,
SetWindowOperation_Block1_Zone1_Wall_4_0_0_0_0_0_Win;

EnergyManagementSystem:Program,
SetWindowOperation_Block1_Zone1_Wall_4_0_0_0_0_0_Win,
!First if-block
if (Block1_Zone1_Wall_4_0_0_0_0_0_Win_OpT>VST)&&(Block1_Zone1_Wall_4_0_0_0_0_0_Win_OutT < VST),
        if Block1_Zone1_Wall_4_0_0_0_0_0_Win_CoolCoil==0,
                if Block1_Zone1_Wall_4_0_0_0_0_0_Win_HeatCoil==0,
                        if
(Block1_Zone1_Wall_4_0_0_0_0_0_Win_OpT<ACST)&&(Block1_Zone1_Wall_4_0_0_0_0_0_Win_OutT>MinOutTemp),
                                if Block1_Zone1_Wall_4_0_0_0_0_0_Win_WindSpeed <= MaxWindSpeed,
                                        set Ventilates_HVACmode2_Block1_Zone1_Wall_4_0_0_0_0_0_Win = 1,
                                else,
                                        set Ventilates_HVACmode2_Block1_Zone1_Wall_4_0_0_0_0_0_Win = 0,
                                endif,
                        else,
                                set Ventilates_HVACmode2_Block1_Zone1_Wall_4_0_0_0_0_0_Win = 0,
                        endif,
                else,
                        set Ventilates_HVACmode2_Block1_Zone1_Wall_4_0_0_0_0_0_Win = 0,
                endif,
        else,
                set Ventilates_HVACmode2_Block1_Zone1_Wall_4_0_0_0_0_0_Win = 0,
        endif,
else,
        set Ventilates_HVACmode2_Block1_Zone1_Wall_4_0_0_0_0_0_Win = 0,
endif,

!Second if-block
if VentCtrl == 0,
        if Block1_Zone1_Wall_4_0_0_0_0_0_Win_OutT < Block1_Zone1_Wall_4_0_0_0_0_0_Win_OpT,
                if Block1_Zone1_Wall_4_0_0_0_0_0_Win_OutT>MinOutTemp,
                        if Block1_Zone1_Wall_4_0_0_0_0_0_Win_OpT > VST,
                                if Block1_Zone1_Wall_4_0_0_0_0_0_Win_WindSpeed <= MaxWindSpeed,
                                        set Ventilates_HVACmode1_Block1_Zone1_Wall_4_0_0_0_0_0_Win = 1,
                                else,
                                        set Ventilates_HVACmode1_Block1_Zone1_Wall_4_0_0_0_0_0_Win = 0,
                                endif,
                        else,
                                set Ventilates_HVACmode1_Block1_Zone1_Wall_4_0_0_0_0_0_Win = 0,
                        endif,
                else,
                        set Ventilates_HVACmode1_Block1_Zone1_Wall_4_0_0_0_0_0_Win = 0,
                endif,
        else,
                set Ventilates_HVACmode1_Block1_Zone1_Wall_4_0_0_0_0_0_Win = 0,
        endif,
elseif VentCtrl == 1,
        if Block1_Zone1_Wall_4_0_0_0_0_0_Win_OutT<Block1_Zone1_Wall_4_0_0_0_0_0_Win_OpT,
                if Block1_Zone1_Wall_4_0_0_0_0_0_Win_OutT>MinOutTemp,
                        if Block1_Zone1_Wall_4_0_0_0_0_0_Win_OpT > ACSTnoTol,
                                if Block1_Zone1_Wall_4_0_0_0_0_0_Win_WindSpeed <= MaxWindSpeed,
                                        set Ventilates_HVACmode1_Block1_Zone1_Wall_4_0_0_0_0_0_Win = 1,
                                else,
                                        set Ventilates_HVACmode1_Block1_Zone1_Wall_4_0_0_0_0_0_Win = 0,
                                endif,
                        else,
                                set Ventilates_HVACmode1_Block1_Zone1_Wall_4_0_0_0_0_0_Win = 0,
                        endif,
                else,
                        set Ventilates_HVACmode1_Block1_Zone1_Wall_4_0_0_0_0_0_Win = 0,
                endif,
        else,
                set Ventilates_HVACmode1_Block1_Zone1_Wall_4_0_0_0_0_0_Win = 0,
        endif,
endif,

!Third if-block
```

```
if HVACmode == 0,
	set Block1_Zone1_Wall_4_0_0_0_0_0_Win_VentOpenFact = 0,
elseif HVACmode == 1,
	if Ventilates_HVACmode1_Block1_Zone1_Wall_4_0_0_0_0_0_Win == 1,
		set Block1_Zone1_Wall_4_0_0_0_0_0_Win_VentOpenFact = 1,
	else,
		set Block1_Zone1_Wall_4_0_0_0_0_0_Win_VentOpenFact = 0,
	endif,
elseif HVACmode == 2,
	if Ventilates_HVACmode2_Block1_Zone1_Wall_4_0_0_0_0_0_Win == 1,
		set Block1_Zone1_Wall_4_0_0_0_0_0_Win_VentOpenFact = 1,
	else,
		set Block1_Zone1_Wall_4_0_0_0_0_0_Win_VentOpenFact = 0,
	endif,
endif;

!STAGE 4___________________________________________________________________________________________

EnergyManagementSystem:OutputVariable,
Comfort Temperature,
ComfTemp,
Averaged,
ZoneTimestep,
,
C;

EnergyManagementSystem:OutputVariable,
Adaptive Cooling Setpoint Temperature,
ACST,
Averaged,
ZoneTimestep,
,
C;

EnergyManagementSystem:OutputVariable,
Adaptive Heating Setpoint Temperature,
AHST,
Averaged,
ZoneTimestep,
,
C;

EnergyManagementSystem:OutputVariable,
Adaptive Cooling Setpoint Temperature_No Tolerance,
ACSTnoTol,
Averaged,
ZoneTimestep,
,
C;

EnergyManagementSystem:OutputVariable,
Adaptive Heating Setpoint Temperature_No Tolerance,
AHSTnoTol,
Averaged,
ZoneTimestep,
,
C;

EnergyManagementSystem:OutputVariable,
Comfortable Hours_No Applicability_Block1_Zone1 (summed),
ComfHoursNoApp_Block1_Zone1,
Summed,
ZoneTimestep,
,
h;

EnergyManagementSystem:OutputVariable,
Comfortable Hours_Block1_Zone1 (summed),
ComfHours_Block1_Zone1,
Summed,
ZoneTimestep,
```

```
,
h;

EnergyManagementSystem:OutputVariable,
Discomfortable Applicable Hot Hours_Block1_Zone1 (summed),
DiscomfAppHotHours_Block1_Zone1,
Summed,
ZoneTimestep,
,
h;

EnergyManagementSystem:OutputVariable,
Discomfortable Applicable Cold Hours_Block1_Zone1 (summed),
DiscomfAppColdHours_Block1_Zone1,
Summed,
ZoneTimestep,
,
h;

EnergyManagementSystem:OutputVariable,
Discomfortable Non Applicable Hot Hours_Block1_Zone1 (summed),
DiscomfNonAppHotHours_Block1_Zone1,
Summed,
ZoneTimestep,
,
h;

EnergyManagementSystem:OutputVariable,
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DiscomfNonAppColdHours_Block1_Zone1,
Summed,
ZoneTimestep,
,
h;

EnergyManagementSystem:OutputVariable,
Ventilation Hours_Block1_Zone1 (summed),
VentHours_Block1_Zone1,
Summed,
ZoneTimestep,
,
h;


EnergyManagementSystem:OutputVariable,
Ventilation Setpoint Temperature,
VST,
Averaged,
ZoneTimestep,
,
C;

EnergyManagementSystem:OutputVariable,
Minimum Outdoor Temperature for mixed mode ventilation,
MinOutTemp,
Averaged,
ZoneTimestep,
,
C;

Output:Variable,
*, Zone Thermostat Operative Temperature, Hourly;
Output:Variable,
*, Adaptive Cooling Setpoint Temperature, Hourly;
Output:Variable,
*, Adaptive Heating Setpoint Temperature, Hourly;
Output:Variable,
*, Adaptive Cooling Setpoint Temperature_No Tolerance, Hourly;
Output:Variable,
*, Adaptive Heating Setpoint Temperature_No Tolerance, Hourly;
Output:Variable,
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*, Comfort Temperature, Hourly;
Output:Variable,
*, Ventilation Setpoint Temperature, Hourly;
Output:Variable,
*, Minimum Outdoor Temperature for mixed mode ventilation, Hourly;
Output:Variable,
Environment, Site Outdoor Air Drybulb Temperature, Hourly;
Output:Variable,
*, Zone Thermal Comfort CEN 15251 Adaptive Model Running Average Outdoor Air Temperature, Hourly;
Output:Variable,
*, Zone Operative Temperature, Hourly;
Output:Variable,
*, Comfortable Hours_No Applicability_Block1_Zone1 (summed), Hourly;
Output:Variable,
*, Comfortable Hours_Block1_Zone1 (summed), Hourly;
Output:Variable,
*, Discomfortable Applicable Hot Hours_Block1_Zone1 (summed), Hourly;
Output:Variable,
*, Discomfortable Applicable Cold Hours_Block1_Zone1 (summed), Hourly;
Output:Variable,
*, Discomfortable Non Applicable Hot Hours_Block1_Zone1 (summed), Hourly;
Output:Variable,
*, Discomfortable Non Applicable Cold Hours_Block1_Zone1 (summed), Hourly;
Output:Variable,
*, Ventilation Hours_Block1_Zone1 (summed), Hourly;
Output:Variable,
Block1:Zone1, Zone Operative Temperature, Hourly;
Output:Variable,
FORSCRIPT_AHST_Block1_Zone1, Schedule Value, Hourly;
Output:Variable,
FORSCRIPT_ACST_Block1_Zone1, Schedule Value, Hourly;
Output:Variable,
Ventilation Hours_Block1_Zone1 (summed), Schedule Value, Hourly;
Output:Variable,
*,Zone Floor Area_Block1_Zone1, Hourly;
Output:Variable,
*,Zone Air Volume_Block1_Zone1, Hourly;
Output:Variable,
*, AFN Surface Venting Window or Door Opening Factor, Hourly;
Output:Variable,
*, AFN Zone Infiltration Air Change Rate, Hourly;
Output:Variable,
*, AFN Zone Infiltration Volume, Hourly;
Output:Variable,
*, VRF Heat Pump Cooling Electric Energy, Hourly;
Output:Variable,
*, VRF Heat Pump Heating Electric Energy, Hourly;
Output:Variable,
*, Cooling Coil Total Cooling Rate, Hourly;
Output:Variable,
*, Heating Coil Heating Rate, Hourly;
Output:Variable,
Block1:Zone1 VRF Indoor Unit DX Cooling Coil,Cooling Coil Total Cooling Rate, Hourly;
Output:Variable,
Block1:Zone1 VRF Indoor Unit DX Heating Coil,Heating Coil Heating Rate, Hourly;
Output:Variable,
Block1:Zone1, Zone Outdoor Air Wind Speed, Hourly;
Output:Variable,
Block1:Zone1, Zone Outdoor Air Drybulb Temperature, Hourly;
```

# Design of airflow ventilation in a confluent jets system

**Eusébio Conceição[1], Mª Inês Conceição[2], Mª Manuela Lúcio[1], João Gomes[3] and Hazim Awbi[4]**

[1] Universidade do Algarve, 8005-139 Faro, Portugal
[2] Instituto Superior Técnico, 1049-001 Lisboa, Portugal
[3] CINTAL, 8005-139 Faro, Portugal
[4] University of Reading, Reading, RG6 6AW, UK

**Abstract:** In this study the airflow obtained inside a virtual chamber equipped with a horizonal confluent jets system is analysed. The horizonal confluent jets system consists of an inlet system and an outlet system. The inlet system considers four vertical ducts with a set of consecutive nozzles, placed in the wall corner. The exhaust system considers a vertical duct, located in the central area of the space. This numerical study is carried out using a Computational Fluids Dynamics numerical model. The three-dimensional air velocity components field, the air turbulence intensity and the turbulent variables were obtained in this work. The results show the airflow topology, promoted by the horizontal confluent jets ventilation system, near the wall surface. The air velocity is distributed along the ground, then follows, with an increasing value, an upward direction towards the exhaustion.

**Keywords:** Applied thermal engineering, Office building, Experimental chamber, Ventilation ducts.

## 1. Introduction

In this work the thermal behaviour of the experimental chamber material is evaluated and the interior system, such as ventilation, occupation, seats and table geometry are considered.

The experimental chamber is made up of modules with two wooden bodies insulated from each other. The insulation system used in this work is made of Styrofoam. In the numerical simulation all thermal characteristics of the experimental chamber are considered.

A set of ducts, made of plasticized material, and fans is considered inside the experimental chamber. Four fans connected to four vertical ducts located at the corners of the walls are considered. Each duct is equipped with two rows of nozzles arranged consecutively, each row being directed parallel to the wall. Among the ventilators, it is considered a group of two ducts in the transport of air from the external environment to the inlet nozzle system.

The ventilation system is promoted along all wall surfaces around the occupants. The airflow is first transported to the occupancy zones and then to the outlet zones. The ascending airflow in the occupation zone carries heat and contaminants directly to the exhaust zone.

This kind of numerical study considers three software that simulate the thermal response of the experimental chamber, the airflow around the occupants and inside the chamber and the thermal response of the occupants.

The software that simulates the thermal response of the chamber, calculates the temperature distribution on all surrounding surfaces of the space and the airflow rate that the occupants are subjected (Conceição et al, 2010; Conceição and Lúcio, 2010). This information is used as input for the software that simulates the airflow inside and around the occupants and the thermal response of the occupants. This numerical model calculates the thermal comfort and the indoor air quality. The thermal comfort was developed by Fanger (1970), and adopted by ISO 7730 (2005). The indoor air quality is evaluated using carbon dioxide concentration released by the occupants in the respiration area (ASHRAE 62.1, 2019). This numerical model considers energy balance integral equations (Conceição et al, 2000), mass balance integral equations, three-dimensional geometries, airflow rate (Conceição et al., 1997), and the HVAC system (Conceição et al., 2009). Other software that simulate the thermal response of the building spaces can be seen in the works of Sailor (2008) and Balaji et al (2013).

The software used to evaluate the thermal response of the occupants calculates the temperature distribution in the person and clothing bodies. This numerical model considers an energy balance integral equation, a mass balance integral equation and a three-dimensional geometry. This numerical model, using experimental and numerical values, can be analysed in Conceição and Lúcio (2001). Studies carried out by Zhang et al (2010) and Tanabe et al (2002), for example, also analyse the thermal response of building occupants.

Examples of the use of the software that calculates the airflow around the occupants and inside the experimental chamber are shown in the works of Conceição et al (2008) Conceição and Lúcio (2010)). For example, the airflow around the occupants and inside a chamber were also analysed by Awbi (1998), Xing et al (2001) and Bhutta et al (2012).

In the design of airflow ventilation in a horizontal confluent jets system is important to consider an inlet and an exhaust system. The inlet, using four quadrangular ducts, located in the wall corners, guarantees a horizontal airflow near the wall and floor surface and the outlet, located in the ceiling level, guarantee an ascendent airflow. In order to promote the ascendent airflow in the occupied space, guarantee the occupants heat and contaminant exhaust, the extraction system should be located above the occupancy area.

## 2. Applied thermal engineering inputs

The experimental chamber has small dimensions (2.7×2.45×2.4 $m^3$), similar to a small office. The ventilation system used in this space is of the horizontal confluent jet type (Figure 1). The inlet of the ventilation system consists of four quadrangular ducts, located in the wall corners, each provided by 50 nozzles (distanced between 200 mm and 700 mm in height from the floor) consecutively aligned and with a spacing of 6 mm between their centres. Each nozzle has a diameter of 6 mm.

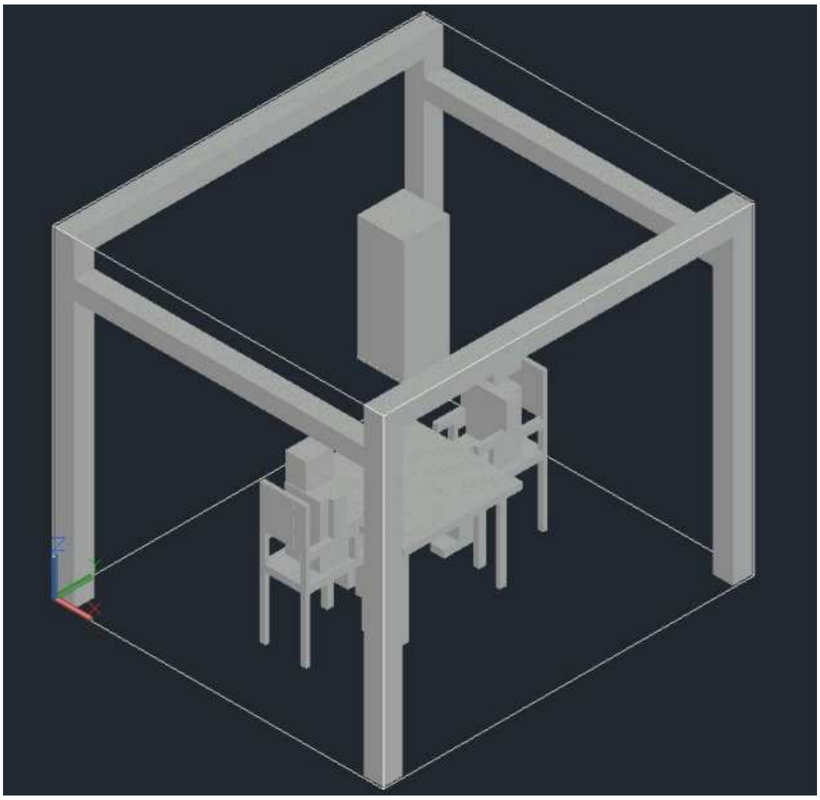

Figure 1. Experimental chamber with the horizontal confluent ventilation jet system.

The exhaust system consists of a quadrangular duct placed at a height of 1.5 m in the central area of the experimental chamber (Figure 1). The exhaust system has a fan placed in the exhaust duct.

The input data are as follows:

- Inlet carbon dioxide concentration of 500 mg/m$^3$;
- Inlet air velocity of 5 m/s;
- Inlet air temperature of 19.3°C;
- Inlet air turbulence intensity of 10%;
- External air temperature of 0°C;
- Experimental chamber wood thickness of 10 mm;
- Experimental chamber Styrofoam thickness of 40 mm.

## 3. Results

This section presents the results of the influence of the virtual chamber (similar to an experimental chamber), the air ducts and ventilation system geometry on the arrangement of the internal airflow in the ventilated space. Special attention is paid to the distribution of the airflow obtained around the two occupants.

In Figure 2 the air velocity field in a x-plan located halfway is presented, while in Figure 3 the air velocity field in a y-plan located halfway is presented.

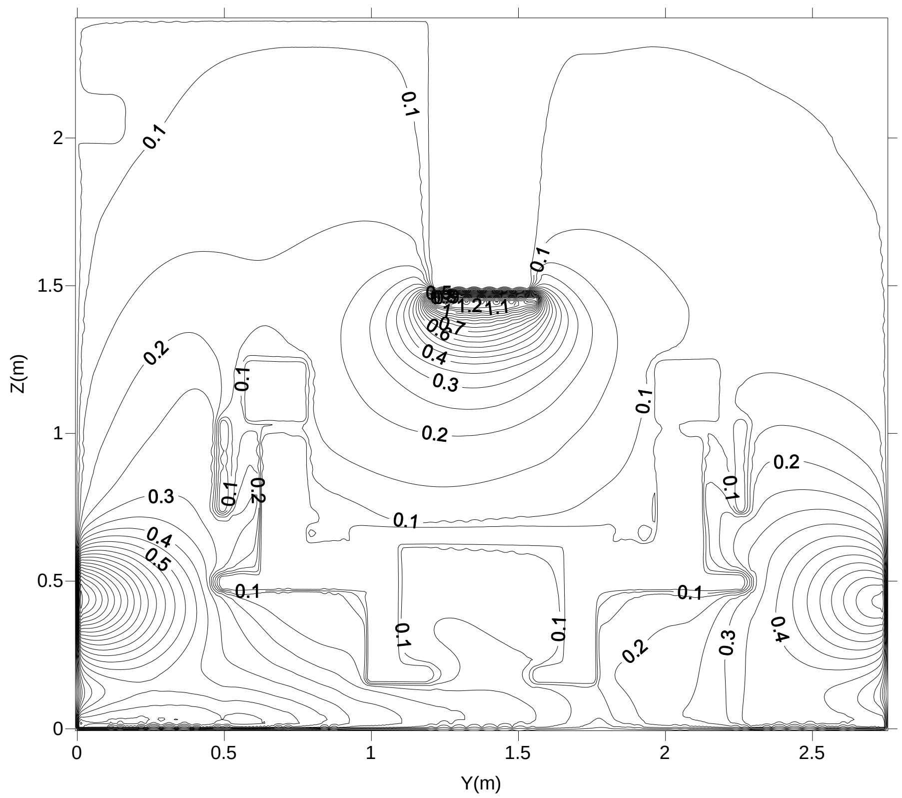


Figure 2. Air velocity field in a x-plan located halfway.

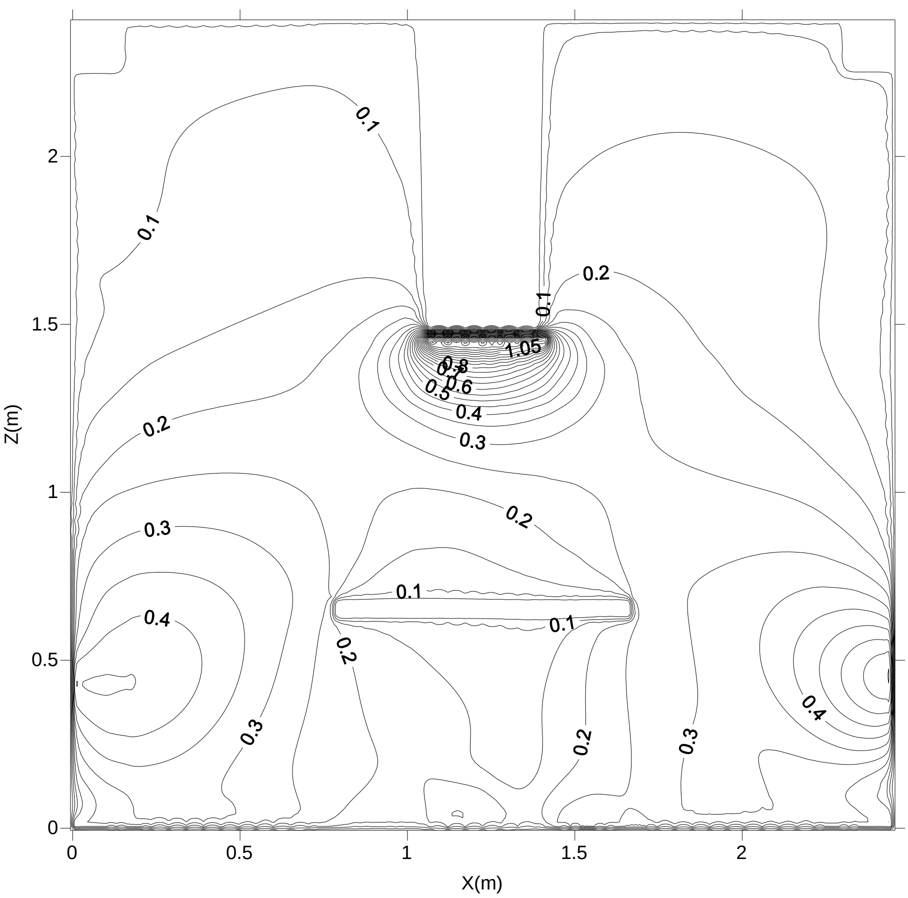


Figure 3. Air velocity field in a y-plan located halfway.

According to the obtained results, the highest air velocities are verified close to the wall, mainly in the inlet system, and in the outlet system. The lowest air velocities are found under the table area and above the air outlet terminal area.

On each wall are two opposing airflows that converge in the middle area. In this area, the interaction of these two airflows increases the velocity of the air close to the wall, as shown in Figures 2 and 3. The airflow moves towards the person's back (see Figure 2) or towards the table (see Figure 3). Both airflows subsequently move to the exhaust.

The interaction between airflows is greater on the unoccupied table side than on the occupant table side.

Occupants are subjected to the airflow with the highest air velocity behind them and the lowest air velocity in front of them. The airflow in the central occupancy area and above the table has an ascending characteristic. This ascendant airflow is very important to transport contaminants from the breathing zone of both occupants to the exhaust duct.

Thus, in accordance with the obtained results, this kind of ventilation, that promotes an ascendant airflow in the occupation area to increase the transport of the occupants' contaminants and heat, in the occupation area, is very important to be applied in cold climates.

## 4. Conclusion

This work described how the geometry of an experimental chamber as well as the use of a horizontal confluent jets ventilation system, with a specific design, influence the airflow arrangement in an occupied space. The study considers the thermal simulation of the virtual chamber, equal to an existing experimental chamber, the internal airflow and the occupants. All the details inside the chamber were also considered, such as the ventilation system used, the chairs and the table.

The main conclusions obtained are the following:

- The highest air velocity values are obtained near the wall, the air inlet devices and the air outlet device;
- The lowest air velocity values are obtained in the central area of the space under the table;
- The interaction between the airflows from oppositely located inlets promotes the increase in air velocity and its movement towards the exhaust duct;
- The upward airflow passes through the occupied zone and, in particular, into the breathing zone of the occupants, removing contaminants to the exhaust.


## 5. Acknowledgement

The authors would like to acknowledge to the project (SAICT-ALG/39586/2018) from Algarve Regional Operational Program (CRESC Algarve 2020), under the PORTUGAL 2020 Partnership Agreement, through the European Regional Development Fund (ERDF) and the National Science and Technology Foundation (FCT).


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# Embodied Carbon Viability of Prefabricated Retrofit Modules for Passivhaus-EnerPHit Standard – a Case Study in Istanbul, Turkey

**Dilek Arslan[1], Haniyeh Mohammadpourkarbasi[1] and Steve Sharples[1]**

[1] University of Liverpool, UK, Dilek.Arslan@liverpool.ac.uk

**Abstract:** The building sector has yet to take drastic steps to lower its carbon emissions to meet net-zero emissions targets by 2050. Although various methods exist to design new buildings with low operational carbon impacts, this is not always true for existing buildings. Improving the operational energy performance of an existing building is difficult, and reducing the overall refurbishment times for existing occupied buildings is challenging. Therefore, prefabrication methods for retrofitting were investigated in this research. The feasibility of using prefabricated retrofit modules that meet the rigorous Passivhaus-EnerPHit standard in Turkey's warm-temperate climate was explored. An existing residential building in Istanbul was modelled in the thermal simulation software DesignBuilder, and calibrated against on-site measurements. The impact on operational energy performance of applying prefabricated retrofit modules to the digital twin was then tested. Carbon emissions related to the production phase of the modules were assessed using OneClick LCA software. Multiple material replacement scenarios were applied to the prefabricated modules to find the optimum solution with low embodied carbon impact. The results showed that, although the prefabricated retrofit modules were successful in decreasing operational energy and carbon, they were not viable in terms of the cost of the modules in the Turkish context.

**Keywords:** Prefabrication, Retrofit, EnerPHit, Embodied Carbon

## 1. Introduction

Around the world, buildings are responsible for about 30% of the carbon emissions and 40% of energy demand (International Energy Agency, 2019). In Turkey, buildings account for about 40% of energy demand (Republic of Turkey Ministry of Climate and Urbanization, 2018) and one-third of direct and indirect carbon emissions (Climate Transparency, 2021). Hence, buildings offer a significant opportunity for decreasing energy demand and carbon emissions. Acknowledging the Paris Agreement, Turkey established her commitment to climate change in 2021. However, a five-year delay in commitment brings the need for more drastic measures to achieve the carbon reduction targets. Although various regulations have been introduced for new buildings to lower energy demand (Republic of Turkey Ministry of Environment and Urbanization, 2011; TS 825:2008, 2008), there are limited options to improve the existing building stock's Energy Performance Certificates (EPCs). EPCs are helpful in showing the performance of a building; however, they do not force any steps to achieve a good rate in existing buildings. Further, countries pledged to the Paris Agreement will soon be presenting their carbon reductions. Therefore, to be on track, Turkey needs an approach to the energy renovation of existing buildings (Climate Transparency, 2021; Climateactiontracker.org, 2022).

For existing buildings, the options are either deconstructing and rebuilding or retrofitting. Existing studies have demonstrated that deconstructing and reconstructing a building is not a viable option in terms of energy used and carbon released during the construction and production of the new materials (Langston et al., 2018; Marique and Rossi, 2018; Cheshire and Burton, 2020). Also, during the deconstruction and rebuild time, the occupants of the buildings need to move from the building, which is not convenient for them (Rovers et al., 2018). It can, therefore, be concluded that energy retrofitting the envelope of the building is a more suitable way of tackling the carbon emissions from the existing building stock. Also, it requires less time and materials compared to rebuilding. However, occupant disturbance is still an issue, and retrofit duration might be affected by factors such supply chain problems and weather conditions.

A more recent approach to retrofit, using prefabricated retrofit modules (PRM), can compensate for the negative aspects of the traditional retrofit methods. Prefabrication can significantly decrease the retrofit duration, reduce occupant disturbance during installation, and is not as affected by adverse weather conditions. PRMs have gained popularity within the European Union, as evidenced in Horizon 2020-EeB-2015 (EU-H2020) projects. There are extensive examples of PRMs in the European context that present a variety of approaches. For instance, while one of the projects uses construction demolition waste (CDW) materials for non-structural façade elements, Re4 (2016) and VEEP (Veep–project, 2016), others use nanotechnology materials like aerogels, SESBE (n.d.) and GELCLAD (n.d.) or focus on building system management in the buildings retrofitted with prefab modules, such as iNSPiRE (2016). Besides bringing new methods and innovations to retrofit, EU-H2020 projects are also effective at decreasing the operational energy demand (energy needed for heating, cooling, domestic hot water, and equipment) by 85% compared to existing buildings and providing a thermally comfortable environment for the occupants (Rovers et al, 2018).

Unlike the numerous studies on operational energy demand and indoor comfort involving PRMs, there are fewer investigations of the embodied carbon of PRMs (Almeida et al., 2020). The embodied carbon (EC) of a material represents the carbon released during the raw material extraction, its transport to the factory, and production (Almeida et al., 2020). EC is often addressed as a hidden impact in building performance evaluations. Until recently, the focus for buildings was on decreasing the operational energy demand rather than the EC. However, recent literature shows that the EC impact could be higher than the operational impact (Zhu et al., 2020; Rodrigo et al., 2019; Koezjakov, 2017). Therefore, in this study, the aim is to show the EC viability of PRMs over their operational carbon savings and examine the feasibility of using the modules in Turkey's climate as a methodology to accelerate the country's climate change mitigation actions.

Another limit of existing PRM approaches is aiming for Net-Zero in operational performance, which may differ from country to country based on their energy mixes and availability of sustainable energy sources. Therefore, PRM needs to ensure the energy performance in existing buildings, specifically in a climate or country context. Energy standards like Passivhaus (PH) can robustly secure how the building will perform after being constructed or renovated. PH is a voluntary energy concept that allows up to 15 kWh/m²/a for heating and cooling demand and 120 kWh/m²/a in total primary energy consumption. Passivhaus has a 'fabric first' approach to reduce operational energy demand, meaning that the building envelope should be airtight and well insulated with a low level of U-value (0.15 W/m²K or less). PH also provides a standard for retrofit projects, called EnerPHit. For retrofitted buildings to meet the EnerPHit standard, the maximum heating demand is climate-related, ranging from 15 kWh/m²/a (very hot climates), to 20 kWh/m²/a (warm temperate climates) and upto 35 kWh/m²/a (Artic climates). The retrofit cooling energy demand limit is the same for all climates at 15 kWh/m²/a, with the primary energy demand being limited to 120 kWh/m²/a. The EnerPHit concept gives importance to thermal comfort in the retrofitted buildings by keeping the overheating below 10% all year round without active cooling and/or adequately adjusted cooling device (Pomponi et al., 2018; Passive House Institute, 2022). Additionally, EnerPHit buildings give freedom to the occupants to adjust the heating and cooling levels in each room however they feel comfortable (Passive House Institute, 2022). Therefore, this paper will investigate the life cycle carbon payback time of applying the Passivhaus-EnerPHit energy criteria to the PRMs.

## 2. Methodology

### 2.1. Case Study

In Turkey and Istanbul, due to rapid urbanisation, almost half of the existing buildings were built in the 1990s (Konukcu et al., 2016). Hence, a mid-rise apartment block in Istanbul was selected as a case study building. The building represents the common construction practices in the 1990s (Figure 1). It has five floors above ground with penthouses on the top floor and one basement. The building is used just for residential purposes; 10 families live in the building, with the total occupied area of the building being 1015 m², and each floor is 2.8m in height. The structure is a concrete frame with concrete slabs, and the external skin is a 200mm uninsulated brick wall. Heating, cooling, and domestic hot water (DHW) in the building are provided by gas boilers installed in each flat. Only three families have air conditioners (AC) installed in one of their rooms to meet their cooling needs.

Figure 1: Case study building, Credit: Dilek Arslan, 2021

### 2.2. Building Energy Simulation and Model Calibration

The apartment block was modelled in a building energy simulation software, DesignBuilder (DB), by using architectural drawings. Then, three months (October, November, and December 2021) of temperature and relative humidity (RH) data were collected from one of the flats at the basement in the building. The data collected from the master bedroom, one bedroom, living room, and kitchen were used to validate the DB model according to the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) requirements. According to the ASHRAE standard, for the model to be valid, the Mean Bias Error (MBE) should be at 10% or below and the Coefficient of Variation of the Root Mean Squared Error CV(RMSE) at 30% or below (ASHRAE Guideline 14 -2014).

In the initial simulations, the MBEs between measured and simulated room temperatures and RH were 11% and -7% for the Master Bedroom, 8% and -19% for the bedroom, 6% and -9% for the living room, and 10% and -15% for the kitchen, respectively. To further lower the error percentages in temperature and RH, different types of iteration parameters were applied as suggested in the literature, such as changing the infiltration rate on building façades, indoor ventilation rate, occupation factors, and temperature setpoints (Chung et al., 2021; Abrahams et al., 2019; Sun et al., 2016). While indoor ventilation rate and occupation factors were not helpful, the façade infiltration rate in the DB Construction tab and temperature setpoints in the Activity tab significantly impacted the error percentages.

After multiple iterations applied in infiltration and temperature setpoints, the MBEs between measured and simulated room temperatures and RH improved to be 10% and 7% for the Master bedroom, 6% and 2%for the Bedroom, 8% and 9% for the Living room, and 10% and 6% for the Kitchen, respectively, which comply with the ASHRAE MBE threshold.

### 2.3. Retrofit Applications

PRMs were designed according to the International Energy Agency (IEA) ECBCS-Annex 50 Guideline (2011) from inside to outside. The guideline requires one equalising layer, a sheathing board, a façade structure with insulation (where all of the ducting and wiring are placed), vapour proofing, a sheathing board, and a second layer of insulation and cladding (Figure 2). Materials selected for the modules were decided according to the most common construction materials used in Turkey (Ikbal and Cetiner, 2013; Kurekci, 2016) and layer thicknesses based on the EnerPHit U-value for opaque façade areas (0.30-0.50 W/m²K, for warm-temperate climates). Based on the thermal requirements, the second insulation layer in the IEA guideline became redundant for this project. In the final stage, the PRM build-up layers were one equalising layer, sheathing board (OSB), insulation (XPS), vapour proofing (polythene), sheathing board (OSB), and finishing (cement board) (Figure 3).

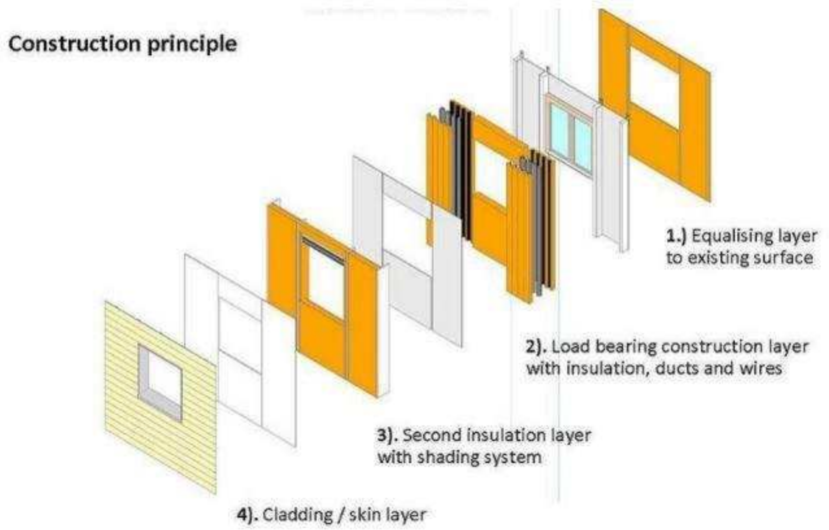


Figure 2: IEA prefabricated retrofit module construction principles (IEA, 2011)

After designing the PRM, the modules were applied to the building façade (walls and roof), a ventilation unit with heat recovery was added, which is a requirement for Passivhaus designs, and boilers were left in the building to avoid carbon emissions related to installing a new system into the building. Further, basement walls, ground floor, and cantilever floors were insulated. The infiltration rate of building skin improved to 1 ac/h@50 Pa due to Passivhaus-EnerPHit requirements for airtightness. Double glazed PVC windows in the existing building were replaced with triple glazed PVC windows with $U_W$ = 0.75 W/m$^2$ K frame and $U_g$ = 0.70 W/m$^2$ K glazing values.

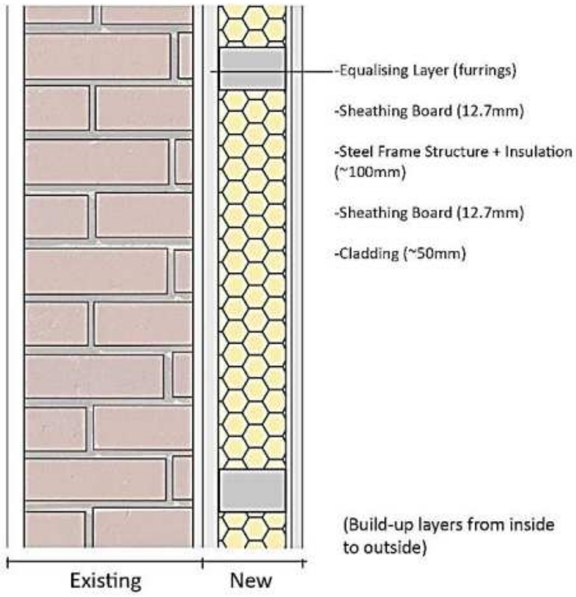


Figure 3: Retrofit layers for 0.30 W/m²K U-value.

### 2.4. Embodied Carbon Calculations

Embodied carbon calculations were conducted via a web tool, One Click LCA, which brings a wide range of material carbon data from the databases around the world, such as EPD Norge (n.d.), EPD International (n.d.), INIES (n.d.) and IBU (2020). The software categorises the material profiles as manufacturer, local, regional and generic data. The priority is to select the available manufacturer and local data; however, if it is not available, then regional or generic data by using the localisation factor should be selected depending on the country's carbon assessment (OneClick LCA, n.d.).

Material profiles were selected according to the thermal and physical properties' input in the DB model, and the quantities subjected to meeting the EnerPHit standard were also inserted into One Click LCA. After creating the base case, material replacement scenarios were adapted by replacing sheathing board materials with plasterboard, plywood, and MDF and replacing the insulation with EPS, rock wool, and glass wool in PRMs. These scenarios are presented in Table 1.

### 2.5. Cost Calculations

Material quantities used for carbon assessment were also used for cost calculations. The unit prices of each material were taken from the Construction Unit Prices 2021 report of the Republic of Turkey Ministry of Environment, Urbanisation and Climate Change (Republic of Turkey Ministry of Environment, Urbanisation and Climate Change, 2021). The price of each material also included its assembly and labour costs. When a material or an equipment's prices was not available (e.g. ventilation unit), the manufacturers' prices were used.

## 3. Results and Discussion

### 3.1. Operational Carbon

Retrofit improvements on the building façade with PRM made significant reductions in the total operational energy demand of the building by 50%. While existing building heating energy demand was 130 kWh/m²/pa, PRMs helped to reduce it to 65 kWh/m²/pa with the best-case scenario for the external façade thermal properties for warm- temperate climate, 0.30 W/m²K U-value. This reduction in energy constitutes about a 35% decrease in operational carbon emissions compared to the existing emissions. Reduction in heating energy demand was the main contributor to the carbon reduction of the building, with 82% of the total energy consumption. This reduction highlights the importance of operational energy reduction in carbon savings, even though the gas currently has a lower carbon intensity than the electricity in countries like Turkey (Gursoy Haksevenler et al., 2020; Turkish Ministry of Energy and Natural Resources, 2021). DHW and equipment demands remain the same since no retrofit strategy were applied. However, even though the consumptions were the same in these categories, the transition to cleaner energy in Turkey shows that DHW and equipment electricity impact can be lowered by about 40% when renewable energies such as sun and wind are applied to the grid in the future (Republic of Turkey Ministry of Energy and Natural Resources, 2021).

The other retrofit scenarios' operational energy and carbon impact had similar results to the base-case retrofit scenario. This was due to selecting similar materials regarding thermal conductivity and density when replacing the material. Thereof they show similar operational performances in DB. Then, the same retrofit scenarios were applied with the components with a 0.50 W/m²K U-value since EnerPHit requirements allow that. The increase in the U-value of the components also slightly increased the operational energy by 6%. This was due to the slight increase in heating demand in the retrofit scenarios regarding reducing the insulating material thicknesses (Table 1).

Table 1: Total Operational Energy Demand Comparison Between Existing and Retrofitted Building.

| Scenario | Results for the PRMs with 0.30 W/m²K U-value | | | Results for the PRMs with 0.50 W/m²K U-value | | |
|---|---|---|---|---|---|---|
| | Retrofit Operational Energy (kWh/m²/pa) | Existing Operational Energy (kWh/m²/pa) | Energy Savings (kWh/m²/pa) | Retrofit Operational Energy (kWh/m²/pa) | Existing Operational Energy (kWh/m²/pa) | Energy Savings (kWh/m²/pa) |
| Base Case | 65.55 | 130 | 64.45 | 69.80 | 130 | 60.20 |
| Sheathing Board Replacement-Plasterboard | 65.50 | 130 | 64.50 | 69.45 | 130 | 60.55 |
| Sheathing Board Replacement-Plywood | 65.53 | 130 | 64.47 | 69.68 | 130 | 60.32 |
| Sheathing Board Replacement-MDF | 65.54 | 130 | 64.46 | 69.34 | 130 | 60.66 |
| Insulation Replacement-EPS | 65.50 | 130 | 64.50 | 69.63 | 130 | 60.37 |
| Insulation Replacement-Rock Wool | 65.54 | 130 | 64.46 | 69.00 | 130 | 61.00 |
| Insulation Replacement-Glass Wool | 65.40 | 130 | 64.60 | 69.49 | 130 | 60.51 |
| Cost Optimum (EPS+MDF) | 65.64 | 130 | 64.36 | 69.62 | 130 | 60.38 |

### 3.2. Embodied Carbon and Carbon Payback Times

The embodied carbon of the prefab modules with a 0.30 W/m²K U-value in the base-retrofit scenario was 89 $kgCO_{2e}/m^2$. The main contribution of the materials' impact was the OSB sheathing, triple glazed PVC windows and XPS insulation with 39%, 16% and 15% of the total emissions, respectively. The *Sheathing Board Replacement – MDF* scenario, with 60 $kgCO_{2e}/m^2$, had the lowest impact since the carbon contribution from the sheathing boards decreased from 35 $tCO_{2e}/m^2$ to 6 $kgCO_{2e}/m^2$. The highest embodied carbon belonged to the

*Insulation Replacement - EPS* scenario with 94 $kgCO_{2e}/m^2$ because of the rising impact figure in the insulation material section from 14 $tCO_{2e}/m^2$ to 19 $tCO_{2e}/m^2$ while other embodied impact figures stayed the same in other material layers (Figure 4). In the options with 0.50 $W/m^2K$ U-value, the highest and the lowest impact scenarios remained the same but with different emission figures of course.

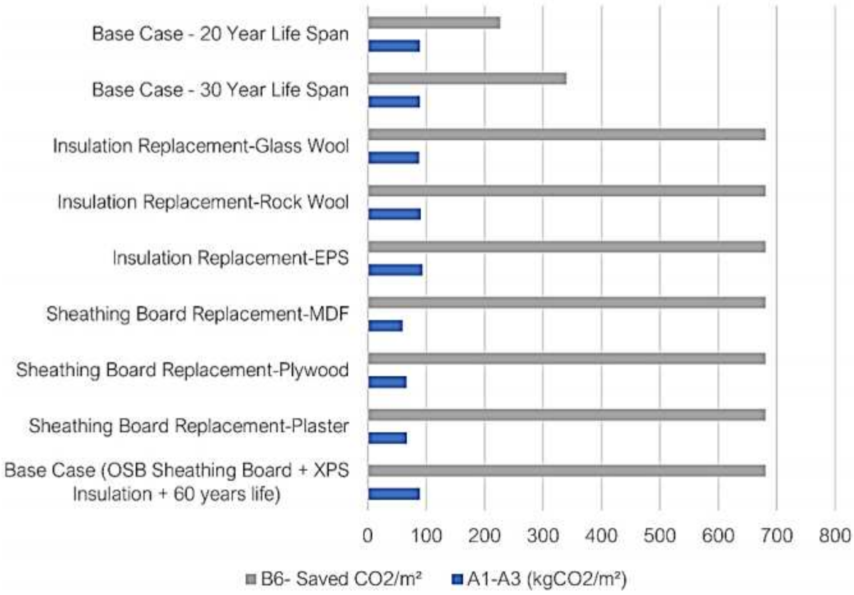


Figure 4: Embodied and operational carbon impacts of the retrofit scenarios

When the carbon saved from the improved operational energy performance was compared to the embodied carbon of the materials used, the results showed that the PRMs could be a viable option for the retrofit projects compared to business-as-usual models. The carbon payback times of the PRMs were not that different among the retrofit scenarios, which ranged between three and five years (Tables 2 and 3).

Table 2: Operational and Embodied Carbon Impact of the PRMs and Carbon Payback Times of Each Scenario for **0.30 W/m²K** U-value.

| Scenario | Retrofit Operational Impact (CO2e/m²/a) | Existing Operational Impact (CO2e/m²/a) | Savings (CO2e/m²/a) | Embodied Impact (kgCO2e/m²) | Carbon Payback (Year) |
|---|---|---|---|---|---|
| Base Case | 36.01 | 56.41 | 20.40 | 89 | 4 |
| Sheathing Board Replacement-Plasterboard | 36.00 | 56.41 | 20.41 | 67 | 3 |
| Sheathing Board Replacement-Plywood | 36.00 | 56.41 | 20.41 | 66 | 3 |
| Sheathing Board Replacement-MDF | 36.00 | 56.41 | 20.41 | 60 | 3 |
| Insulation Replacement-EPS | 36.00 | 56.41 | 20.41 | 94 | 5 |
| Insulation Replacement-Rock Wool | 36.00 | 56.41 | 20.41 | 91 | 4 |
| Insulation Replacement-Glass Wool | 35.98 | 56.41 | 20.43 | 88 | 4 |
| Cost Optimum (EPS+MDF) | 36.03 | 56.41 | 20.38 | 64 | 3 |

Table 3: Operational and Embodied Carbon Impact of the PRMs and Carbon Payback Times of Each Scenario for **0.50 W/m²K** U-value.

| Scenario | Retrofit Operational Impact ($CO2e/m^2/a$) | Existing Operational Impact ($CO2e/m^2/a$) | Savings ($CO2e/m^2/a$) | Embodied Impact ($kgCO2e/m^2$) | Carbon Payback (Year) |
|---|---|---|---|---|---|
| Base Case | 36.88 | 56.41 | 19.53 | 81 | 4 |
| Sheathing Board Replacement-Plasterboard | 36.81 | 56.41 | 19.60 | 60 | 3 |
| Sheathing Board Replacement-Plywood | 36.85 | 56.41 | 19.56 | 59 | 3 |
| Sheathing Board Replacement-MDF | 36.77 | 56.41 | 19.64 | 53 | 3 |
| Insulation Replacement-EPS | 36.77 | 56.41 | 19.64 | 84 | 4 |
| Insulation Replacement-Rock Wool | 36.84 | 56.41 | 19.57 | 83 | 4 |
| Insulation Replacement-Glass Wool | 36.80 | 56.41 | 19.61 | 80 | 4 |
| Cost Optimum (EPS+MDF) | 36.83 | 56.41 | 19.58 | 55 | 3 |

### 3.3. Cost Results and Payback Times

The cost calculation results show that while the *Sheathing Board Replacement – Plywood* was the most expensive, the *Sheathing Board Replacement – MDF* was the cheapest option among the other retrofit scenarios. The difference between the cheapest and the most costly option was about 26%. Further, the capital cost of *Insulation Replacement – EPS* was also quite close to *Sheathing Board Replacement – MDF* option. Therefore, a small iteration took place to explore the EPS + MDF as a cost-optimal scenario. It has been seen that 5% embodied carbon reduction can be achieved with the EPS + MDF than the cheapest option in existing scenarios (*Sheathing Board Replacement – MDF).*

Although the new iteration enabled a cost reduction, the payback time of the PRMs was not that attractive for the homeowners. Tables 4 and 5 show the shortest payback time, with the *Cost Optimum* scenario in both components with U-values of 0.30 and 0.50 W/m²K of 47 and 53 years, respectively. These long payback times may be due to the current electricity unit prices, which are more expensive than gas.

Increasing the building's airtightness was not helpful for summer conditions in the retrofitted building in this project. While high infiltrations were useful for building cooling, the building needed mechanical cooling and ventilation to decrease overheating, increase thermal comfort, and meet the EnerPHit standard. This increases the reliance on the electrical energy demand and, therefore, the operational cost.

Table 4: Existing and Retrofitted Cost of the Building Operation and Materials and Cost Payback Times of Each Scenario for **0.30 W/m²K** U-value.

| Scenario | Operational Cost (TL/a) | Existing Operational Cost (TL/a) | Savings (TL/a) | Refurbishment Cost (TL) | Cost Payback (Year) |
|---|---|---|---|---|---|
| Base Case | 60249.0 | 79114.2 | 18865.1 | 1110611.6 | 58.9 |
| Sheathing Board Replacement-Plasterboard | 60234.2 | 79114.2 | 18880.0 | 1210031.3 | 64.1 |
| Sheathing Board Replacement-Plywood | 60236.4 | 79114.2 | 18877.8 | 1441241.8 | 76.3 |
| Sheathing Board Replacement-MDF | 60240.4 | 79114.2 | 18873.8 | 1067714.5 | 56.6 |
| Insulation Replacement-EPS | 60234.0 | 79114.2 | 18880.2 | 1086000.2 | 57.5 |
| Insulation Replacement-Rock Wool | 60235.6 | 79114.2 | 18878.5 | 1103281.6 | 58.4 |
| Insulation Replacement-Glass Wool | 60205.3 | 79114.2 | 18908.9 | 1102387.6 | 58.3 |
| Cost optimum (MDF+EPS) | 57883.2 | 79114.2 | 21230.9 | 1004139.1 | 47.3 |

Table 5: Existing and Retrofitted Cost of the Building Operation and Materials and Cost Payback Times of Each Scenario for **0.50 W/m²K** U-value.

| Scenario | Operational Cost (TL/a) | Existing Operational Cost (TL/a) | Savings (TL/a) | Refurbishment Cost (TL) | Cost Payback (Year) |
|---|---|---|---|---|---|
| Base Case | 61326.3 | 79114.2 | 17787.9 | 1072944.8 | 60.3 |
| Sheathing Board Replacement-Plasterboard | 61242.8 | 79114.2 | 17871.4 | 1172364.5 | 65.6 |
| Sheathing Board Replacement-Plywood | 61298.4 | 79114.2 | 17815.8 | 1400614.6 | 78.6 |
| Sheathing Board Replacement-MDF | 61190.8 | 79114.2 | 17923.4 | 1030047.7 | 57.5 |
| Insulation Replacement-EPS | 61281.8 | 79114.2 | 17832.4 | 1059776.8 | 59.4 |
| Insulation Replacement-Rock Wool | 61103.8 | 79114.2 | 18010.3 | 1071093.0 | 59.5 |
| Insulation Replacement-Glass Wool | 61229.6 | 79114.2 | 17884.6 | 1068103.7 | 59.7 |
| Cost optimum (MDF+EPS) | 61262.7 | 79114.2 | 17851.5 | 953666.7 | 53.4 |

## 4. Conclusion

### 4.1. Summary

This study showed that significant energy savings with PRMs for an EnerPHit building in a warm-temperate climates are possible. In addition, it has been highlighted that the carbon payback time of this retrofit approach and materials selected for the Turkish context makes the PRMs a viable option in climate change mitigation strategies. Moreover, it is possible to achieve lower embodied impacts and more thermal comfort by retrofitting to the EnerPHit standard. However, the cost side of the modules hinders the PRM approach as a climate change strategy due to the long payback time. High cost brings the need for a funding scheme for retrofit projects supported by the government to lower the payback time. Otherwise, although the PRM approach significantly reduces operational energy demand, such capital investment in improving a 30-year-old concrete building might not be sensible as a retrofit over its operational cost savings.

### 4.2. Limitations and Recommendations

This study's main limitation is finding an Environmental Product Declaration (EPD) relevant to the Turkish context in the OneClick LCA database. Even though sometimes there was material information for Turkey, it was not suitable for the analysis in terms of not matching the thermal conductivity and density features of the materials in energy simulation. This situation prompts the tool user to select materials from other countries or regions that affect the reliability of the results and increase the contingencies.

Recommendations for a further study would be applying these modules to actual buildings to analyse the limitations and issues faced during the production, transportation, and assembly processes of the PRMs, then monitoring the thermal comfort and energy consumption in the retrofitted building. Additionally, surveys can be conducted with the occupants of the building, asking about their experiences and requirements and conducting interviews with the professionals involved in this process to understand the approaches and willingness to this kind of retrofit as another feasibility study. Lastly, comparing how much the thermal comfort criteria suggested in EnerPHit performance complies with the Turkish occupants' thermal comfort expectations could be an interesting insight into the Passivhaus standard in warmer climates and different cultural backgrounds.

## 5. Acknowledgements

This PhD project is funded by the Republic of Turkey Ministry of Education Study Abroad Program, including tuition fees and student expenses.

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# How do occupants perceive thermal comfort in a hybrid office space? A case study of a co-working space in London

**Jiayu Pan[1*], Ronita Bardhan[1] and Shushen Chen[1]**

[1] Department of Architecture, University of Cambridge, Cambridge CB2 1PX, United Kingdom;
[*] Correspondence author, jp844@cam.ac.uk

**Abstract:** The work pattern has been reshaped towards a hybrid style since the lockdown in the pandemic, while the office design needs to be evolved with the change in working mode. It is important to understand how to design the workspace to meet the new demand. This study investigates the environmental performance of a flexible co-working space in London by a longitudinal field study, with a specific focus on thermal comfort and lighting sensations and preferences. The field study is composed of a questionnaire survey about occupants' thermal comfort sensations and environmental preferences and a concurrent measurement of indoor environmental data (temperature, relative humidity, air velocity and illumination level). This paper presents a preliminary analysis of the data collected in spring 2022. A total of 79 responses are recorded over three months. The findings in this study are expected to provide new insight into environmental design solutions for the hybrid and flexible work setting.

**Keywords:** Thermal comfort, Future of work, Office design, Co-working space, Hybrid working

## 1 Introduction

The indoor environment in offices is important for occupants' health and productivity (Kamarulzaman *et al.*, 2011). As the use of office space has been reshaped significantly from the traditional 9-to-5 style to a hybrid working mode after the pandemic, the office design has evolved towards a more flexible pattern. The new type of office space, like co-working space with a hot-desking system and flexible working hours (Weijs-Perrée *et al.*, 2019), has become a popular alternative option. Therefore, occupants' preferences on office space are altered corresponding to this new change, while the office design evolves with the new demand. There is a rising demand for investigating how environmental design factors could affect the use of offices, especially the hybrid co-working space, in the post-pandemic era.
Based on the hypothesis of people tend to seek the places that are comfortable for them to stay, this study investigates the environmental performance of the flexible working space with a case study of a co-working space in London, with a specific focus on thermal comfort and lighting sensations and preferences. We conduct a standard thermal comfort questionnaire survey and record the indoor environmental parameters around the workspace, such as temperatures, air flow, relative humidity and illuminance level. This field survey follows the standard process of monitoring the in-situ thermal environment while asking the questions. Also, a set of questions about occupants' environmental preferences on seat selection are included in the survey. With the collected set of empirical data from the case study site, this study aims to demonstrate how environmental design factors, such as thermal comfort, ventilation and lighting condition, have affected occupants' seat preferences. This is a preliminary attempt to respond to the significant change brought by the COVID-19 pandemic and deliver more resilient and flexible design strategies for the post-pandemic office space. We expect to suggest corresponding design solutions based on the analysis and

findings in a later stage. In this paper, the preliminary results collected in spring 2022 are reported as a demonstration of the potential for future study. This paper is structured as follows: Section 2 reviews the literature on the environmental comfort in office space and the rise of new office design. Section 3 introduces the study site and data collection and analysis methods. Section 4 is the presentation of preliminary results and a discussion of the existing results, and Section 5 gives the conclusion and future research direction.

## 2 Literature review

The literature review part gives an overview of the background of this study, while it aims to demonstrate the rationale behind the study. The existing studies on two different topics, the environmental comfort in office environment and the transformation of the post-pandemic working environment, are illustrated.

### 2.1 Environmental comfort in office spaces

Environmental characteristics of offices have been widely studied in the existing literature (Kamarulzaman *et al.*, 2011). Environmental factors like ventilation, thermal comfort, lighting condition and noise level are found to have a significant impact on the occupants' well-being and productivity. This section reviews the impact of environmental design factors on the use and perception of offices.

An office space with good ventilation, high-quality daylight, less noise and comfortable thermal condition is found to have a positive effect on users' overall experience. Ventilation affects the quality of air in the space, while poor air quality leads to concerns about health and poorer productivity (Seppanen, Fisk and Lei, 2005; Aye and Chiazor, 2006; Alker *et al.*, 2015). The presence of daylight is associated with visual comfort, while the use of more natural lighting has an energy-saving potential (Turan *et al.*, 2020). Maximising daylight availability is considered an optimal strategy (Abdollahzadeh, Tahsildoost and Zomorodian, 2020). The noise causes distraction, which undermines the expected efficiency and productivity. The participants in an experimental study report more tiredness and less motivation to work in a noisy environment (Jahncke *et al.*, 2011). A correlation is found between disturbance by noise and dissatisfaction with the environment (Sundstrom *et al.*, 1994). Thermal comfort is determined by temperature, air movement and humidity, while occupants' perceptions depend on their thermal preference, clothing and acceptability (Alker *et al.*, 2015). A high Indoor temperature leads to a reduction in productivity (Kamarulzaman *et al.*, 2011). Studies have observed multiple different types of thermal adaptive approaches in offices, including mechanical adjustments like turning on cooling or heating devices and personal actions like drinking cold drinks and adding clothes (Liu *et al.*, 2012; Liu and Wang, 2019).

A mix of quantitative and qualitative methods is applied to understand the physical environment of office space. Large-scale occupants surveys are effective in collecting the occupants' satisfaction level and subjective well-being sensations on the indoor environmental quality (Huizenga *et al.*, 2006; Newsham *et al.*, 2009; Steemers and Manchanda, 2010). Questionnaire surveys and in-situ environment monitors are commonly used to understand thermal comfort (Kuchen and Fisch, 2009; Akimoto *et al.*, 2010; De Vecchi *et al.*, 2017). Simulation and experiments in laboratory also provide insight into daylight, ventilation and thermal comfort performances (Seppanen, Fisk and Lei, 2005; Tanabe, Nishihara and Haneda, 2007; Turan *et al.*, 2020). However, the existing studies mainly focus on the traditional type of offices, with the feature of fixed send cubicle or open plan structures.

The following section discusses the variations in work styles and office design after the pandemic and demonstrates the research gap in understanding the indoor environment in new types of office.

### 2.2 The rise of hybrid workspace

The pandemic has reshaped the norm of modern working by implementing the large-scale forced 'work-from-home' experiment. The rise of remote working has enabled the workers with different options of working location. The working mode is gradually shifting towards a hybrid style. In mega-cities like London, though the increase in population brings new jobs and opportunities, the existing office space needs to be revitalised and rebuilt to meet the new demand. The structured office space may no longer be required, while the space could be transformed into a multi-use communal space for work, communication and collaboration (AECOM, 2022). Also, the occupancy rate is expected to decrease as fewer employees would come to offices. This is seen as an opportunity for expenditure saving on rent, maintenance fees and operation costs for business (Boland *et al.*, 2020). Flexible seats and layout can be provided to office occupants as an alternative solution. There is an emerging trend of renovating the existing office spaces with new design standards in the post-pandemic time. For example, a £27 million refurbishment plan has been announced by an office provider in London, including providing alternative spaces in office to work and relax and upgrading the energy efficiency (Neville, 2022). The Microsoft report identifies employees' tendency of prioritising health and well-being over work (Microsoft, 2022). The conceptual model developed by Sorensen *et al.* (2021) emphasizes the importance of workspace and working conditions in ensuring workers' safety, health and well-being. An interview-based study points out organisations' main considerations in designing new offices, including flexibility, functionality, advantage, noise level and sense of community (Nanayakkara, Wilkinson and Ghosh, 2021). In conclusion, in the future of office design, the factors like health and wellbeing, collaboration, resiliency, flexibility and sustainability are expected to be considered more to provide high-quality environment and encourage the use of office (Nanayakkara, Wilkinson and Ghosh, 2021; AECOM, 2022; Ajith *et al.*, 2022).

While working at home leads to the concerns of mental depression, difficulties in concentration and struggles in work-life balance management (Teevan, Hecht and Jaffe, 2021), the local co-working spaces start to become one of the potential solutions when the pandemic restrictions are removed. Employees could get access to the nearby co-working hub without commuting. Compared to the traditional offices with fixed seats and working hours, the occupants have more freedom and flexibility to decide the time they spend working and the location they sit and stay in the co-working space. Several previous studies have demonstrated the understanding of co-working space in research. The co-working space is defined with the concepts of flexibility, change, mobility, community-building and idea-sharing (Fuzi, Clifton and Loudon, 2014; Makaklı, Yücesan and Ozar, 2019). It provides an individual working environment with temporal flexibility, common spaces for events and food facilities (Makaklı, Yücesan and Ozar, 2019). The users choose co-working spaces because they tend to look for a workplace outside their home that enables them to have an inspiring working environment, while the accessibility and atmosphere are two important factors they may consider (Weijs-Perrée *et al.*, 2019). Similar findings are also reported in a later study, with convenient location, open space layout, shared facilities and knowledge sharing as significant factors for user satisfaction (Tan and Lau, 2021).

Therefore, how occupants use and interact with the workspace in this new hybrid norm remains an unknown to be explored, while understanding the driving factors behind occupants' environmental preference could inform the co-working space design in the future. The current understanding of office design is insufficient to deliver better strategies for future and needs to be evolved with the changing pattern of work. This remains a gap in the research area. It is vital to respond to the change and develop design solutions to build a risk-free, healthy and productive working environment for employers and employees. In this study, a case study of a co-working space in London is used as an example to build up understandings on this research gap.

## 3 Data and Methods

This section introduces the study site and the data collection method. The longitudinal field survey is conducted in a co-working space in London, United Kingdom (UK). A questionnaire survey is designed to understand the subjective thermal comfort and environmental preferences of the occupants in a co-working space while the in-situ measurement of environmental parameters is conducted.

### 3.1 Study site

London (51° 30′ 26″ N, 0° 7′ 39″ W) is the capital and largest city of the United Kingdom. The city features a subtropical oceanic variety in Köppen climate classification (Köppen, 1884), with the character of cool to mild winters and warm to hot summers. The monthly variation of weather in London is demonstrated in Figure 3.1 (EnergyPlus, 2022). The monthly average temperature ranges from 5°C (January) to 14 °C (July and August) (Figure 3.1a). The monthly average relative humidity varies from 70% (June) to 88% (December). The average wind speed is around 2 to 4 meters per second (m/s) (Figure 3.1b).

The case study site, the depot_ (18 Wenlock Road, London, N1 7TA), is an experimental creative hybrid co-working space near Old Street. It is found and designed by the lab_ collective and opened in early 2020. The depot_ also functions as an exhibition and event space and a local café. It opens from 9am to 6pm on weekdays. Figure 3.2 shows the plan and indoor environment of the depot_. It occupies the ground floor (Figure 3.2 right) and basement (Figure 3.2 left) of a building. The ground floor is used as a café with a reception and open working space, while the basement area functions as the meeting area with two enclosed meeting rooms and several open flexible meeting spaces. The maximum capacity of the space is around 70. A mixed-mode cooling system with a combination of natural and mechanical ventilation is applied in the space.

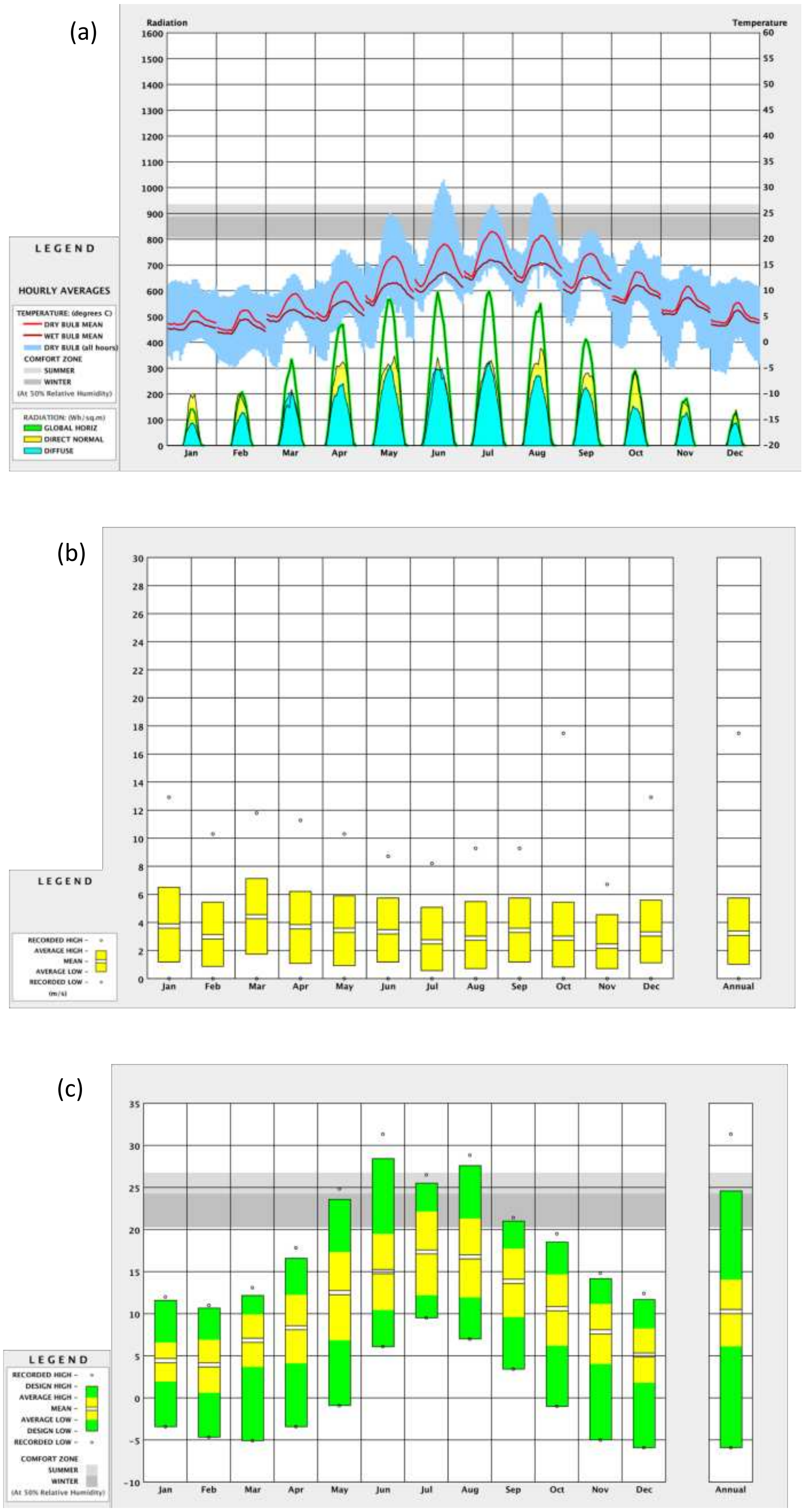



Figure 3.1. Annual weather variation (temperature, humidity (a), windspeed (b) and radiation (c)) in London (EnergyPlus, 2022)

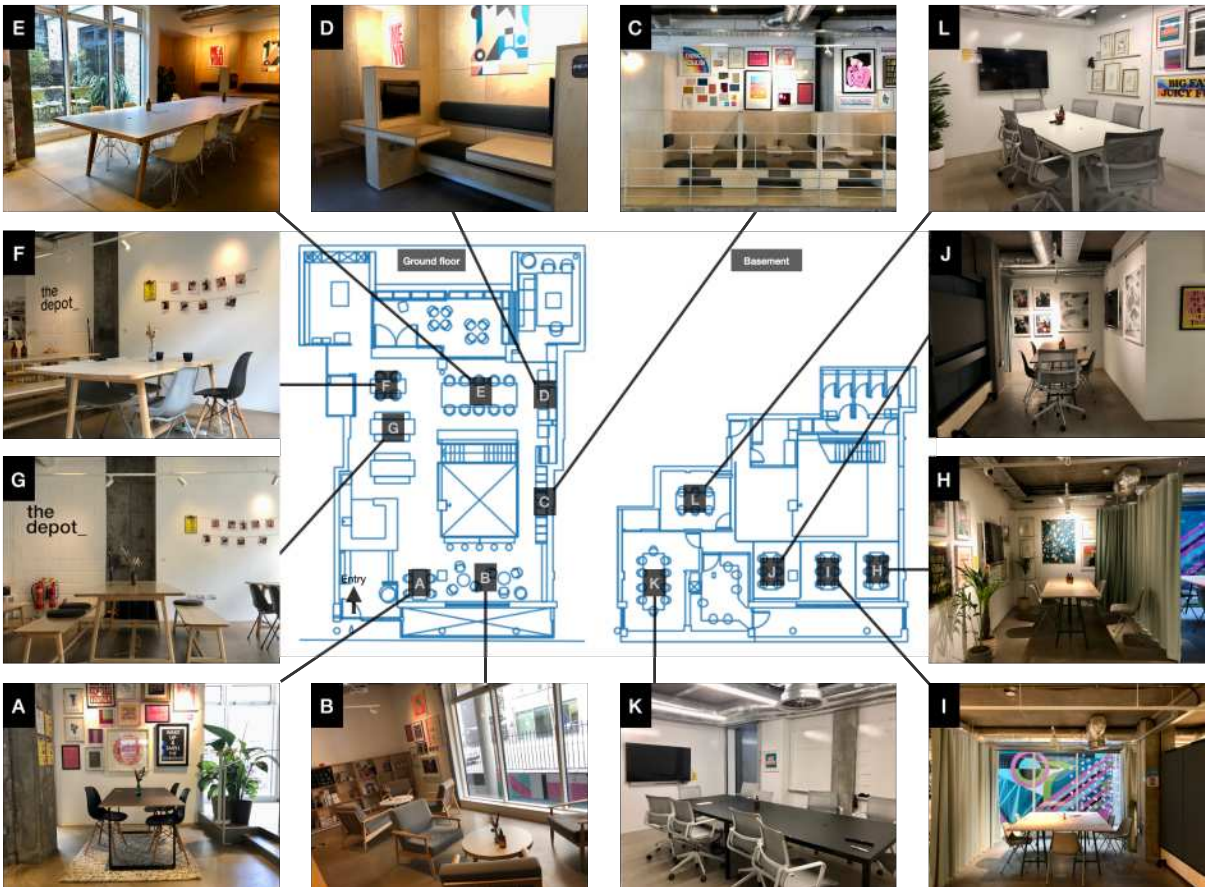



Figure 3.2. Case study, the depot_ (18 Wenlock Road, London N1 7TA): Plan, layout and photos of workspace

### 3.2 Field study and measurement

A longitudinal field study is conducted to understand the thermal comfort level of occupants, which conforms to the ASHRAE Class II protocol. The data collection is expected to spread over different seasons to capture the diversity in the thermal environment. The standard thermal comfort data collection comprises two parts: the subjective part (thermal comfort sensation questionnaire) and the instrumental part (indoor climate measurement). They are recorded at the same time (Földváry Ličina *et al.*, 2018). This method has been applied in a wide group of thermal comfort studies in various types of environments, such as office spaces in Brazil (De Vecchi *et al.*, 2017), slum rehabilitation housing in India (Malik *et al.*, 2020; Malik and Bardhan, 2021), schools and classrooms in the tropics (Wong and Khoo, 2003; Hamzah *et al.*, 2018) and residential units in Ethiopia (Yadeta *et al.*, 2022). In addition to the standard thermal comfort questions, this study explores the influence of environmental variables on seat preferences with several further questions.

This questionnaire adopted in this study is composed of 3 parts with a total of 20 questions, demographic profiles (age, gender and occupation), subjective comfort votes and environmental variable preferences. The field study is planned to run from March 2022 to March 2023, covering the four seasons in a whole year, in order to capture the variation in thermal sensations. Ethics approval was applied and obtained from the Faculty of Architecture and History of Art Research Ethics Subcommittee at University of Cambridge. According to the ethics requirement, all participants are informed of the project process and contacts. They provide verbal consents to participate in the survey, and they are aware of the right to drop off at any stage. The following subsections introduce the procedure and details of the survey in three parts: the subjective comfort questionnaire, environmental data monitor and the questionnaire on environment and seat preference.

### *3.2.1 Subjective comfort survey*

The understanding of subjective comfort is composed of three parts: demographic information, subjective thermal comfort votes and personal variables. The demographic profile includes gender, age group and occupation of respondents. The collection of subjective thermal information includes thermal sensation votes (TSV), thermal preference votes (TPV), humidity sensation votes (HSV), humidity preference votes (HPV), air movement sensation votes (ASV, air movement preference votes (APV), lighting sensation votes (LSV), daylight preference votes and artificial lighting preference votes. ASHRAE's seven-point scale of thermal sensation and Nicol's five-point scale of preference are applied as listed in Table 3.1 (Humphreys, Nicol and Roaf, 2016). The personal variables include clothing insulation level and activity level. The calculation of clothing insulation level is extracted from ASHRAE standard 55-2010 (ASHRAE, 2013). Respondents' activities in the past 15 minutes are enquired to calculate the corresponding metabolic rates (Engineering ToolBox, 2004a). The indoor environmental controls are not considered due to the limitation of the site. The openings, cooling and heating system are subject to central control, which are not available to occupants.

Table 3.1. Sensation scales (Humphreys et al., 2016)

| | **Thermal sensation** | **Humidity sensation** | **Air movement sensation** | **Lighting sensation** | **Thermal preference** | **Humidity preference** | **Air movement preference** | **Daylight preference** | **Artificial light preference** | **Overall acceptability** |
|---|---|---|---|---|---|---|---|---|---|---|
| **-3** | Cold | Very dry | Very still | Too dark | | | | | | |
| **-2** | Cool | Dry | Moderately still | Dark | Much warmer | Much more humid | Much more air movement | Much more daylight | Much more artificial light | |
| **-1** | Slightly Cool | Slightly dry | Slightly still | Slightly dark | A bit warmer | A bit more humid | A bit more air movement | A bit more daylight | A bit more artificial light | |
| **0** | Neutral | Neither humid nor dry | Neutral | Neutral | No change | No change | No change | No change | No change | Acceptable |
| **+1** | Slightly Warm | Slightly humid | Slightly moving | Slightly bright | A bit cooler | A bit drier | A bit less air movement | A bit less daylight | A bit less artificial light | Not acceptable |
| **+2** | Warm | humid | Moderately moving | Bright | Much cooler | Much drier | Much less air movement | Much less daylight | Much less artificial light | |
| **+3** | Hot | Very humid | Much moving | Too bright | | | | | | |

### *3.2.2 Field measurement*

The outdoor temperature is extracted from the nearest local weather station in London (Met Office, 2022). The indoor climate is monitored by Kestrel 5400 (Kestrel Meters, 2020), which measures air temperature, globe temperature, heat index, relative humidity and air velocity (details about accuracy and range are shown in Table 3.2). The instrument is placed near the participants at about the working plane level while they fill in the questionnaire. The illumination readings are taken at two levels with a URCERI light meter: the working plane/desk level and the human eye level. Each measurement is repeated three times. Figure

3.3 shows an example from the field study which includes the instrumental setup and clothing characteristics.

Table 3.2. Indoor environment measurement (Kestrel Instrument, 2020)

| | | Range | Resolution | Accuracy |
|---|---|---|---|---|
| **Kestrel 5400** | **Air temperature** | -29.0 to 70.0 °C | 0.1 °C | 0.5 °C |
| | **Globe temperature** | -29.0 to 60.0 °C | 0.1 °C | 1.4 °C |
| | **Heat index** | N/A | 0.1 °C | 4.0°C |
| | **Relative humidity** | 10 to 90%, 25°C noncondensing | 0.1 %RH | 2%RH |
| | **Air velocity** | 0.6 to 40.0 m/s | 0.1 m/s | Larger of 3% of reading |
| **Light meter** | **Illuminance** | 0 lux to 200,000 lux | 0.1 lux | N/A |

Figure 3.3. Example of measurement and survey

### *3.2.3 Environment and seat preference survey*

In addition to the thermal comfort perception, seat preferences and the importance of environmental variables on seat selection are enquired in the questionnaire survey. The participants are asked whether they are sitting at their preferred seats and requested to point out their preferred seats. They indicate the importance (scale 1 to 5) of a range of environmental and non-environmental factors on their seat preference, such as daylight, artificial light, ventilation, privacy and closeness to people and facilities (listed in Table 3.3). As a validation, the participants also rank their preferences among seven different factors. At last, the respondents rate the whole co-working environment on a scale of 1 to 5 from six different perspectives: ventilation, quietness, thermal comfort, lighting, privacy and overall environmental quality.

Table 3.3. Environmental preference questions

| Question type | Factors | Scale |
|---|---|---|
| **Rate the importance** | Good daylight | Scale 1 to 5, 1 as not important, 5 as very important |
| | Good electric/artificial lighting | |
| | Good ventilation | |
| | Thermally comfortable | |
| | Quieter | |
| | Near power sockets | |
| | Close to other people | |
| | Distant from other people | |
| | Close to window | |
| | Nice view | |
| | Only a few people passing by | |
| | The closest available seat | |
| | Close to the cafe/reception | |
| **Ranking the factors** | Closeness to window | Rank 1 to 7, 1 as most impactful, 7 as least impactful |
| | Thermal comfort | |
| | Lighting | |
| | Ventilation | |
| | Privacy | |
| | Closeness to facilities (e.g. printer, toilet, cafe and reception) | |
| | Noise level (quietness) | |
| **Rate the environment** | Ventilation | Rate 1 to 5, 1 as not satisfied, 5 as very satisfied |
| | Quietness | |
| | Thermal Comfort | |
| | Lighting | |
| | Privacy | |
| | Overall | |

## 4 Results and Discussion

This section presents the results and analysis from the preliminary field study conducted in Spring 2022 (March, April and May). The descriptive data are sample sizes and personal variables, followed by the thermal comfort analysis and an analysis of the impact of environmental parameters on seat preferences.

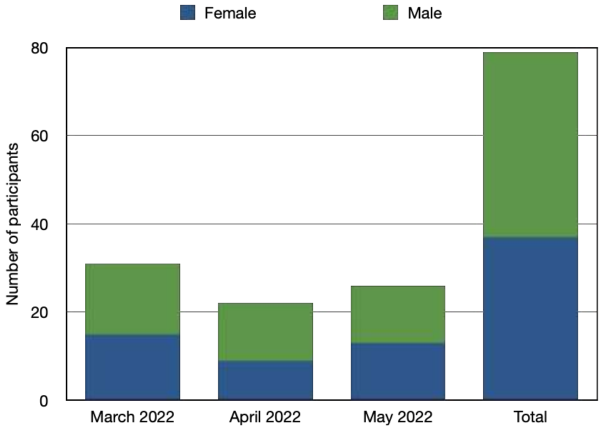
### 4.1 Descriptive results

#### *4.1.1 Sample size and demographics*

A total of 80 participants filled the survey from March to May 2022, with one invalid response. Figure 4.1 illustrates the distribution of the number of participants with respect to time, gender and age group. There are 31, 22 and 26 sets of responses recorded in March, April and

May respectively. The sample size depends significantly on the presence of occupants on the survey day and their availability and willingness to participate. Gender distribution is relatively equal, with around 47% female respondents and 53% male respondents. A majority of participants are in the age group of 18 to 54. The younger population, at the age between 18 to 34, accounts for over 60% of the respondents. There is no significant variation in the participants' age among different months.

Figure 4.2 shows the distribution of occupations. A total of eleven different types of occupations are identified in the questionnaire. A large number of respondents (around 57%) work in the Architecture and Engineering industry, because employees and partners in the lab_ collective use the depot_ as their major in-person workspace and the company mainly works in the built environment industry. There are also a group of participants working in Management (10%), Art and Design (8%) and Sales and Related (5%).



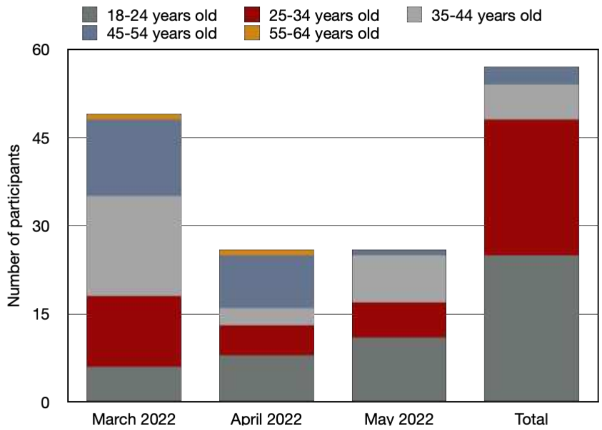




Figure 4.1 Sample size distribution with respect to time, gender and age

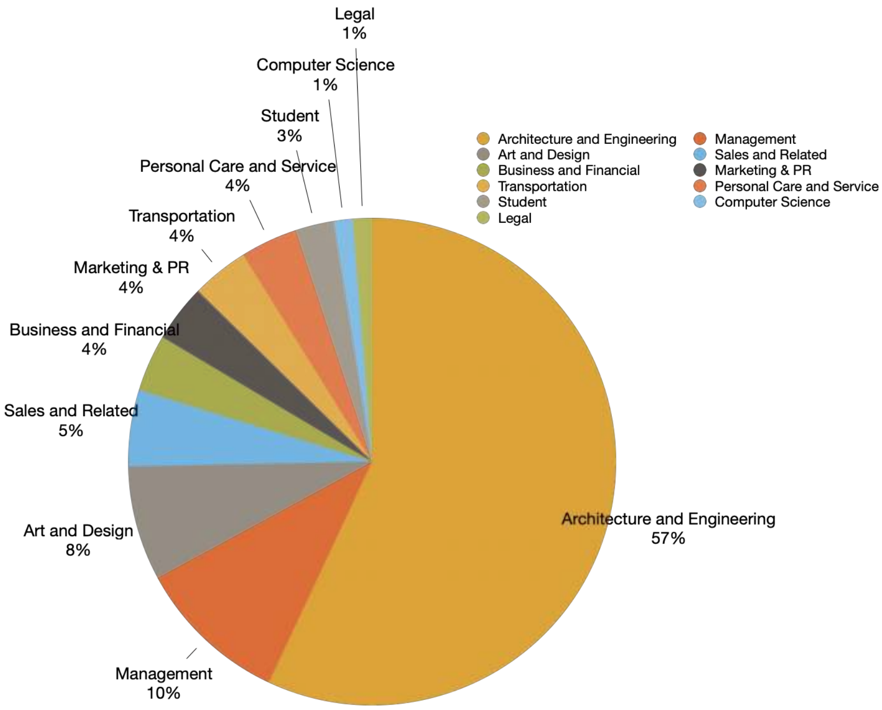



Figure 4.2 Sample distribution with respect to occupations

### *4.1.2 Personal variables*

The personal variables include the clothing insulation and activities over the past 15 minutes. The major clothing combination of occupants is jeans, trousers or skirt as the bottom, shirt, T-shirt or jumper as the top. The mean clothing insulation of all participants is 0.61 clo. The maximum clothing value is 1.09 clo, representing the combination of trousers, long sleeve shirts, jacket, thermal top and socks and shoes. The minimum clothing value is 0.24 clo. The average clothing insulation level decreases from March to May as the weather becomes warmer. Figure 4.3(a) shows the summary of clothing insulation of the participants across different months.

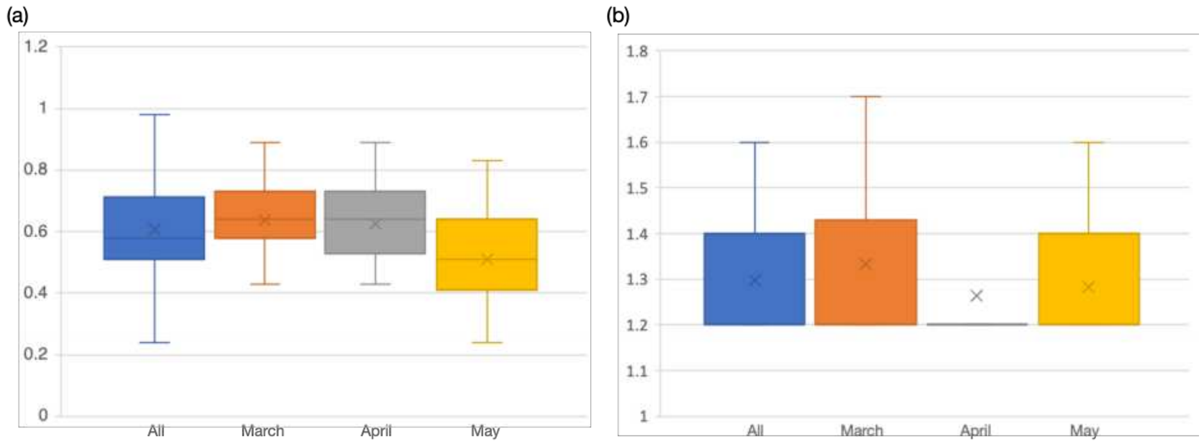



Figure 4.3 (a) Plot of clothing insulation; (b)plot of metabolic rate

Most of the activities reported in the survey are sitting, standing and walking, which corresponds to the typical office activities. Occupants' sedentary activities (1.2 met) include meeting, working and eating and drinking, and their standing activities are mainly standing relaxed (1.2 met) and standing with light and medium activities (1.6 and 2.0 met respectively) (Engineering ToolBox, 2004). The mean metabolic rate is 1.3 met, with a maximum rate of 1.9 and a minimum rate of 1.2 (demonstrated in Figure 4.3(b)). Only six people report they are slightly sweating when answering the questions, while the rest of the respondents indicate 'no sweating'.

### *4.1.3 Environmental conditions*

Outdoor weather conditions on survey days are plotted in Figure 4.4, including the daily variation (from 9am to 6pm) of air temperature, humidity and wind speed. The mean outdoor temperature is around 18.35 °C, and the average humidity and windspeed are 48.11% and 2.1m/s. The highest temperature is recorded at 27°C at 10:00 and 11:00 on the survey day in May, while the lowest temperature is 8.9 °C at 9:00 in April. The temperature in April is relatively low, with relatively higher humidity and air velocity observed. The wind speed in May is 0m/s throughout the whole survey day according to the record.

Indoor climate data is measured by Kestrel 5400 and a light meter. The indoor air temperature varies between 20.1°C and 24.8°C. The average air temperature is around 22.4°C, with a mean of 22.0°C in March, 21.9°C in April and 23.3°C in May. The relative humidity lies in an acceptable range from 38.9% to 50.8%, while the average relative humidity is 44.08%. The illuminance level is measured at the eye level and the desk level separately, with the average illuminance value of 124.06 lux and 170.42 lux respectively. The range of illuminance levels varies significantly for different seats and areas, with a minimum value of 23.1 lux (human level) and 22.9 lux (desk level) and a maximum value of 469.8 lux (eye level) and 668.6 lux (desk level). Normally, the suggested illumination level for office is about 250 to 500 lux at the desk level (Engineering ToolBox, 2004b).

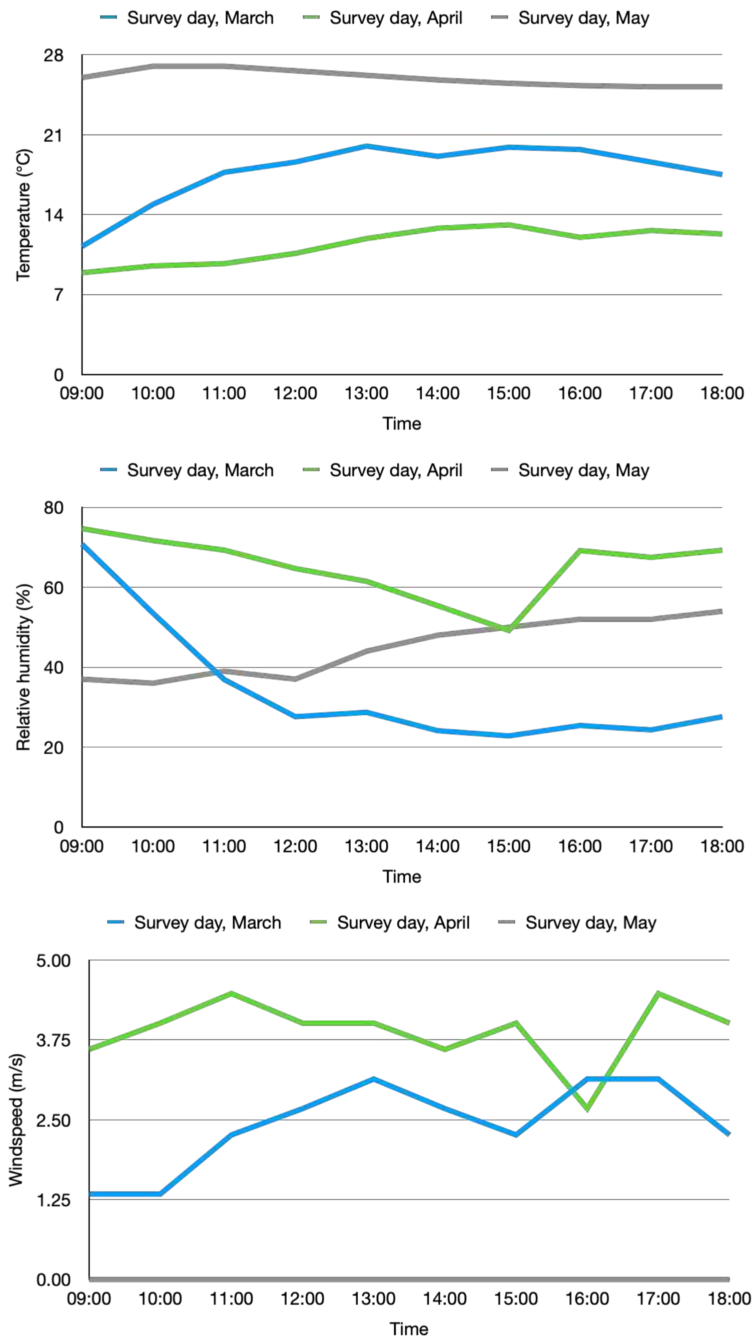



Figure 4.4 Outdoor environment condition extracted from the nearby local weather station (temperature, relative humidity and wind speed)

## 4.2 Subjective thermal and lighting comfort responses

### *4.2.1 Thermal sensation and thermal preference votes*

The thermal sensation of occupants is measured on a seven-point scale (see Table 3.1), from very cold (-3) to hot (+3). The monthly distribution of TSV is shown in the top chart in Figure 4.5. About 80% of respondents vote within the comfortable range, from slightly cool (-1) to slightly warm (+1), while almost half (47%) of them vote for neutral thermal sensation (0). At the same time, about 14% of participants report for warm sensation (+2), 5% for cool (-2) and 1% for cold (-3) across the three months. The average TSV value is 0.06, which is very close to the neutral sensation. In March and May, the mean TSV values are 0.06 and 0.15 separately, showing a slightly warm sensation. The mean TSV in April is slightly below zero with a value of -0.05, which is on the cool side.

The thermal preference is represented in a five-point scale, from much warmer (-2) to much cooler (+2). A mean TPV value of -0.1 is observed, which indicates a slight tendency toward warmer sensations. The distribution of TPV in each TSV point is shown in Figure 4.5 (b). Around 54% of respondents vote for no change (0), while 29 participants (approximately 37%) select both neutral sensation (0) and a preference for no change (0). Around 28% of people prefer a bit cooler (+1) environment, whereas 18% desire a bit warmer (-1) environment. No one wants a much warmer (-2) or much cooler (+2) environment. The correlation analysis shows the correlation coefficient between TSV and TPV is 0.7, indicating a robust positive association.

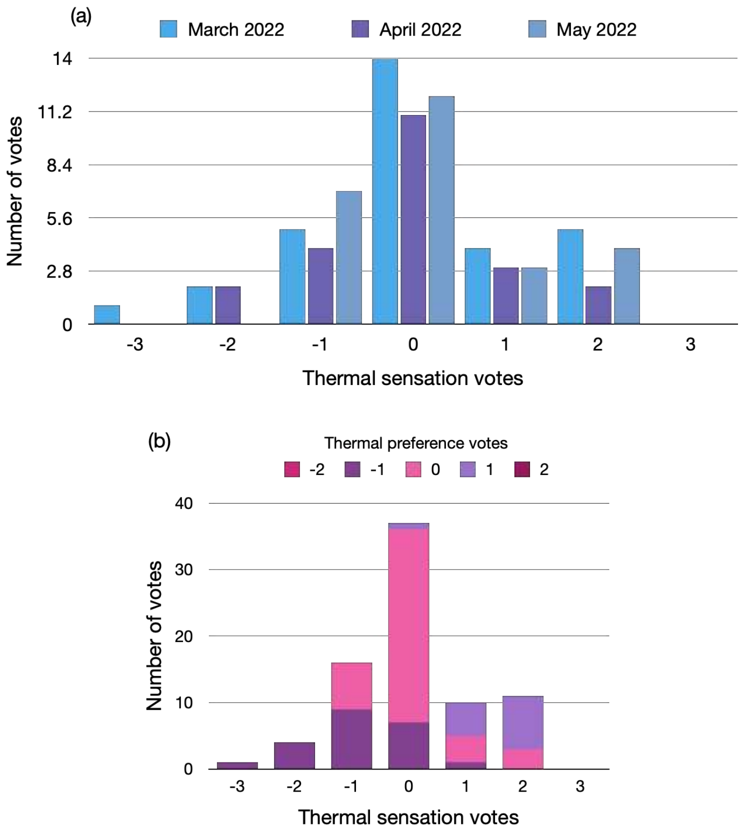



Figure 4.5 (a) Monthly distribution of thermal sensation votes; (b) Cross-tabulation of subjective thermal votes

### *4.2.2 Humidity and air movement subjective votes*

Humidity and air movement sensation and preference are also enquired as they have some impacts on thermal comfort perceptions (Fountain and Arens, 1993; Kitagawa *et al.*, 1999). The monthly distribution of HSV is illustrated in Figure 4.6 (a), and the cross-tabulation of subjective humidity votes is shown in Figure 4.6 (b). All HSV responses lie in the range of dry (-2) to slightly humid (+1), with an average value of -0.19, indicating a relatively neutral sensation but on a slightly dry side. More than 95% of respondents choose within the comfortable humidity range of slightly dry (-1), neutral (0) and slightly humid (+1), while only three occupants feel the environment is dry. The mean HPV value corresponds to the average

HSV with a value of -0.19, which demonstrates a preference for a bit more humid environment but close to no change. A group of 44 people (56%) make neutral selections, with neither humid or dry sensation (0) and no change (0) preference. Four respondents feel slightly dry (-1) but prefer no change (0), while the same amount of people feel slightly humid (+1) but prefer no change (0) too. About 27% of participants desire a bit more humid environment (-1) and 8% prefer a bit drier environment (+1). The correlation between HSV and HPV is positive with a coefficient of 0.7.

Although the instrument fails to detect any wind speed, the sensation of air movement varies among the respondents. The descriptive results of ASV and APV are shown in Figure 4.7. ASV sensations range from very still (-3) to moderately moving (+2). Only 80% of responses are in the range from slightly still (-1) to slightly moving (+1). Seven participants (about 9%) indicate a very still (-3) sensation, and five (6%) choose moderately still (-2). The mean air flow sensation is -0.18, which is close to neutral with a small tendency to still air movement. Meanwhile, the average APV value is -0.44, representing a general preference for more air movement. While 49% of respondents prefer no change (0), there are 47% desire more air movement (-1 or -2). Nine respondents indicate their desire for more air movement even when they sense slight or moderate air movement (1 or 2). The correlation between ASV and APV is positive but not robust with a coefficient of 0.48.

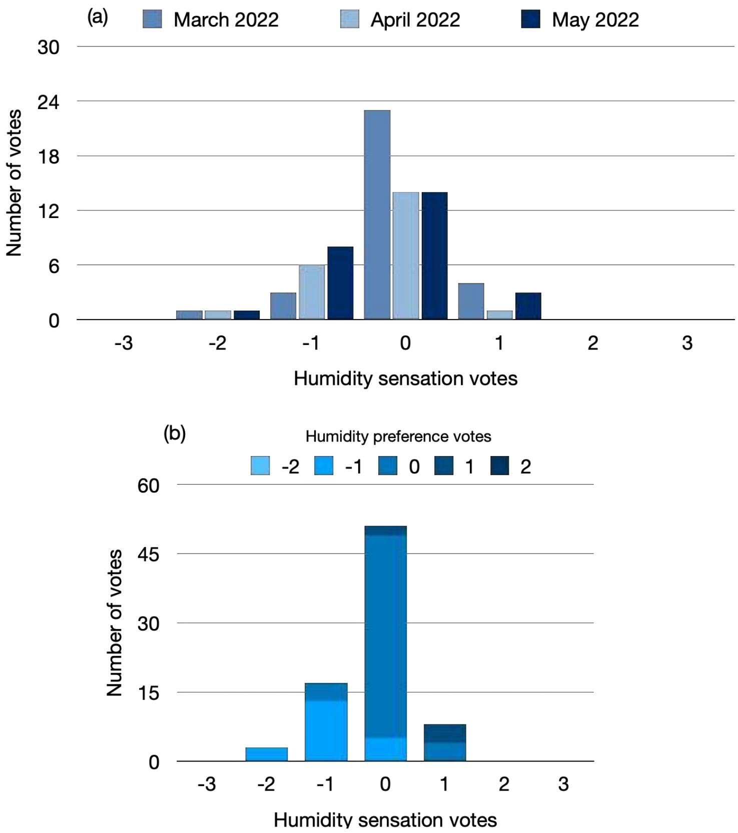



Figure 4.6 (a) Monthly distribution of humidity sensation votes; (b) Cross-tabulation of subjective humidity votes

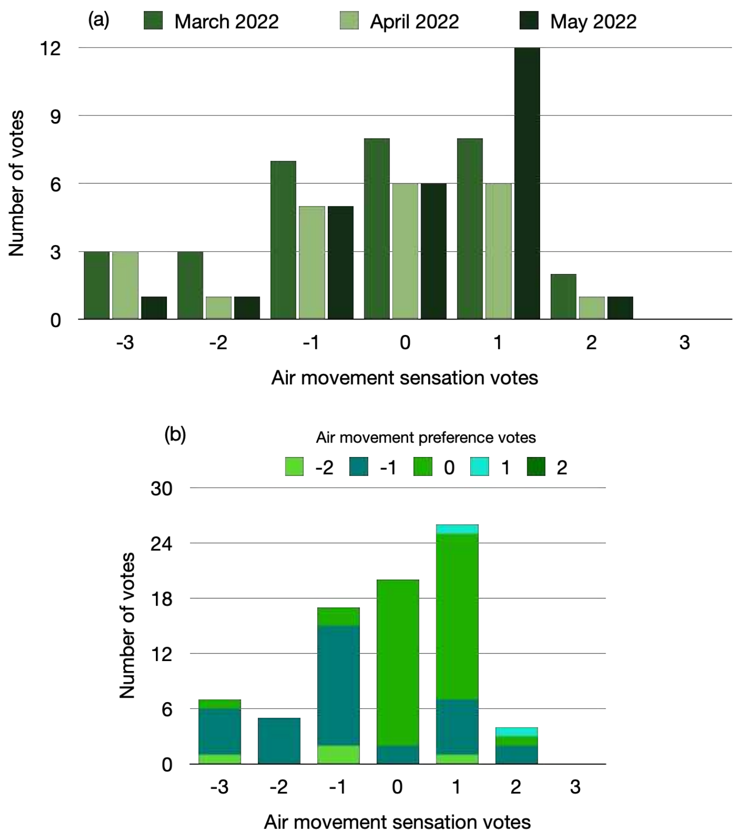



Figure 4.7 (a) Monthly distribution of air movement sensation votes; (b) Cross-tabulation of subjective air movement votes

### *4.2.3 Lighting sensation and preference votes*

The sensation of lighting conditions is also examined in this study, following the same scaling method as above. The lighting preferences are enquired, with two different preference choices regarding daylight and artificial light. Participants can choose their preferences for both. The corresponding results are plotted in Figure 4.8. Around 84% of participants vote within the acceptable range of slightly dark (-1) to slightly bright (+1), with 41% feeling slightly dark (-1), 35% feeling neutral (0) and 8% feeling slightly bright (+1). Five respondents report a dark sensation (-2), while eight suggest a bright sensation (+2). The mean LSV value is -0.25, indicating that the general sensation has a propensity to slightly dark. The average LSV values in March and April are -0.32 and -0.45 respectively, while the mean value in May is neutral (0). Mean LPV shows a preference for a brighter environment, with a value of -0.9 for daylight and -0.27 for artificial light. There are 18% of respondents standing for neutral sensation and no change in daylight and 30% for neutral sensation and no change in artificial light. About 67% of occupants want an environment with more daylight (-1 and -2), while only 22% of occupants prefer an environment with more artificial light. No one votes for less daylight (+1 or +2) while one person wants less artificial light (+1) given her sensation vote of bright (+2). Eleven respondents feel slightly dark (-1) and desiring for much more daylight (-2). Eight respondents choose the slightly bright (+1) or bright (+2) sensations but still prefer more daylight (-1 or -2). Correlation analysis finds a relatively weak positive correlation between LSV and LPVs. The correlation coefficients of LSV and LPVs for daylight and artificial light are both around 0.4.

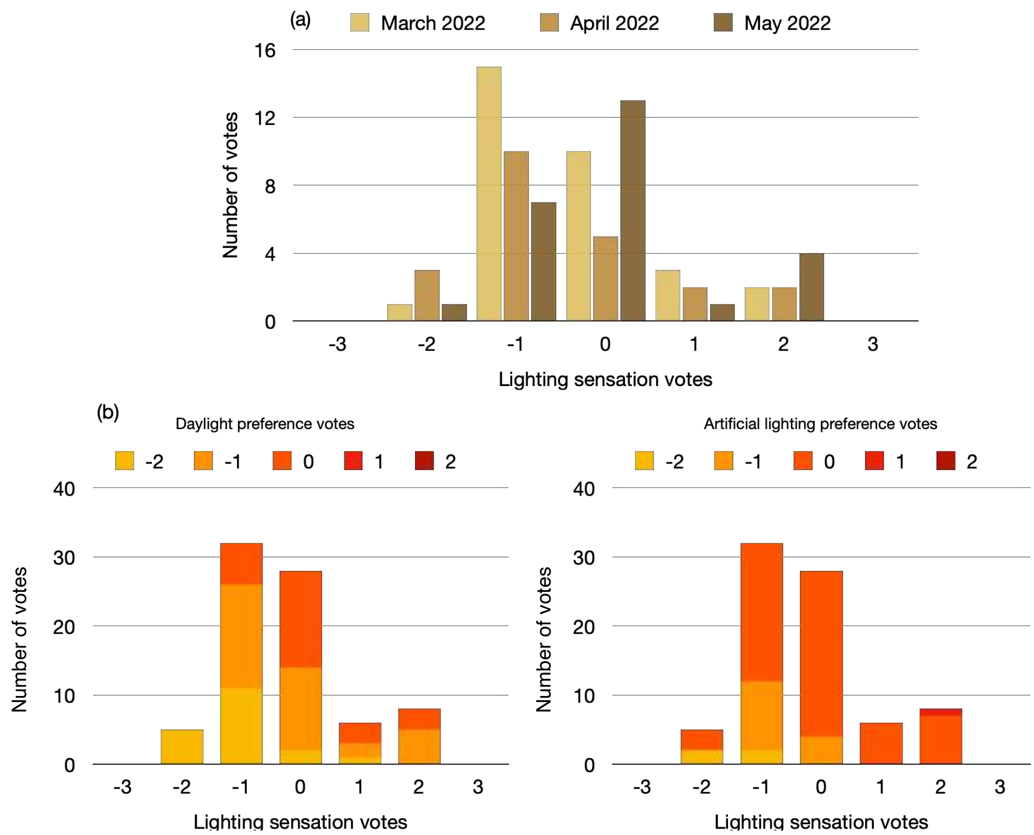



Figure 4.8 (a) Monthly distribution of lighting sensation votes; (b) Cross-tabulation of subjective lighting votes, left: daylight preference votes, right: artificial lighting preference votes

### *4.2.4 Overall comfort acceptability*

The overall comfort acceptability is collected as binary data: acceptable as 0, and unacceptable as 1. Only one person finds the environment not acceptable, while most of the respondents choose ‘acceptable’. The results found in this question are also validated by the environment satisfaction rating question (discussed in Section 4.3), while an acceptable average score of 3.68 out of 5 on the environment is given by respondents.

## 4.3 Seat preference and environmental variables

The participants are enquired about their seat preferences. Most of the respondents (nearly 80%) report that they are sitting at their preferred seats, while only 15 respondents point out their preferred seats are not available. The seats close to a large window, type E in Figure 3.2, are selected as the most popular seat. Figure 4.9 presents the importance of each statement in regard to seat selection. Occupants consider ‘good daylight’, ‘near power sockets’ and ‘thermally comfortable’ as the three most important factors, with the mean importance level of 4.3, 4.2 and 4.0 respectively. The second tier of important factors includes ‘close to window’, ‘good ventilation’ and ‘nice view’, with corresponding average importance rates of 3.92, 3.77 and 3.58. The least important factors are ‘closest available seat’, ‘close to café and reception’, ‘distant to other people’ and ‘close to other people’ with the importance value under 3. Participants also rank their preference among seven different factors (results shown in Figure 4.10). The ranking results reveal the importance of the factors like closeness to window, lighting condition and thermal comfort when occupants decide where to sit. The participants may give less consideration to closeness to facilities and privacy in their seat preference.

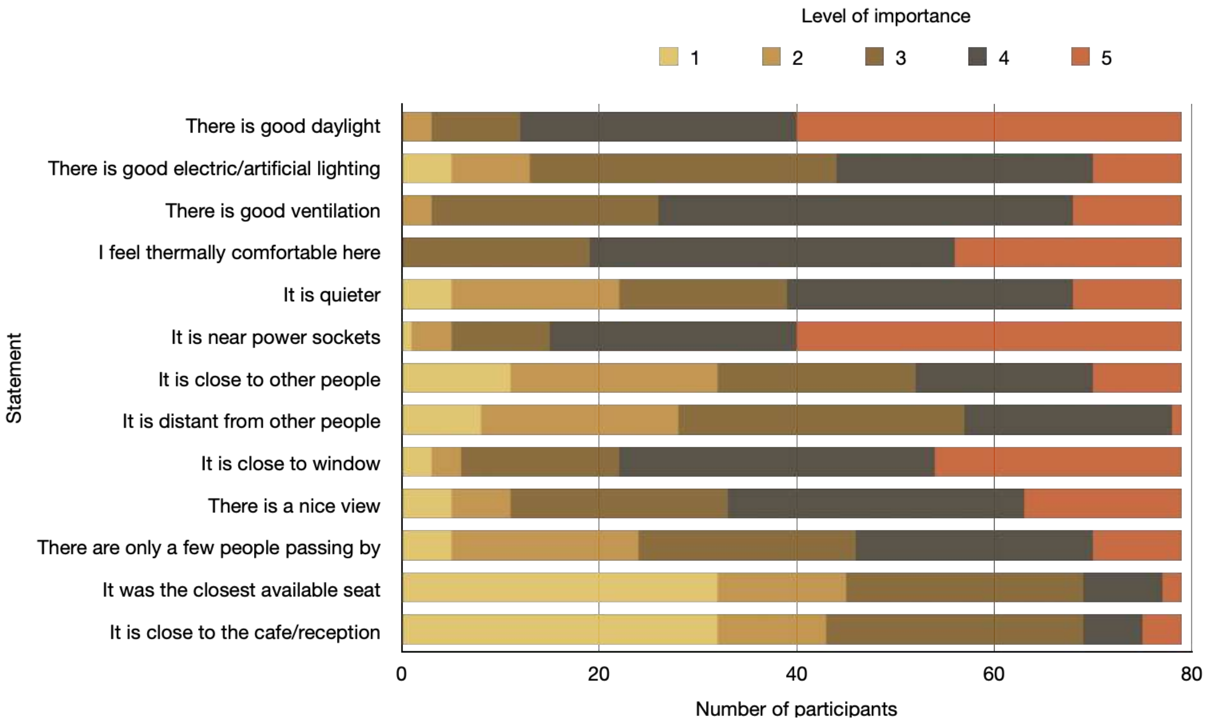



Figure 4.9 Level of importance of each statement in regard to seat selection

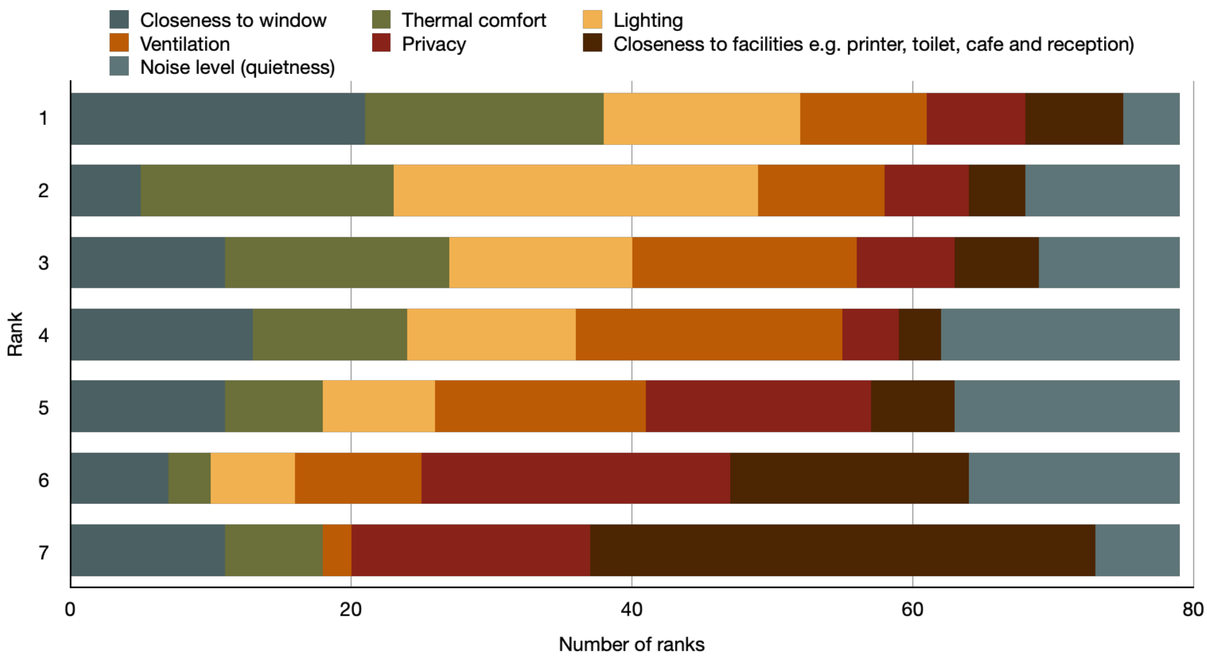



Figure 4.10 Ranking results among seven design factors

At the end of this questionnaire, participants rate this co-working space based on their satisfaction with five different environmental parameters and one overall score (see Figure 4.11). Ventilation, lighting and thermal comfort receive higher scores compared to privacy and quietness. The average overall score is around 3.68, which is an acceptable level of satisfaction.

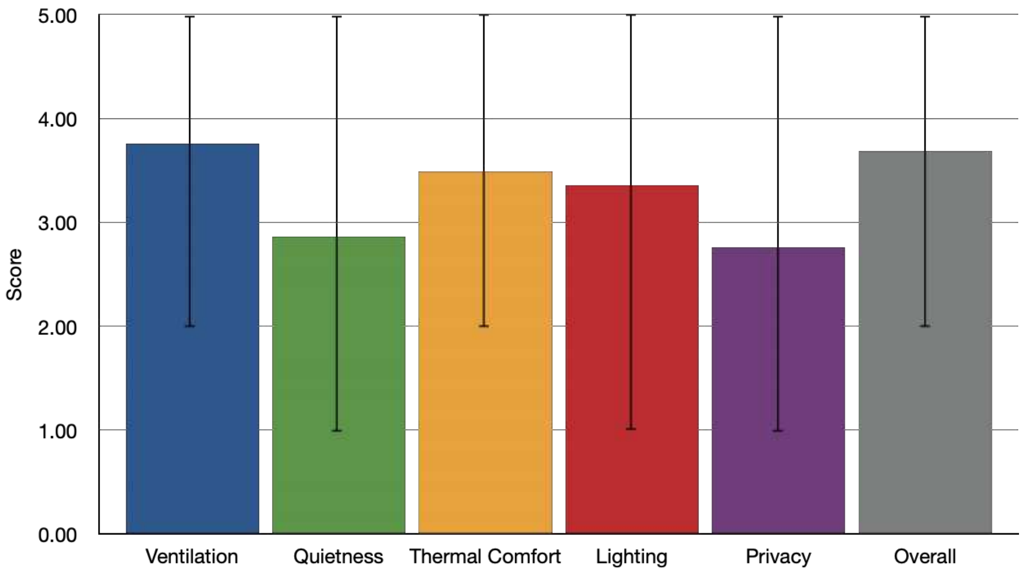



Figure 4.11 Overall evaluation of the environment

## 4.4 Discussion

The preliminary results with 80 participants from the field study in a co-working space conducted in Spring 2022 confirm the impact of environmental design factors on seat preference. Two major findings are summarised as follows:

- Firstly, thermal comfort sensation is generally acceptable in the space, with a slight overall tendency on warm, dry and still movement sensation. At the same time, the occupants tend to adjust to a neutral thermal comfort and humidity situation by indicating a preference for a slightly cooler and a bit more humid environment. Also, thermal comfort is considered an important factor to the occupants when choosing their seats.
- Secondly, a strong preference for more daylight and more air movement is observed in the survey results, regardless of participants' actual sensations. Daylight and ventilation are also two factors favoured by the occupants. They suggest they would consider the daylight and closeness to window as two key factors regarding seat preferences. This argument is double-validated by their actual choice of seat and selection of preferred seat – the table near the large window (type E) is the most popular place. This finding corresponds to the former research on office physical environment, that more daylight and ventilation and outside window are preferred and lead to higher satisfaction (Newsham *et al.*, 2009; Alker *et al.*, 2015).
- Overall, this co-working environment is generally acceptable for occupants. Although its performance of privacy level and noise is relatively unsatisfying, most of the occupants are satisfied with this working environment.

## 5 Conclusion

The indoor physical environment in offices plays an important role in promoting users' perception, health and well-being (Kamarulzaman *et al.*, 2011), at the same time, providing a high-quality environment by natural design strategies can contribute to building operational energy saving (Steemers and Manchanda, 2010). While the type and design of modern offices are expected to be transformed significantly in the post-pandemic time, a gap of lack of understanding of effective design for new office types is identified. This investigation intends to fill this gap by conducting a longitudinal field survey on thermal comfort analysis and environmental perceptions and preferences of the occupants.

In this preliminary analysis, the thermal comfort level in the case study office space Spring 2022 is demonstrated with a field survey in a co-working space in London. Generally, the results have reflected a generally acceptable situation regarding thermal and lighting comfort, and they consider the factors like thermal comfort, daylight and closeness to window important to them when deciding where to sit. More daylight and air movement are desirable options for many occupants.

In conclusion, this study captures the thermal experience and environmental preference in a co-working flexible office using a questionnaire survey and in-situ measurements. The number of participants presented in this writing is relatively small, while more data is expected to be collected over the following year and more findings would be revealed as the survey responses accumulate. Further investigation is going to be developed along with the calculation of radiant temperature and operative temperature and simulation methods to predict thermal comfort level in the space. The analysis and results are expected to provide an insight into how to design for a better environment in the future workspace.

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# Life cycle carbon assessment of a contemporary house in the UK built to zero carbon.

**Venkatesh Kalidoss[1] and Haniyeh Mohammadpourkarbasi[2]**

[1] School of Architecture, University of Liverpool, Liverpool L69 7ZN, UK or email venkateshkalidoss@gmail.com

[2] School of Architecture, University of Liverpool, Liverpool L69 7ZN, UK or email Haniyeh.MPK@liverpool.ac.uk

**Abstract:** This research presents for the first time the Life cycle assessment (LCA) of a contemporary zero energy terraced house built using MMC in the UK and compares the results with a traditional terraced house. The UK has set a net-zero target and the pace of achieving the target depends on how the contemporary houses are built. The current regulations by the government focus only on reducing the operational carbon of houses rather than looking from a life cycle perspective. This leads to an increase in embodied carbon emissions in newly built houses. There are 244000 houses built every year approximately in the UK and many are overlooked as zero-carbon houses which are only zero operational energy use, and the embodied emissions are unknown. Therefore, a real-life contemporary (zero energy) terraced house built using MMC in Liverpool, UK is chosen as a case study and LCA was conducted using one-click LCA software to calculate the lifetime carbon emission. Though operational carbon has achieved net zero by MMC, it is identified from this research that the embodied carbon of contemporary houses (62tCO2e) has increased by 2.3times the traditional house (26tCO2e). Further, Strategies and methods to reduce embodied carbon were discussed.

Further, the top five carbon contributing building elements of the case study were identified and different scenarios were proposed to understand the potential impact of choosing low carbon products and organic materials as alternatives.

**Keywords:** Net-zero target, low carbon, new house, Life cycle assessment (LCA), embodied carbon.

## 1. Introduction

The emission of carbon dioxide and other greenhouse gases emission is the leading cause of global warming. The construction and operation of buildings contribute to carbon emissions, increasing over the years. According to the Intergovernmental Panel on climate change (IPCC), the global temperature has already risen by 1°C from the preindustrial level roughly due to human activities, and it is expected to increase further by 1.5°C by 2040 if the current warming rate continues (IPCC, 2021, Rabani et al., 2021). Therefore, Countries such as Uruguay, Finland, Austria, and Iceland have set an earlier target by 2035 and 2040. Yet, the earliest target enforced in law is Sweden's 2045 target (Climate action, 2021).

The building sector's carbon emission is more adverse than the world average in the UK. 45% of the total UK carbon emission is from the built environment, with 27% from domestic buildings and 18% from non-domestic buildings (IGPP, 2021, U. K. Construction Online, 2018). The Climate Change Act in the UK was amended in 2019 and passed laws to achieve a net-zero target by 2050 (change and the environment, 2021, Gov.Uk, 2019). This means that the UK will have to bring all greenhouse gas emissions to net zero by 2050; incorporating carbon offset activities such as planting trees and using new technologies to capture and store any emissions (Gov.Uk, 2019).

Though several sources indicate the UK has reduced 38% carbon emission from 1990 levels, it is predominantly from the energy supply sector by generating more renewable energy (Broad et al., 2020). From the latest report by the Department of Business Energy and Industrial Strategy (BEIS), it is found that the carbon emissions in the residential sector have reduced only to 69.1 $MtCO_2e$ from 80.1 $MtCO_2e$ in the past 20 years, as shown in Figure 1 (BEIS, 2021a). This is equivalent to less than a 15% reduction in the past two decades from 1990 levels. Many analysts have suggested that given the difficulty of saving carbon in other sectors we are likely to need to come close to complete decarbonisation of our building stock by 2050 (Energy Saving, 2017).

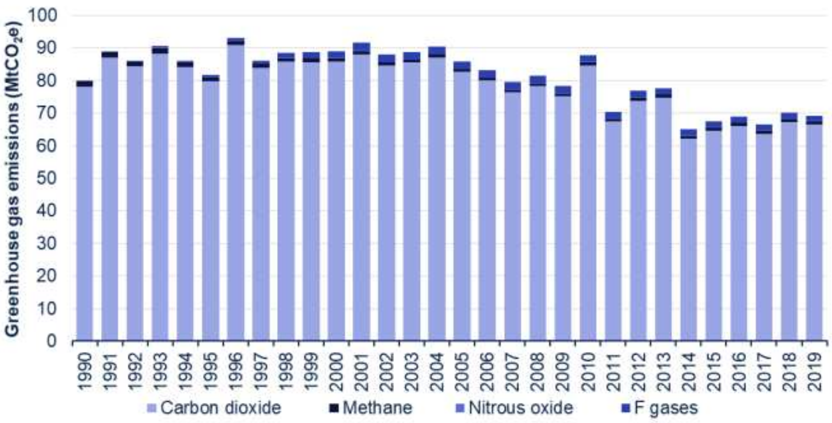


Figure 1. Residential carbon emissions from 1990-2019 (BEIS, 2021a).

The residential sector can be classified into existing and new buildings built each year. The Ministry of Housing, Communities and Local government (HCLG) indicates that 244,000 new homes were built in 2019, and 24.4 million homes will exist by 2050 (HCLG, 2022, Statista, 2022). In addition, the contemporary (new) houses built every year are designed to high-performance standards with renewables and promoted in the construction market as net-zero buildings, which are only net-zero operational, and the true lifetime carbon emission is unknown. Sturgis (2019) indicated the same in his book that the current use of the term 'zero carbon' refers to zero operational carbon emissions only, which is incorrect and misleading as they still have a carbon impact on the environment due to embodied emissions. Therefore, this research intends to determine the life cycle carbon emissions of contemporary (new) houses.

### 1.1. Life cycle carbon emission of buildings

Life cycle carbon emissions in the buildings can be classified as operational and embodied carbon (Sturgis, 2019). The whole life cycle carbon emission of buildings is the sum of embodied and operational carbon emitted over a building lifecycle (Sturgis, 2019).

### 1.2. Challenge – UK Current regulations and importance of the life cycle carbon assessment

In response to the increase in greenhouse gas (GHG) emissions, the UK government has implemented many regulations on operational carbon emissions and there are no regulations on embodied carbon emissions (Almeida et al., 2016, Sahagun and Moncaster, 2012). It is found that 84% of newly built properties have achieved low operational carbon emission with an EPC rating of A or B (Epc for, 2018). However, embodied carbon emission is completely neglected by regulations (Sanchez, 2021). The carbon trajectory by the London Energy Transformation Initiative (LETI) guidelines indicates that the embodied emissions would hold a significant share of carbon emissions from 2030 (LETI, 2021). Architecture 2030 iterates that the embodied carbon possesses more than 50% risk in the future (Building, 2018).

As there are no regulations to control embodied carbon emissions, organisations such as UK Green Building Council (UKGBC), and LETI are alerting and insisting on incorporating embodied carbon as part of regulations. The UK Green building council has released the first "whole life carbon net-zero road map" (UKGBC, 2021b). Climate emergency design guidelines by LETI has set a limiting factor of 500 kg $CO_2e/m^2$ (embodied carbon) and 35kWh/$m^2$/yr (operational energy use) for small and medium scale houses (LETI, 2021).

Sturgis (2019) indicated in his book that considering operational or embodied emissions in insolation can lead to poor decision making with unintended consequences. From the author's point of view, the potential method identified to calculate the true carbon emissions of houses is by life cycle assessment (LCA) method as it calculates operational and embodied carbon emissions collectively over a building lifetime (from construction till the demolition of the building). Yang et al. (2021) iterated the same that LCA is an effective method to analyse the lifetime carbon emissions of buildings.

### 1.3. Reasons for this research and contribution

This research contributes to a growing knowledge of the environmental impact of new residential construction in the UK by conducting LCA on a real-life contemporary net-zero energy house. The research would elaborate and present the carbon associated with all the building elements or materials used in the case study. It would aid developers, architects, and builders in understanding the carbon emissions of conventional building materials used in practice.

### 1.4. Research Aims, Objectives, methodology

The research aims to identify the life cycle carbon emissions of contemporary houses in the UK, which are overlooked as zero-energy houses and proposes possible measures to reduce embodied carbon emissions by:

- Identifying the share of embodied and operational carbon emission in life cycle carbon emission of a contemporary house in the UK.

- Comparing the contemporary house (21st century) LCA results with the traditional house (20th century) in the UK to identify the trend of carbon emission in the UK houses.

The life cycle carbon emissions of the house are calculated through a standardised methodology, LCA, using One-Click LCA software.

## 2. Literature review

### 2.1. History of LCA

The concept of life cycle analysis was developed over the years, especially in the 1970s and has been used in the building sector since 1990 (Passer et al., 2012, Cabeza et al., 2014). Life cycle analysis focuses on quantifying the materials, energy used and waste released back to the environment over its lifecycle (Cabeza et al., 2014, Sharma et al., 2011). Over the years, Life cycle analysis has been called life cycle assessment (GRDC, 2021). Life cycle assessment is a multi-step procedure for calculating the environmental impact of a product or service over its lifetime. It is often considered a “cradle to grave” approach to the calculation of environmental impact (Cabeza et al., 2014, Ciambrone, 2019, Joshi, 1999).

### 2.2. Standards and components of LCA study and Evolution of EPD

Standardisation is required to implement the sustainability concept into the construction industry (Passer et al., 2012). The International standardization organization (ISO) prepared the first standard for the construction sector. These standards are found in the LCA methodology in ISO 14040 (Passer et al., 2012). Based on ISO, the European Committee for standardization developed the framework “Sustainability of construction works – Assessment of Buildings” (EN15643, EN15804 and EN1597)(Passer et al., 2012, Passer et al., 2016).

Buildings are complex with several materials, and the appropriate LCI or LCIA data of materials is required to conduct a life cycle assessment (Takano et al., 2014). Building LCA is more sensitive to background data selection and it is a data-intensive method (Takano et al., 2014). There are several databases available for LCA such as Gabi, Ecoinvent, IBO, CFP and Synergia.

Takano et al. (2014) compared five different databases for the same design, and the results revealed that the LCA results are different according to the different databases. However, all five cases demonstrated that carbon emission of the concrete building is higher than timber building. This shows that the databases are broadly reliable for life cycle assessment (LCA) but not precise due to significant variation in data between databases. EPD's were introduced to overcome this variation in LCA results due to different databases (Bragança et al., 2007, Buyle et al., 2013).

Environment product declarations (EPD) are the third-party verified and standardized descriptions of the environmental impact of products during their lifetime. EPDs are developed based on life cycle assessment calculations according to the ISO 14040, ISO14044 and EN15804 standards in European countries (One click LCA, 2021).

### 2.3. Operational carbon VS Embodied carbon in LCA

The share of operational carbon (OC) and embodied carbon (EC) in buildings has been long debated in several articles. Ramesh et al. (2010) found in their study that embodied carbon (EC) contributes to only 10% while operational carbon (OC) accounts for 80-90% of life cycle carbon emissions in conventional residential buildings. Chastas et al. (2016) demonstrated EC emissions as 6-20%, while Kovacic et al. (2018) mentioned as 10-20% and Sartori and Hestnes (2007) identified as 2%-38% in their respective studies for conventional buildings. It should be noted that the low contribution of EC mentioned above in all the studies is for conventional buildings. It is contrary to low energy or zero energy buildings, as EC holds a significant share due to low OC emissions (Sanchez, 2021).

**I**ncrease in EC with the decrease in OC:

Hurst and O'Donovan (2019) developed a graph by analysing several case studies (see figure 2). Figure 2 represents the reduction in life cycle carbon with a reduction in OC until a saturation point of passive houses. Further reduction of operational energy to zero by self-sufficient buildings increases the embodied carbon significantly (due to high consumption of insulation and building services) and thus increases the life cycle carbon emissions ultimately (see figure 2). Further, the study mentioned that the EC emission accounts for 26-57% for a low energy building but could increase up to 74-100% for a self-sufficient building as in figure 2 (Hurst and O'Donovan, 2019).

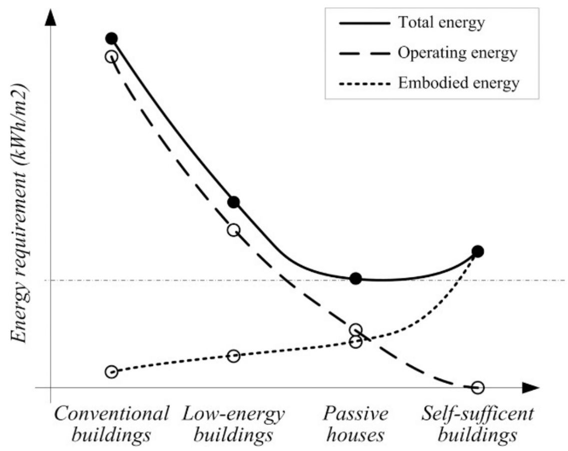

Figure 2. Relationship between embodied and operational energy (Hurst and O'Donovan, 2019)

Concluding, though there is variation among different studies, it is seen that EC increases with low or zero energy buildings contributing to more than 50% or near 100% when the building achieves net-zero operational carbon emission. Hence it is essential to investigate embodied carbon emissions through life cycle assessment (LCA) incorporating all stages of carbon emissions. Sahagun and Moncaster (2012) indicated in his studies that one should avoid shifting carbon emissions from one part (operational carbon) of the lifecycle to another (embodied carbon). Therefore, life cycle carbon emission is calculated using Life cycle Assessment (LCA) investigating operational and embodied carbon emissions collectively.

Several LCA studies have been conducted to calculate the environmental impact of the buildings. There are LCA studies of houses (Cuéllar-Franca et al., 2012, Monahan and Powell, 2011, Asif et al., 2007, Bribian et al., 2009), apartments (Blengini, 2009), universities (Lukman et al., 2009) and office buildings (Junnila and Horvath, 2003) in Europe.

In the UK housing sector, only five LCA case studies have been identified by the author. Monahan and Powell (Monahan and Powell, 2011) compared the embodied carbon of a contemporary timber frame construction in the UK with two traditional houses. However, this study only considered construction stage emissions and all LCA stages (cradle to grave) were not included in the study. Hammond and Jones (2008) conducted an LCA study on several houses in the UK but also considered only the construction stage emissions. Asif et al. (2007) calculated the embodied energy for a three-bedroom house in Scotland while Hacker et al. (2008) considered only the construction and use stage emissions.

As far as the author is aware, Cuéllar-Franca and Azapagic (2012) is the only study in the UK that conducted a whole life LCA on houses that includes modules from A1-C4 (cradle to grave). However, this LCA study was on three traditional dwellings, and there is no whole life LCA study found on contemporary houses in the UK. Indeed, no study in the UK also compares the lifetime carbon emissions of the contemporary house (new) with the traditional house (old). Therefore, the study's goal is to identify the whole life cycle carbon emissions (cradle to grave) of a contemporary house using LCA and compare the results with the traditional house (Cuéllar-Franca and Azapagic, 2012) to identify the trend of carbon emission in the UK houses.

## 3. Methodology

There are different types of contemporary houses concerning various construction techniques practised, and their carbon emissions vary drastically. Therefore, a quantitative analysis might result in an imprecise result. To calculate the house's carbon emissions through LCA, it is fundamental to identify the quantity of materials used in the building. Therefore, the methodology section of the research presents the material quantity calculation, followed by the parameters and boundaries of the LCA study.

### 3.1. Approach for data collection and case study selection

Offsite manufacture and modern method of construction (MMC) are energy-efficient construction techniques with low material wastage and a quicker time frame when compared with conventional in-situ construction. The UKGBC roadmap proposes increasing MMC investment (UKGBC, 2021a). Farmer (2016) recommends in his report that the UK government should promote the use of pre-manufactured solutions and incorporate them into policies.

In 2017, The UK government announced a £44bn in funding for five years to boost housing delivery and prioritise offsite construction (GCR, 2017). It is seen that MMC is growing rapidly, and many houses are expected to build using MMC in the coming years. Therefore, selecting a house built using offsite construction would be more optimal for this research to conduct LCA. The research case study, New Ferry House by Starship Group developers, incorporated complete offsite construction with all building elements made offsite except the foundation. In addition, the New Ferry house type (terraced) and it’s gross internal area are identical to the traditional house’s LCA study conducted by Cuéllar-Franca and Azapagic (2012). Therefore, to facilitate a better comparison between contemporary (this research) and traditional (Cuéllar-Franca and Azapagic, 2012), the New Ferry project by Starship Group developers is selected as the case study for this research.

### 3.2. Description of case study and parameters

The selected case study is located in a temperate climate zone in Wirral, near Liverpool, UK. It was designed by Shack Architecture and built by Starship Modular developers in 2021. The house elements were premade using panelised construction technique (offsite construction) in the Dee Side factory located 40 km away from the site (see figure 3). Further, the building elements were assembled on-site (see figure 4). The project comprises three zero energy terraced houses (see figures 5 and 6), with only one house considered for this research.

Figure 3. Offsite manufacture at Deeside factory (Starship Group, 2021)

Figure 4. MMC - assembly of building elements at site (Starship Group, 2021)

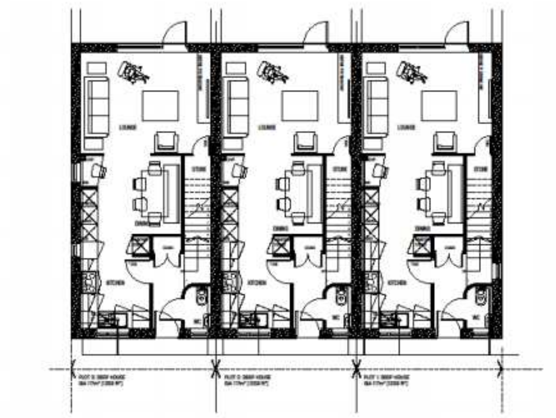

Figure 5. Ground floor plan (Starship group, 2021)

Figure 6. Completed zero energy house (Starship group, 2021)

A two-storied terraced house with a kitchen, dining and living rooms on the ground floor extending to a small backyard (see figure 5). The first floor comprises two bedrooms with a toilet and the second floor incorporates a master bedroom with an attached bathroom. Foundation is made of ready-mix concrete. The main structure is light gauge steel, which is the frame for attaching the building envelope (roof, floors, and exterior walls). The external walls comprise rock wool insulation, PIR insulation, timber studs, brick cladding and light gauge steel frame. The internal walls are made of timber stud framework, insulation in between and plasterboards on both sides. The roof is made primarily of the Light gauge steel frame, rock wool insulation, composite panel, and roof tiles. Floors comprise mainly PIR insulation, chipboard and carpets. Windows are low emissive, argon filled, triple glazed with UPVC frames. Doors are made of UPVC. The key parameters of the zero-energy terraced house are indicated in Table 1 below.

**Table 1.** Case study parameters:

| Parameters | Case study description |
|---|---|
| Location/Climate | The United Kingdom/Temperate Climate |
| Building/Usage type | Residential, new built |
| Construction type | Offsite construction |
| Gross Floor Area | 138m$^2$ |
| Internal Floor Area | 114m$^2$ |
| Heating and Cooling system | 8kW Air source heat pump |
| PV system | 4.62kWp Monocrystalline photovoltaic system |
| MVHR | 91% efficiency |
| Number of floors | 3 |

The thermal standards of the building were identified from the SAP report collected from the builder and indicated in Table 2 below

Table 2. Thermal standards of the building

| | | | |
|---|---|---|---|
| **External Wall** | 0.13 $W/m^2k$ | **Air permeability** | 3.1$m^3/m^2h$ @50Pa |
| **Floor** | 0.13 $W/m^2k$ | **Air change rate** | 2.5ach |
| **Roof** | 0.11 $W/m^2k$ | **DER** | -0.8kg $CO_2e/m^2$ |
| **Openings** | 1.44 $W/m^2k$ | **DFEE** | 39 $KWh/m^2/yr$ |
| **Window** | 1.01 $W/m^2k$ | **Door** | 1.0 $W/m^2k$ |

### 3.3. Modelling and quantity calculation

From the architecture and detailed drawings provided by Starship Group developers, the house was modelled in Revit to get the quantities of all materials used in the construction of house. Every building element, such as foundation, external walls, party walls, internal walls, floor, roof, internal and external doors, windows were modelled (see figure 7). Refer to Table 3 for the building elements and components included in this research and their quantities. Components such as furniture, plumbing fixtures, electrical fixtures, kitchen interiors, sanitary fixtures, toilet tiles, lighting fixtures, switchboards, staircase, screws, bolts, and energy systems, were not modelled and not considered in the scope of LCA for this research. Outdoor elements such as parking and fence were not considered in this study due to limited timeframe.

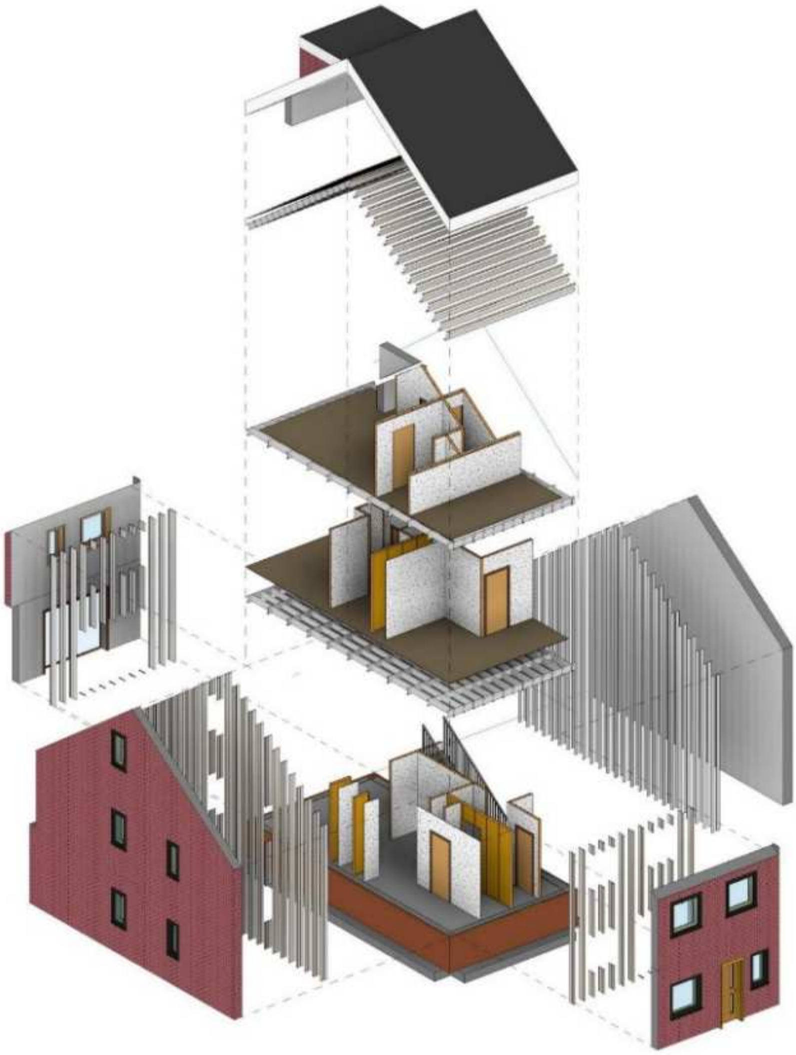

Figure 7. Exploded view of the building elements modelled in Revit

Table 3. Materials used for the construction of the case study

| Element | Thickness (mm) | Components/materials | Surface ($m^2$) | Volume ($m^3$) |
|---|---|---|---|---|
| 1. Foundation and substructure | | Foundation and grade beam | - | 16.65 |
| | | Concrete blocks | - | 6.45 |
| | | Concrete T beam | - | 4.30 |
| | | Hollow bricks | - | 3.64 |
| 2.VERTICAL STRUCTURE | | | | |
| 2.1 External walls | 15 | Brick Slip and mortar cladding | 113 | 1.70 |
| | 12.5 | Cement Particle board | 114 | 1.42 |
| | 120 | PIR insulation | 115 | 13.71 |
| | 12.5 | Glassroc X sheathing board | 115 | 1.44 |
| | 100 | Rockwool Insulation | 249 | 26.83 |
| | 15 | Gyprock board (British gypsum) | 498 | 7.46 |
| | 12.5 | Cedral Cladding | 36 | 0.22 |
| | - | Self-adhesive breather membrane (Wraptite) | 116 | - |
| | 0.15 | Vapour Control layer | 249 | - |
| | | Treated timber batten (50mmx25mm) | | 0.54 |
| | 50 | Mineral wool insulation | 5 | 4.99 |
| | 11 | Orient Strand board | 1.4 | 1.46 |
| 2.2 Load bearing structure | 100x1.5 | Light gauge steel frame (Column, beam, Slab) | | 0.6 |
| 2.3 Internal Walls | 50 | Isover Insulation | 78 | 3.9 |
| | 12.5 | Gyproc plaster board | 206 | 2.58 |
| | 38 | Timber studs (38mmx75mm) | 27.6 | 1.07 |
| 3. HORIZONTAL STRUCTURE | | | | |
| 3.1 Floor and Ceiling | 75 | Floor Screed | 43 | 3.23 |
| | 150 | PUR insulation | 43 | 6.46 |
| | 19 | Chipboard Flooring | 86 | 1.90 |
| | 9 | Carpet | 129 | 1.16 |
| | 0.15 | Vapour Control Layer | 43 | - |
| | - | Damp-proof membrane | 52 | - |
| | 12.5 | Gypsum board (ceiling) | 120 | 1.5 |
| 3.2 Roof | 0.05 | Metal Slate roof tile | 73 | |
| | 120 | Sandwich/composite Panel | 73 | 8.71 |
| | 100 | Rockwool Insulation | 73 | 7.26 |
| | 12.5 | Gyprock board | 145 | 2.18 |
| | - | Self-adhesive breather membrane (Wraptite) | 145 | - |
| 4. OTHER | | | | |
| 4.1 Windows and Door | - | UPVC doors | 23.09 | - |
| | - | UPVC Triple glazed windows | 10.12 | - |
| | | | Total | 131.3 |

### 3.4. Life cycle assessment (LCA) methodology and input parameters

Following the quantity calculation of building materials, the carbon emissions of those materials are calculated through life cycle assessment (LCA) using One-Click LCA software. It is a web-based software designed explicitly for LCA of construction products and incorporates

EPDs, completed together with upstream data from the established LCA database (Rabani et al., 2021). The One-Click LCA software is compliant with EN 15978 standards (Petrovic et al., 2019). In One-Click LCA, EPD is the primary source of information; LCI and LCIA data required for life cycle assessment (LCA) are included within the EPD (Shaun, 2021).

There are four different types of data available in OneClick LCA for the users: generic, manufacture, private, and plant data. Manufacture data includes EPDs provided by the manufacturer for the specific product, and it is used when the exact manufacturer and model of the product are known. Generic data EPD is the average emission of a product, which is country specific. It could be used when the exact manufacturer is unknown (OneClickLCA, 2018). Plant data presents the EPD of products based on specific factories where it is manufactured, and this option is used when products are directly sourced from nearby plants (Steven, 2021).

As this research's case study is already built and the builder provided information (manufacturer name and model) of most material used, the order of preference with data type choices while selecting the EPDs in OneClick LCA is as follows:

1. When the exact manufacturer and model of the building material are known, manufacturer data was chosen to get the precise results.
2. Though the manufacturer and model name are known, some manufacturers' EPDs were unavailable in the OneClick LCA database. In this scenario, materials' density and thermal conductivity were identified, and similar EPDs from other manufacturers were chosen.
3. Some building materials by the builder were purchased from dealers, and neither the model number nor the density of materials was known. In this scenario, generic EPDs representing UK average emissions were chosen.
4. When the UK generic EPD is unavailable, generic EPD from the closest European countries such as the Netherlands, Belgium, and France was selected.

### 3.5. LCA Boundaries

Table 4 represents the life cycle modules considered in the lifecycle assessment for the New Ferry case study. The following sections present the source of data for each stage of analysis.
Table 4. LCA boundaries of the case study

| Product stage | | | Construction stage | | Use stage | | | | | | | End of life stage | | | | Beyond system boundary | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Raw material supply | Transport | Manufacturing | Transport to site | Construction and Installation | Use | Maintenance | Repair | Refurbishment | Replacement | Operational energy | Operational water | Deconstruction & Demolition | Transport | Waste processing | Disposal | Reuse | Recovery | Recycling |
| A1 | A2 | A3 | A4 | A5 | B1 | B2 | B3 | B4 | B5 | B6 | B7 | C1 | C2 | C3 | C4 | D | D | D |
| ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| *✓ - modules included in LCA for this case study | | | | | | | | | | | | | | | | | | |

Product stage (A1-A3):

The product stage covers cradle to gate process emission for building elements (components/materials) used for building construction. 26 different building materials were identified in this case study, excluding doors and windows. The product stage emissions of all these materials are calculated in the software. Table 5 represents the 26 different material and their respective EPDs chosen in OneClick LCA.

Construction stage (A4, A5):

*A4:* The software automatically includes transport distance and mode based on the parameters chosen in the software. The parameter determined is "UK-RICS". This incorporates transport distance (UK average) and transportation mode according to RICS guidelines. Refer to table 5 for transport distance considered for all 26 materials.

*A5:* As it is an offsite manufacturer incorporating MMC, only the energy consumption for excavation is included in A5 stage emissions. From the foundation drawings provided, it was found that a total of 44.2m$^3$ of land was excavated for this case study. "UK generic data for excavation work" representing 1.3kg$CO_2$e/m$^2$ removed is chosen in the software. This LCA study did not include energy consumed by small machinery such as impact wrench tools for bolting.

Use stage (B1-B7):

B1-B5: The B4 and B5 stage emissions are dependent on the service life of the materials used in the building (OneclickLca, 2021). 'Technical service life' was determined as it is the recommended option by the software when the service life of all materials is unknown. See Table 5.

*B6:* As the case study house was recently built in 2021 and unoccupied yet, neither the energy bills nor the post-occupancy evaluation (POE) is available to calculate the operational energy use. Therefore, the SAP report provided by the developer was used. The Dwelling fabric energy efficiency (DFEE) is 39 kWh/m$^2$/yr. This is equivalent to 4436kWh heating demand annually, summing to 221,800kWh operational energy use for 50 years. Please note that this calculation has ignored future warmer climates and possible heating demand reduction in the houses. The operational energy use is converted to operational carbon emissions using the UK electricity conversion factor of 0.233kg$CO_2$/kWh (BEIS, 2021b). From the calculation, it was found that the operational carbon emission of this case study is 51,710 kg$CO_2$e.

*B7:* As the house is unoccupied, assumptions of annual water usage have to be made from other literature studies. Cuéllar-Franca and Azapagic (2012) assumed occupancy of 2.3 people for an average UK household size with daily water consumption of 150L per person in their traditional house LCA study. This is equivalent to 6280$m^3$ of water usage over a 50year period. The same amount of water usage has been considered in this study. In the software, "UK generic tap water, clean" emissions representing 0.3kg$CO_2$e/$m^3$ of water consumed are chosen to calculate the operational carbon emissions of water usage.

Demolition stage (C1-C4):

In the software, the "Material locked (recommended)" option was chosen for the End-of-life calculation method. In this option, the C1-C4 end of life emissions are grouped, and the emissions are calculated automatically by the software (Shaun, 2022). Deconstruction/demolition emissions from RICS guidelines representing 3.4kg $CO_2$e/$m^2$ of GIA demolished are considered by default in the software for UK projects.

Building service life:

RICS recommends a service life of 60years for LCA study (RICS, 2017). However, many authors have considered 50 years as the service life for research purpose (Cuéllar-Franca and Azapagic, 2012, Bribian et al., 2009, Ortiz et al., 2009). To facilitate the comparison of results with other papers, 50 years is considered as the service life for this research.

Table 5. One-click LCA EPD, service life and transport distance of building materials

| Components/Materials | Trans port (km) | Service life (years) | One-click LCA EPD chosen | Technical specification (Density, thermal resistance) |
|---|---|---|---|---|
| 1. FOUNDATION AND SUBSTRUCTURE | | | | |
| Foundation and grade beam | 50 | 50 | Ready-mix concrete | C32/40 – 10% recycled |
| Concrete blocks | 300 | 50 | Precast concrete block | 1425.0 $kg/m^3$ |
| Concrete T beam | 300 | 50 | Precast T beam | 33.4 kg/m |
| Hollow bricks | 300 | 50 | Hollow bricks | 127.0 $kg/m^2$ |
| 2.1 EXTERNAL WALLS | | | | |
| Brick Slip and mortar cladding | 300 | 50 | Red brick average | 1485$kg/m^3$ |
| Cement Particle board | | | | |
| PIR insulation | 300 | 50 | Fibre cement board | 1300$kg/m^3$ |
| Glassroc X sheathing board | 300 | 50 | PIR rigid insulation | 33.08 $kg/m^3$,R=5.45$m^2k/W$ |
| Rockwool Insulation | 300 | 40 | Gypsum sheathing | 758$kg/m^3$ |
| Gyprock board (British | 300 | 50 | Rockwool Insulation | 50$kg/m^3$, R=2.89$m^2k/W$, |
| gypsum) | 300 | 50 | British Gypsum board | 668$kg/m^3$ |
| Cedral Cladding | 300 | 50 | Fibre cement slates | 1950$kg/m^3$ |
| Self-adhesive breather membrane (Wraptite) | 1500 | 30 | 4layer vapour permeable underlay | 0.173 $kg/m^2$ |
| Vapour Control layer | 1500 | 30 | Plastic vapour control | 933$kg/m^3$, (0.15mm thick) |
| Treated timber batten (50mmx25mm) | 1500 | 50 | Treated GLT | 450$kg/m^3$ |
| Mineral wool insulation | 300 | 50 | Glass wool | 75$kg/m^3$, R=3.03$m^2k/W$ |
| Orient Strand board | 300 | 50 | Orient strand board | 610$kg/m^3$ |
| 2.2 LOAD BEARING STRUCTURE | | | | |
| Light gauge steel frame (Column, beam, Slab) | 10000 | 50 | Structural hollow steel, Cold rolled | 7850$kg/m^3$, 20% recycled content |
| 2.3 INTERNAL WALLS | | | | |
| Isover Insulation | 300 | 50 | Glass/mineral wool(iso | 24$kg/m^3$, I=0.039w/mK |
| Gyproc plaster board | 300 | 50 | British Gypsum plaster | 668$kg/m^3$ |
| Timber studs (38mmx75mm) | 1500 | 50 | Planed timber, conifer | 420$kg/m^3$ |
| 3.1 FLOOR, CEILING | | | | |
| Floor Screed | 50 | 50 | Floor screed mortar | 1500$kg/m^3$ |
| PUR insulation | 300 | 50 | PIR insulation board | 32$kg/m^3$, R=3.33$m^2k/W$ |
| Chipboard Flooring | 300 | 50 | Chipboard, untreated | 633$kg/m^3$ |
| Carpet | 1500 | 15 | Carpet tiles | 4.462$kg/m^2$ |
| Vapor Control Layer | 1500 | 30 | Plastic vapor control | 933$kg/m^3$, 0.15mm thk |
| Damp proof membrane | 1500 | 30 | Damp insulation | 0.08$kg/m^2$ |
| Gypsum board (ceiling) | 300 | 50 | Gypsum plasterboard | 668$kg/m^3$ kg $CO_2e$ |
| 3.2 ROOF | | | | |
| Metal Slate roof tile | 10000 | 50 | LW steel roofing tile | 8.6$kg/m^2$, 0.6mm thk |
| Sandwich/composite Panel | 1500 | 50 | Sandwich panel | 104.2$kg/m^3$, R=7.14$m^2K/W$ |
| Rockwool Insulation | 300 | 50 | Rockwool insulation | 50$kg/m^3$, R=2.89$m^2k/W$ |
| Gyprock board | 300 | 50 | Gypsum plasterboard | 668$kg/m^3$ |
| Self-adhesive breather membrane (Wraptite) | 1500 | 30 | 4layer vapor permeable underlay | 0.173$kg/m^2$ |
| 4.1 WINDOWS AND DOOR | | | | |
| UPVC doors | 1500 | 40 | PVC frame doors | 79.5$kg/m^2$, R=1.6$m^2k/W$ |
| UPVC Triple glazed windows | 1500 | 40 | Triple glazed PVC frame window | 27.4$kg/m^2$ |

## 4. Results

The results section will discuss the whole life cycle carbon emissions of the New Ferry case study (contemporary house), and its operational and embodied carbon contribution.

### 4.1. Life cycle carbon: Classification by modules (stages)

For the New Ferry case study, it was found that the operational carbon contributes to 51t $CO_2e$ (45%) in the B6 module, whereas the embodied carbon contributes to 62t$CO_2e$ (55%) in A1-A3, B1-B5 and C1-C4 modules. figure 8 represents the operational, embodied carbon contribution of the New Ferry case study and its respective life cycle module.

The contemporary house's total life cycle carbon emission is 113t$CO_2e$ over 50 years. Considering future decarbonization of grid energy, it is possible that operational carbon can become zero, and embodied carbon could contribute to 100% emissions.

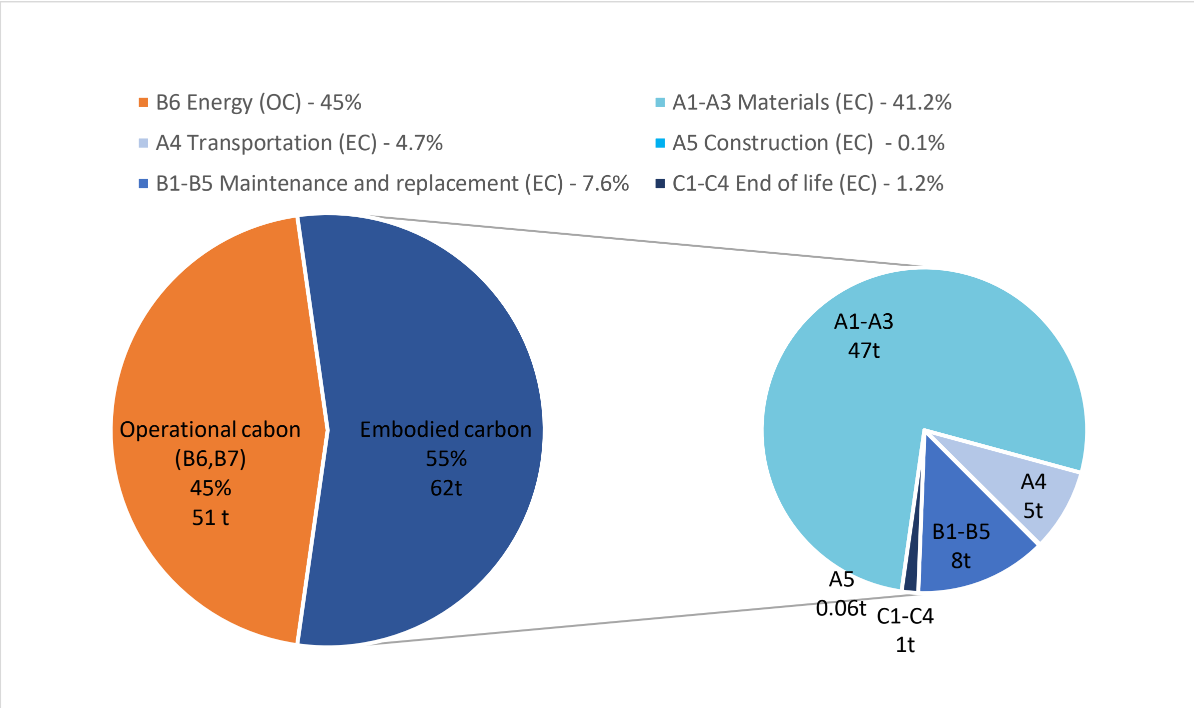


Figure 8. Carbon emissions of the case study (contemporary) over its lifetime; the share of embodied and operational carbon in different LCA modules [tonnes$CO_2e$]

### 4.2. Comparison with a traditional terraced house – embodied carbon doubled

The LCA results of the contemporary house in this study are compared with another traditional house LCA results to identify the drift in carbon emissions in the UK houses. The LCA study conducted by Cuéllar-Franca and Azapagic (2012) on traditional terraced house revealed that the operational and embodied carbon emissions are 282t$CO_2$e and 26t$CO_2$e, summing up to a total of 309t$CO_2$e during its lifetime. The operational carbon emissions of the contemporary house (this research) are 51t$CO_2$e, whereas the embodied emissions are 62t$CO_2$e, summing to a total of 113t$CO_2$e (see figure 9).

From the comparison, it is evident that the improved fabric of the contemporary houses built these days have aided in reducing total life cycle carbon emissions of houses by reducing the operational carbon significantly from 282t$CO_2$e to 51t$CO_2$e. However, the embodied carbon has increased by 2.3 times of the traditional house, from 26t$CO_2$e to 62t$CO_2$e. This is due to the high amount of steel frame, insulation, UPVC doors, and triple glazing in contemporary houses.

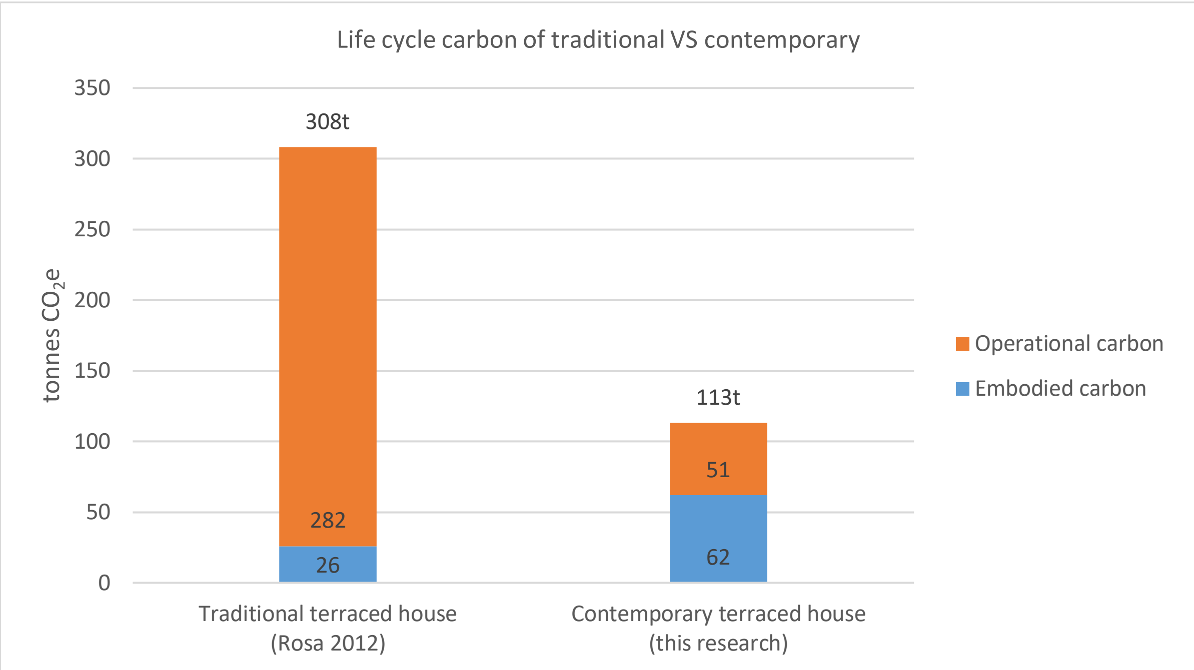


Figure 9. Lifetime carbon emission comparison of traditional house with contemporary house (this research); the share of embodied and operational carbon

### 4.3. Embodied carbon

The building accounts for 62t$CO_2$e over a period of 50 years. This is equivalent to 543kg$CO_2$e/$m^2$ of gross internal floor area (GIA). As seen in figure 10, the majority of embodied emissions are from the product stage (A1-A3) itself, accounting for 412kg$CO_2$e/$m^2$ (75%); followed by the B1-B5 use stage with 75kg$CO_2$e/$m^2$ of (14%); A4 transport stage with 47kg$CO_2$e/$m^2$ (9%); C1-C4 End of life stage with 11kg$CO_2$e/$m^2$ (2%) respectively.

The embodied carbon contribution of different building elements in tonnes and their percentage contribution is as follows:

- Horizontal structure (floor slabs, ceiling, roof) - 15.3t$CO_2$e (25%)
- External walls and façade – 15t$CO_2$e (24%)
- Load bearing structure (column, beam) – 13t$CO_2$e (22%)
- Foundation and substructure – 10t$CO_2$e (16%)
- Windows and doors – 7.3t$CO_2$e (12%)
- Internal walls – 0.9t$CO_2$e (1.5%)

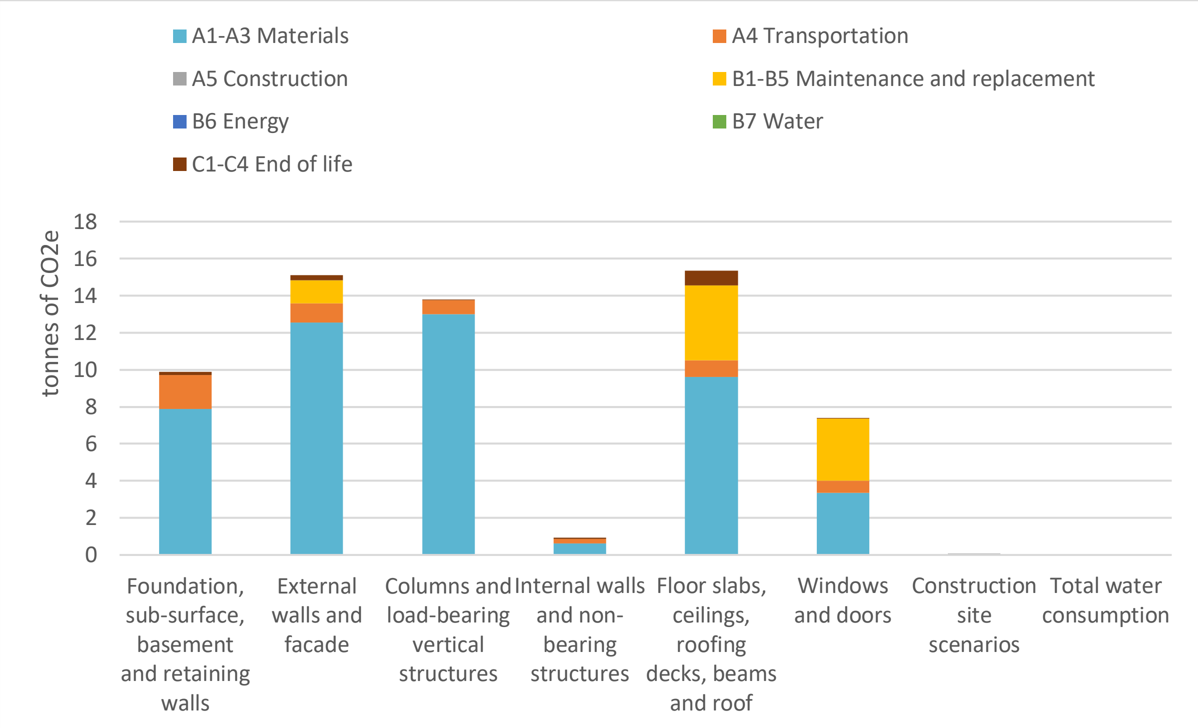


Figure 10. Embodied carbon emissions with respect to building elements in different life cycle stages

A1-A3:

The product stage emissions are highest in load-bearing structures (column, beam), followed by external walls (see figure 10). This is due to the use of light gauge steel for framing, which accounts for 14t$CO_2$e (22%) of total life cycle carbon emissions.

B1-B5:

Horizontal structure and openings alone account for more than 80% of maintenance replacement emissions (B1-B5) (see figure 10). This is due to the shorter service life of carpets (15years), and doors and windows (40 years). Thus, it is seen that building elements with shorter service life increases the embodied carbon emissions.

## 5. Discussion

Life cycle carbon emissions of a contemporary house in the UK have been assessed through LCA. The research now focuses on the main strategies and material alternatives to reduce embodied carbon emissions in buildings.

### 5.1. Major carbon contributors from this case study

The Embodied carbon emissions of building elements in this case study is 62 tonnes CO2e. Detailed analysis of materials resources used in the buildings revealed that steel frames, insulation, and openings themselves account for more than 60% of total embodied carbon emissions (see figure 11). Therefore, further research was conducted to find the alternatives for these materials with various scenarios. Emissions from these three resources and the individual building element are presented in figure 11.

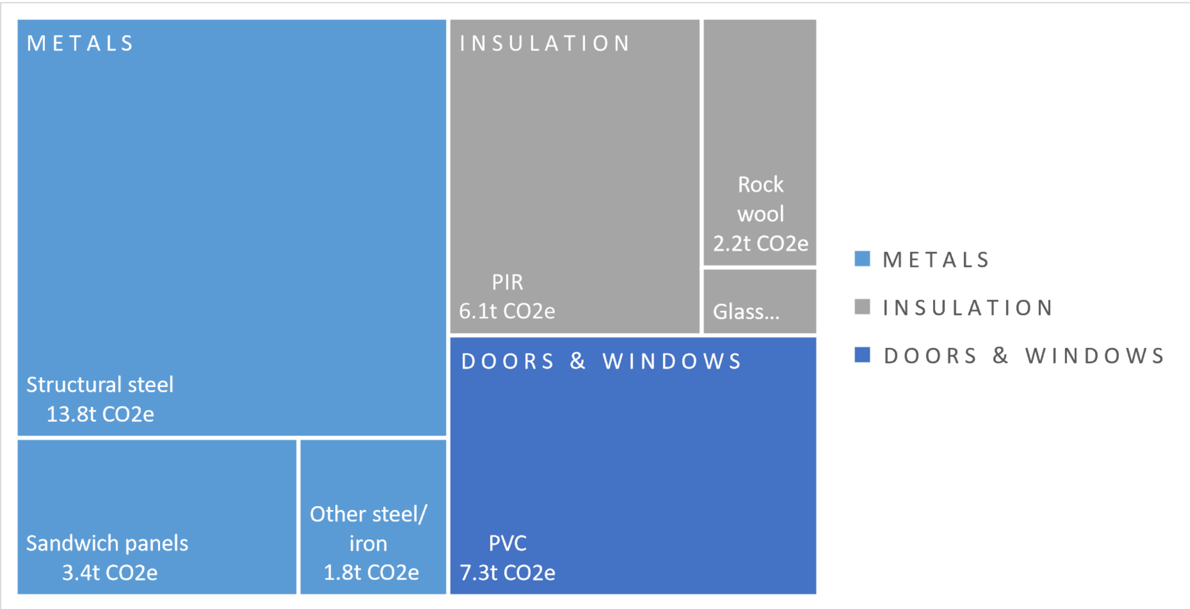


Figure 11. Major embodied carbon contributors (metals, insulation, openings) of the case study; building materials and respective carbon emissions [expressed in tonnes kgco2e]

### 5.2. Scenario 1 – Low carbon manufacturers or products alternative

The first scenario looks at alternative sourcing of the same materials from other low carbon manufacturers. This scenario is to insist on the benefits of sourcing the same materials from low carbon-emitting manufacturers or products as alternatives without any changes to the thickness or size of the existing materials. While selecting the alternatives, the same density and thermal resistivity were considered for steel, insulation. Refer to Table 7 for existing materials and the respective alternatives chosen in different scenarios.

The results show that the embodied carbon emissions can be reduced by 15t$CO_2$e from 62t$CO_2$e to 47t$CO_2$e when sourced from manufacturers and selecting products which has low embodied carbon (see figure 13).

### 5.3. Scenario 2 – Organic material alternative

The second scenario considers organic elements as an alternative that serves the same purpose. This scenario does affect the design of the existing house as the size and thickness of the building elements have to be altered to achieve the same strength or thermal standards. For example, cellulose insulation proposed in this scenario needs double the thickness of existing PIR insulation to achieve the same thermal resistivity. This scenario incorporates a timber structure replacing steel structure as shown in figure 12.

The results show that the embodied carbon emissions can be reduced by 24t$CO_2$e from 62t$CO_2$e to 38t$CO_2$e when organic materials are selected as alternatives (see figure 13).

Figure 12. Proposed timber frame structure

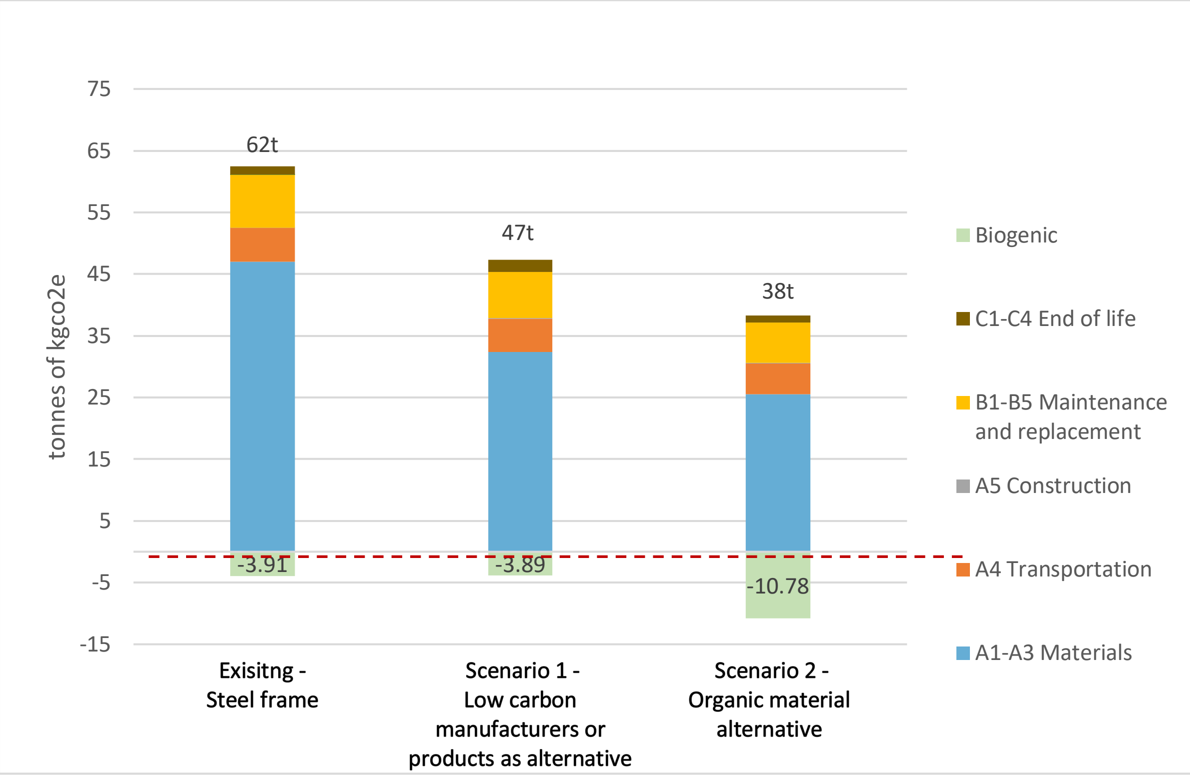


Figure 13. Existing case study embodied carbon and proposed scenarios embodied carbon emission

From the above scenarios, it is seen that the embodied carbon of contemporary houses can be reduced from 62t$CO_2$e to 47t$CO_2$e with a material selected from low carbon manufacturers or products (scenario 1) (see figure 13). In comparison, a more significant reduction in embodied carbon emission to 38t$CO_2$e is possible with organic materials (scenario 2) such as timber frames, cellulose insulation and wooden frames for openings. Therefore, for the practitioners (Architects, developers and builders), low carbon or organic products are crucial to reduce embodied carbon in their practice.

### 5.4. Biogenic carbon:

Biogenic carbon is the carbon stored in biologic materials such as plants or soil. The biogenic carbon in the existing building and scenario 1 are approximately 3.9t$CO_2$e, whereas the biogenic carbon in scenario 2 increased drastically to 10.7t$CO_2$e (see figure 13). This is due to the use of organic building elements which has high biogenic as indicated in table 7.

In scenario 2, when the biogenic carbon storage (10.7t$CO_2$e) is subtracted from the life cycle emissions, the house's carbon emissions reduce from 38t$CO_2$e to 28t$CO_2$e over its lifetime. Therefore, in addition to a selection of low carbon materials, it is essential that indicating building elements with high biogenic content would also aid in reducing lifetime carbon emissions significantly.

Table 7. Existing case study materials and proposed alternatives

| **Existing** | **Scenario 1 – Low carbon manufacturer or product alternative** | **Scenario 2 – Organic material alternative** |
|---|---|---|
| ***Load bearing structure***<br>Cold rolled steel, generic, 20 % recycled content<br>GWP: 21628.12 kg $CO_2$e / m$^3$ | Structural steel profiles, generic, 90% recycled content<br>GWP: 5808.05 kg $CO_2$e / m$^3$ | Glued laminated timber (GLT) Duobalken® und Triobalken®<br>GWP: 291.4 kg $CO_2$e / m$^3$<br>Biogenic: 932.0 kg $CO_2$e / m$^3$ |
| ***Wall insulation***<br>PIR rigid insulation boards (KNAUF)<br>GWP: 153.33 kg $CO_2$e / m$^3$<br>***Floor insulation***<br>Floor: PIR insulation board (Quinn)<br>GWP: 174.55 kg $CO_2$e / m$^3$ | PIR insulation board (Xtratherm Limited)<br>GWP: 137.42 kg $CO_2$e / m$^3$<br><br>PIR rigid insulation boards (KNAUF)<br>GWP: 134.62 kg $CO_2$e / m$^3$ | Blown loose-fill cellulose insulation R=7 m$^2$K/W (ECIA)<br>GWP: 7.4 kg $CO_2$e / m$^3$<br>Biogenic: 17.5 kg $CO_2$e / m$^2$<br>Blown loose-fill cellulose insulation R=7 m$^2$K/W (ECIA)<br>GWP: 7.4 kg $CO_2$e / m$^3$<br>Biogenic: 17.5 kg $CO_2$e / m$^2$ |
| ***Doors***<br>Dark coloured PVC frame doors and windows, R = 1.6 m$^2$K/W (GIMM Menuiseries)<br>GWP: 73.6kg $CO_2$e/m$^2$<br>***Window***<br>Triple-glazed PVC frame window (Munster Joinery)<br>GWP: 139kg $CO_2$e/m$^2$ | White coloured, PVC frame doors and windows, R = 1.6 m$^2$K/W (GIMM Menuiseries)<br>GWP: 54.0 kg $CO_2$e / m$^2$<br><br>Triple-glazed PVC frame window (Munster Joinery)<br>GWP: 76.4 kg $CO_2$e / m$^2$ | Wooden frame Doors<br>GWP: 12.74 kg $CO_2$e / m$^2$<br>Biogenic: 23.83 kg $CO_2$e / m$^2$<br><br>Triple glazed Wooden frame windows<br>GWP: 80.4 kg $CO_2$e / m$^2$<br>Biogenic: 28.7 kg $CO_2$e / m$^2$ |

## 6. Conclusion

Many practising firms and the UK government are promoting to delivery of 'zero operational energy house' to reduce carbon emissions from buildings. Therefore, this research conducted LCA on a real-life contemporary terraced house built using MMC and found that the 'zero operational energy house' emits 78t$CO_2$e of embodied carbon over its lifetime.

It was found that the contemporary house (New Ferry case study) contributes to 62t$CO_2$e (55%) embodied carbon and 51t$CO_2$e (45%) operational carbon summing up to a total of 113 tonnes of carbon emission over a lifetime of 50 years. Compared with a traditional house, the results revealed that the contemporary houses have significantly reduced operational carbon emissions from 390t$CO_2$e to 51t$CO_2$e . However, the UK's embodied carbon of contemporary (new built) houses has increased by 2.3 times the of traditional houses. And when the building services that aid in achieving net-zero operational carbon are included in LCA, the embodied carbon further increases, accounting for 100% life cycle emissions.

With the shift in increasing embodied carbon emissions of houses in the UK, the research investigated strategies and alternatives to reduce embodied carbon emissions. Further, this research looked at different scenarios for top five carbon contributing materials and revealed that embodied carbon emissions could be reduced by 20% with a selection from low carbon manufacturers/products and by 40% with organic materials.

Material recycling and future work:

Building material recycling is crucial in reducing end-of-life emissions. Many materials in this case study could be recycled with the recent innovations in recycling. Further studies could be carried out on material recycling of net zero operational houses to identify the percentage of possible recycling.

In this case study, the steel containing the highest embodied carbon is highly recyclable. However, the energy consumed to recycle steel is significantly higher compared to other building materials recycling processes. Therefore, it is an important factor to examine the recycling process in addition to the use of recycled materials in buildings.

Limitations of this study:

There are 26 different materials involved in this New Ferry case study. Due to the limited timeframe, the alternative scenarios proposed (section 5.3) considered low carbon alternatives only for the top five carbon contributing building elements. With the optimal low carbon material alternatives chosen for all the 26 materials of the building, it is clearly ambitious to achieve the life cycle zero energy house standards (LCZEB) or even a lifetime carbon-negative house.

## 7. Acknowledgement

Special thanks to Ms Yashika Narula for helping me with the data collection and supporting me throughout the research.

I would like to thank Mr Karl Ventre from Starship group developers for showing interest and providing information about the zero-energy house in Liverpool.

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# The influence of indoor thermal environment on the performance of university students

**Mosaab Alaboud[1] and Hanan Al-Khatri[2]**

[1] Department of Architectural Engineering, Faculty of Engineering, Taibah University, Medina, 42353, Saudi Arabia, maboud@taibahu.edu.sa

[2] Department of Civil and Architectural Engineering, College of Engineering, Sultan Qaboos University, Oman, khatri@squ.edu.om

**Abstract:** Cooling buildings in all year-round high temperatures associated with Saudi Arabia's extreme climatic conditions has become increasingly expensive. To reduce the operating cost of its HVAC system, Taibah University has introduced an energy and cost saving programme in its facilities. The aim of the programme is to adjust indoor thermal conditions while maintaining comfort at acceptable levels for the majority of occupants. Considering the importance of thermal comfort for the health and productivity of students, this paper evaluates thermal comfort conditions in three architectural studios in the Department of Architectural Engineering at Taibah University. The studio environments were assessed both objectively and subjectively and their influence on students' productivity was evaluated. The objective assessment included measuring indoor air temperature, globe temperature, air velocity, and relative humidity, whereas the subjective assessment questioned the students' thermal sensations and preferences to assess their general comfort conditions. It was found that 59.3% of the investigated students were (slightly cool), (neutral), or (slightly warm); yet, an equal percentage preferred to be (a bit cooler), which highlights the influence of the climatic and cultural background. It is worth mentioning that around 54.7% and 53.5% reported overall discomfort state and unacceptance of their thermal ambience. The relation between the thermal conditions and productivity was statistically insignificant. Applying Griffiths' method revealed a comfort temperature of 24.3 ± 2.76 °C and 23.4 ± 2.76 °C in terms of indoor air and globe temperatures, respectively. Apparently, the energy saving programme has no negative effect on the students' thermal perception or productivity. Yet, this may be due to the usage of self-reported questions about productivity. Future research is highly recommended to investigate the students' productivity applying other measures and to explore the environmental and economic impact of the followed energy saving programme.

**Keywords:** Thermal comfort, Comfort temperature, Students, Performance, Educational buildings

**Nomenclature**

| | |
|---|---|
| **HVAC** | Heating, ventilation, and air conditioning |
| **ATC** | Adaptive thermal comfort |
| **PMV** | Predicted mean vote |
| **PPD** | Predicted percentage of dissatisfied |
| **ASHRAE** | American Society of Heating, Refrigerating and Air-Conditioning Engineers |
| **TSV** | Thermal sensation vote |
| **HSV** | Humidity sensation vote |
| **AVSV** | Air movement sensation votes |
| **TPV** | Thermal preference vote, |
| **HPV** | Humidity preference vote |
| **AVPV** | Air movement preference votes |
| $T_a$ | Air temperature, [°C] |
| $T_g$ | Globe temperature, [°C] |
| $T_c$ | Comfort temperature, [°C] |

## 1. Introduction

Saudi Arabia holds the second largest oil reserves and the sixth largest natural gas reserves in the world (GASME, 2016), which may illustrate the untenable ongoing energy consumption in the country. It is estimated that the domestic consumption accounts for approximately 35% of the total oil and gas production (Fawkes, 2014). Buildings' operation alone is responsible for consuming 29% of energy. Accordingly, and in line with 'Vision 2030', energy efficiency initiatives were established in buildings, industry, and transportation sectors. Indeed, the decrease in electricity usage by governmental buildings has increased by 11.1% in 2020 compared to 2019. Referring to the three sectors, i.e. buildings, industry, and transportation, the saving from energy efficiency initiatives was estimated as 357k oil barrels a day in 2020 compared to 2019. It may worth mentioning that around 82% of this decrease was from buildings' sector alone.

Moreover, a primary aim of 'Vision 2030' is to decrease oil usage locally in the three key sectors of building, transport, and industry, to a degree that equates to approximately 1.5 million barrels per day (SEEC, 2022). Thus, a reform policy of energy price was established with the aim of encouraging rational consumption of energy and gradually removing the energy subsides (including electricity price). It is planned to arrive at market prices by 2025, while restructuring the social safety net to support eligible citizens and families (Fiscal Balance Program, 2019). Currently, the electricity tariff of governmental buildings is the highest at 32 halalh/kWh. Considering the extreme climatic conditions of Saudi Arabia, it is not surprising that cooling load represents 70% of the electrical energy consumption in buildings. It is worth mentioning that the electricity demand is expected to increase to 22 GW by 2030 because of the high demand on cooling (ECRA, 2020).

In line with these attempts, Taibah University has introduced an energy and cost saving programme in its facilities. Taibah University is a Saudi governmental university in Medina city. Founded in 2003, there are currently 69210 students enrolled in different programmes in the university. Most the university buildings are pre-fabricated buildings including the investigated one. The aim of the programme is to adjust indoor thermal conditions while maintaining comfort at acceptable levels for the majority of occupants. Accordingly, the Heating, ventilation, and air conditioning (HVAC) system is turned off from November to March and partially turned on in April.

A variable indoor temperature standard will help save energy in both free running and air-conditioned buildings (Nicol & Humphreys, 2002). The adaptive thermal comfort model allows for a temperature comfort range that can lead to significant energy reduction especially from the cooling and heating systems. However, according to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 55's, adaptive thermal comfort (ATC) guidelines may be applied to buildings where among other requirements, no mechanical cooling or heating system is operational (Mishra et al., 2016). On the other hand, the heat balance model is recommended for mechanical system buildings. This static model of thermal comfort, however, underestimates the comfort level of the occupants in air conditioning buildings. Al-ajmi and Loveday's (2010) field study conducted during the summers of 2006 and 2007 investigated the indoor climate and occupants' thermal comfort in 25 air-conditioned domestic buildings in the dry-desert climate of Kuwait. It was found that the actual mean vote of the occupants in air-conditioned buildings is higher than that of the predicted mean vote by around 2 °C. Accordingly, the authors suggested the application of the adaptive approach to account for a range of adaptation effects that might cause this differential.

Nicol (2016) critically discussed the assumption that buildings with a mechanical heating or cooling system have a narrower indoor temperature range than those without. The author illustrates that the heated and cooled regions have a greater range of indoor temperature (about 15 K) than does the free-running region (about 8-10 K). This outcome contradicts the result expected in most standards and guidelines which assume that conditioned buildings will have the narrower temperature range (Nicol, 2016). Moreover, Alshaikh & Roaf (2016) investigated the thermal performance and thermal comfort level of 17 air-conditioned buildings in Dammam, Saudi Arabia. Field measurements and surveys were carried out in August 2013 to assess the occupants' thermal comfort by using the adaptive thermal comfort (ATC) method. From the findings, it is evident that people accommodate a widely varying range of indoor temperatures during their day-to-day lives (between 20 °C to 35 °C). It is obvious that occupants in AC residential buildings in Saudi Arabia have adapted to higher temperatures, and this tolerance or adaptation reduces the use of electrical energy.

Fanger's 1970 definition of thermal comfort as "the condition in which the subject would prefer neither warmer nor cooler surroundings" is similar to Markus and Morris's definition (1980) as "that state in which a person will judge the environment to be neither too cold nor too warm — a kind of neutral point defined by the absence of any feeling of discomfort". The literature acknowledges that the perception of comfort is subjective; it is subject to physiological variables such as gender, age, and physical conditions. Individuals in the same place at the same time may be dissatisfied with their environmental conditions for reasons related to biological, emotional, and physical variances (Jitkhajornwanich, 1999). Therefore, although comfort is beyond objective measurement, the literature sets out a range of conditions within which 80% or more of people would feel comfortable, and this range is known as the "comfort zone".

Although human physiology can be measured and numerically expressed, the different responses of physiologically similar individuals to share thermal conditions cannot be expressed in a formula (Jitkhajornwanich, 1999). Indeed, there is no single temperature which is universally recognized as a guarantor of thermal comfort. As confirmation of cultural and regional discrepancies, a 1976 study estimated British notions of indoor comfort at 17 °C, while Iraqi notions were estimated at around 32°C (Humphreys, 1976). These discrepancies in neutral temperatures reflect the role of acclimatisation, i.e. adapting to different climates, and, therefore, emphasises the value of performing micro-level studies of thermal comfort (Al-Khatri et al., 2021). An example of the comfort zone is estimated at temperatures between 21°C and 28°C (in tropics, 24-30 °C), with relative humidity 30% to 70% (Jitkhajornwanich, 1999). This range is an approximation as there is no precise criterion by which comfort can be evaluated. Indeed, such zones vary depending on the choice of clothing worn, activities performed, as well as the individual's acclimatisation or familiarity with the climatic conditions. There is, therefore, no exact boundary of the comfort zone.

The absence of an exact boundary is unsurprising given that thermal comfort is evaluated using different models and indices, some of which exclude the analysis of individual needs. Given the variety of indices used for comfort assessment, Lamberti et al., (2021) recommend that the configuration of any proposed model for the evaluation of classroom thermal comfort should take into account the individual needs and preferences of the occupants. Therefore, research must go beyond what the literature calls "single dose-response systems" which may, for example, rely upon previously validated notions of indoor comfort based on the needs of adults rather than up-to-date requirements of adolescents in classroom-based studies. A methodology for understanding the impact of the indoor environment should be formulated around interactions at both human and environmental levels.

### 1.1. Thermal comfort and productivity

The identification of an optimum thermal environment that empowers students to perform to the best of their abilities while controlling a building's energy consumption at a time of unprecedented increases in the energy cost has attracted significant attention (Jowkar et al., 2019). Predicting thermal comfort in a built environment is increasingly relevant because thermal comfort model has great potential for energy saving (Zhao et al., 2021). Additionally, the importance of providing healthy indoor environments has become even more evident in the wake of the COVID-19 pandemic, which required people to spend more time in a healthy indoor atmosphere.

Thermal comfort is a non-negotiable condition of university classrooms and lecture halls because it underpins the educational aim of maximising learning and productivity performance. The post-pandemic challenge to achieve thermal comfort in university buildings under the extreme conditions associated with the hot dry climates has become more significant given the difficulties in providing and maintaining indoor air quality without compromising thermal comfort and energy consumption. To meet the challenge, an accepted definition of thermal comfort as well as the measurement model best suited to monitor it must be agreed upon. Lamberti et al., (2021) suggested that post-pandemic, the focus on achieving thermal comfort should include preventing negative effects as well as creating positive effects for human health. Educational buildings must be designed or adapted to post-pandemic and climate change conditions, while maintaining a human-centred approach. Given the variety of indices that have been used for comfort assessment, it is important to define a model for the evaluation of global thermal comfort in classrooms, which should take into account the individual needs and preferences of occupants.

Thermal comfort in any environment is determined by several environmental and individual factors. The environmental factors are air temperature, radiant temperature, relative humidity and air speed, while the individual factors are clothing and metabolic rate. The interactions of these six factors determine a thermal boundary in which an individual feels comfortable. This boundary is also subjective and, therefore, it is quite complex to define what combinations of these factors will produce a feeling of 'thermal neutrality', where the building occupant is neither too hot nor too cold i.e. comfortable (Ogwezi et al., 2012). The literature links potential reductions in energy consumption to the design characteristics of a building's envelope and to poorly monitored HVAC systems (Lamberti et al., 2021).

Mushtaha & Helmy (2016) compared the thermal comfort levels of mosques in the UAE to determine the best performing geometrical shape. Choosing the optimal design, the incorporation of passive elements, particularly envelope thermal insulation, into the mosque construction significantly improved thermal comfort and could reduce the annual energy consumption by 10%. However, this 10% reduction could not by itself achieve thermal comfort. The introduction of an ancillary hybrid air-conditioning system could reduce the annual energy consumption by 67.5%, thereby permitting the design of a smaller HVAC system which would deliver thermal comfort.

Kamar et al., (2019) study examined strategies for improving thermal comfort inside a mosque building in Malaysia. Initial measurements indicated that airflow velocity, air temperature, relative humidity and the mean radiant temperature contributed to uncomfortable conditions. To increase airflow velocity and reduce air temperature, it was found that ten exhaust fans, one metre in diameter, and placed at a height of 6 metres from the floor, could reduce the predicted mean vote (PMV) index between 75% and 95% and the predicted percentage of dissatisfied (PPD) index between 87% and 91%.

To conclude, the adaptive approach is a more dynamic interpretation of thermal comfort. It is based on the assumption that occupants take conscious actions in addition to the body's involuntary physiological responses (sweating, shivering etc) to achieve thermal comfort. The adaptive model is responsive to reductions in energy usage, which is becoming an economic imperative in hot climatic conditions. The adaptive model is popular because it is considered more straightforward and user-friendly than the PMV model. Besides, outdoor air temperature values are the only data needed to estimate the comfort range (Djamila, 2017).

There is a large comfortable temperature range under adaptive thermal comfort, which means that the energy usage from cooling and heating systems can be lowered effectively (Mishra et al., 2016). However, the heat balance model is suggested when it comes to mechanical system buildings. In addition, it should be noted that the occupants' comfort level in buildings with air conditioning is often underestimated under the static model of thermal comfort.

Furthermore, the use of different models to analyse comfort can influence field studies' outcomes and should be carefully planned. Future studies should focus on the most rational evaluation of thermal comfort, also considering how local discomfort can impact the perception of an environment. Several studies refer to the inter-locking relationship between HVAC systems, building envelopes and thermal comfort, and in an era characterised by the increased price of energy, their effect on energy consumption is also referenced.

Student evaluation of the comfort of their environment is not restricted to thermal comfort alone; consideration of indoor air, acoustic, and visual quality will influence student perceptions of what constitutes a healthy environment and indeed contribute to increased productivity. Thus, educational buildings must be adapted to post-pandemic and climate change conditions.

This paper evaluates thermal comfort conditions in three architectural studios in the Department of Architectural Engineering at Taibah University. The studio environments were objectively and subjectively assessed and any links between them and changes in students' productivity has been recorded. The objective assessment included measuring indoor air temperature, globe temperature, air velocity, and relative humidity, whereas the subjective assessment questioned the students' thermal sensations and preferences to assess their general perceptions of comfort conditions. Lamberti et al., (2021) emphasise that a model to evaluate global classroom thermal comfort should account for individual student needs and preferences. Local individual discomfort should be assessed to inspect students' satisfaction and to investigate why students located in certain positions achieve higher productivity in the classrooms.

### 1.2. Case study climatic conditions

The investigated case study is located in Medina city, Saudi Arabia (latitude 24.4° N and longitude 39.6° E). The city is Located in the Hijaz region in the west of Saudi Arabia and 500 kilometres north of Makkah. The three selected studios are located on the first floor of a building located in a district called Taibah, west of Medina, as presented in Figure 1. One of the studios is facing south west and the other two are orientated to the North West.

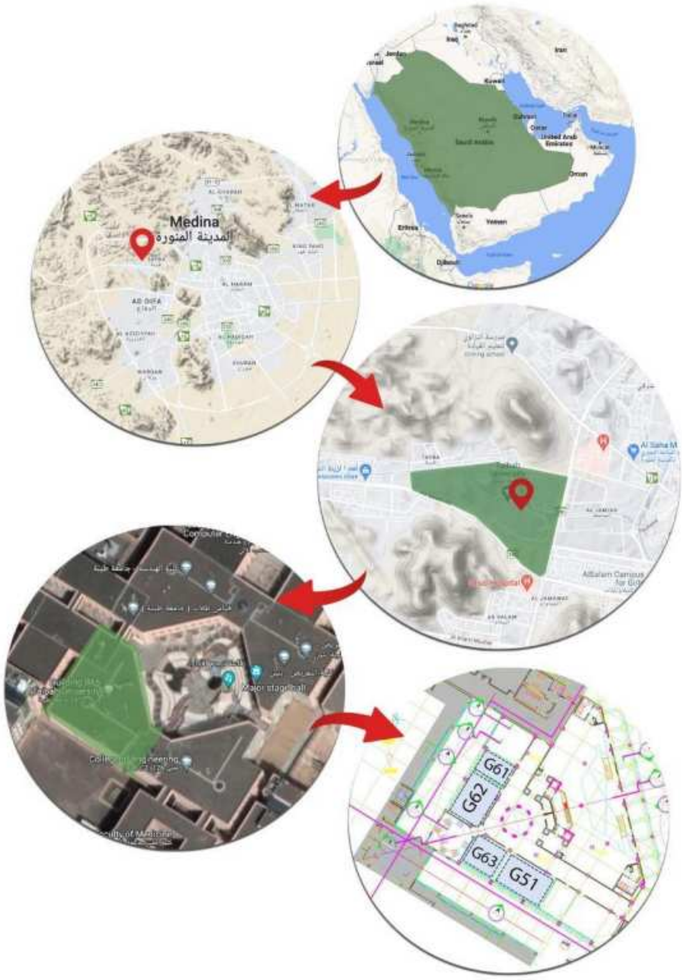



Figure 1. The case study location

The historical climatic graphs of Medina city are presented in Figure 2. Air temperature varies throughout the year between 12 °C to 44 °C. The hot season includes June, July, and August when the average monthly temperature is roughly 38 °C and the relative humidity ranges from 5 to 20%. In winter, which extends from November to February, the average temperature is 20 °C and the humidity ranges between 20 and 50%. Throughout the year, the average daily incidence of solar radiation varies substantially from more than 8 kWh/m$^2$ in summer (except for cloudy days, where it is lower) to roughly 5 kWh/m$^2$ in winter. The length of the day in Medina varies from around 11 to 13 hours over the year. Besides, wind speed has an average of 3 m/s of the year, rising to around 4 m/s in summer and falling to 2.5 m/s in winter.

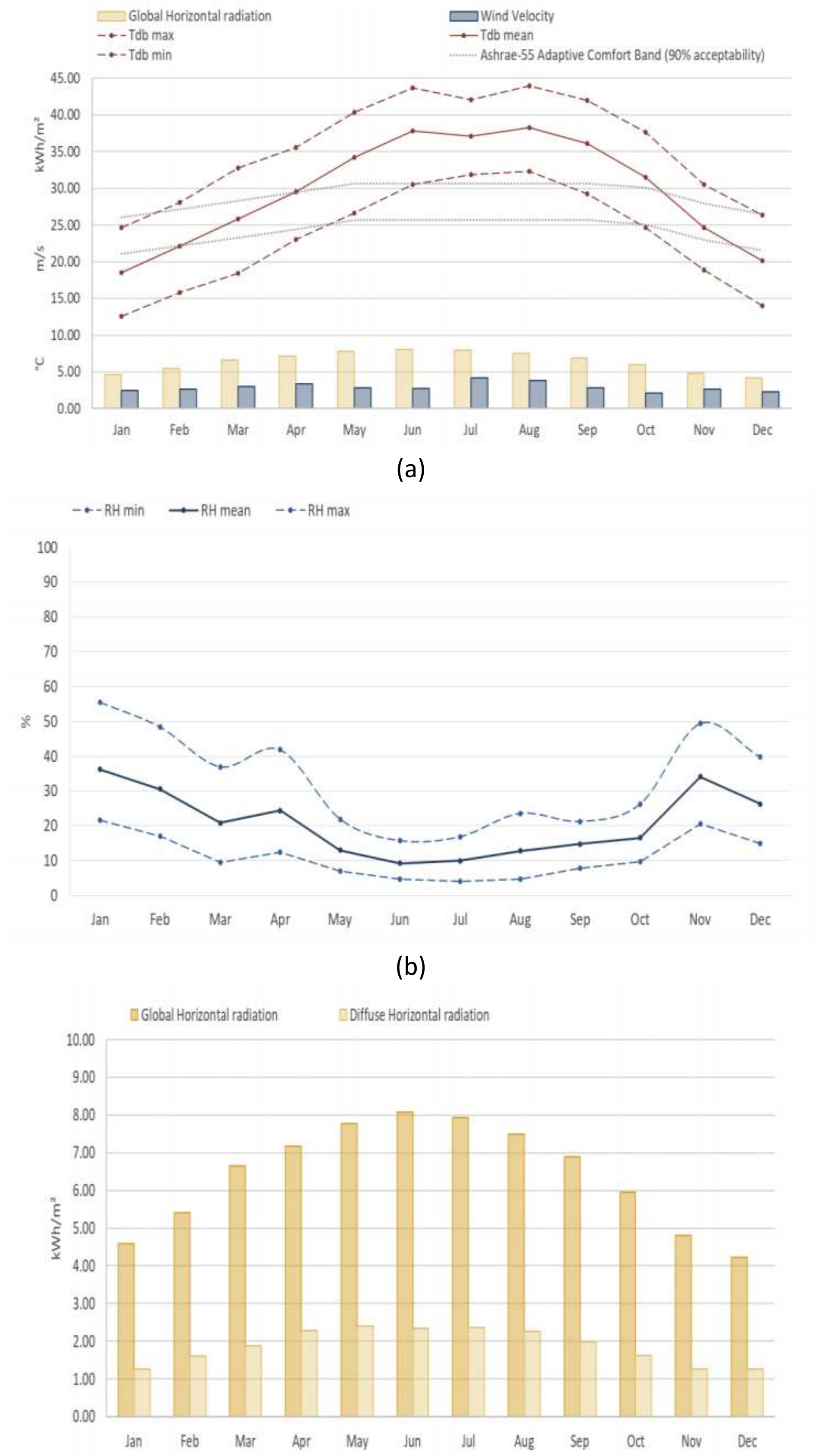



Figure 2. Historical climatic graphs of Medina city: (a) Monthly average climate conditions, (b) Average monthly relative humidity, and (c) Average monthly global and diffuse solar radiation

## 2. Methodology

Considering the occupation pattern of the studios, the measurements were conducted nine times over three days in three studios. Table 1 lists the sensors that collected the objective data. For the subjective data, a questionnaire that consists of five sections was prepared. These sections were personal data, thermal conditions, activities, self-reported productivity, and clothing. ASHRAE thermal sensation scale and Nicol preference scale were applied. For the self-reported productivity, the questions of (Lipczynska et al., 2018) as displayed in Table 2 were adopted. It is worth mentioning that the questionnaires' distribution coincided with the fasting month when the students terminate consuming food from sunrise to sunset.

Table 1. Sensors used for collecting objective data

| Variable | Sensor | Range | Accuracy | Note |
|---|---|---|---|---|
| Indoor air temperature | Tecpel AVM714 Hot wire anemometer & Extech HT30 Globe temperature | 0 to 50 °C | ±0.8 °C<br>±1.0 °C | Spot measurement<br>Spot measurement |
| Globe temperature | Extech HT30 Globe temperature | 0 to 80 °C | ±2 °C | Spot measurement |
| Air velocity | Tecpel AVM714 Hot wire anemometer | 0.2~20.0 m/s | ±3% + 1 digit | Spot measurement |
| Relative humidity | Extech HT30 Globe temperature | 0 to 100% | ±3 % | Spot measurement |
| Surface temperature | ANGGO Infrared Thermometer Temperature | −50 to +420 °C | ±1.5 °C | Spot measurement |

Table 2. Questions of self-reported productivity: 1 means the lowest score and 5 means the highest score (Lipczynska et al., 2018)

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| I am sleepy | | | | | | I am alert |
| It is difficult for me to concentrate | | | | | | It is easy for me to concentrate |
| I do not fell productive | | | | | | I feel very productive |

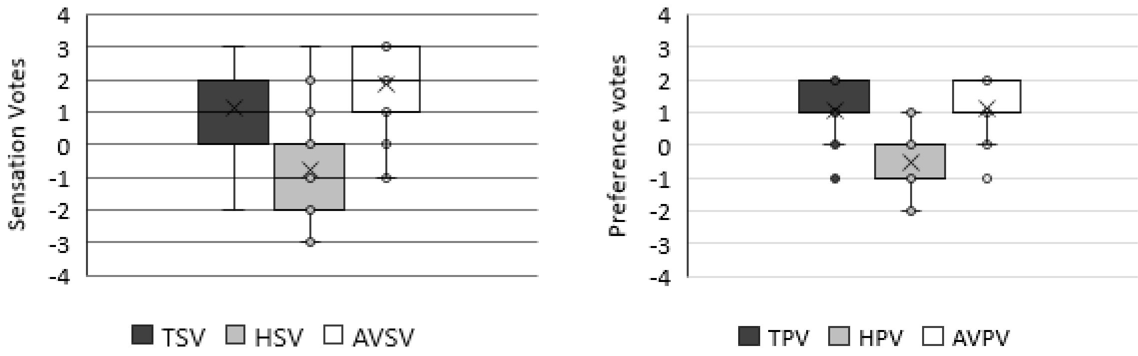
## 3. Results and Discussion

A total of 114 questionnaires were distributed in nine times in 3 studios. Around 24.6% of the distributed questionnaires were rejected due to incomplete or inconsistent answers. An answer was considered inconsistent if the sensation and preference were on opposite sides of the thermal continuum. Considering the analysed questionnaires, more than 65% of the students were 21 and 22 years old. Likewise, more than 87% reported healthy status.

Applying Fisher's exact test with a significance level of 0.05 revealed an extremely statistically significant association between comfort and acceptance among the participants.

This means that the students related their comfort state to the thermal conditions of their ambience. Indeed, around 54.7% and 53.5% of the students reported being uncomfortable and unaccepting the thermal environments of the explored studios, respectively.

The spread of the students' sensations and preferences are presented in Figure 3. The students' sensations and preferences skewed to the warm side of the continuum, except those of humidity. This may be related to the absence of humidity receptors in the human body, which makes it difficult to sense or evaluated humidity levels in the surrounding environment as far as they are within a normal range, i.e. 40% to 60%. Another reason may be related to the possible social embarrassment that a student may feel if reported being wet. Moreover, around 31.4%, 22.1%, 19.8%, and 19.8% of the students were (neutral), (slightly warm), (warm), and (hot), consequently. Collectively, the students with the three central sensations, i.e. slightly cool to slightly warm, formed 59.3% roughly. Interestingly, 12.8%, 59.3%, and 25.6% approximately preferred (no change), (a bit cooler), and (much cooler), respectively. This may be related to the influence of the students' climatic and cultural background, which was reported in previous studies within a similar context (Al-Khatri et al., 2021; Al-Khatri et al., 2020). For the air movement sensation votes (AVSV), almost 10.5%, 17.4%, 31.4%, and 37.2% reported (neutral), (slightly slow), (slow), and (very slow), respectively. This resulted in falling of around 8.1%, 64.0%, and 25.6% of the preferences in (no change), (a bit faster), and (much faster) categories, consequently.




(a) (b)

Figure 3. The boxplots of students': (a) Sensation votes and (b) Preference votes

Furthermore, the distribution of the students' preferences on the sensation categories was explored as presented in Figure 4. It is observed that all students with (slightly warm), (warm), or (hot) sensations preferred to be (a bit cooler) or (much cooler). Around 83.3% of those reported being (wet) or (slightly wet) preferred to be (a bit drier) and almost 80.0% of those (slightly dry) or (very dry) preferred to be (a bit wetter). Considering air movement, it is noticed that around 93.3%, 77.8%, and 50.0% of those reported (slightly slow), (slow), and (very slow) respectively preferred (a bit faster) air movement. (Much faster) movement was the preference of almost 22.2% and 50.0% of the students who reported (slow) and (very slow) air movements, respectively.

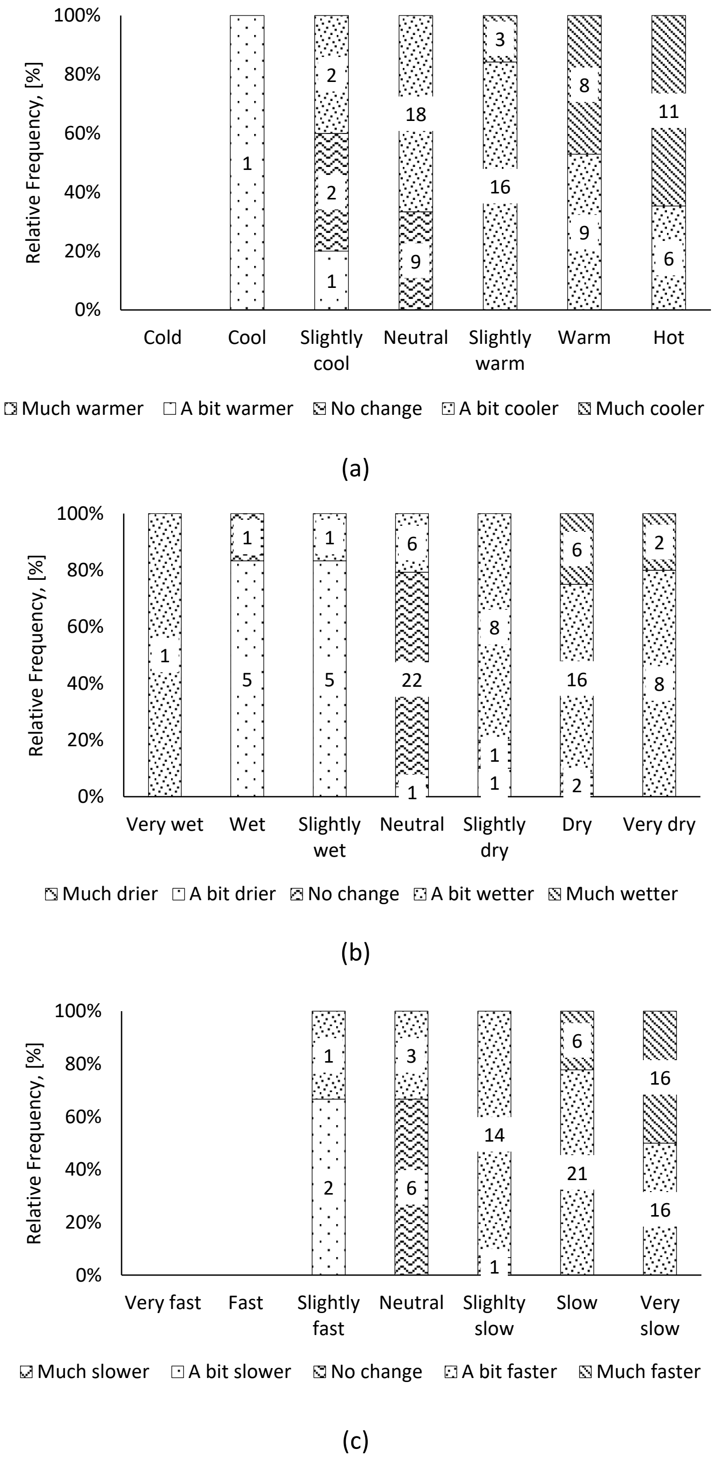



Figure 4. Distribution of preference votes on sensation categories: (a) thermal, (b) relative humidity, and (c) air movement (Labels are students' numbers)

The students were involved in limited activities during the last 15 minutes before distributing the questionnaires with almost 52.5% and 24.6% of the students sitting involved in active and passive work, respectively. Other activities were standing and walking indoors and outdoors. It is worth mentioning that such activities had no influence on the students' overall comfort, acceptance, sensation votes, or preference votes as the correlations were very weak. Similarly, the clothing level had no influence on the students' perception of their studios. Almost one third of the investigated students wore the traditional clothing, i.e. thowb or dishdasha.

The productivity levels as reported by the students are displayed in Figure 5. In spite of their cluster on the warm side of the thermal continuum, only around 17.4%, 14%, and 15.1% of the students reported the lowest levels of alertness, ability to concentrate, and overall productivity, respectively. The consequent percentages of the students that reported the third level, which can be considered neutral, were around 26.7%, 36.0%, and 45.3%. Besides, 19.8%, 11.6%, and 15.1% approximately reported the highest levels in the three categories, respectively.

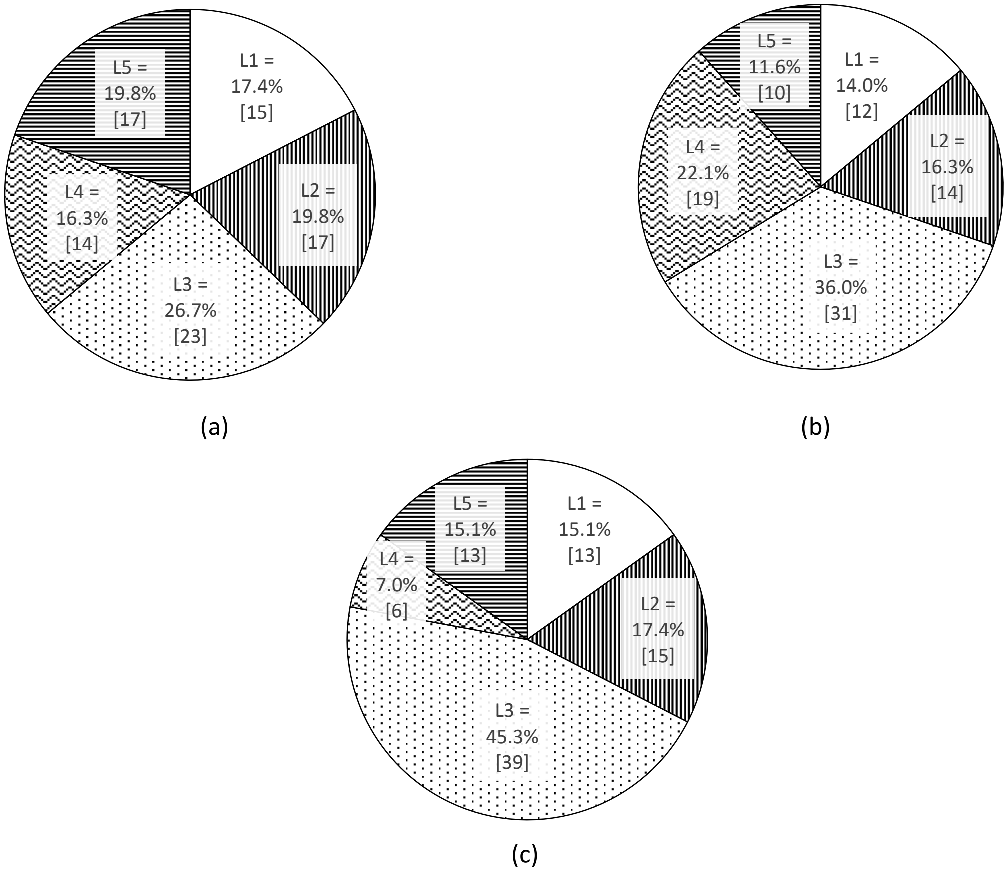



Figure 5. Levels of self-reported productivity: (a) Sleepiness/Alertness, (b) Concentration, and (c) Overall productivity (L1 is the lowest and L5 is the highest)

The association between acceptance, comfort, the three central sensation votes, (no change) preference, alertness, concentration, and productivity was investigated as displayed in Table 3. As expected, acceptance and comfort were strongly correlated with a coefficient of +0.790. Likewise, the correlation between humidity sensation and preference was +0.714. Considering students' productivity, it was correlated to their alertness and concentration with positive moderate coefficients of +0.456 and +0.646, respectively. Interestingly, the relations between productivity and the students' sensations or preferences were statistically weak. This may be related to the timing of questionnaires' distribution as mentioned earlier.

Table 3. Association between acceptance, comfort, central sensation votes, (no change) preference, alertness, concentration, and productivity (bold indicate moderate or strong association)

| | Acceptance | Comfort | TSV | TPV | HSV | HPV | AVSV | AVPV | Alertness | Concentration | Productivity |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Acceptance** | - | 0.790 | -0.661 | -0.519 | 0.147 | 0.096 | -0.525 | -0.330 | -0.042 | 0.050 | 0.004 |
| **Comfort** | 0.790 | - | -0.623 | -0.381 | 0.230 | 0.109 | -0.529 | -0.435 | -0.077 | 0.168 | 0.099 |
| **TSV** | -0.661 | -0.623 | - | *0.694* | -0.147 | -0.198 | 0.651 | 0.548 | 0.154 | -0.047 | 0.062 |
| **TPV** | -0.519 | -0.381 | 0.694 | - | -0.123 | -0.169 | 0.540 | 0.477 | 0.061 | 0.042 | 0.010 |
| **HSV** | 0.147 | 0.230 | -0.147 | -0.123 | - | 0.714 | -0.190 | -0.253 | 0.075 | -0.062 | 0.040 |
| **HPV** | 0.096 | 0.109 | -0.198 | -0.169 | 0.714 | - | -0.124 | -0.350 | 0.127 | -0.040 | 0.050 |
| **AVSV** | -0.525 | -0.529 | 0.651 | 0.540 | -0.190 | -0.124 | - | 0.679 | 0.031 | -0.069 | -0.009 |
| **AVPV** | -0.330 | -0.435 | 0.548 | 0.477 | -0.253 | -0.350 | 0.679 | - | 0.091 | -0.048 | 0.032 |
| **Alertness** | -0.042 | -0.077 | 0.154 | 0.061 | 0.075 | 0.127 | 0.031 | 0.091 | - | 0.382 | 0.456 |
| **Concentration** | 0.050 | 0.168 | -0.047 | 0.042 | -0.062 | -0.040 | -0.069 | -0.048 | 0.382 | - | 0.646 |
| **Productivity** | 0.004 | 0.099 | 0.062 | 0.010 | 0.040 | 0.050 | -0.009 | 0.032 | 0.456 | 0.646 | - |

Considering the relatively small size of the participants, Griffiths' method was applied to compute the neutral or comfort temperature ($T_c$) using the equation (Indraganti & Boussaa, 2018; Manu et al., 2016):

$$T_c = T + (0 - TSV) / G \quad (1)$$

A slope (G) of 0.5 was used following the recommendations of (Al-Khatri et al., 2021; Haddad et al., 2019). The neutral temperature of the investigated students was 24.3 °C ± 2.76 and 23.4 °C ± 2.76 in terms of indoor air and globe temperatures, respectively. In a comparison with the findings of (Al-Khatri et al., 2021), these temperatures tend to be cooler and their ranges are wider. Besides, the 80% and 90% acceptability levels were calculated as presented in Table 4.

Table 4. Thermal acceptability limits

| | **Lower limit** | | **Upper limit** | |
|---|---|---|---|---|
| | **$T_a$, [°C]** | **$T_g$, [°C]** | **$T_a$, [°C]** | **$T_g$, [°C]** |
| **80% acceptability level** | 22.6 ± 2.8 | 21.7 ± 2.8 | 26.0 ± 2.8 | 25.1 ± 2.8 |
| **90% acceptability level** | 23.3 ± 2.8 | 22.4 ± 2.8 | 25.3 ± 2.8 | 24.4 ± 2.8 |

## 4. Conclusions

An energy saving programme was applied at Taibah University to efficiently manage the usage pattern of the HVAC system in the educational spaces. The influence of the thermal conditions of three architectural studios on the students' productivity was evaluated in this paper by means of a questionnaire and physical measurements. The findings revealed that almost 54.7% of the investigated students were thermally uncomfortable and around 53.5% considered the studio's environments unacceptable. However, 59.3% were comfortable based on the three central categories of the ASHRAE thermal sensation scale. The neutral temperature was calculated using Griffiths' method and a slope of 0.5 as 24.3 ± 2.76 °C and 23.4 ± 2.76 °C expressed as indoor air and globe temperatures, respectively. Additionally, the students' productivity was weakly related to their thermal perceptions, which may be associated with the bias of the applied method. Therefore, it is recommended to apply other means to quantify the students' productivity to explore the effect of their thermal environments. Furthermore, the environmental and economic savings of the energy saving programme applied in the university are worth exploring.

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# Impact of building design variables on natural ventilation potential and thermal performance: An evaluation in New Delhi, India

**Radhakrishnan Sanjeev Krishnan[1], Shobhit Chaturvedi[1,2] and Elangovan Rajasekar[1]**

[1] Indian Institute of Technology Roorkee, India, email: sr@ar.iitr.ac.in
[2] Pandit Deendayal Energy University, Gandhinagar, India

**Abstract:** Natural ventilation (NV) potential is a crucial factor in determining the indoor environment quality and occupant comfort of residential buildings. Optimisation approaches focused on energy efficiency do not always guarantee sufficient natural ventilation for health and comfort. This paper presents an optimisation framework for simultaneously enhancing the building's NV potential and energy performance. A mid-sized residential apartment unit located in the composite climate of New Delhi (Köppen climate classification: BSh) is considered. Particle Swarm Optimization (PSO) algorithm coupled Energy Plus simulations is employed for optimising building orientation, thermal property of wall & window, and window size parameters. PSO is implemented over a population of 50 solutions for 25 generations using a flexible graphical user interface to define the design variables, performance objectives and optimisation settings. We present a comparative assessment of the natural ventilation, indoor comfort and energy demand of solutions obtained from single objective and multi-objective optimisation approaches. The solution obtained using the proposed optimisation framework has significantly higher natural ventilation with a marginal increase in energy use. This study highlights the need to consider NV potential in building performance studies and highlights its relevance to the present-day context.

**Keywords:** Building Optimization, Particle Swarm Optimization, Natural Ventilation, Cooling Energy Demand, Thermal Comfort

## 1. Introduction

Buildings account for up to 40% of the global energy demand and 30% of $CO_2$ emissions. Improving building sector energy performance is vital to slow down the damaging effects of global warming and climate change (IEA, 2017; Kelso, 2012). Although buildings are responsible for substantial environmental impacts, they also offer a huge opportunity to achieve substantial $\mathrm{CO_2}$ reductions at little societal costs. Building Energy Codes (BECs) provide pathways to reduce energy consumption and improve thermal, visual comfort and indoor air quality. Several global regulatory frameworks, BREEAM, Green Building Label of China and LEED, USA, have incentivised sustainable construction practices (Evins, 2013; Shi et al., 2016). Implementing BECs is especially critical in Asia, Africa and South America, where a substantial portion of the building stock is yet to be constructed (Chaturvedi, Rajasekar, and Natarajan, 2020; Evins, 2013). Consequently, building energy efficiency improvement is becoming a core focus for designers and officials worldwide.

The Covid 19 pandemic has dramatically affected the building performance and comfort expectations. Individuals' daily life and behavioural patterns changed drastically during the pandemic. Many professionals and students now enjoy the flexibility to work or study at home, swelling residential energy demands (Cuerdo-Vilches et al., 2021; Mouratidis and Papagiannakis, 2021; Todeschi et al., 2022). People with medical problems like chronic respiratory disease, cardiovascular disease, diabetes, or even high blood pressure and cancer are expected to be at higher risk of Covid 19 (Agarwal et al., 2021). Thus, people, particularly those over 65 or anyone advised shielding for health reasons, now spend more time at home (Andreoni, 2022; Rume and Islam, 2020). The growing evidence of the rapid spread of Covid 19 spread in confined spaces has raised the need to improve building indoor air quality. Ventilation rates are recommended to be increased from the existing minimum requirement (CSIR, 2022; BIS, 2016) (Table 1). Thus, there is a growing focus on including indoor air quality in the building design process.

Table 1. Recommended values for ventilation rate (air changes per hour) in residential buildings.

| S. No. | Space | Air Changes per Hour (ACH) as per the National Building Code of India(NBC) 2016 | Recommended ACH in SARS-CoV-2 Scenario |
|---|---|---|---|
| 1 | Living | 3-6 | 4-7 |
| 2 | Bedroom | 2-4 | 3-5 |
| 3 | Kitchen | 6, Min. | 10, min. |
| 4 | Toilet | 6-10 | 8-12 |

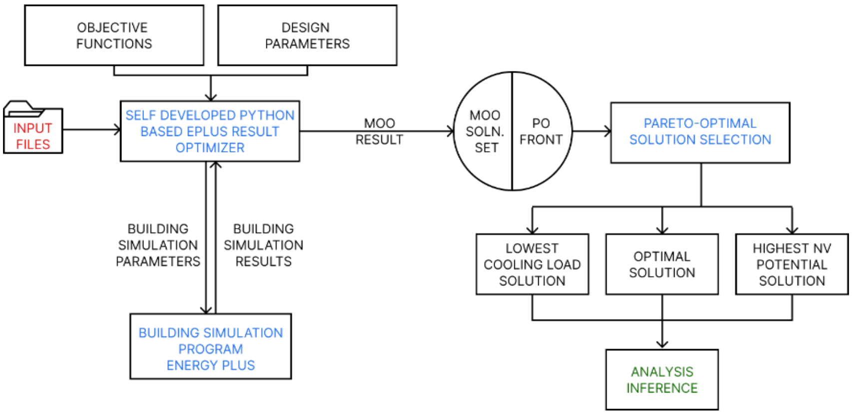
Building design involves systematically assessing numerous design parameters with complex interactions. Building Simulation Programs (BSPs) enable whole building analysis for assessing the integrated performance of building envelope, HVAC, lighting and renewable energy systems (Machairas, Tsangrassoulis, and Axarli 2014; Mariano-Hernández et al., 2021; Shi et al., 2016). BSPs like EnergyPlus, Trnsys and ESP-r facilitate rapid performance assessment of construction materials, building layouts, glazing types, air conditioners and electrical systems. Further, BSPs can perform optimisation to identify high-performance design solutions. Unlike the computationally intensive and time-consuming Brute-Force approach, which involve serial searching through every possible design option, optimisation approaches employ intelligent meta-heuristic (MH) algorithms like Genetic Algorithms, Particle Swarm Algorithms etc., at their core. MH algorithms rapidly identify the best possible building option by screening a vast array of design possibilities. Consequently, several studies adopted MH algorithms for building design optimisation problems. For instance, Vukadinovic et al. (Vukadinović et al., 2021) applied the NSGA II algorithm for the structural and architectural optimisation of a passive building with a sunspace in Serbia. Wang et al. (Wang, Lu, and Feng, 2020) investigated the benefits of including window ventilation and shading on building energy performance in Cold Climates via sensitivity analysis and multi-objective optimisation processes. Recently, Abdou et al. (Abdou et al., 2021) applied the NSGA II algorithm to combine optimal architectural energy efficiency practices with renewable energy production to obtain compromised building life cycle costs, energy-saving and thermal comfort across six Moroccan climate zones.

The studies, till now, focus predominantly on energy demand reduction (Ciardiello et al., 2020; Lee, Trcka and Hensen, 2013; Tuhus-Dubrow and Krarti, 2010), or energy demand reduction along with thermal comfort enhancement (Chegari et al., 2021; Hawila and Merabtine, 2021; Solmaz, 2018). Ventilation or Indoor air quality is not considered an optimisation objective along with energy consumption and discomfort hours reduction in any of the studies. Keeping in view the critical need for reducing India's residential energy demand and the growing focus on improved air quality, this study intends to present an MH optimisation approach for energy demand reduction while ensuring effective natural ventilation and thermal comfort. The objectives of the study are (1) to identify pareto-optimal solutions for enhancing NV and reducing energy demand using Particle Swarm Optimization(PSO) algorithm and (2) to demonstrate the potential impact on Indoor Air Quality(IAQ) and thermal comfort by incorporating ventilation effectiveness in Whole

Building Simulations(WBS). The approach is demonstrated considering a mid-sized residential apartment unit in India's composite climatic region.

## 2. Methodology

The methodology adopted for this study is shown in figure 1. We consider a mid-sized residential apartment unit with a floor area of 70 $m^2$ (figure 2), located in New Delhi, India. New Delhi (28.61° N, 77.21° E) represents BSh: Hot Semi-Arid region according to Köppen Geiger climate classification (Composite region as per India's National Building Code).



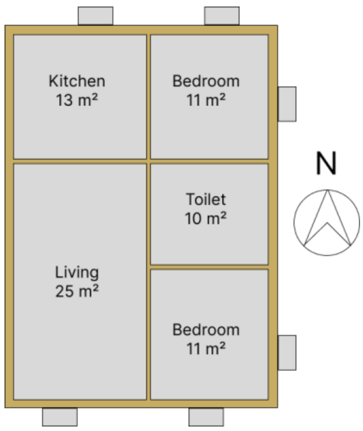




Figure 1. The building design optimisation process for minimising energy demand and enhancing NV.

Figure 2. Floor plan of the residential unit considered for simulations.

The building is modelled in Energy Plus (v8.9) simulation program. As shown in figure 2, the building model consists of five zones, namely, Living(L), Kitchen(K), Toilet(T), Bedroom 1(B1), and Bedroom 2(B2). Out of these, living, kitchen, and toilet are naturally ventilated zones, and Bedrooms 1 & 2 are mixed-mode operated zones. In naturally ventilated zones, occupants rely on ceiling fans and window operation to regulate thermal comfort. In contrast, in mixed-mode zones, flexibility in shifting between air-conditioners and window operation is provided to the occupants. The model considers 1.5 tons capacity air-conditioners with a typical operation schedule of 9 hours per day (2 pm – 5 pm) and (10 pm – 8 am) for six months (March to August). Air-conditioner and window operation set points are configured at 24°C and 20°C, respectively. The baseline case considers North orientation, burnt clay brick wall construction (U= 2.3 W/$m^2$K, 25% window-to-wall ratio, single glazed window (U = 0.58W/$m^2$K; SHGC = 0.85). New Delhi's Typical Meteorological Year(TMY) weather file is considered for all the simulations.

### 2.1. Input parameters and optimisation objective functions

The input parameters considered and respective ranges are shown in table 2. The final goal of the optimisation process is to obtain pareto-optimal solutions of design parameters which can minimise the annual cooling energy load and maximise the natural ventilation potential simultaneously. For this purpose, we introduce the term Annual Air Changes, which is the sum of air changes per hour for all 8760 hours of a year. Two objectives of the optimisation process are (1) Annual Cooling Energy Consumption (kWh)(minimise) and (2) Annual Air Changes (ach)(maximise).

Table 2. Building design parameters and its possible options considered for optimisation.

| S. No. | Building Design Parameter | Options |
|---|---|---|
| 1 | Building Orientation | [0, 45, 90, 135, 180, 225, 270, 315] degrees |
| 2 | Wall Construction Material | Aerated Concrete Blocks, Fly Ash Bricks, Concrete Block, Burnt clay brick, Machine Moulded Brick. |
| 3 | Window type | Single Glazing 6 mm clear glass (U = 5.78 $W/m^2K$),<br>Double Glazing 6 mm clear glass / 6 mm air (U = 3.094 $W/m^2K$) |
| 4 | Glazing SHGC | 0.45, 0.5, 0.55, 0.6, 0.65, 0.7, 0.75, 0.8, 0.85 |
| 5 | Window to Wall Ratio | [5, 10, 15, 20, 25, 30]% |

Table 3 describes the physical properties of the various wall construction materials considered.

Table 3. Building design parameters and its possible options considered for optimisation

| S. No | Wall Construction Material | Layers | Thickness (mm) | Density ($kg/m^3$) | Specific Heat Capacity (J/(kgK)) | Thermal Conductivity (W/(mK)) | U value ($W/(m^2K)$) |
|---|---|---|---|---|---|---|---|
| 1 | Aerated Concrete Block | 1 | 300 | 600 | 870 | 0.16 | 0.49 |
| 2 | Fly Ash Brick | 1 | 200 | 1400 | 1000 | 0.48 | 0.51 |
| | | 2 | 55 | 15 | 1450 | 0.04 | |
| 3 | Concrete Block | 1 | 200 | 2300 | 1000 | 1.61 | 1.49 |
| | | 2 | 15 | 10 | 1400 | 0.04 | |
| 4 | Burnt Clay Brick | 1 | 200 | 1850 | 1000 | 0.62 | 2.04 |
| 5 | Machine Moulded Brick | 1 | 130 | 1700 | 880 | 0.72 | 2.84 |

The optimisation is performed using a python based optimisation tool (netzed-bopt). The ranges of input of variables, objective functions, choice of optimisation algorithm, and relevant parameters of the chosen Optimisation algorithm (e.g., in the case of PSO, number of particles(n), Number of iterations, Inertia weight($w_i$), Cognitive parameter($c_1$), and Social parameter($c_2$)) are defined in Netzed-Bopt. The tool performs coupled simulations using Energy Plus input file(.idf) and fetches the solution of every simulation run as well as the pareto-optimal front as outputs in '.csv' format.

## 3. Results and Discussions

### 3.1. Obtaining pareto-optimal front

The pareto-optimal front is the set of non-dominated solutions of that particular Multi-Objective Optimisation (MOO) process. Particle Swarm Optimization(PSO) is used as optimization algorithm in the study for its robustness to control parameters, and computational efficiency, when compared with other meta-heuristic algorithms (Lee and Park, 2006). PSO is run for 25 iterations with n=50, $w_i$=0.5, $c_1$=2, and $c_2$=2, and the required MOO solution set, and the pareto-optimal front is obtained as shown in figure 3.

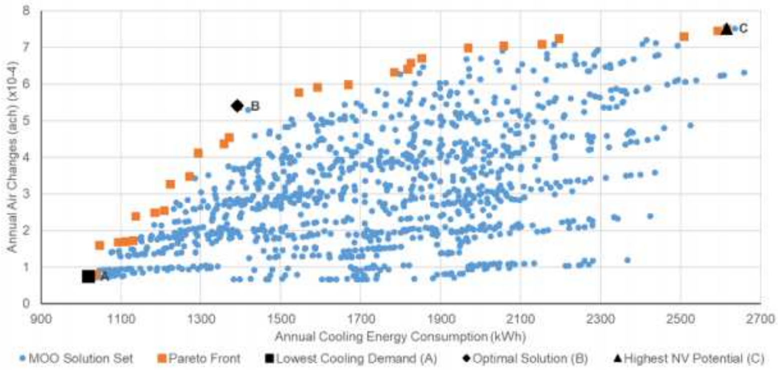



Figure 3. The building design optimisation process for minimising energy demand and enhancing NV.

A total of 1250 cases(50 particles, 25 iterations) are simulated. Variations in annual cooling energy consumption among these cases range from 1018.11 kWh to 2659.23 kWh. The annual total energy demand of these 1250 cases goes between 2747.7-4388.82 kWh, amounting to 7.53-12.02 kWh per day. Variation in annual air changes lies within 6581.70-75236.18 ach, which amounts to 18.03-206.13 ach air changes per day.

### 3.2. Obtaining pareto-optimal solution

The pareto-optimal front contains 29 non-dominated solutions. Wang Z. and Rangaiah G.P., (2017) discussed various methods for selecting an optimal solution from the pareto-optimal front obtained by multi-objective optimisation. One of those methods is Simple Additive Weighting(SAW). The pareto-optimal front is considered as an m × n matrix, where m is the number of solutions present in the front and n is the number of objective functions. The score $A_i$ of each optimal solution, i.e., row i in the objective matrix, is obtained by summing the product of normalised objective j and its weight, $w_j$. The selected solution is that having the largest score.

$$F_{ij} = \frac{f_{ij}}{f_j^+} \text{ for a maximisation criterion, where } f_j^+ = Max_{i \in m} f_{ij}$$

$$F_{ij} = \frac{f_j^-}{f_{ij}} \text{ for a minimisation criterion, where } f_j^- = Min_{i \in m} f_{ij}$$

$$v_{ij} = F_{ij} \times w_j$$

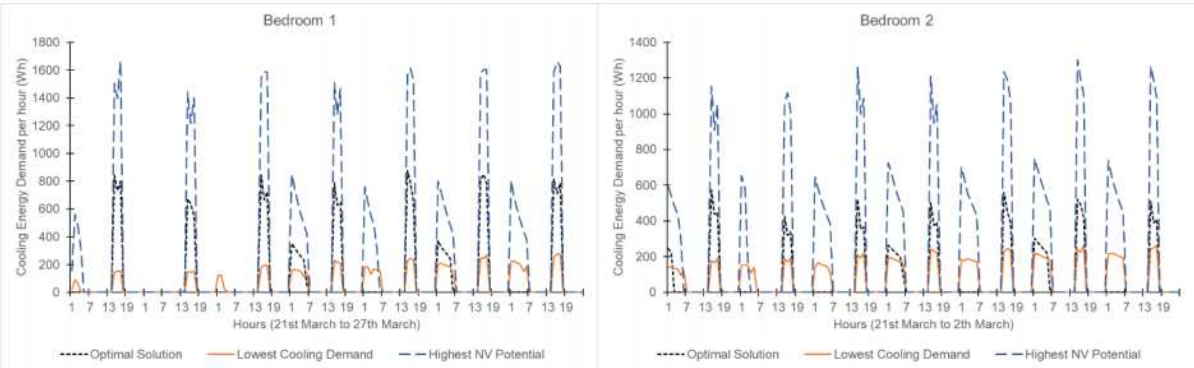
$$A_i = \sum_{j=1}^{n} v_{ij}$$

In this case, m=29 and n = 2: Annual Cooling Energy Consumption(minimize)(j=1) and Annual Air Changes(maximize)(j=2). Equal weightage is given to both the objectives ($w_1$=0.5, $w_2$=0.5) and the pareto-optimal solution is obtained. Similarly, the lowest cooling demand solution is obtained with $w_1$=1, $w_2$=0 and the highest NV potential solution is obtained with $w_1$=0, $w_2$=1. Details of the selected input parameters of the three cases obtained, namely, lowest cooling demand solution(case A), optimal solution(case B), and highest NV potential solution(case C), are shown in table 4.

Table 4. Selected input parameters for cases A, B and C.

| Case | Building Orientation | Wall Construction Material | Window Type | WWR | Glazing SHGC |
|---|---|---|---|---|---|
| Case A | 0° | Fly Ash brick | Double glazed window (U = 3.094 W/m2K) | 5% | 0.65 |
| Case B | 270° | AAC block | Double glazed window (U = 3.094 W/m2K) | 30% | 0.45 |
| Case C | 225° | Machine Mld Brick | Double glazed window (U = 3.094 W/m2K) | 30% | 0.85 |

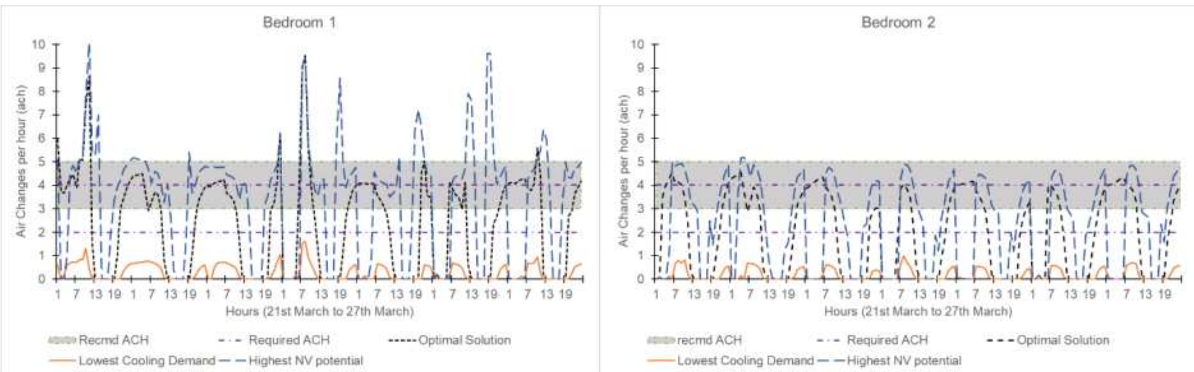
For all three cases A, B, and C, hourly data of Indoor dry-bulb temperature($T_i$; °C), outdoor dry bulb temperature ($T_o$; °C), Cooling Energy Demand ($E_c$; Wh), and air Changes per hour ($R_v$) are analysed for the zones B1 and B2 for a duration of 1 week starting from 21st March to 27th March (fig. 4-6). The reason for choosing this particular week is that, as per the climatic conditions of New Delhi, during this week, existence of both ventilation and cooling demand is prominently observed. Also, this period comes around equinox (22nd March), and hence diurnal variations are evidently visible.




(a) (b)

Figure 4. Hourly variation of $E_{c(A)}$, $E_{c(B)}$, and $E_{c(C)}$ in zones (a) B1 and (b) B2 for the period 21st - 27th March

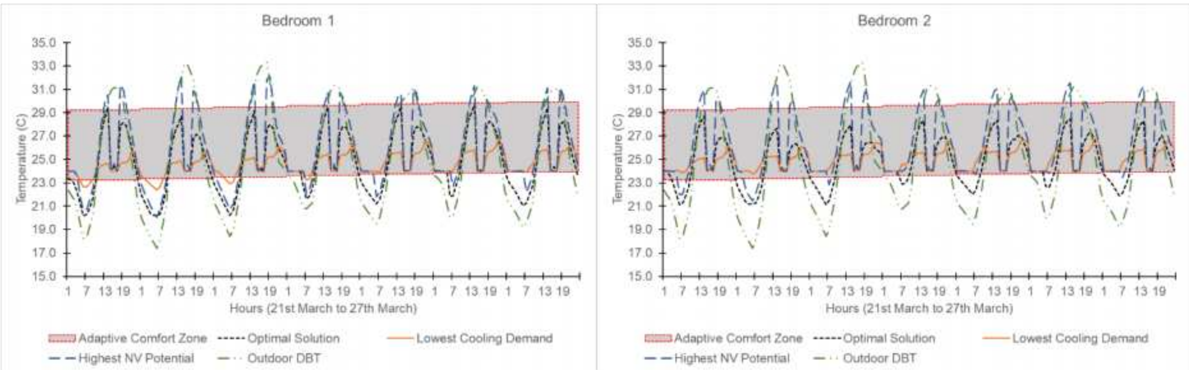
In case A, Peak $E_c$ is as low as 270Wh in both B1 and B2 during the air-conditioner operational hours. In case B, Peak $E_c$ is 870Wh in B1, which is 600Wh more than case A and 590Wh in B2, which is 320Wh more than case A, during air-conditioner operational hours. In case C, in B1, the peak $E_c$ is 1665Wh, which is 1395Wh more than case A, and in B2, $E_c$ is 1270Wh, which is 1000Wh more than case A, during air-conditioner operational hours. The highest cooling energy consumption is observed in case C (figure 4).




(a) (b)

Figure 5. Hourly variation of $R_{v(A)}$, $R_{v(B)}$, and $R_{v(C)}$ in zones (a) B1 and (b) B2 for the period 21st - 27th March

In case A, $R_v$ lies within 0-1.6 ach, which is 0.6 ach lesser than the minimum required level pre- SARS-CoV-2 scenario and 1.4 ach lesser than the recommended level post-SARS-CoV-2 scenario. Required air changes per hour is never met in case A during the period under study. In case B, $R_v$ of B1 lies within the range of 2.5-10 ach during ventilated hours and crosses the minimum recommended level for post-SARS-CoV-2 scenarios during 86 hours out of total 168 occupied hours and in B2, $R_v$ lies within 2.5-4.5 ach during ventilated hours and crosses the minimum recommended level for post-SARS-CoV-2 scenarios during 75 hours out of 168 occupied hours. In case C, air changes is found in the range of 3.5-10 ach in B1 and 3.5-5.2 ach in B2 during ventilated hours. This crosses the minimum recommended level for post-SARS-CoV-2 scenarios during 114 hours of total 168 occupied hours in B1 and 84 hours in B2 (figure 5).




(a) (b)

Figure 6. Hourly variation of $T_o$, $T_{i(A)}$, $T_{i(B)}$, and $T_{i(C)}$ in zones (a) B1 and (b) B2 for the period 21st - 27th March

In case A, $T_i$ remains within the adaptive comfort temperature band (22.5°C to 26.5°C) for 105 hours out of total 168 occupied hours in zones B1 and B2. In case B, $T_i$ is within the allowed adaptive comfort temperature band for 15 hours per day (9 am to 12 am) in zones B1 and B2. Also, $T_i$ is observed moving close to $T_o$ in the duration when $T_o$ lies within the adaptive comfort zone, implying that outdoor air is utilised well during the period when $T_o$ is comfortable. This decreases the cooling load and enhances thermal comfort without compromising NV potential. In case C, $T_i$ is observed to cross the adaptive comfort band up to 2°C, in both B1 and B2, during peak day time, and the comfort hours is coming out to be 10 hours per day, which is the least among all three cases (figure 6).

Table 5. Daily average NV efficiency parameters data for the period 21st – 27th March.

| NV Efficiency Parameters for the period 21st-27th March | Bedroom 1 | | | Bedroom 2 | | |
|---|---|---|---|---|---|---|
| | Case A | Case B | Case C | Case A | Case B | Case C |
| Daily Average Ventilated hours(hr) | 11.14 | 15.14 | 17.71 | 9.14 | 14.71 | 15.86 |
| Daily Average Ventilated Air Volume($m^3$) | 207.64 | 1828.67 | 2697.60 | 133.77 | 1518.26 | 1826.73 |

In terms of NV efficiency, per day, case B ventilates 1621$m^3$ more than case A in B1 and 1384.5$m^3$ more in B2, with an appreciable increase in daily ventilated hours (4 and 5.5 hours more than case A in B1 and B2 respectively). Also, the difference between case B and C in NV efficiency is not as remarkable as the difference observed between case A and B. Case C moves 869$m^3$ and 308.5$m^3$ more air per day than case B, with an increase of 2.5 and 1 hours in ventilated hours in B1 and B2 respectively (table 5).

Case A has minimum cooling energy but fails to provide enough air changes. Also, the adaptive comfort model limits stand good only with adequate ventilation, which is clearly not available in case A. In case B, the compromise in cooling energy demand is equalised by the improvement in NV potential. In case C, the excess NV potential accommodated is being negated by the high cooling energy demand and the increased discomfort hours. Overall, case B is noticed to have a proper trade-off between thermal comfort, indoor air quality(IAQ), and cooling energy demand.

## 4. Conclusion

This study identified the pareto-optimal solution for enhancing natural ventilation and reducing energy demand, using Particle Swarm Optimization(PSO) algorithm, for a residential building located in the composite climate region of India. Building orientation, wall material, window type, window wall ratio(WWR), and Glazing SHGC were optimised to minimise the annual cooling energy consumption(kWh) and to maximise the Annual Air Changes(ach). One optimal solution was obtained from the pareto solution set using the Simple Additive Weighting(SAW) method. The process recommended $270^o$ Orientation, AAC block wall construction, Double glazed window (U = 3.094 W/m2K), 30% WWR and 0.45 SHGC for the optimal solution. Similarly, the lowest cooling demand solution and the highest NV potential solution were identified. All three solutions were analysed for the impact of ventilation effectiveness on thermal comfort and Indoor Air Quality(IAQ) separately for two zones, Bedroom1(B1) and Bedroom2(B2). In the optimal solution case, the indoor air temperature was found to be within the comfortable condition for 15 hours per day with a peak cooling energy demand of 870Wh and 600Wh in B1 and B2, respectively. The ventilation rate was above the minimum suggested ventilation rate post- SARS-CoV-2 scenario. The lowest cooling demand solution maintained minimum cooling load, with a peak of 270Wh, and the indoor temperature was maintained within the comfortable range for 20 hours per day. Ventilation rate was minimum among the three cases at $207.64m^3$ per day over 11.14 hours and $133.77m^3$ over 9.14 hours in B1 and B2, respectively. This NV rate lies below the recommended levels. Among all three cases, Highest NV potential solution’s comfort hours was the least (10 hours per day), and the peak cooling demand the highest (1665Wh in B1 and 1270Wh in B2). It had the highest NV efficiency, with $2697m^3$ of air per day being moved in 17.71 hours in B1 and $1826.73m^3$ of air in 15.86 hours in B2. It is evident that the optimal solution case has the perfect trade-off between thermal comfort, indoor air quality(IAQ), and cooling energy demand. The research approach demonstrated in this paper can help architects and engineers design buildings and mechanical ventilation systems to enhance ventilation and IAQ without compromising thermal comfort and cooling energy demand reduction.

## 5. Acknowledgement

The research described in this paper is financially supported by the Department of Science and Technology, Government of India Grant number[DST/TMD/UKBEE/2017/17] and Engineering and Physics Research Council, United Kingdom Grant number[EP/R008612/1].

The authors thank Prof. Gade Pandu Rangaiah, Department of Chemical and Biomolecular Engineering, National University of Singapore, Singapore, for providing us with the tool developed as part of his research to find an optimal solution from the Pareto-Optimal Front obtained by Multi-Objective Optimisation (Wang Z. and Rangaiah G.P., 2017).

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## The thermal and energy performance of the glazed studio apartments under the current and future climate scenarios in São Paulo

**Shaiane Viana[1], Thais Kanada[2], Ana Alice Barbosa[3], Marcelo Mello[4], Alberto Hernandez Neto[5] and Denise Duarte[6]**

[1] Architect, Master Candidate, School of Architecture and Urbanism, FAUUSP, São Paulo, Brazil, shaiane@usp.br;
[2] Undergraduate student, School of Architecture and Urbanism, FAUUSP, São Paulo, Brazil, thaissayuri@usp.br;
[3] Undergraduate student, Polytechnic School of the University of São Paulo, POLIUSP, São Paulo, Brazil, anaclimacobarbosa@usp.br;
[4] Architect and Civil Engineer, Post-doctoral Researcher, Polytechnic School of the University of São Paulo, POLIUSP, São Paulo, Brazil, marcelorafmello@gmail.com;
[5] Associate Professor, Polytechnic School of the University of São Paulo, POLI USP, São Paulo, Brazil, ahneto@usp.br
[6] Full Professor, School of Architecture and Urbanism, FAUUSP, São Paulo, Brazil, dhduarte@me.com

**Abstract:**
The number of residential apartments has grown since the approval of the Strategic Master Plan of the City of São Paulo in 2014, and a significant part of these launches are one-bedroom apartments with small useful area. Given the increase in local air temperature around 1.6°C in the last 30 years, overlaid with the occurrence of the urban heat island, it is essential to characterise and study the thermal performance of small glazed apartments in future scenarios considering climate change. Therefore, this work aims to catalog and analyse the stock of apartments of residential buildings of up to 50m² newly launched or built in São Paulo. The objective is to evaluate the comfort of users in two Studio apartments standards of a residential building through thermodynamic simulation in the TAS software to analyse the thermal performance of the apartment considering the current and future weather scenarios, and the longer periods of permanence of residents at home, caused by the change of habits arising from the pandemic. The smaller studio (19m2) has a worst performance than the bigger studio (25m2) for the present and future climate scenarios. To improve the thermal performance, the authors suggest an increase in shading devicesize, better glazing material and the inclusion of openings for cross ventilation.
**Keywords:** Residential buildings; Studio apartments; Thermal analysis; Thermal comfort; Energy performance

## 1. Introduction

Mankind finds itself in the context of a partially controlled pandemic and a race to minimize extreme climate effects from now on. The SARS-COVID-19 pandemic compelled the world population to adopt some sanitary measures, including social isolation, which may become necessary in the subsequent decades if the causes of climate change are not mitigated. Since heat waves would make people, from almost all over the world, avoid outdoor environments, confinement may become the norm if we can't stop climate change (UN Global Compact, 2020)[1].

[1] The Global Compact is an initiative promoted by the United Nations for companies to have their strategies aligned with the universal principles of Human Rights, Labor, Environment and Anti-corruption. In April 2020, an interview with the Brazilian scientist Carlos Nobre was carried out to analyze the relationship between the Sars-Cov-2 virus pandemic and the effects of climate change. The interview addresses the lessons that can be learned from isolation during the COVID-19 outbreak.

Before the spread of the SARS-COVID-19, the scientific community was already concerned about the current production of the built environment. Building designers were moving gradually towards a new paradigm of low-carbon, high-performance, mixed-mode buildings (Rysanek, 2022), but after the *lockdown*, the attention given to residential buildings' performance was intensified, since most activities started to take place at home. The *home office* was one of the options during social isolation, which tends to remain in many people's lives. According to a survey of 800 executives, at least a tenth of their employees could work remotely two or more days a week (Lund et al, 2020). The hybrid or full-time online work model calls into question the indoor environment quality of residential buildings, especially compact apartments.

In São Paulo, at the end of the 1930s, there were the first records of residential buildings with apartments with one living room and one bedroom or one-room apartments, the so-called kitchenettes (Somekh, 2014). Over the years, compact apartments underwent transformations caused by legislation changes, there was an increase in the glazed area of the facades, a decrease in ventilation openings, absence of solar shading elements and, according to the EMBRAESP annual reports from 1985 to 2000, there was a significant reduction in the average floor area of the one-bedroom apartments. Also, there is a considerable reduction in the average floor area of this typology in the city of São Paulo over the years (Queiroz et al, 2008). The area reduction is one of the factors that currently impact the indoor thermal quality of many apartments built in the city.

In the 1990s, flats and lofts appeared in the real estate market and reshaped the visibility of one-bedroom apartments, which were previously considered for low-income residents. This change in the design was due both to the location, in the high-income neighborhoods of São Paulo, and to the increase in area, as explained by Queiroz and Tramontano:

> The segment that underwent a transformation in the market during this period was the one-dormitory– including units that do not have a specific room to sleep, usually called studios and lofts. Market numbers confirm that apartments in this segment are no longer associated with the idea of minimal and cheap housing as the kitchenettes in past decades, they now aim at a public with greater purchasing power and are often located in high-value neighborhoods. (Queiroz, Tramontano, 2009)

After the approval of the Strategic Masterplan of the City of São Paulo, on July 31, 2014, there was an increase in the number of compact apartment releases, which totaled 6,044 properties with floor areas between 20m² and 35m², in 2019 alone. Real estate builders and developers reconciled market demands with the Masterplan's new rules and the Zoning Law - LPUOS (Quintão, 2019).

It was found that the central region of São Paulo was the one that had a significant amount of one-bedroom apartment releases. These properties (medium and high standard) showed a growth of 32%, with 18,400 units in 2021 (SECOVI-SP, 2022). These numbers, together with the decrease in the floor areas of contemporary kitchenettes and the increase in the square meter price of these apartments, demonstrates that the market has a new target audience, the middle and upper class, making housing unaffordable for people of low income, as stated by Rolnik in a text referring to a 10m² apartment released in São Paulo:

> (...) At a cost of almost 10.000 reais per square meter, one of the largest in the city, these apartments in Vila Buarque - São Paulo will not be at all affordable for most of the population. In this context, this launch seems to be much more related to the open possibilities of, drastically reducing useful areas, to provide significant increases in the profit margins of the developer. (Rolnik, 2017)

São Paulo has a considerable housing deficit while the real estate market builds for profit and not for affordable housing for everyone. The rising square meter-built price is increasingly moving the financially disadvantaged population away from the central areas of the city. A clear strategy to increase prices, for the studio apartments, was to resemble luxurious apartments and gradually apply the glazed external appearance brought for those new kitchenettes, which are currently called studio apartments. This mimicry is present in both middle and lower classes' properties.

A literature review was carried out on the following topics: thermal performance, energy efficiency, built environment of residential buildings, climate change and the production of residential stock in recent years in the city of São Paulo. It was noticed, in the studio apartments released in recent years in São Paulo, some common characteristics are identified: an absence of balcony and windows for cross ventilation, possibility (or even incentive) for fully glazed facades and use of air conditioning. In the post-pandemic scenario in which online work is expected to increase, dependence on air conditioning becomes unsustainable, especially with the new energy tariff flag installed in the country in recent years. Air conditioning provides a crutch for poor climatic design and makes living in dense, homogenous high-rise buildings possible if there is a reliable electricity supply (Cook, M. et al, 2020).

Natural ventilation is essential for the air exchange efficiency in the indoor built environment as it contributes to thermal comfort and control of respiratory infections in buildings. Therefore, as a pilot study, an evaluation of the thermal performance of glazed studio apartments starting from recently systematized data is sought, for the current and future climate, also considering the new residential uses demanded by the pandemic and in the face of the increasing global and local temperature.

## 2. Objective

The main objective of this study is to quantify the thermal performance of two compact apartments in a partially glazed multi-family residential building, recently released in the city of São Paulo, evaluating the thermal comfort of users and the energy efficiency in the context of global and local climate changes, under the current and future climate scenarios. This evaluation will also be considered the new residential uses resultant from the confinement, now demanded by the pandemic and post-pandemic habits.

## 3. Method

From the literature review, a significant increase in real estate releases in 2014 was identified, stimulated by the new guidelines established by the Strategic Master Plan of the City of São Paulo.The chronological framework of residential developments produced in the years 2014 to 2021 was defined for systematization and characterization.

Santa Cecília and República districts were identified as potential study areas, due to the convergence of different reasons. A land surface temperature analysis of the city of São Paulo showed that those chosen areas have precarious conditions of green areas that impact the thermal perception of pedestrians in the public space and even the facade of some buildings. Another factor that contributed to the definition of the study area was the high number of studio apartments built in the República district in recent years, many with fully or partially glazed façades identified during the systematization  of apartment typologies, which can be seen in Figures 1 and 2.

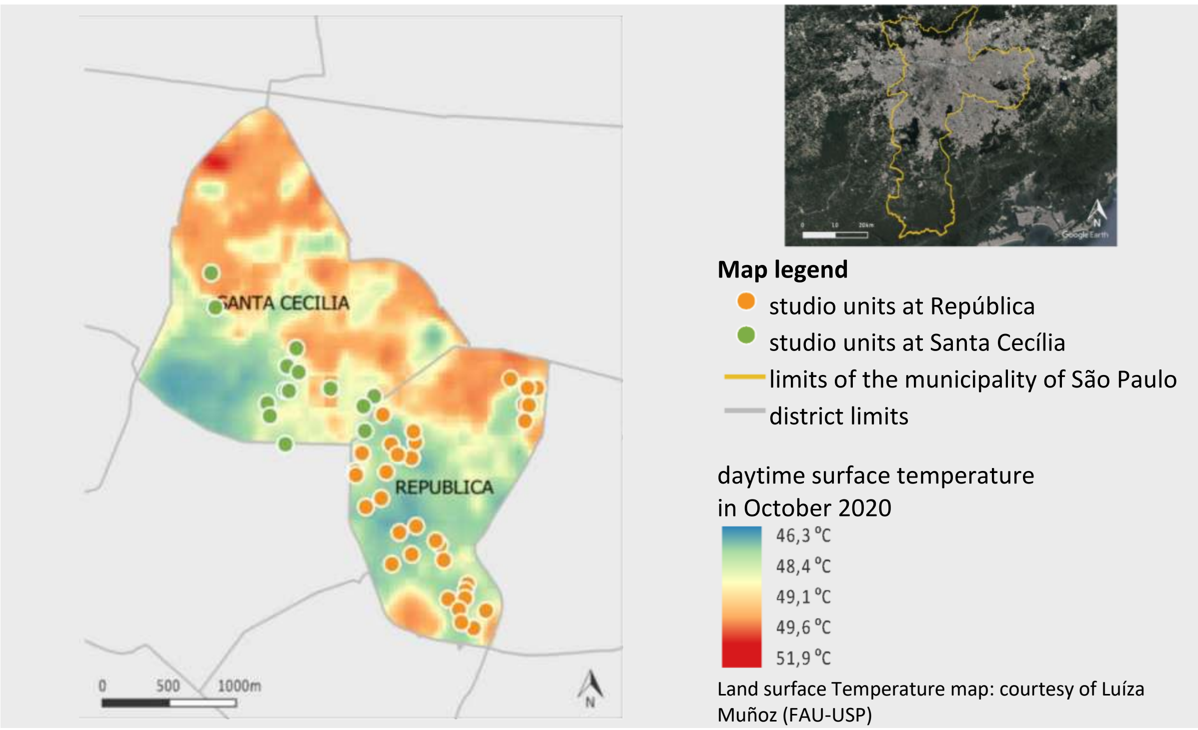



Figure 1. Daytime land surface temperature in October 2020

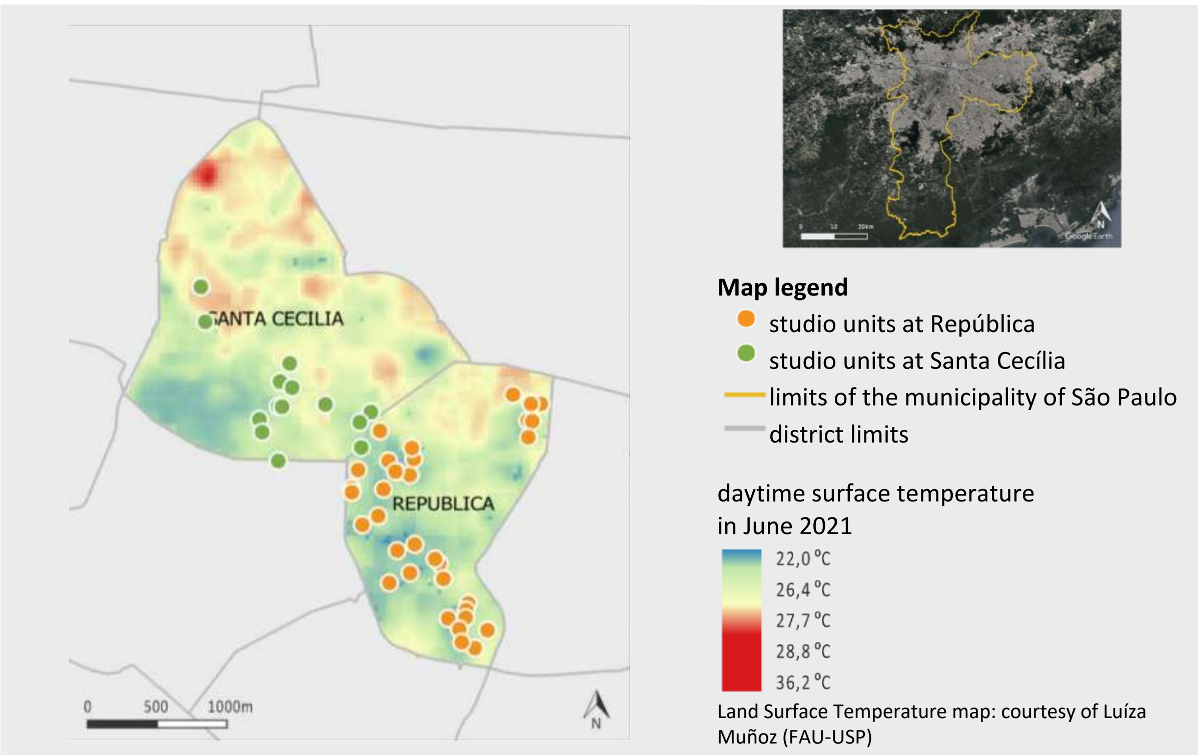



Figure 2. Daytime land surface temperature in June 2021

For the **data systematization,** the following databases were used to obtain information on real estate releases: GeoEmbraesp and GeoSecovi, two companies of real estate market analysis that provide georeferenced data, the first free of charge (trial) and the second by signing the service.

Among the samples obtained from those databases, single-room residential units of up to 50m² in multi-story buildings were selected for this study. The following information was collected from each unit: a) name of the building; b) number of bedrooms (studio, 1 bedroom); c) net floor area of the unit; d) district (Republic or Santa Cecília); e) address; f) building plan; g) source of information.

In the process of surveying recent residential buildings in São Paulo, we sought to find the most recurrent typologies in newly built small apartments, with facades fully or partially glazed. Since the beginning of the research, it was possible to observe the existence of some design patterns related to the environments close to the facades. Two types of studio apartments were then chosen from one of the multi-family buildings found, as representative of that recurrent typology. (Figure 3).


Figure 3. Vila Buarque building facade, and chosen studio apartments' with 19m² and 25m² (MAC, 2021)

The **generation of the weather file** for future years was done by encompassing air temperature, air humidity, air velocity and globe temperature, in a Comma-Separated-Values - CSV format. These data were used for simulating the year 2076 (Alves, 2015). The air temperature and humidity data were simulated by the researcher Marta P. Llopart (IAG-USP) and made available by professor Rosmeri P. da Rocha from the models: *regional RegCM4* and *global Max-Planck Institute for Meteorology* (MPI) considering the Representative Concentration Pathways (RCP 8.5) scenarios from IPCC AR5, which represents the highest estimated emissions levels by the Intergovernmental Panel on Climate Change (IPCC). The CSV underwent a downscaling[2] so it could be used in the climate file, allowing it to simulate the thermal performance of buildings considering the future increase in temperature.

After selecting the typology for this study, **modelling 3D** began in the TAS software *(Thermal Analysis Software Environmental/ Design Solutions Limited)* version 9.5.1, which currently has a free version for students. TAS is a software with 3D modeller, building

[2] Climate models are created for a global scale, then, to represent the local scale, it is necessary to downscale the data for the local surface climate scale in order to ensure more accurate climate variables.

simulator and results viewer, having formal validation[3] of ASHRAE 140-1 (ANSI/ASHRAE, 2007). For the modelling, the parametersshown in Table 1 were used and the modeling was not calibrated. The analised building is under construction and was chosen because it represents the current production of studio apartments.

Table 1. Characterization

| Element | Layer | Dimensions [mm] | Thermal conductivity [W/m.K] | Density [kg/m3] | Specific heat [J/kg.K] | Solar absorption | Long wave emissivity |
|---|---|---|---|---|---|---|---|
| Internal wall | Plaster | 12.5 | 0,35 | 750 | 840 | 0,40 | 0,90 |
| | Air space | 50 | Thermal resistance of the air layer = 0.17 m2.K/W | | | | |
| | Plaster | 12.5 | 0,35 | 750 | 840 | 0,40 | 0,90 |
| External wall | Mortar | 25 | 1,15 | 2000 | 1000 | 0,50 | 0,90 |
| | Concrete | 25 | 1,75 | 2400 | 1000 | 0,50 | 0,90 |
| | Air space | 140 | Thermal resistance of the air layer = 0.17 m2.K/W | | | | |
| | Concrete | 25 | 1,75 | 2400 | 1000 | 0,50 | 0,90 |
| | Mortar | 25 | 1,15 | 2000 | 1000 | 0,50 | 0,90 |
| Ceiling | Ceramic coating | 10 | 1,05 | 2000 | 920 | 0,70 | 0,90 |
| | Mortar (underfloor) | 40 | 1,15 | 2000 | 1000 | 0,50 | 0,90 |
| | Concrete | 100 | 1,75 | 2400 | 1000 | 0,70 | 0,90 |
| Floor | Ceramic coating | 10 | 1,05 | 2000 | 920 | 0,70 | 0,90 |
| | Mortar (underfloor) | 40 | 1,15 | 2000 | 1000 | 0,50 | 0,90 |
| | Concrete | 100 | 1,75 | 2400 | 1000 | 0,70 | 0,90 |
| Window (facing the noisy region)) | Aluminum frame | Largura =50 | 56,0 | 2700 | 920 | 0,58 | 0,90 |
| | Glass | Transparent laminate 5mm + Transparent PVB + Transparent 5mm – Lapidated= 10mm | Thermal transmittance=5.7 W/m2.K | | | Solar factor=0.87 | ---- |
| Window (not facing noisy region) | Aluminum frame | Largura =50 | 56,0 | 2700 | 920 | 0,58 | 0,90 |
| | Glass | Transparent laminate 3mm + PVB Transparent +Transparent 3mm – Laminate= 6mm | Thermal transmittance=5.7 W/m2.K | | | Solar factor=0.87 | ---- |

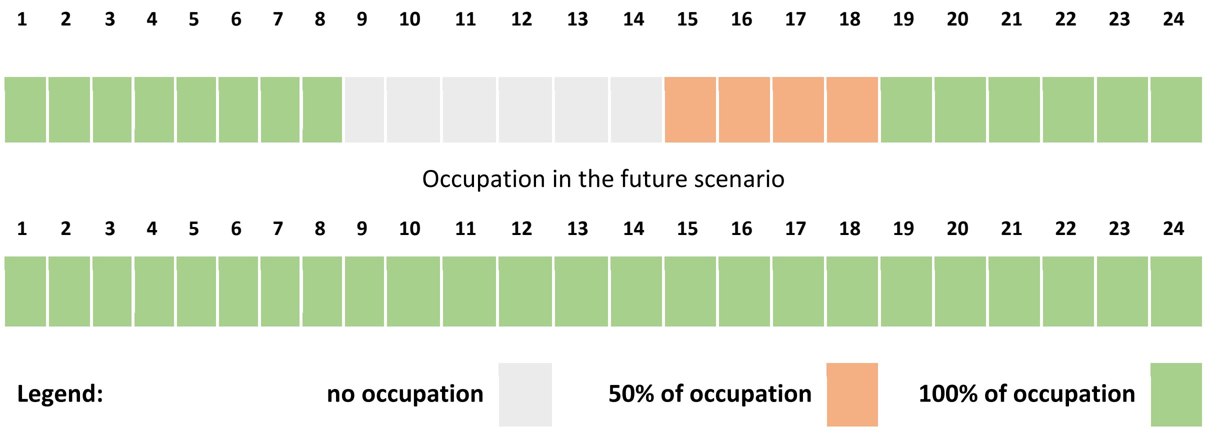
[3] TAS validations can be consulted at: https://www.edsl.net/validation/ (Accessed: 1 April 2021).

After that, the **simulations** were carried out in three-dimensional models, considering the apartments on the first floor (above the ground floor). The model considers the surroundings for shading effects but does not consider longwave radiation. The thermal simulations were designed in two scenarios: traditional occupancy (during the night and early morning) and 100% occupancy (for home office). The simulation scenarios were performed with the current weather file and future climate file (year 2076), for the end of the century, which is the deadline initially proposed by the Paris Agreement to limit the increase in global temperature to 2 °C – ideally 1.5°C.

The new residential usage patterns resulting from the pandemic, with home office, remote education and confinement, generate different occupancy scenarios, with users staying hypothetically for 100% of the time in long stay rooms, to evaluate the thermal performance, energy and comfort under different conditions of use.

Table 2. Profile of occupation of two people per room per hour

Occupation in the current typical scenario




Studio apartments usually lack cross ventilation, thereby the facade window impairs the air inlet and outlet. Thus, for the simulation, the TAS natural ventilation option called *Aperture Types* was used, considering that it establishes opened windows for passive cooling at temperatures between 26 °C at 26,1 °C, and closed windows for keeping the thermal load at temperatures between 18 °C to 26 °C, also making a critical reading of these criteria given the results found. The thermal load to be removed determines whether or not there is a demand for air conditioning, according to NBR 15575 and other references found in the literature review.

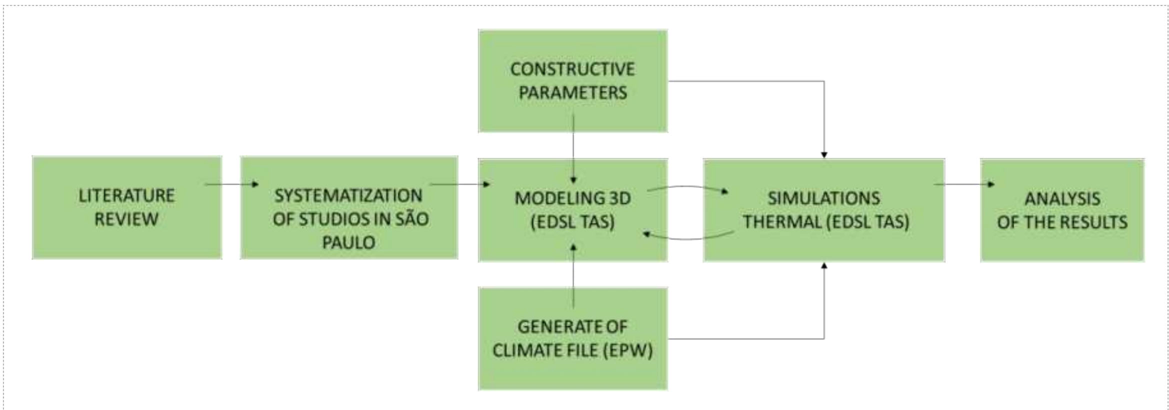



Figure 4. Flowchart of methodology

## 4. Results

The systematisation resulted in a data collection of 151 residential units in 78 different buildings. Among these 151 apartments, 52 (approximately 34%) correspond to studios. The average net floor area of this type of unit is 30m², with the largest unit found having 49m² and the smallest, only 10m². In addition, 85% of them have a balcony, many with the possibility (or even incentive) for integrating the transition space with the internal environment by glazing the facade, also being sold with ready infrastructure for the installation of the air conditioning.

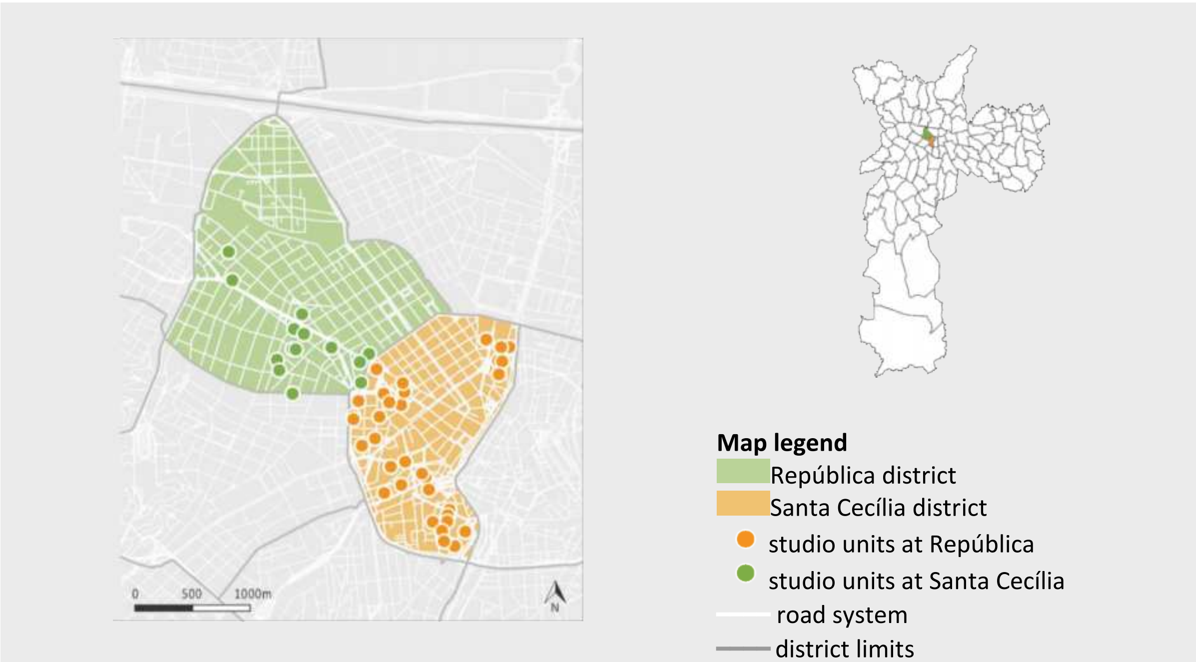



Figure 5. Systematized studio apartments

In the systematization of the studio apartments, two typologies were selected, belonging to the same multifamily residential building, for the models in the TAS. The two typologies have openings in the same solar orientation (North), however, there are other apartments of the same typologies distributed throughout the pavement (Figure 6). The first typology is a studio of 19m², with a bedroom and kitchen support, the window is glazed and unshaded. The second typology is a studio of 25m², with a spatial configuration similar to the first typology. However, the 25m² studio has a small balcony but does not have a window in the bathroom, therefore, both do not allow cross ventilation.

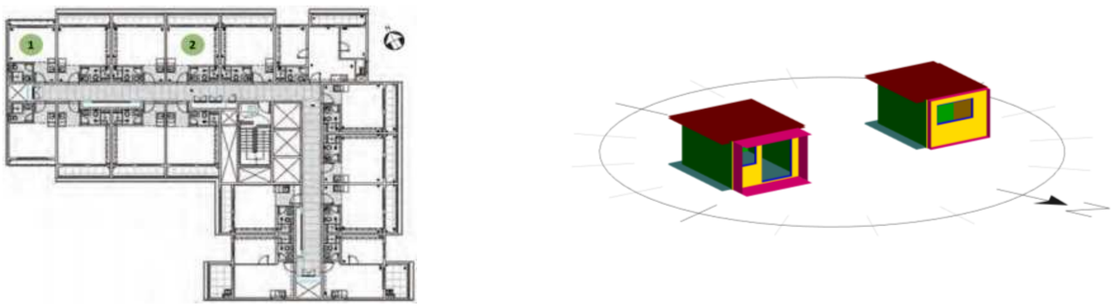



Figure 6. Floor plan for residential building (1 - Studio 19m² and 2 - Studio 25m²) and 3D model on TAS (MAC, 2021)

### 4.1. 4.1 Thermal performance evaluation

The evaluation of thermal performance demonstrates the importance of the glazed area of the facades concerning the floor area of the studio apartments and also becomes relevant to the existence of secondary openings, in addition to the windows on the main facades, for air exchange and ventilation of comfort, even in small studio apartments. Given the modeling of the two studios, it was verified by thermal simulation that the smaller apartment (19m²), because it had a smaller glazed area (2.50m²) on the facade, obtained a lower temperature throughout the year, than the apartment of 25m² that has a glazed area of (5.42m²), as it can be seen in Figure 7 for the common situation (Night and early morning occupation).

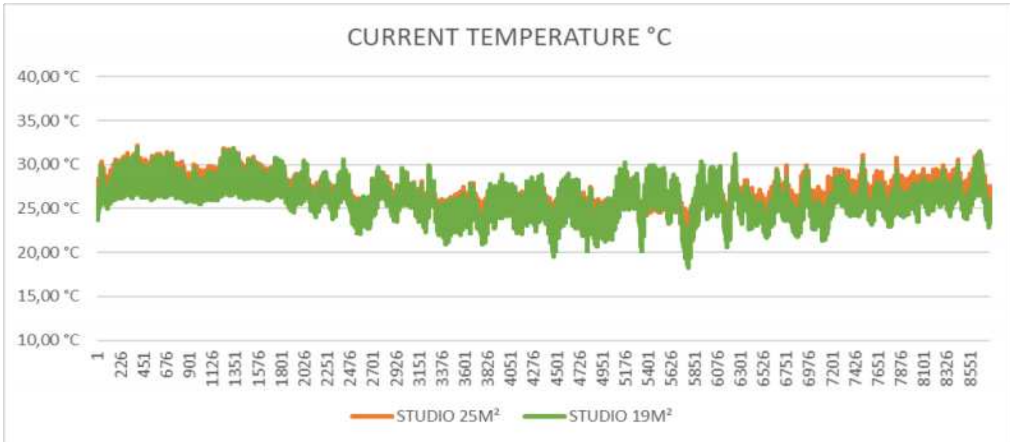
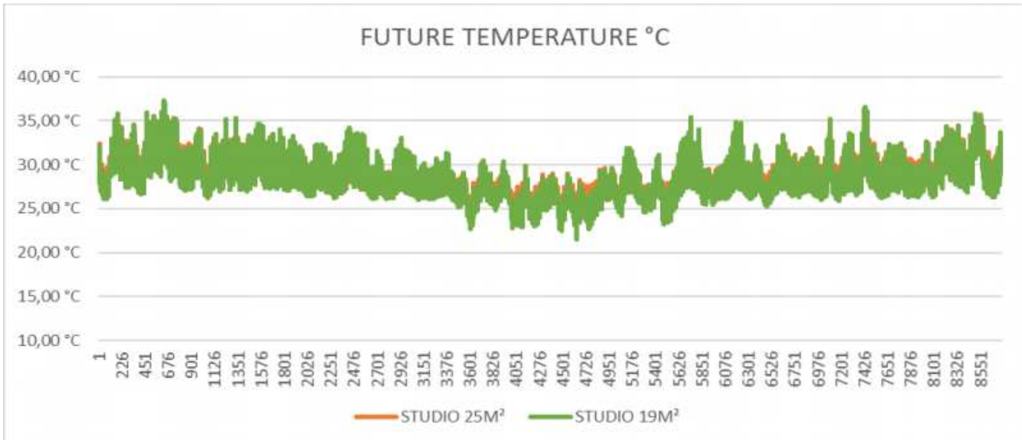



Figure 7. Studio of 19m² and 25m² in the current typical scenario




4.2. Figure 8. Studio of 19m² and 25m² in the future scenario

The building thermal performance simulation results were analysed comparatively. The Operative Temperature (OT) was adopted. The internal temperature of the studio of 19m² in the current climate scenario (Figure 7) compared to the future scenario (Figure 8) showed a variation of the maximum temperatures of 5.54°C (31.82 - 37.36°C) and between the minimum temperatures of 3.24°C (18.30 - 21.54°C). While the Studio apartment of 25m² demonstrated the variations of maximums between scenarios of 5.03°C (32.14 - 37.17°C) and minimums of 2.58°C (21.15 - 23.73°C). One can notice that the Studio of 25m² presented a variation of the maximum temperatures almost half a degree Celsius more than the Studio of 19m².

However, when considering temperatures in general, without looking only at the variation, one has at the end of the century the probability of feeling internally the temperature of 37.17°C in an apartment of 25m². Even with sun protection and the opening of 50% of the glasses, as there is no secondary opening for performing cross ventilation, it is not possible to thermally improve this environment if not by mechanical ventilation.

This scenario may be compounded for people who have a remote work routine according to Figure 9 which comprises the typical current scenario with home office occupancy (24 hours a day and 7 days a week), equipment and lights are turned on for 16 hours, 6 hours longer than the simulation of the current typical scenario, both generate a higher specific heat for home office simulation presented in Figure 9:

Pandemic situation (Home office - Full occupancy every day of the week)

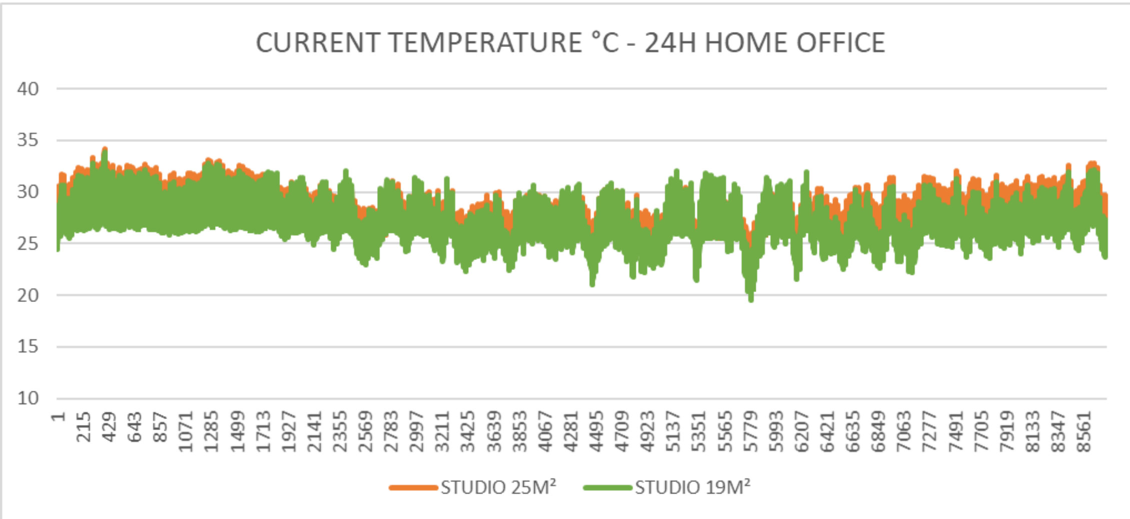



Figure 9. Studio of 19m² and 25m² in the current typical scenario

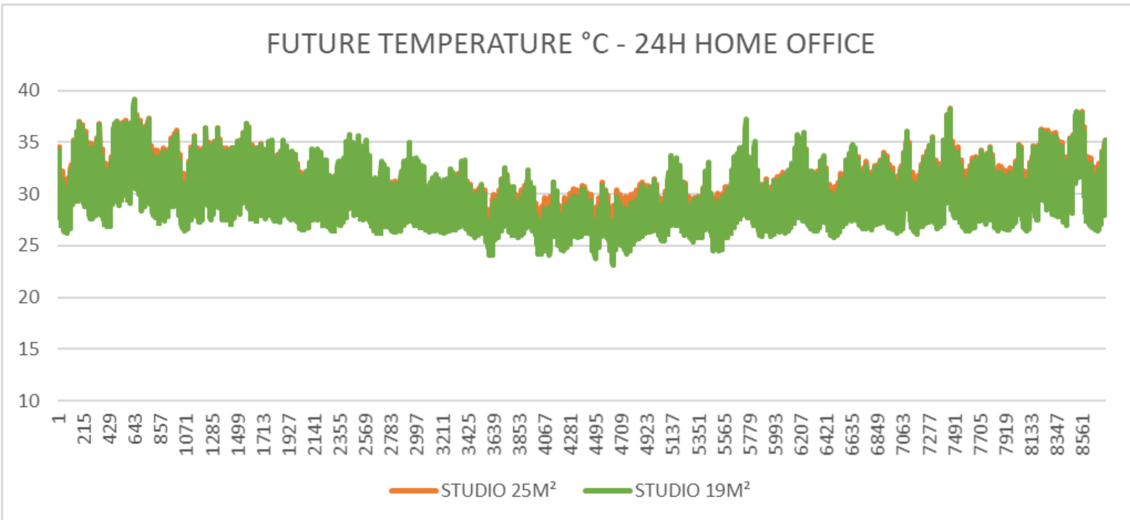



Figure 10. Studio of 19m² and 25m² in the future scenario

It can be verified that, in a studio apartment of 19m², the temperature variation in the temperature maximums between the current typical scenario and the future is 5.28°C (33.85 - 39,13°C), while the minimum reaches 3.60° (19.55 -23.15°C). In the apartment of 25m², the maximums is 4.89°C (34,17 - 39.06°C) and the minimum is 2.71°C (22.41- 25.12°C). In the studio of 19m², we have a temperature difference between the typically common occupation and work occupation in home office with a the maximum of 1.77°C. In the future scenario of the home office, some maximums of the studio of 19 exceed the maximums achivied in the studio of 25m². In the Studio of 25 m², the internal temperature reaches 39.6 °C, which aggravates the thermal comfort conditions (see Graph 4).

### 4.1.1 Total degrees-hours of cooling

The evaluation criterion indicated by RTQ - R (BRASIL, 2012) is the calculation of the degrees-hour for cooling with a base temperature of 26 °C. Thus, after the simulation, all hours with operative temperature above 26 °C in the long-stay environments are added and, using the following equation, the indicator of degrees-hour for cooling is calculated.

$$GHR = \Sigma (To - 26\ °C)$$

Where: GHR = indicated degrees-hour for cooling

To = operating temperature

The "degree-hour" parameter is determined as the sum of the time difference when the hourly temperature is higher than the base temperature in the case of cooling, or lower than the base temperature for heating degrees-hour. A demonstration of this parameter is presented in Figure 11, where the green and orange bars represent temperature values of 26°C and represent the amount of degrees-hours for cooling, which we consider here degrees-hour of discomfort. The degrees-hour are usually calculated for air temperatures. However, the amount of degree-hours in this study was calculated for operating temperatures.

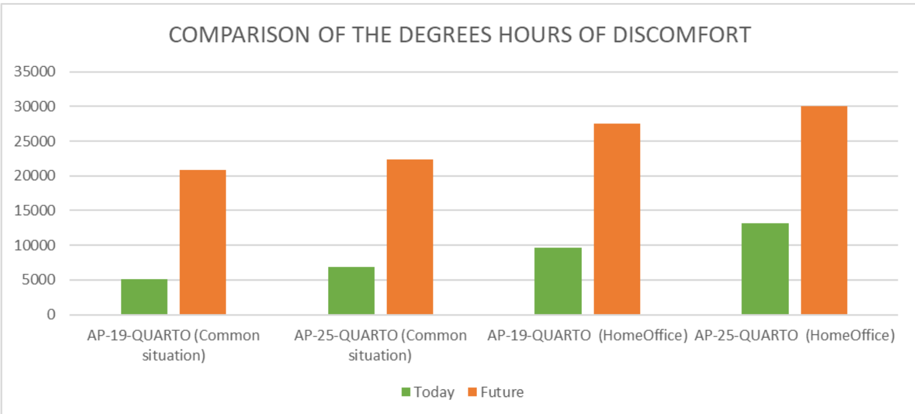



Figure 11. Comparison of the degrees hours of discomfort

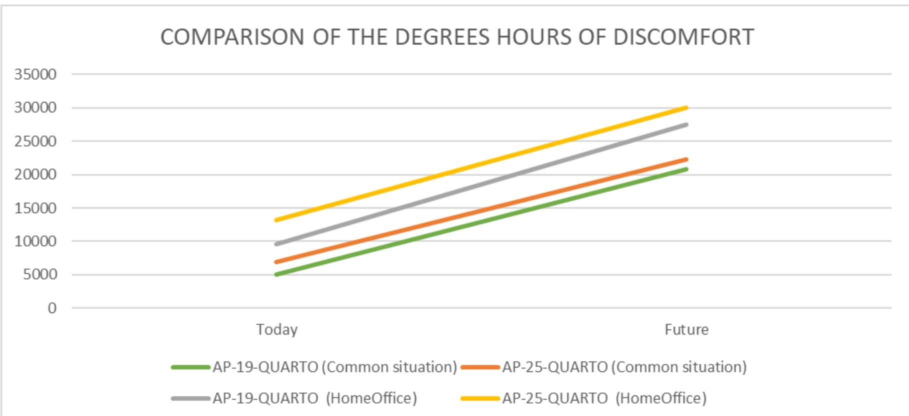



Figure 12. Comparison of the degrees hours of discomfort

The discomfort in degrees-hours in the apartment of 19m² is 313% higher in the future 2076 than in the current typical year and in the apartment of 25 m² the degrees discomfort hours in the future are 227% more than the current typical year. In the home office scenario, the apartment of 19m², in the future, has 187% more degrees-hours of discomfort than in the present and the apartment of 25² has 128% more for the same situation.

## 5. Conclusions

Based on the results, it is visualised that the models presented, Studios with glazed closure, are not prepared for the increase in temperature caused by climate change, since, both in the current scenario and in the future scenario, they present limitations for the user to operate the ideal air outlet only by opening the available windows, and it is not possible to perform cross ventilation. In addition, the occupant presence one hundred percent of the hours of the day in the home office scenario, with lights and equipment connected, increases half degree in operating temperature in the typical current and future scenario.

It is verified that the apartment of a smaller area (19m²) peaks at operating temperatures (TO) at higher maximums than the apartment of larger area (25m²), both with the same orientation for the current and future scenario. This fact occurs because the apartment of 19m² is located in the left corner of the building, having two walls exposed to solar radiation and also by the depth of the marquee of the balcony be small and do not perform shading necessary for glazed areas. The Studio of 25m² has more hours of discomfort, despite having only one face exposed to solar radiation and its balcony has a reasonable size for shading. This behaviour can be explainedby its glazed area of the façade exceeding 20% of the floor area, a percentage indicated as ideal by the Performance Standard (NBR 15575/2021). Both apartments do not have secondary windows for cross ventilation which could improve the thermal performance of the internal environment, since there would be more air changes and renovation per hour.

The existing standards in Brazil are not mandatory but it is legally enforced when incorporated into the civil building code, which could significantly improve the internal thermal performance of the new buildings, to be more adapted to climate change. It is emphasised that existing standards suggest the minimum acceptable parameters for efficient buildings, but do not predict the increase in temperature caused by climate change and in a short time will be out of time. However, the minimum standardisation of the energy efficiency of the buildings is important, because it was found in this research that as the external temperatures become higher, the index of glazed area in proportion to the floor area, the quality of glass and the envelope area exposed to radiation, if below than is required by NBR 15575/2021, aggravate the internal operating temperature increase of the built environment.

According to the NBR Standard 15575/2021, ideally the transparent areas should be 20% of the floor area (floor area lower 20m² ) and 4m² (floor area greater than 20m² ). For the studios analysed here, the 19m² has a floor area of 13.95m² in the bedroom and the studio of 25m² has a floor area in the room equivalent to 16.25m². Its transparent areas should be respectively 2.79 and 3.25m². The apartment of 19m² reaches an area smaller (2.50m²), but the 25m² exceeds, reaching 5.42m².

Based on the results found here and because this article is part of a diagnosis of a larger and ongoing research, the next steps to be performed are simulations with the same studios mentioned in this article, but with new characteristics: greater protection for shading in the studio of 19m², reduction of the glazed area in the apartment of 25m² and insertion of glasses with better quality solar factor in both apartments for performing a comparison of the hours of discomfort comfort.

The main concern for this research is that the future thermal behaviour presented in this article, predicted by the end of the century in the simulations developed, may arrive faster than supposed, because according to the AR6 report of the Intergovernmental Panel on Climate Change (IPCC, 2022), so that global warming is limited to 1.5°C, emissions need to decrease in 2025, otherwise there is a 50:50 chance that the average global annual temperature will temporarily reach 1.5°C above the pre-industrial level for at least one of the next five years (WMO, 2022)

## 6. Acknowledgments

This research was partially supported by the Coordination for the Improvement of Capes Higher Education Personnel - master's scholarship no. 88887.637462/2021-00, by the National Council for Scientific and Technological Development - CNPq Foundation - for the Research Productivity Grant 312592/2021-3 and by the University of São Paulo - USP/PRP/PIPAE USP 2021.1.10424.1.9. Thanks to Dr. Rosmeri Porfirio da Rocha - IAG/USP for the treatment and availability of future data.

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# Balancing increased ventilation and thermal comfort in educational buildings: a case study

**Giulia Lamberti**[1]

[1] DESTEC, Dept. of Energy, Systems, Territory and Constructions Engineering, School of Engineering, University of Pisa, Largo Lucio Lazzarino, 56122 Pisa, Italy

**Abstract:** The pandemic situation has recently led to an increased focus on the importance of indoor air quality. Indeed, enhanced ventilation can lead to a reduction in the infection probability in indoor environments, resulting in a healthier environment. However, many buildings are naturally ventilated, as are often classrooms, so the only way to ensure ventilation is to open windows. This can be particularly critical during the winter period, as increased ventilation can lead to considerable thermal discomfort.
This paper investigates the conditions of air quality and thermal comfort before and during the pandemic using naturally ventilated university classrooms as a case study. The effect of the increased ventilation on thermal comfort and indoor air quality was analysed by studying changes in thermal neutrality due to students' adaptation to the new conditions. It was found that adaptation affects people's thermal neutrality, lowering the neutral temperatures of the students. This adaptive capacity can be correctly exploited to improve indoor conditions and balance air quality and thermal comfort even in the post-pandemic period.

**Keywords:** Adaptive thermal comfort; Ventilation; Indoor Air Quality; Classrooms; Covid-19

## 1. Introduction

Providing indoor environmental quality in educational buildings is particularly challenging, as students spend a consistent amount of time indoors and they can be therefore exposed to poor environmental quality (Bluyssen, 2016). Indeed, schools should provide the best learning conditions for students (Mendell and Heath, 2005). Providing thermal comfort in these buildings is particularly challenging, as comfort may depend on several aspects such as the educational stage (i.e. kindergartens, primary, secondary schools, and universities), the climate zone (i.e according to the Köppen-Geiger classification (Beck et al., 2018)), and the operation mode (i.e naturally or mechanically ventilated classrooms) (Lamberti et al., 2021). Different ranges of comfort temperatures can be found in the literature depending on these factors (Singh et al., 2019; Zomorodian et al., 2016), thus identifying the environmental conditions that should be maintained in classrooms is particularly difficult.
Another issue that has been faced in the last years is the need for increased ventilation to maintain the classrooms safe due to the Covid-19 pandemic. Indeed, room ventilation can reduce the infection probability (Morawska et al., 2020), especially in crowded spaces (Noorimotlagh et al., 2021). Accordingly, international organizations such as the Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA) or the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) recommended preventive measures to improve ventilation and reduce the risk, both in mechanically and naturally ventilated classrooms (ASHRAE, 2020; REHVA, 2020).
However, especially in the Mediterranean climate, several educational buildings are naturally ventilated and the only method to guarantee proper ventilation is by opening windows, with clear effects on thermal discomfort, especially during the winter period. For this reason, several studies have been carried out to investigate indoor air quality and thermal comfort

during the pandemic period. Alonso et al. (Alonso et al., 2021) analysed the effect of the Covid outbreak on thermal comfort in Spanish classrooms with mechanical ventilation and showed that situations of thermal discomfort occurred even if indoor air quality was improved. Schools were also investigated by Vassella et al. (Vassella et al., 2021), who showed that natural ventilation in Swiss classrooms is not acceptable during the winter period due to the cold discomfort that opening windows causes, suggesting mechanical ventilation to improve air quality. The same trend was recorded by Lovec et al. in kindergartens (Lovec et al., 2021), which showed better indoor air quality during the pandemic, but low changes in indoor air temperature, at least for the case study of Slovenia. Miranda et al. (Miranda et al., 2022) studied the combined effect of thermal comfort and indoor air quality during the winter season and showed that the improvement of air quality decreased thermal comfort. Moreover, studies on adaptive behaviours in buildings such as clothing changes or window operations have been carried out in residential buildings during the pandemic (Tahmasebi et al., 2022; Thapa et al., 2020).

The need for maintaining the infection probability lower than a certain threshold value is evident, especially in educational buildings (Fantozzi et al., 2022) and ventilation can improve indoor conditions. However, especially during the winter period, providing natural ventilation without impairing thermal comfort can be a real challenge. There is then the need for balancing the aspects of increased ventilation with thermal comfort to provide healthy and comfortable spaces. This paper aims to understand the extent to which it is possible to balance these two aspects by analysing air quality and thermal comfort in naturally ventilated university classrooms. In particular, occupants' adaptation to the environment was analysed, considering the variations in thermal neutrality before and during the pandemic.

## 2. Methodology

### 2.1. The case study

For the investigation, the classrooms located in the School of Engineering of the University of Pisa were selected. Pisa is located in the climate zone Csa (Mediterranean climate), according to the Köppen-Geiger classification (Beck et al., 2018). During the year, the temperature generally ranges from 3 °C to 30 °C and is rarely below -3 °C or above 33 °C (Meteonorm, 2022). The School of Engineering is composed of buildings with diverse characteristics in terms of period and construction type (Figure 1). Building A was built in 1932 and is a three-floor load-bearing masonry structure, the Building B is a four floors construction built between 1966 and 1967 with a steel structure and infill walls in prefabricated plasterboard. Building C is a five-floor construction built in 1980 with a steel structure with brick walls and the Building F is the result of a refurbishment of a single-storey industrial building, renovated in 2008.

The classrooms were selected from these four buildings to provide a wide sample of conditions and construction types. The classrooms presented different room volumes and occupancy and were located at different heights, as shown in Table 1. All the classrooms were naturally ventilated.

### 2.2. The measurement campaign

The measurement campaign was carried out before and during the pandemic period between 2018 and 2021, as shown in Table 1. The pre-pandemic data were acquired as a part of a measurement campaign to analyse Indoor Environmental Quality in university classrooms. The post-pandemic campaign followed the protocol used for the previous one, to allow a comparison between the two periods. In total, 22 onsite measurements were carried out, 7 before and 15 after the pandemic. The campaign was carried out during the heating season, which in Pisa refers to the period between the 1st of November and the 15th of April and during the measurements the heating system was switched on. This period can be considered the most critical in terms of balancing thermal comfort and increased ventilation, especially in naturally ventilated buildings since the outdoor temperatures are low and opening windows for providing ventilation can lead to thermal discomfort. The environmental parameters such as air temperature ($T_a$), relative humidity (RH), air velocity ($V_a$), and globe temperature ($T_g$) were measured and the mean radiant temperature ($T_r$) was calculated using a microclimate datalogger, in compliance with ISO 7726 standards (ISO 7726, 2001). The metabolic rate (M) was estimated from the activity carried out by the students during the lectures, while the clothing insulation ($I_{cl}$) was evaluated from questionnaires. $CO_2$ concentration was also measured during the campaign to assess the air quality conditions during the lectures. The probes were located in representative positions of the classrooms to assess the real conditions of the students, at a height of 1.1 m to evaluate the sitting position. The campaign started 30 minutes before the beginning of the lectures and continued for 2, 3, or 5 hours, depending on the duration of the lecture. Data were acquired with a measuring interval equal to 60 seconds, to include possible variations in the environmental parameters.


Figure 1. Three-dimensional view of the School of Engineering of the University of Pisa.

For the evaluation of thermal comfort, Fanger's rational (Fanger, 1970) and adaptive (Nicol et al., 2012) models have been used. In particular, the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) indices were calculated according to the ISO 7730 standard (ISO 7730, 2006), while the comfort temperatures were analysed in accordance with the European EN 16798-1 standard (EN 16798-1, 2019).

Meanwhile, questionnaires were submitted to the students to assess their subjective perception of the thermal environment after at least one hour of exposure, during the breaks and before students left the classroom. In particular, personal information including age, sex, and garments worn during the measurements (according to ISO 9920 standard (ISO 9920, 2009)) and the Thermal Sensation Vote (TSV) expressing the thermal sensation of the students on a 7-points scale were collected. Students were free to interact and modify their thermal environments, to assess possible adaptive actions that may occur to restore thermal comfort and improve indoor air quality. In total, 872 questionnaires were collected in the survey, from students in the age between 20 and 26 years old.

Table 1. Characteristics of selected classrooms in the School of Engineering of the University of Pisa.

| ID | Building | Floor | Area ($m^2$) | Volume ($m^3$) | N (pers) | V/N ($m^3$/pers) | Period |
|---|---|---|---|---|---|---|---|
| 1 | A | 2 | 71 | 228 | 31 | 7.4 | Pre |
| 2 | A | 2 | 134 | 605 | 31 | 19.5 | Pre |
| 3 | B | 0 | 190 | 510 | 31 | 16.5 | Pre |
| 4 | C | 3 | 48 | 243 | 19 | 12.8 | Pre |
| 5 | F | 0 | 126 | 438 | 31 | 14.1 | Pre |
| 6 | F | 0 | 131 | 778 | 31 | 25.1 | Pre |
| 7 | F | 0 | 126 | 438 | 42 | 10.4 | Pre |
| 8 | A | 1 | 86 | 476 | 25 | 19.0 | During |
| 9 | A | 2 | 71 | 228 | 16 | 14.3 | During |
| 10 | A | 2 | 143 | 371 | 19 | 19.5 | During |
| 11 | A | 2 | 77 | 199 | 13 | 15.3 | During |
| 12 | A | 2 | 71 | 228 | 11 | 20.7 | During |
| 13 | A | 1 | 86 | 476 | 17 | 28.0 | During |
| 14 | A | 2 | 77 | 199 | 10 | 19.9 | During |
| 15 | A | 2 | 71 | 228 | 13 | 17.5 | During |
| 16 | A | 2 | 143 | 371 | 20 | 18.6 | During |
| 17 | B | 2 | 40 | 116 | 9 | 12.9 | During |
| 18 | B | 2 | 40 | 116 | 6 | 19.3 | During |
| 19 | B | 2 | 95 | 270 | 9 | 30.0 | During |
| 20 | B | 2 | 40 | 116 | 9 | 12.9 | During |
| 21 | C | 4 | 43 | 125 | 15 | 8.3 | During |
| 22 | C | 4 | 43 | 125 | 11 | 11.3 | During |

## 3. Results and discussion

### 3.1. Measurements of environmental parameters

Table 2 reports the mean, maximum, minimum, and standard deviation of the air temperature, relative humidity, and $CO_2$ concentration in the classrooms. The running mean outdoor temperature ($T_{rm}$) was calculated according to EN 16798-1 (EN 16798-1, 2019) considering the daily mean outdoor temperatures recorded in the seven days before the campaign. The running mean outdoor relative humidity ($RH_{rm}$) was calculated in the same way, considering the daily mean outdoor relative humidity. The classrooms' environment was uniform, as the mean difference between $T_a$ and $T_r$ was -0.3°C and the air velocity was in most cases low (mean $V_a$=0.02 m/s).

Regarding the outdoor conditions, $T_{rm}$ ranged between 5.0°C and 14.6°C, while $RH_{rm}$ was between 68.2% and 90.5%. In the pre-pandemic period, the $T_{rm}$ ranged between 9.8°C and 11.2°C, while during the pandemic period the range of outdoor temperatures was wider, as it comprised values between 5°C and 14.6°C.

Considering the indoor conditions, the mean air temperatures varied between 17.6°C during the pandemic period and 24.9°C in the pre-pandemic period, with a standard deviation between 0.1°C and 1.4°C. From Table 2 it can be noticed that the air temperatures in the classrooms were generally higher before the pandemic, and in several cases during the pandemic were much lower than the 22°C that is recommended for classrooms (ISO 7730, 2006). The mean indoor relative humidity varied between 24.7% and 64.8%, with a standard deviation between 0.3% and 4.0%. In several cases, RH was lower than 40%, which may be the cause of unhealthy conditions and can favour the transmission of infectious diseases (Taylor and Graef, 2020). Finally, the mean $CO_2$ concentration ranged between 564 and 3451, with peaks reaching 4797 ppm in the pre-pandemic periods and lower values during the pandemic of 538 ppm, which is an indicator of good ventilation. This means that during the pandemic the classrooms were often properly ventilated unless the outdoor conditions were severe ($T_{rm}$ around 5°C) when the thermal discomfort caused by opening windows did not allow occupants to increase ventilation. The lower $CO_2$ concentration in this period can be related to the increased awareness of the necessity to improve ventilation but also to the lower occupancy in the classrooms.

Table 2. Values measured for outdoor conditions, air temperature, relative humidity, and $CO_2$ concentration during the measurement campaign.

| ID | Outdoor | | $T_a$ (°C) | | | | RH (%) | | | | $CO_2$ (ppm) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $T_{rm}$ | $RH_{rm}$ | Max | Min | Mean | SD | Max | Min | Mean | SD | Max | Min | Mean | SD |
| 1 | 10.1 | 89.0 | 23.4 | 20.8 | 22.5 | 0.7 | 68.3 | 61.5 | 64.8 | 1.3 | 4797 | 1907 | 3451 | 782 |
| 2 | 9.8 | 84.8 | 23.4 | 19.9 | 22.4 | 0.9 | 37.8 | 35.5 | 35.9 | 0.3 | 1434 | 867 | 1145 | 167 |
| 3 | 10.1 | 89.0 | 23.9 | 18.4 | 22.2 | 1.4 | 53.9 | 46.7 | 48.1 | 1.3 | 1585 | 604 | 1180 | 261 |
| 4 | 11.2 | 86.7 | 25.1 | 24.2 | 24.9 | 0.2 | 37.3 | 32.4 | 34.6 | 1.1 | 2507 | 1832 | 2088 | 196 |
| 5 | 9.9 | 90.5 | 23.3 | 21.8 | 22.7 | 0.4 | 60.8 | 51.7 | 56.8 | 1.4 | 2260 | 882 | 1630 | 336 |
| 6 | 9.9 | 90.5 | 23.7 | 21.5 | 21.8 | 0.5 | 63.9 | 52.0 | 61.3 | 2.6 | 2714 | 2194 | 2485 | 135 |
| 7 | 10.8 | 70.8 | 25.8 | 22.2 | 24.6 | 0.9 | 53.7 | 49.3 | 52.3 | 0.8 | 2672 | 1338 | 2051 | 405 |
| 8 | 14.6 | 68.2 | 20.7 | 20.0 | 20.2 | 0.2 | 46.3 | 43.5 | 44.9 | 0.7 | 1057 | 620 | 753 | 142 |
| 9 | 14.6 | 68.2 | 20.3 | 19.6 | 19.8 | 0.1 | 51.7 | 41.7 | 46.6 | 2.4 | 640 | 540 | 564 | 10 |
| 10 | 10.7 | 88.1 | 23.7 | 22.0 | 23.0 | 0.4 | 56.6 | 47.6 | 50.9 | 2.8 | 1490 | 602 | 1042 | 357 |
| 11 | 11.6 | 88.1 | 22.5 | 20.5 | 21.9 | 0.5 | 48.1 | 36.0 | 39.9 | 2.7 | 685 | 538 | 617 | 34 |
| 12 | 11.6 | 88.1 | 22.7 | 20.6 | 22.0 | 0.3 | 37.8 | 35.6 | 36.8 | 0.5 | 833 | 547 | 727 | 65 |
| 13 | 10.7 | 75.7 | 22.1 | 21.2 | 21.8 | 0.2 | 44.7 | 41.8 | 42.6 | 0.6 | 734 | 609 | 669 | 26 |
| 14 | 8.7 | 70.8 | 21.2 | 17.8 | 20.5 | 0.7 | 35.2 | 23.4 | 27.4 | 2.5 | 944 | 664 | 834 | 62 |
| 15 | 8.7 | 70.8 | 22.3 | 21.4 | 22.0 | 0.1 | 41.8 | 29.1 | 36.9 | 2.9 | 2823 | 1211 | 2214 | 365 |
| 16 | 5.0 | 80.7 | 24.6 | 22.5 | 23.6 | 0.8 | 29.5 | 25.5 | 27.9 | 1.4 | 1234 | 641 | 970 | 229 |
| 17 | 10.7 | 88.1 | 21.9 | 19.6 | 20.9 | 0.7 | 62.8 | 53.3 | 56.6 | 2.6 | 641 | 565 | 594 | 15 |
| 18 | 11.3 | 80.7 | 23.8 | 20.1 | 22.2 | 1.0 | 33.8 | 21.4 | 24.7 | 2.6 | 633 | 556 | 586 | 18 |
| 19 | 10.5 | 78.3 | 22.1 | 20.0 | 21.4 | 0.6 | 52.2 | 48.3 | 50.8 | 1.1 | 974 | 627 | 858 | 101 |
| 20 | 5.0 | 83.5 | 23.0 | 18.0 | 19.5 | 1.3 | 37.4 | 33.2 | 35.3 | 0.8 | 1258 | 626 | 743 | 177 |
| 21 | 5.0 | 82.0 | 18.2 | 16.4 | 17.6 | 0.4 | 59.0 | 50.1 | 54.9 | 2.3 | 3294 | 1866 | 2553 | 371 |
| 22 | 5.2 | 82.4 | 19.3 | 17.7 | 18.5 | 0.5 | 56.1 | 42.8 | 51.9 | 4.0 | 2588 | 659 | 1684 | 623 |

### 3.2. Analysis of thermal comfort

Thermal comfort was investigated according to the rational and the adaptive models, considering the mean environmental ($T_a$, RH, $T_r$, $V_a$) and individual (M, $I_{cl}$) parameters measured during the lectures. The metabolic rate was considered equal to 1 met, as students were carrying out sedentary activities (sitting position while attending the lectures), while the mean clothing insulation varied according to the data collected from questionnaires. Table 3 reports the mean values of air temperature ($T_a$), relative humidity (RH), air velocity ($V_a$), mean radiant temperature ($T_r$), operative temperature ($T_{op}$), and clothing insulation ($I_{cl}$) encountered during the measurement campaign. From these parameters, PMV and PPD indices have been calculated. $T_a$, $T_r$, and $T_{op}$ were higher before the pandemic, while the relative humidity was variable in both cases. The mean $V_a$ remained generally low, with a maximum of 0.13 m/s during the pandemic. The clothing insulation varied between 0.8 and 1.1 clo, which are typical values during winter periods. From these parameters, the PMV and PPD indices were calculated, and it resulted that during the pandemic the thermal environment was attested to sensations of cold, while before students were mostly thermally neutral. This is a result of the increased ventilation, which modified the indoor environmental conditions.

Table 3. Mean value of $T_a$, RH, $V_a$, $T_r$, $T_{op}$, $I_{cl}$, M measured and PMV and PPD indices calculated from the field study.

| ID | $T_a$ (°C) | RH (%) | $V_a$ (m/s) | $T_r$ (°C) | $T_{op}$ (°C) | $I_{cl}$ (clo) | PMV | PPD (%) | Period |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 22.5 | 64.8 | 0.07 | 22.0 | 22.3 | 1.0 | -0.1 | 5.3 | Pre |
| 2 | 22.4 | 35.9 | 0.01 | 22.6 | 22.5 | 1.0 | -0.3 | 6.5 | Pre |
| 3 | 22.2 | 48.1 | 0.00 | 23.4 | 22.8 | 1.0 | -0.1 | 5.3 | Pre |
| 4 | 24.9 | 34.6 | 0.00 | 24.8 | 24.9 | 1.0 | 0.4 | 7.7 | Pre |
| 5 | 22.7 | 56.8 | 0.00 | 21.7 | 22.2 | 1.0 | -0.2 | 5.8 | Pre |
| 6 | 21.8 | 61.3 | 0.01 | 21.7 | 21.7 | 1.0 | -0.3 | 6.9 | Pre |
| 7 | 24.6 | 52.3 | 0.01 | 24.7 | 24.7 | 0.8 | 0.2 | 5.5 | Pre |
| 8 | 20.2 | 44.9 | 0.04 | 20.2 | 20.2 | 1.1 | -0.7 | 15.2 | During |
| 9 | 19.8 | 46.6 | 0.06 | 20.8 | 20.3 | 0.8 | -1.3 | 38.3 | During |
| 10 | 23.0 | 50.9 | 0.01 | 23.0 | 23.0 | 0.9 | -0.2 | 5.8 | During |
| 11 | 21.9 | 39.9 | 0.00 | 22.2 | 22.0 | 0.9 | -0.5 | 10.9 | During |
| 12 | 22.0 | 36.8 | 0.01 | 22.3 | 22.2 | 0.9 | -0.5 | 11.0 | During |
| 13 | 21.8 | 42.6 | 0.00 | 22.6 | 22.2 | 0.8 | -0.7 | 14 | During |
| 14 | 20.5 | 27.4 | 0.00 | 21.0 | 20.8 | 1.0 | -0.8 | 19.9 | During |
| 15 | 22 | 36.9 | 0.00 | 21.5 | 21.8 | 0.9 | -0.7 | 13.9 | During |
| 16 | 23.6 | 27.9 | 0.13 | 23.8 | 23.7 | 0.9 | -0.4 | 8.1 | During |
| 17 | 20.9 | 56.6 | 0.01 | 21.3 | 21.1 | 1.0 | -0.6 | 12.4 | During |
| 18 | 22.2 | 24.7 | 0.01 | 22.9 | 22.5 | 0.9 | -0.5 | 10.3 | During |
| 19 | 21.4 | 50.8 | 0.01 | 21.6 | 21.5 | 1.0 | -0.5 | 11.2 | During |
| 20 | 19.5 | 35.3 | 0.01 | 21.8 | 20.7 | 1.1 | -0.7 | 15.2 | During |
| 21 | 17.6 | 54.9 | 0.00 | 17.2 | 17.4 | 1.1 | -1.3 | 41.5 | During |
| 22 | 18.5 | 51.9 | 0.00 | 19.2 | 18.8 | 1.0 | -1.1 | 30.5 | During |

Figure 2 shows the relationship between PMV and PPD and the mean operative temperature. The red squares indicate the pre-pandemic measurements and the yellow triangles the during-pandemic assessment. As previously stated, in the pre-pandemic situation the operative temperature ($T_{op}$) recorded indoors was much higher than the ones during the pandemic, which is reflected in higher values of PMV. The PMV calculated for the classes after the Covid-19 breakdown was always attested to cold sensations, with a higher percentage of dissatisfied. This is a clear indicator of the effect that increased ventilation through opening windows can have on the thermal environment, which may cause discomfort among students. According to the rational model, students are comfortable in all the cases before the pandemic (PPD<10%), but only in two cases during it. From the regression between $T_{op}$ and PMV shown in Figure 2 ($R^2$=0.80), it is possible to calculate the neutral temperature at which students are thermally neutral according to Fanger's model, which is 23.9°C. However, as can be noticed from Table 3, in most cases the $T_{op}$ was much lower than this value, especially during the pandemic. From the polynomial regression between $T_{op}$ and PPD (Figure 2) was also possible to calculate the comfort temperature at which the percentage of dissatisfied reaches the minimum, which is equal to 24.8°C. Even in this case, most of the measurements carried out during the pandemic period presented a percentage of dissatisfied higher than 10%.

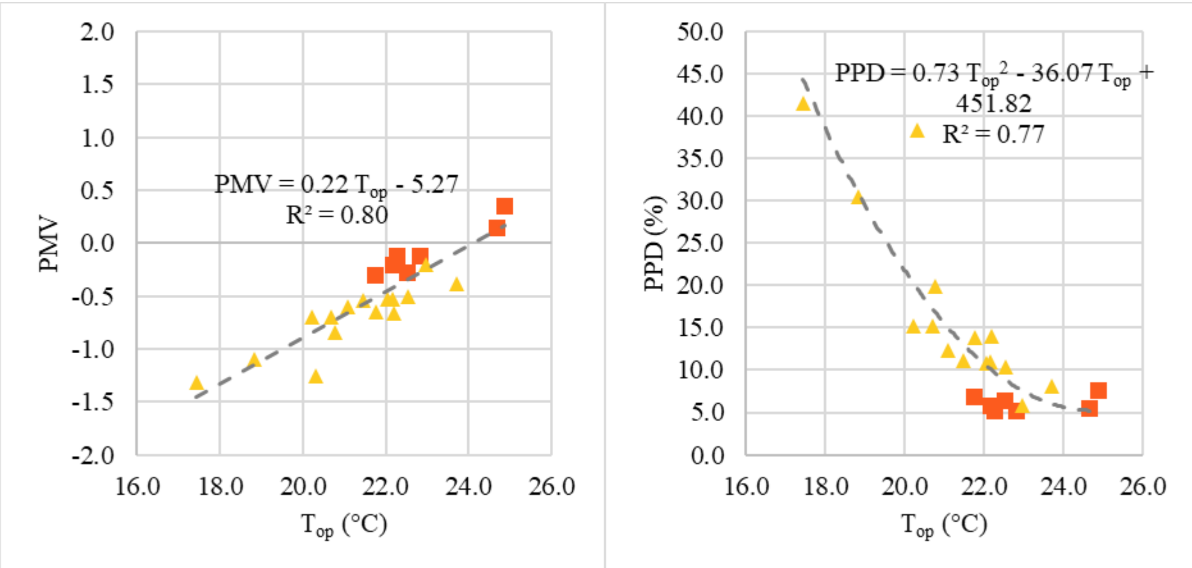


Figure 2. Relationship between PMV and PPD and operative temperature. The red squares represent the pre-pandemic measurements and the yellow triangles the during-pandemic assessment.

The mean operative temperatures obtained from the measurement campaign were then reported in the adaptive model provided by EN 16798-1 (EN 16798-1, 2019) standard (Figure 3). The adaptive relationship has been extended for running mean outdoor temperatures lower than 10°C, as adaptation can occur even in colder climates (Humphreys et al., 2016; Nicol et al., 2012). In this case, all the operative temperatures are included in the comfort band described by the adaptive model. The adaptive model defines three Categories of comfort, from the most (Category I) to the least restrictive (Category III) (EN 16798-1, 2019). In most situations, the operative temperatures laid in Category I, and only for four classes during the pandemic period temperatures were outside this range. This result shows that with an adaptive model, it is possible to provide thermal comfort under a wider range of conditions than those shown by the rational model, even as a function of external climatic conditions. Compared to the Fanger model, there are more predicted conditions under which students are thermally comfortable, even though in the post-pandemic period the temperatures are all shifted towards the lower end of the comfort band.

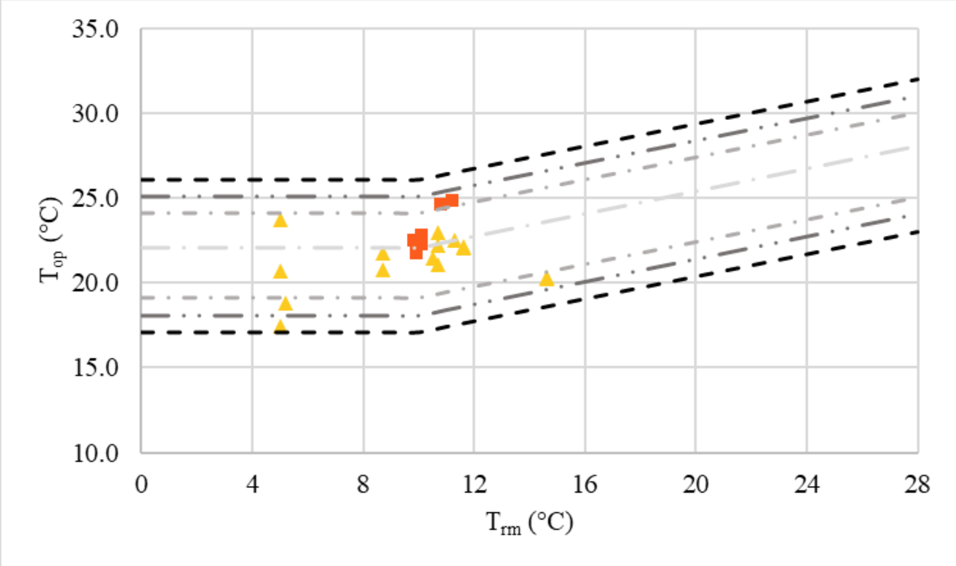

Figure 3. Adaptive relation provided by the European standard EN 16798-1 (EN 16798-1, 2019). The red squares represent the pre-pandemic measurements and the yellow triangles the during-pandemic assessment.

### 3.3. Evidence for thermal adaptation during the pandemic period

It is recognized that the mechanisms for thermal adaptation can be various and can include behavioural, physiological, and psychological adaptation (de Dear and Brager, 1998). People can restore thermal comfort by actively changing their environments (e.g. opening/closing windows and doors, switching on/off fans, etc.) or modifying their clothing and activity. Furthermore, physiological, and psychological adaptation can occur to restore thermal comfort. During the pandemic, people were forced to increase the ventilation inside buildings, which means that in naturally ventilated classrooms they had to open windows even when the outdoor conditions were quite severe and may cause thermal discomfort. However, occupants were also aware of the importance of increasing ventilation to keep environments safe, and they may have been more tolerant to lower temperatures, adapting to their normal thermal environment.

For this reason, the subjective responses obtained from the questionnaire were investigated to understand possible shifts in neutral temperature that may have been caused by the thermal adaptation of the students. Figure 4 shows the relationship between the operative temperature and the TSV obtained from questionnaires for the pre (in red) and during (in yellow) pandemic periods, clustered for 0.5°C steps of $T_{op}$. It can be noticed a clear difference between the thermal sensations associated with the $T_{op}$ pre and during the pandemic. Indeed, the thermal sensation for the pre-pandemic period is always attested to neutral sensations for a temperature range between 22°C and 26°C, which are relatively high for winter periods with evident consequences also on energy consumption. In this case, it is not possible to derive a relationship between $T_{op}$ and TSV to calculate a comfort temperature ($R^2$=0.05), but the tendency to adapt to different conditions is evident. Students also adapted to overheated classrooms, defining neutral temperatures higher than 22°C even in winter. On the contrary, for the pandemic period, it is possible to estimate a relationship between $T_{op}$ and TSV ($R^2$=0.62) and to derive a neutral temperature equal to 21.9°C. In this case, higher temperatures were related to sensations of warmth. Compared to the neutral temperature obtained from PMV (23.9°C) and to the pre-pandemic period, the neutral temperature calculated from TSV during the pandemic is much lower, with evident impacts on energy consumption.

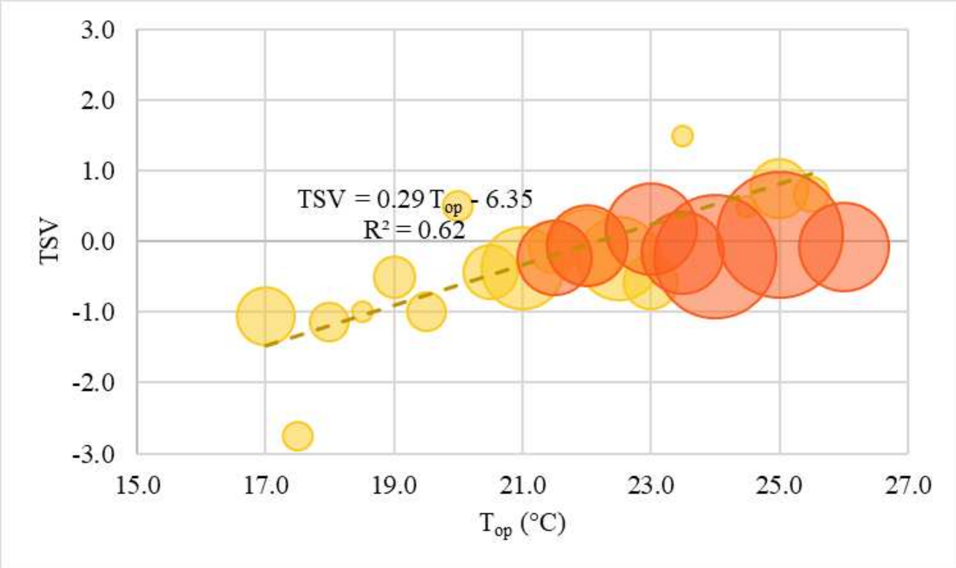


Figure 4. Relationship between the operative temperature and the TSV obtained from questionnaires for the pre (in red) and during (in yellow) pandemic periods.

The main implication of this study is the evidence for adaptation in university classrooms. Especially during the pre-pandemic period, classrooms were often overheated, with indoor air temperatures reaching values up to mean values of 25°C indoors, despite low outdoor temperatures (Tables 2-3). In this scenario, students were able to adapt to very high temperatures even in winter and thermal neutrality was found also at 26°C. This is, however, an incorrect way of using people's adaptation, which results in an unnecessary increase in consumption. On the contrary, the need for increased ventilation by opening windows resulted in lower neutral temperatures during the pandemic period, especially when compared to other studies in university buildings (Lamberti et al., 2021; Zomorodian et al., 2016) and showed the students' ability to adapt to colder conditions. This obviously resulted in increased heat loss due to ventilation, however, it also highlighted the students' adaptive capacity to winter conditions. Indeed, during the pandemic period, students adapted to colder thermal conditions, and $T_{op}$ that before were considered neutral were producing sensations of warmth.

This adaptation cannot be related to physiological adaptation, as it often occurs in extreme conditions (Fox, 1974) and requires long periods to take place (de Dear and Brager, 1998). It cannot be linked neither to behavioural adaptation, as the measurement campaign was carried out during the heating season (heaters were switched on in both cases), occupants were “forced” to open windows and doors to provide ventilation, and the control of the environment was inhibited. Furthermore, clothing modifications did not occur and the mean $I_{cl}$ was equal to 1 clo before the pandemics and 0.9 clo during, thus people wore warmer clothing before than during the pandemics, despite the colder conditions in this last case. Therefore, this modification in thermal neutrality should be related to psychological adaptation and to the fact that people’s awareness of the need for increased ventilation led them to adapt to the thermal environment.

The significance of this finding is that the awareness of one's surroundings leads occupants to adapt to different thermal conditions, to the extent that thermal neutrality changes as shown by the different neutral temperatures during the pre and pandemic periods. This is the same principle that applies, for example, to perceived control, whereby people who feel they can control their environment are generally more satisfied and modify their thermal neutrality towards lower temperatures in winter and higher temperatures in summer (Xu and Li, 2021; Yun, 2018).

Obviously, it would not be correct to make people exclusively adapt to buildings, but a balance between occupants' requirements and buildings' operation is necessary. The direct consequence is that increased awareness of building use by occupants can lead to improved air quality conditions without compromising thermal comfort, for example using intelligent $CO_2$ monitoring systems that allow windows to be opened when they are needed (Fantozzi et al., 2022). Moreover, people's adaptability is a resource that must be properly exploited to improve indoor comfort and reduce consumption. Indeed, the adaptation of students to overheated classrooms during the winter period results in unnecessary waste of heating energy.

## 4. Conclusions

The need for increased ventilation during the pandemic to maintain safe environments led to the necessity to balance the aspects of indoor air quality and thermal comfort. Indeed, in most cases, classrooms are naturally ventilated and the only way to provide clean air is to open windows, which can be a cause of discomfort during the winter period. For this reason, thermal comfort and indoor air quality were analysed in naturally ventilated university classrooms pre and during the pandemic. The effect of increased ventilation in the last period is reflected in the decrease of the $CO_2$ concentration in classrooms, but also in the lower operative temperatures that were detected indoors. Analysing the data with Fanger's rational model, the PMV predicts cold discomfort during the pandemic and thermal neutrality before it. The adaptive model shows instead that the operative temperatures remain within the comfort bands, but on the cold side during the pandemic period.

To understand the real conditions of the students, the Thermal Sensation Vote (TSV) expressing the sensation of the students on a 7-points scale, was estimated from questionnaires. It resulted that there is evidence for psychological adaptation, as occupants were neutral at high $T_{op}$ before the pandemic (even at 25-26°C during winter), while the neutral temperature reduced to 21.9°C during it. This shows that students can adapt to different thermal conditions, even to classrooms overheating. This last is, however, incorrect use of adaptation as it brings unnecessary increased energy consumption.

The results show that indoor air quality and thermal comfort are not necessarily in contrast to each other, but they need to be balanced. It is indeed possible to improve air quality without impairing thermal comfort thanks to the thermal adaptation of the occupants, as long as they are aware of their environment. Smart systems that can indicate when it is necessary to ventilate classrooms can be used to improve air quality while maintaining thermal comfort and not increasing energy consumption. This will be also useful in the future to reduce energy waste and improve air quality and thermal comfort in buildings.

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# Taking into account occupant behaviour during heatwaves in building simulation

**Mathilde Hostein[1,2], Bassam Moujalled[1,3], Marjorie Musy[1,3] and Mohamed El Mankibi[2]**

[1] BPE research team, Cerema, France;
[2] LTDS, Ecole Nationale des Travaux Publics de L'Etat (ENTPE), CNRS UMR 5513, France;
[3] LOCIE, Université Savoie Mont Blanc, CNRS UMR 5271, France.

**Abstract:** Occupants have a strong impact on the indoor environment through their presence and actions. Their behaviour is therefore taken into account in an increasingly detailed way in building performance simulations. However, most of the researches have focussed on the heating period, due to the impact of behaviours on energy consumption. Heatwaves represent a particular context during which occupants prioritize their thermal comfort. However, occupant behaviour during heatwaves is still rarely studied. These extreme events are likely to become more frequent and intense with climate change. The air conditioning equipment is already increasing all over the world, also highlighting the problem of summer energy consumption. Through its impact on the indoor environment, the future climate will also affect behaviour. Finally, the urban context generates urban heat islands but also nuisances (noise, pollution, insecurity, etc). This article identifies the latest advances, but also the blocking points in considering occupant behaviour during heatwaves, as well as the perspectives of development.

**Keywords:** Occupant Behaviour, Heatwave, Building Simulation

## 1. Introduction

Buildings are designed to provide occupants with a good indoor environment while minimising their energy needs. The behaviour of future buildings is therefore simulated prior to their construction in order to assess their performance, mandatory step in many regulations. There are several Building Performance Simulation (BPS) softwares that can be used.

In order to achieve this objective, the phenomenon of climate change currently needs to be taken into account. It will have a direct effect on the indoor environment and the energy demand of buildings. Heating needs will decrease, while cooling needs will increase considerably to avoid thermal discomfort and even health risks related to the increase in indoor overheating (IPCC, 2022a).

However, this thermal discomfort can be mitigated without resorting to energy-intensive air-conditioning systems through climate change adaptation measures (Silvero et al., 2019). There is a growing interest in passive solutions and therefore a need to evaluate their effectiveness (Machard et al., 2020).

The use of controllable external solar shading and over-ventilation by opening windows are the two most effective solutions identified by van Hooff et al. (van Hooff et al., 2015). Occupants play an important role in the successful implementation of these solutions. However, most studies consider statistical or idealized scenarios, in which windows are for example always open when outdoor conditions are favourable for cooling (Alessandrini et al., 2019). In reality, the occupant may decide to close the window for many reasons independent of the outside temperature, such as noise, risk of insecurity, draughts, pollution, privacy, social relationships... (van Hooff et al., 2015).

The issue of occupants is therefore central in the design of low-energy buildings, both new and renovated. It has been well understood by the architects who are pioneers in the design of efficient buildings (Molina et al., 2018). Indeed, occupants strongly impact the indoor environment through their presence and actions (Yan and Hong, 2018). The impact is particularly important in residential buildings which allow more freedom (Laaroussi et al., 2020).

The impact of occupants is highlighted by the modelling of existing buildings, especially low-energy buildings. Indeed, several studies have compared the energy consumption of existing buildings with the one obtained by simulation. The results can differ significantly: this difference is called the performance gap (Harputlugil and de Wilde, 2021), which is mainly caused by occupants. There is therefore a need to integrate Occupant Behaviour (OB) into BPS.

In the context of climate change, this article will therefore focus on OB during heatwaves. Extreme weather events such as these will become more intense, more severe and more frequent (IPCC, 2022b). They will lead to extreme temperatures, especially in cities (IPCC, 2022b), where specific constraints are added that may limit occupants' adaptation actions.

In the first part, we will look at the actions that occupants can take to adapt to extreme heat, taking into account the context of climate change and the challenges imposed by cities. We will then discuss how to model these behaviours with the aim of integrating them into BPS, in order to provide a better holistic view in the design of buildings.

## 2. Occupant adaptation actions

We will first see what actions occupants can take to protect themselves from indoor overheating in a residential context, then we will discuss the impact of climate change on future behaviour and finally we will see how the urban context limits these behavioural solutions.

### 2.1. Daily OB to improve summer thermal comfort

Occupants act to satisfy their needs and ensure their comfort. This includes (but is not limited to) thermal comfort, which is particularly important during heatwaves. In this case, they can adopt several solutions to adapt to hot weather.

Hellwig et al. (Hellwig et al., 2019) list several adaptive responses to a warm or cold environment. It is noteworthy that automatic systems that take control away from the user are often a source of dissatisfaction (Gaetani, 2019). This is linked to the notion of adaptive opportunity (de Dear and Brager, 1998). It can be explained with the theory of adaptive comfort (Humphreys et al., 2016; Nicol et al., 2012), whose concept is based on three principles of adaptation: behavioural, physiological and psychological. Behavioural adaptation is related to the direct actions of the occupant to ensure comfort. Physiological adaptation or acclimatisation is the reaction of the human body after a thermal stress outside its comfort range. Psychological adaptation is related to the occupant's perception and degree of control that he feels he has over its environment (Hellwig et al., 2019).

We have chosen to classify heat adaptation techniques into seven categories, presented in the following and summarised in Table 1.

On a personal level, an occupant can adjust his clothes or his activity. This will not alter the indoor environment, and therefore will not compete with the needs of other occupants, unlike the other actions described later. Lightweight garments are preferred during hot days. In some contexts, occupants may still be required to comply with a restrictive dress code (Schiavon and Lee, 2013). When studying clothing behaviour, one can look at both the choice of clothing at the beginning of the day, which is strongly influenced by outdoor conditions, or the adjustment of clothing during the day (De Carli et al., 2007). An occupant may then choose to stop or not start an activity that will increase his metabolism if he is too hot or anticipates such thermal discomfort. However, in some cases, he will be obliged to carry out an activity for reasons external to thermal comfort without being able to adapt his schedule. In some cultures, it is common for people to take a nap in the early afternoon. One inhabitant questioned by Molina and Allagnat (Molina and Allagnat, 2019) even talks about breathing exercises to fight against the stifling heat. An occupant can also hydrate by drinking water, take a shower or spray himself with water to improve his thermal comfort (Machard, 2021).

Reducing heat-raising activities is a technique that occupants can apply to limit indoor overheating. By this term we mean limiting the use of all heat-producing appliances. However, the use of appliances may be linked to the occupants' activities and therefore impossible to avoid. For example, an occupant may have to turn on the iron to press his clothes, even if this causes him thermal discomfort. However, occupants can try to minimise heat-raising activities in the dwelling, for example by avoiding using the oven in summer (Subrémon, 2010). Subrémon (Subrémon, 2010) also observed a family who created a summer kitchen in the laundry room to cook food without heating the house. There are also solutions based on vernacular customs, such as laying out wet sheets at the beginning of the day or wetting the floor tiles (Molina and Allagnat, 2019).

Opening windows for natural ventilation can allow occupants to cool their homes. When the outside temperature drops, occupants can open windows to cool the building and create draughts (Subrémon, 2010). Night ventilation is a solution used by the inhabitants (Molina and Allagnat, 2019). However, natural ventilation is a solution that is less effective in single oriented dwellings. Occupants use windows for thermal comfort, especially in summer, and possibly for indoor air quality (Carlucci et al., 2020; Rijal et al., 2018; Sansaniwal et al., 2021). This action is also highly dependent on household routines (Laaroussi et al., 2020).

Occupants can also use solar protections. By this term we mean orientable or non-orientable devices, interior curtains and blinds, and shutters or exterior solar protections. It should be noted that not all these devices are equally effective. There are even more rudimentary solutions such as cardboard taped to the windows, sheets or even parasols (Molina and Allagnat, 2019). Occupants use solar shading for thermal and visual comfort (Carlucci et al., 2020), as well as for privacy (Sansaniwal et al., 2021; Yan and Hong, 2018). They tend to close blinds in uncomfortable situations, such as glare (Sansaniwal et al., 2021), but are less likely to reopen them when conditions are more suitable (Gaetani, 2019). Although it is often the visual aspect that is highlighted in studies, closing the shutters of exposed rooms during the hottest hours is a solution used by occupants to prevent indoor overheating (Subrémon, 2010).

Air conditioning is a energy-consuming device. It can be used by occupants to ensure their thermal comfort. However, Pellegrino (Pellegrino, 2013) has noted in India that the use of air conditioning is not related to thermal comfort, but is used to demonstrate economic and social status. For air conditioning, one can look at the decision to turn the device on or off, the operation schedule and the set temperature. The issue of affordability is important with this equipment, as installation and running costs may limit its use.

Fans consume less energy than air conditioners (Tartarini et al., 2022). Fans can be an alternative to air conditioning, with a much lower environmental and financial impact. This universal solution can be seen as a personal adaptation action if they are individual fans, but there are also ceiling fans. They are an effective solution during heatwaves, because the increase in airflow improves evaporative losses due to the sweating of the human body, and remain a low-cost cooling technique (Tartarini et al., 2022). They greatly improve occupants' thermal comfort in Langevin's study (Langevin et al., 2014).

It should be noted that presence of occupants in the dwelling is a key condition for the execution of these actions. Occupancy models are used to determine the presence, number and movement of occupants in rooms (Carlucci et al., 2020). As they can be linked to activities, occupancy models can be constructed using time use surveys (TUS) (Reynaud et al., 2017). Occupancy can also be considered as adaptation action to heat. Indeed, some occupants leave the dwelling to go to an air-conditioned building or to a park (Molina and Allagnat, 2019). On the contrary, if the dwelling is cool, occupants may decide to confine themselves and keep their activities indoors (Molina and Allagnat, 2019; Subrémon, 2010). Occupants may also avoid the warmest rooms of the dwelling (Molina and Allagnat, 2019; Subrémon, 2010).

Table 1. Occupant adaptation actions to hot temperatures: examples of virtuous behaviour

| Type of adaptation action | Examples of such action |
|---|---|
| **Personal adjustments** | Choice of clothes in the morning<br>Adding or removing a layer of clothing<br>Changing its posture<br>Being less active<br>Taking a nap<br>Taking a shower |
| **Reduction of heat-raising activities** | Avoiding using appliances such as the oven |
| **Windows** | Creating draughts<br>Opening when the outside temperature drops<br>Night ventilation |
| **Solar shading** | Lowering the blinds<br>Closing the shutters<br>Opening the sunshade<br>Taping cardboard to windows |
| **Air-conditioning** | Switching on the air conditioning<br>Adjusting the set temperature<br>Setting up the operation schedule |
| **Fans** | Switching on the fan<br>Using ceiling Fan |
| **Occupancy** | Leaving the dwelling to go to a cooler place<br>Confining himself in the dwelling<br>Avoiding some rooms that are too exposed |

Finally, it is important to consider the anticipation of occupants when studying adaptation solutions linked to their behaviour. Indeed, occupants do not only cope and react to a change in their environment. They adapt and are often proactive, meaning that they can also predict the evolution of the environment and act in the case of hypothetical future uncomfortable conditions (von Grabe, 2016), for example closing shutters in the morning during the summer. The occupants have indeed some comfort expectations which are created by their past experiences (de Dear and Brager, 1998).

### 2.2. Future occupant behaviour

Climate change is an undeniable reality. It already has a direct effect on the indoor environment and the energy demand of buildings. Extreme events, such as heatwaves, are expected to become more intense and frequent (IPCC, 2022b). Building resilience does not only rely on technical improvements but also on occupants (Pisello et al., 2017). It is therefore important to consider the evolution of the daily occupant behaviour with the future climate and the new adaptation possibilities. Indeed, when we assess the impact of climate change on buildings, we input meteorological files that take this phenomenon into account, generally without changing the data related to OB. However, OB is likely to change. We do not know how to predict future OB, but in this section, we would like to highlight the points on which particular attention can be paid in exploring this context.

It is interesting to focus on the use of air conditioning. It should be noted that the new French regulation RE2020 now includes a heatwave scenario in the calculation of the summer thermal comfort indicator with a requirement for low and high thresholds, which take into account the possible use of air conditioning (MTE and Cerema, 2021). Limiting energy consumption is a challenge in the context of the energy transition, but the changes in behaviour are not necessarily those expected in terms of actual heating practices. Indeed, despite the incentives provided by public authorities, hedonism leads to a priority search for comfort (Fijalkow and Maresca, 2020). With climate change, indoor overheating will become common during summer and will lead to thermal discomfort (Silvero et al., 2019) or an increasing need for air conditioning to avoid this problem (Liu et al., 2020). In addition to increasing the energy consumption of the building sector, air conditioning can cause electricity demand peaks during heatwaves (Tartarini et al., 2022). One can also ask whether future energy crises will lead to a reduced use of air conditioning, especially because of the economic constraints linked to the increase in the price of electricity.

These reflections are limited because we do not know what future technological or social innovations will come. After hearing about an innovation, an occupier goes through a whole process before eventually changing his behaviour and sharing the feedback with others so the new solution can be spread (Wilson and Dowlatabadi, 2007). It can be noted that habits have a huge influence on OB and are difficult to reverse (Bourgeois et al., 2017). We can therefore understand the importance of educating occupants about alternative climate change mitigation strategies (Pisello et al., 2017).

OB will also depend on the ability of buildings to adapt to heatwaves. Several resilience strategies exist to reduce indoor overheating. Firstly, it is essential to ensure proper thermal insulation and air tightness. The use of light-coloured paint on external walls, materials with high thermal inertia or phase change, external solar shading and natural ventilation are effective cooling solutions. Buildings will therefore need to adapt. Requirements that take into account summer comfort during heatwaves are beginning to appear in regulations for new buildings, such as the new French regulation as mentioned above (MTE and Cerema, 2021). However, the problem of existing buildings remains.

Next, we investigate occupants' adaptation actions over the long term, as opposed to the changes in daily behaviour described above. This involves looking at the evolution of the population studied, i.e. the characteristics of the household and the dwelling. To improve foresight exercises, Le Gallic et al. (Le Gallic et al., 2014) examine the evolution of lifestyles over the long term in the context of the energy transition. The lifestyles of inhabitants are constructed on the basis of their climatic experiences, i.e. the urban microclimate, daily and seasonal variations and the occurrence of extreme events such as heatwaves (Molina and

Allagnat, 2019). Their knowledge is constructed not only from their individual experiences, but also through social exchanges (Molina and Allagnat, 2019).

The first strategy focuses on air conditioning. Will passive solutions be sufficient or will air conditioning become necessary (Alessandrini et al., 2019)? The focus here is not on the daily use of air conditioning, discussed earlier, but on the purchase of air conditioning. Only 11.1% of French households currently own an air conditioner or dehumidifier (Insee, 2020). We can wonder how this rate of equipment will evolve. It would therefore be interesting to look at the trigger that pushes occupants to invest in air conditioners (after or during an extreme heat wave, following a longer climatic experience such as a summer, etc.). This possibility is linked to the socio-economic characteristics of the household, as tenants will not be entirely free and the installation of an air conditioner is still quite expensive (Tartarini et al., 2022).

Improving insulation is another solution that requires a significant investment from households (Molina and Allagnat, 2019) which can be partially covered by state support as it also reduces heating needs in winter. But the problem of rebound effects is present in the same way as for the reduction of heating needs. Globally, this question also arises for all technological innovations for cooling buildings.

Another adaptation solution for occupants is related to mobility. Heat may cause people to move. Some people consider buying a home in a cooler climate, especially for their retirement, in anticipation that they will not be able to bear the heat as they age (Molina and Allagnat, 2019). How can these future migrations be taken into account?

### 2.3. Disadvantages of the city

The urban context can limit the adaptive actions detailed before. Indeed, occupants act to ensure their general comfort, not only their thermal comfort. Indoor environmental quality is mainly studied through indoor air quality and thermal, visual and acoustic comfort (Sansaniwal et al., 2021). Some needs may therefore compete with thermal comfort (von Grabe, 2016). In the city, noise or pollution can deteriorate the comfort of occupants and make them close the windows. The feeling of insecurity or the need for privacy can lead citizens to close their shutters. Fear of intrusion particularly limits the possibilities of night-ventilation by opening windows (von Grabe, 2016). Not specific to the urban context, rain and draughts can also cause occupants to close windows.

Lack of space is an issue in urban context. Dwellings in large cities are generally smaller than in the countryside and do not necessarily allow the occupants to cook outside the house or to stay in less exposed rooms. Dwellings can also have openings on only one façade and therefore have only one exposure. Buildings, especially multi-family dwellings in cities, may not have space to install an outdoor unit leading occupant to invest in removable air conditioners that require opening a window for the discharge of warm air to the outside.

The city is also a context where the heat can seem more suffocating. Inhabitants interviewed by Molina and Allagnat (Molina and Allagnat, 2019) described the heat in Lyon, a large French city, as exacerbated by the combination of high temperatures and pollution. Some decide to leave the city during periods of hot weather, either for the day or for a longer period on holiday. Some have second homes in cooler climates or in the mountains, for example. However, one has to be able to afford it, and so it creates inequalities (Molina and Allagnat, 2019).

The temperature increase during heatwaves is exacerbated in cities because of the urban heat island (UHI) effect. The urban context limits the night-time cooling of the air in summer, which leads to a difference in air temperature between the city centre and the suburban areas, particularly at the end of the day. This microclimate is due to the impervious surfaces and the built form which induces solar trapping, and reduce wind speeds and sky view factors (Lauzet et al., 2019). However, only a few inhabitants are aware of this effect (Pisello et al., 2017). The UHI effect limits night-ventilation potential. It should be noted that anthropogenic emissions, such as road traffic or air conditioning discharges, aggravate the UHI effect. Air conditioning therefore has a boomerang effect. Individual actions work against collective needs: it is a vicious circle that leads to a social dilemma (Molina and Allagnat, 2019).

## 3. Integration of OB models in BPS

In the first part, we saw how occupants adapt to heatwaves, especially those living in cities. In order to simulate building performances taking into account these behaviours, it is first necessary to model them and integrate them into BPS. We will therefore look at the factors that influence OB and can therefore be inputs to OB models, then at the different types of OB models and finally at the challenges to their application in practice.

### 3.1. Factors influencing OB

According to Fabi et al (Fabi et al., 2012), factors influencing OB can be physical, contextual, social, physiological or psychological.

Physical factors include all variables of the indoor and outdoor environment, such as air temperature, humidity, air velocity... Some behavioural models are based only on physical parameters (Cho et al., 2021; Haldi and Robinson, 2008), but other types of factors impact OB.

Indeed, the context in which the occupant is located can also influence its behaviour. The type of building is particularly important, as occupants will not have the same opportunities to adapt. An example is the dress code in the office which restricts occupants in adjusting their clothing. Most studies focus on office buildings, and are therefore not applicable to residential buildings, where OB tends to be more complex (Laaroussi et al., 2020). The season or time of day can also influence the occupant, as they will not necessarily have the same expectations (Laaroussi et al., 2020). The location of the building may also induce constraints restricting the occupants' actions (Rijal et al., 2018), such as the urban context discussed earlier. Finally, the geographical or cultural context is important to take into account. A model developed for one country may require additional data to be applied to others (Schumann et al., 2021). Indeed, some cultures have developed habits and vernacular solutions. These behaviours may have been adopted to adapt to the local climate, but have now become part of everyday life. Examples include traditional clothes or the early afternoon nap in some hot countries.

Several physiological parameters have also been studied. To our knowledge, their study in relation to behaviour is however limited to age or gender (Andersen et al., 2009; Chen et al., 2017; Schweiker and Shukuya, 2008; Shi et al., 2020). Some physiological factors also strongly influence thermal comfort, which in turn drives OB. These also include age and gender, but also weight, body shape and health status (Enescu, 2017).

The socio-economic characteristics of the occupant are also factors to consider. In residential buildings, the occupant is indeed part of a household, composed of one or more individuals. Budgetary constraints may restrict households in their purchase of domestic appliances or leisure equipment, or cause them to reduce the use of some appliances depending on the price of energy (Lévy et al., 2014). Households with at least one smoker are more likely to open windows (Shi et al., 2020). A landlord will not have the same opportunities as a tenant, so this condition may impact OB (Andersen et al., 2009). Chen et al. (Chen et al., 2017) also found that the education level influences the use of air conditioning. The number of occupants can be important (Schweiker and Shukuya, 2008).

The occupant generally acts to ensure his comfort, but some behaviours cannot be explained in this way. The psychological aspect is indeed relevant (von Grabe, 2016). Past experiences are also very important. Human activity indeed includes a cognitive dimension (Schumann et al., 2021). Individual preferences, but also the perception of the effectiveness of the actions taken, strongly influence OB (Schweiker and Shukuya, 2008).

### 3.2. The various types of OB models

There are several types of models, each with advantages and disadvantages. The objective is to predict a realistic behaviour for the case under study with the simplest possible model (Gaetani, 2019). They can be divided into four categories: schedules and deterministic models, stochastic models, agent-based models and data-driven models.

The simplest models are schedules and deterministic models. Schedules are typically given in BPS for a whole day, with the possibility of differentiating between weekdays and weekends, or even holiday periods. Deterministic models are rules where actions are seen as a consequence of an environmental factor. For example, artificial lighting will be switched on below a minimum illuminance. Researchers agree that these models are too simplistic to describe the complex behaviour of occupants. However, they may perform better when based on measured data for a specific case, but cannot be generalised (Gaetani, 2019). They are easily usable, as they are not very complex and are usually used in BPS.

Stochastic models are also used. Their output is usually a probability distribution. For each time step, action is taken if the probability estimated by the model exceeds a randomly generated number between 0 and 1. To obtain reliable results, simulations with stochastic models must be run several times (Gaetani, 2019). They allow simulating the behaviour of a set of occupants. Their complexity remains reasonable. They are a good compromise for simulations over long periods (Li et al., 2019). However, many observations are needed to correctly represent a behaviour. SUNtool (Robinson et al., 2007), obFMU and occupancy simulator (Yan and Hong, 2018), and proccS (Wolf et al., 2019) are examples of tools in which OB is modelled stochastically.

An agent-based model (ABM) consists of three elements (Alfakara and Croxford, 2014):

- a set of agents, which are individual and autonomous objects in a certain state;
- a topology, i.e. a set of rules that defines the relationships between the agents;
- an environment in which the agents interact.

Personal information is entered for each agent, which constitutes a set of rules of conduct, that allow them to react according to the changes they perceive in their environment (Berger and Mahdavi, 2020). The limitations of this method are linked to its complexity. The simulation time is long, and a good knowledge of the domain is necessary. Coupling or communication with BPS can be complicated as it has to be adapted to each software (Li et al., 2019). Moreover, a large amount of information has to be given as input to the model (Gaetani, 2019). However, the advantages are multiple: the interactions between agents and with their environment are realizable, the learning process is possible, the heterogeneity of the agents can be taken into account, the modeling is flexible and the represented system can be complex (Schumann et al., 2021).

Such models have been implemented through programming languages such as Python (Vellei et al., 2021), Matlab (Lee and Malkawi, 2014) or Java. Specific multi-agent simulation tools have been used in the building sector, such as Repast (Alfakara and Corxford, 2017;

Alfakara and Croxford, 2014), PMFserv (Jia et al., 2018; Jia and Srinivasan, 2020), NetLogo (Andrews et al., 2011; Putra et al., 2017), Swarm, MASON, AnyLogic (Berger and Mahdavi, 2020) or BRAHMS (Gaaloul et al., 2013; Kashif, 2014). Finally, multi-agent platforms have been developed for application to buildings : Occupancy Simulator (Yan and Hong, 2018), SMACH (Schumann et al., 2021), No-Mass (Chapman et al., 2017; Darakdjian, 2017), BOT-ABM (Dziedzic et al., 2019) or HABIT (Langevin et al., 2014).

Data-driven methods link input data to output data through a black box model. The objective is not to understand the behaviour of occupants but to predict it (Carlucci et al., 2020). Decision trees, Bayesian networks, association rule mining or cluster analysis are examples of data-mining techniques used in the building domain (Li et al., 2019). According to Carlucci et al. (Carlucci et al., 2020), machine learning is a promising method for concrete applications involving occupant modelling. However, the internal rules of the model are not understandable by a human. This lack of interpretability can be a barrier to its use in the building context. Furthermore, machine learning methods require a large amount of data (Carlucci et al., 2020). Data-mining methods allow the study of both numerical and categorical data. Socio-economic, psychological and physiological factors, which can be categorical, can thus be taken into account. However, these models are static and therefore cannot simulate the dynamic dimension of human activity (Li et al., 2019). Fuzzy logic is another approach used in artificial intelligence. It aims to get closer to human reasoning by not using real numbers but linguistic variables. Usually used in the building sector for regulation systems, it could be implemented to transcribe the perception of the occupant (Göktepe et al., 2015).

**3.3. Challenges in the modeling of OB**

One of the issues that is identified by most studies on OB is related to data. Indeed, there is a lack of available data (Berger and Mahdavi, 2020; Yan and Hong, 2018), and there are no standards regarding its collection (Harputlugil and de Wilde, 2021) or validation (Laaroussi et al., 2020). For ethical reasons, data acquisition is more limited in dwellings due to privacy requirements (Harputlugil and de Wilde, 2021; Laaroussi et al., 2020). Recent studies often involve a small number of buildings (Harputlugil and de Wilde, 2021). Another issue is the diversity of data to be collected: with low-cost devices, physical variables can be more easily measured than occupant and equipment conditions data. Three approaches can be used: in-situ and laboratory studies, and surveys (Yan and Hong, 2018). When used in combination with in-situ or laboratory studies, surveys can help to understand the individual reasons for the actions observed. For Dziedzic et al. (Dziedzic et al., 2019) any study on occupants should include surveys or interviews to understand individual preferences.

It is important to build models from field data to simulate realistic situations. In addition to the development of a common data collection and analysis protocol, which would be beneficial (Harputlugil and de Wilde, 2021), it is important to evaluate the models developed (Carlucci et al., 2020).

There is then a lack of comprehensive consideration of occupant behaviour. This is reflected in two aspects:

- The majority of studies on OB focusses on individual actions, which does not provide a holistic view (Harputlugil and de Wilde, 2021; Schumann et al., 2021). Actions are studied separately while they influence each other. For example, Sansaniwal et al. (Sansaniwal et al., 2021) found that blind use was dependent on the state of the window.
- Secondly, most models take into account a limited number of parameters. We saw in the second question that the influencing factors are not only physical but

also social or psychological. The study of occupant behaviour therefore requires an interdisciplinary approach (Laaroussi et al., 2020). It is necessary to be able to take into account the diversity of occupants, while maintaining consistency at the household level (Schumann et al., 2021).

The limits of each type of model have already been mentioned in the previous section. The choice of modelling therefore involves particular challenges. In addition to theses issues, it is necessary to integrate OB into BPS (Schumann et al., 2021). Most BPS software take into account OB with schedules or deterministic models, but some may consider the stochastic dimension. A list of the possibilities to include OB in several BPS has been made in IEA EBC Annex 66 (Yan and Hong, 2018). If a separate OB model is developed, it will have to be coupled to the BPS, either in a standardised way as with the functional mock-up interface (FMI) or through a middleware, such as BCTVB and MLE + Toolbox (Li et al., 2019). Figure 1 is a diagram of the co-simulations that have been performed between an ABM and a BPS.

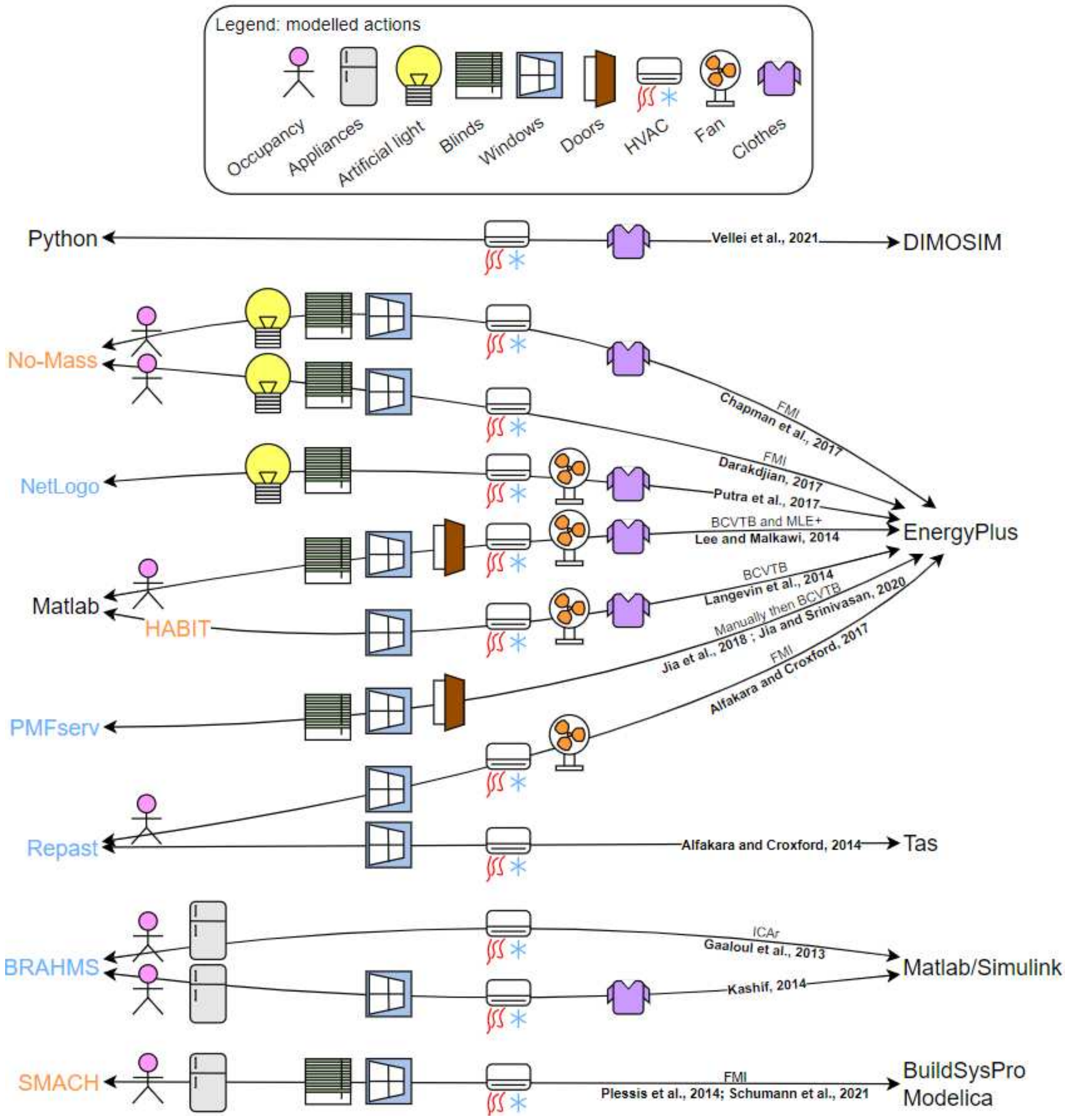

Figure 1. Co-simulations between ABM and BPS. ABM are on the left of the diagram. Names in blue are general platforms for agent-based modelling. Names in orange have been developed specifically for building application. BPS are on the right of the diagram.

These studies are recent, as the oldest is from 2013 (Gaaloul et al., 2013). The most used BPS is EnergyPlus: it has been coupled with five different ABMs. Results of Occupancy Simulator can also be integrated in EnergyPlus (Yan and Hong, 2018): however it is not a coupling but rather a chaining so it is not shown in this figure. Regarding the actions taken into account, the use of the HVAC system is always modelled, except in the coupling with PMFserv (Jia and Srinivasan, 2020). We grouped the setting of the operating schedule, the setpoint temperature and the switching on and off of the heating or cooling system in the HVAC category. Use of windows is the second most modelled action, as it concerns 9 out of 12 studies. Concerning occupancy (presence, location or activities), some studies generate schedules before simulation, but these are fixed and do not evolve according to the environment variables: it is then not considered as an action modelled in the agent-based system. All ABMs take into account at least two different actions. Of the agent-based platforms developed specifically for building applications, only BOT-ABM (Dziedzic et al., 2019) has not been coupled with a BPS and therefore does not appear in this figure. No-Mass and HABIT were coupled with EnergyPlus, while SMACH was coupled with BuildSysPro Modelica. Four different general platforms for agent-based modelling have been coupled with BPS.

## 4. Conclusion

This paper provides a qualitative description of occupants' adaptive actions during hot temperatures in cities and in the context of climate change. In residential buildings, occupants can move inside or out of the dwelling, adjust their clothing or activity, reduce heat-related activities, or use windows, shades, fans and air conditioning. The urban context limits the adaptative opportunities, and the urban heat island effect aggravates thermal discomfort. Climate change will have an impact on future behaviours.

The question that remains is how to integrate these results into BPS? Indeed, the major challenge is to synthesise qualitative behaviours into numerical variables (Lévy et al., 2014). The factors influencing OB are multiple. The study of OB therefore requires an interdisciplinary approach. It is difficult, if not impossible, to consider all the factors involved. The objective is rather to predict realistic behaviour.

Agent-based models seems to be a good opportunity to assemble results from different disciplines to take into account the complexity of human behaviour (Schumann et al., 2021). Developing such models and integrating or coupling them with BPS can be complicated, but complementing the existing ones could allow a faster progression towards tools to help assessing cooling strategies. Indeed, the existing models show the potential of this approach in hindsight, but are developed from context-specific data. It may be interesting to adapt them to other contexts, to complete them with new actions or influencing factors, and to make them more reliable by confronting them with in-situ data.

The heatwave context is very specific. Concerns were previously focused on winter for energy savings, but now there is a need to focus on summer comfort to avoid the increase in air cooling needs with climate change. The development of behavioural models in summer or during hot temperatures is therefore an important avenue for evaluating the effectiveness of passive occupant-dependent cooling strategies. However, data collection is an essential step for the development and reliability of the models.

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# Climatic, energy retro-fit and IEQ mitigation scenario modelling of the English classroom stock model

**Duncan Grassie[1], Yair Schwartz[1], Filiz Karakas[2], James Milner[2], Anna Mavrogianni[1], Zaid Chalabi[1], and Dejan Mumovic[1]**

[1] UCL Institute of Environmental Design and Engineering, London, UK. Correspondence email duncan.grassie.16@ucl.ac.uk

[2] London School of Hygiene and Tropical Medicine, London, UK

**Abstract:** Health and cognitive performance in UK school classrooms is dependent on building fabric performance as well as heating and ventilation system operation in maintaining Indoor Environmental Quality (IEQ), comprising thermal comfort and air quality. While archetype models can be used to simulate IEQ for different stock-wide location and construction eras, a predictive approach also necessitates the use of longitudinal scenarios. As a key component of the UK's decarbonisation strategy, these scenarios should account for fabric retro-fit adaptations to reduce carbon emissions, and changes in operation of the building for overheating mitigation as well as changes in external climatic conditions.

The IEQ of three representative classroom archetypes, representing the stock of 18,000 English schools, have been analysed for 24 pair-wise retro-fit and operational scenarios across three climatic scenarios. Retro-fitting, while effective in reducing energy demand, may risk compromising indoor air by requiring ventilation at times of the day when external conditions are least conducive to air quality and overheating. Additionally, while North facing classrooms can tackle overheating through single effective IEQ mitigation measures, South facing and 2080 climates will necessitate cumulative effects of multiple measures to be realised. Future work involves incorporating educational and construction stakeholder preferences through multi-criteria decision analysis, to derive suitable metrics.

**Keywords:** UK school building stock modelling, indoor environmental quality, building simulation

## 1. Introduction

British children spend 30% of their lives at school on average, and around 70% of that time spent within a classroom environment (Csobod, 2014). Within such environments, linkage has been demonstrated between Indoor Environment Quality (IEQ), comprising not only air quality and thermal comfort, but also health (Chatzidiakou et al., 2014) and attainment (Wargocki et al., 2020) of children. Within the building IEQ also interacts with heating loads, ventilation and management of internal gains (Becker et al., 2007) within the building envelope. Hence the importance of determining operational IEQ performance of the school building envelope in defining health and attainment outcomes of school pupils in different settings.

As public buildings, schools are required to meet standards in overheating through Building Bulletin 101 (Education and Skills Funding Agency (ESFA), 2018) and nitrogen dioxide ($NO_2$) and particulates smaller than 2.5 microns ($PM_{2.5}$) through the World Health Organisation (World Health Organisation, 2021). As non-domestic buildings, schools are subject to additional constraints, as the UK has legislated to meet net zero carbon emissions by 2050 (UK Committee on Climate Change, 2019) and non-domestic buildings contribute 18% of total emissions (Carbon Trust, 2009). In spite of these multiple objectives, monitoring campaigns exploring the dynamic behaviour of the ingress of $NO_2$ and $PM_{2.5}$ contaminants (Stamp et al., 2022) and susceptibility to overheating (Mohamed et al., 2021) necessarily investigate these phenomena separately from post occupancy evaluation of energy use in schools (Pegg et al., 2007), although there has been a drive to consider them in parallel due to their co-dependence (Becker et al., 2007; Cabovská et al., 2021). Subsequently, when such work has been scaled up to include a wider portfolio of UK school buildings using statistical or physics-based models, the need to address each objective separately has been retained.

### 1.1. UK building stock modelling

Recent stock-level energy models of the non-domestic building stock (Steadman et al., 2020) have been able to integrate top-down statistical characteristics from large-scale dis-aggregated national datasets (Hong et al., 2021) with bottom-up, causal, physics-based modelling of individual buildings (Kavgic et al., 2010). For UK schools, stock modelling through the Data dRiven Engine for Archetype Models of Schools (DREAMS) framework (Schwartz, Korolija, Dong, et al., 2021) has facilitated the use of archetypes to define era and geographical region, demonstrating a reasonable match with measured Display Energy Certificate (DEC) data. This modelling has been further developed to incorporate classroom-level orientation (Schwartz, Korolija, Symonds, et al., 2021), rather than whole-building level modelling and additionally airflow network modelling (Grassie, Schwartz, et al., 2022), demonstrating the interactions between external air and heat flows with the windows and walls that the weather is incident upon.

An additional step is required to ensure that the outputs of simulation modelling can be translated into appropriate outcomes (Grassie, Karakas, et al., 2022) for policymakers to act upon. However such an approach also requires scenario modelling to demonstrate longitudinal changes, to demonstrate that these outcomes are also appropriate outside of an individual snapshot in time. In the case of the UK school building stock, these longitudinal scenarios should incorporate three separate effects:

- Energy efficiency retro-fitting: improvements in heat transfer and building energy efficiency required to meet net zero carbon emissions.
- Classroom operational changes: mitigating against overheating and indoor air quality by preventing ingress of heat or improving ventilation characteristics.
- External changes in climate and contaminants: impacting ventilation and heating requirements to maintain an acceptable learning environment.

Isolating the effects of each individual measure as a snapshot is only meaningful over a short time-frame due to the dynamic nature of the stock (Tian & De Wilde, 2011), hence a methodology is required for combining these effects into scenario modelling of the UK school building stock.

### 1.2. Research question

The previous section described the need for future building simulation tools to account for the effects of future energy efficiency retro-fit on IEQ. These simulation tools could be used by policymakers to inform decisions on different sectors of the UK school stock based on both the predicted effectiveness of energy improvements through retro-fit and mitigation subsequent IEQ issues, while accounting for anthropogenically driven changes in climate. Hence the research question addressed in this paper is as follows:

*What is the predicted optimal pairwise combination of retro-fit energy efficiency measure and operational strategy in terms of health and attainment metrics derived for three archetypal UK classrooms, and do these strategies remain suitably robust for future climatic periods?*

This question has been addressed by splitting the work into the following research objectives:

1. To generate building simulation models of three base archetypes which are representative of the UK school building stock.

2. To develop pair-wise scenarios incorporating energy efficiency retro-fit and building service operational measures, while addressing dynamic climatic conditions within modelling.

3. To determine performance of a number of key health and attainment metrics and discuss performance of the various pairwise combinations of energy efficiency and operational scenarios for different climatic scenarios.

To address these objectives, the next two sections describe the incorporation of retro-fit, IEQ and climatic scenarios into previous school building stock models and a three stage methodology of generating simulation models, development of scenarios and simulation and post-processing. Results of this analysis are presented in Section 4, prior to a discussion of the significance of the findings and future adaptations and applications of these models. The paper concludes in Section 6 by summarising the main findings from a policy-maker perspective.

## 2. Literature review

### 2.1. The use of building stock modelling to derive health and attainment metrics

Building stock modelling has already been widely established for generating predictive energy demand profiles for domestic and non-domestic buildings, through the auto-generation of simulation models from national level datasets (Kavgic et al., 2010; Steadman et al., 2020). While the use of building simulation to derive IEQ measures across a sector of the stock has been carried out previously in the UK residential sector (Symonds et al., 2016), a greater heterogeneity of available data sources for fabric (Bruhns et al., 2006) for different sub-sectors of the non-domestic stock, have required bespoke methods to categorise and characterise buildings. For example, for energy demand within the school sector, it has been possible to construct archetypes by era (Bull et al., 2014) which have then been fitted to different era buildings described across the stock within the Property Data Survey Programme (PDSP) (Education Funding Agency (EFA), 2012) dataset (Schwartz, Korolija, Dong, et al., 2021) to calculate annual heating load.

Due to functionality within a modelling platform for schools (Schwartz et al., 2019) for individualised geometries based on laser imaging, detection and ranging (LIDaR) acquired polygons, archetypes have also been developed for different era geometries (Schwartz, Korolija, Dong, et al., 2021). However for calculations of IEQ rather than energy, a data-driven whole building approach would account only for known geometric differences, including height of ceiling, number of storeys and glazing ratio, when calculating heating and ventilation requirements across the stock. The lack of key data on orientation and location of classrooms and occupants within the building would affect the calculation of solar gains and ventilation within classroom areas. This could lead to over- or under-prediction of internal temperatures within specific zones where classes are taught when coupled with airflow network models (Grassie, Schwartz, et al., 2022; Symonds et al., 2016), which are dependent on external weather conditions.

In terms of occupancy and building service operation, the National Calculation Methodology (NCM) (Communities and Local Government, 2013) provides a set of rules for calculating energy asset ratings for the non-domestic stock, including definition of daily and annual school occupancy to aid the comparison of similar buildings. However there is a conflict when overheating is a required metric, since overheating calculations within UK school building models defined in Building Bulletin 101 (BB101) (Education and Skills Funding Agency (ESFA), 2018), consider summer utilisation of school buildings to derive overheating metrics. Since IEQ metrics are the dominant feature of such modelling, the year-round BB101 approach has been preferred for this research to explore the full extent of cooling as well as heating seasons.

### 2.2. Retro-fit and operational scenario modelling within the non-domestic sector

Looking outside the scope of building stock modelling to the domain of individual buildings, a number of research projects have defined resilience of buildings using scenarios in different sub-sectors of the non-domestic stock:

- The Climacare project (Oikonomou et al., 2020) investigated a range of hard (structural) and soft (non-structural) measures across the UK care-home sector, a number of which have been referenced for the operational scenarios given in the methodology section, considering these measures individually and cumulatively rather than exhaustive combinations of hard and soft.
- A sensitivity analysis of annual heating and cooling loads for a Plymouth-based higher education building (Tian & De Wilde, 2011) under different climatic conditions, included wall and window U-values and infiltration within a matrix of cases to be simulated. While demonstrating ideal loads for both heating and cooling seasons is useful for design of future ventilation and air conditioning systems, performance of window airflows are likely to be of particular interest in the school stock, where more than 95% of buildings are still naturally ventilated (Grassie, Karakas, et al., 2022).
- An analysis of overheating avoidance in existing German school buildings (Camacho-Montano et al., 2020) provided commentary on cognitive performance and capital costs and effectiveness of a number of passive measures such as night ventilation and window opening options for summer months only. While the minimisation of "hours of discomfort" was used in optimisation, it was unclear how robust this snapshot alone would be in the face of changing climatic conditions.

While methods of testing robustness of the stock to various retro-fit and operational measures have been demomstrated, there is also a need to incorporate climate resilience into analysis of IEQ and energy simulation in UK school buildings (Department for Education (DfE), 2021).

### 2.3. Accounting for climate resilience within the non-domestic sector

The use of Chartered Institute of Building Services Engineers (CIBSE) weather files based on future projections of greenhouse gases (CIBSE, 2016) in the sensitivity analysis of higher educational buildings (Tian & De Wilde, 2011) demonstrated how resilience of educational buildings to changes in climate could be determined. In addition to climate, external contaminants are also known to have varied over time. The projections on which the CIBSE weather files are based define the UK's Clean Air Strategy (Department for Environment Food & Rural Affairs, 2019) to reducing external $NO_2$ and $PM_{2.5}$.

Summarising, the incorporation of IEQ into building stock models adapted from energy demand modelling has demonstrated a need to understand in more granular detail how occupancy patterns and classroom orientations affect airflow impacting both overheating and ingress of contaminants. When such details have been included in more focussed studies, retro-fit and operational scenarios have often been applied as a series of individualised measures, rather than a matrix of independent retro-fit and operational scenarios. Hence the research explored by this work is the use of pairwise combinations of retro-fit and operational scenarios to determine resilience of UK school building stock to changes in climate.

## 3. Methodology

### 3.1. Generation and selection of archetype models

A base model geometry for the investigation of IEQ across the UK school building incorporating four classroom orientations has been defined previously (Schwartz, Korolija, Symonds, et al., 2021) using the open-source EnergyPlus building simulation software (US Department of Energy, 2015). A series of modifications has been made to the single external wall to facilitate airflow network modelling of ventilation (Grassie, Schwartz, et al., 2022) and the OpenStudio (Guglielmetti et al., 2011) representation of this façade is shown below in Figure 1, together with the base model geometry.

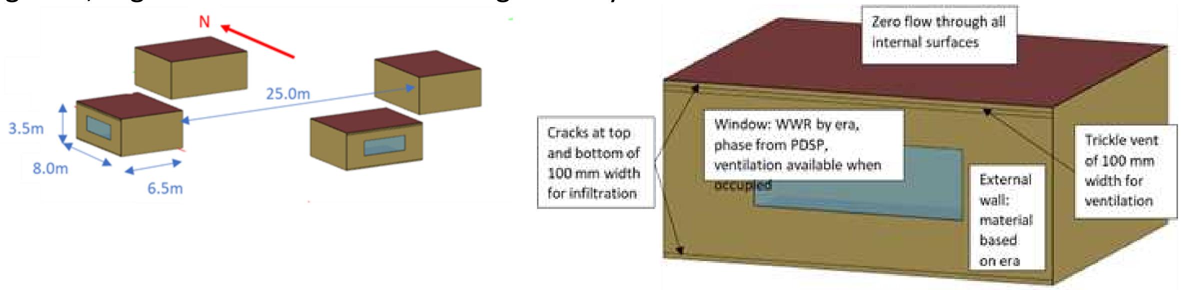


Figure 1. Schematic of classrooms and description of infiltration and ventilation

Table 1 contains a summary of how internal gains and various systems are operated within the building. As described previously, although the NCM (Communities and Local Government, 2013) provides a suitable set of rules for energy calculations, the values in the table have been sourced from BB101 (Education and Skills Funding Agency (ESFA), 2018), due to the need to apply overheating calculations on simulation output.

Table 1: Input values and schedules used in seed model

| Parameter | Value / Setpoint | Schedule |
|---|---|---|
| **Occupancy** | Density: 0.55 student/m$^2$<br>Internal gains: 70 W<br>$CO_2$ generation: 3.82 e$^{-8}$ m$^3$/s/W | 100% 09-16 every weekday of the year, otherwise 0% |
| **Lighting** | 7.2 W/m$^2$ | 100% 07-18 every weekday of the year, otherwise 0% |
| **Equipment** | 4.7 W/m$^2$ | 100% 07-21 every weekday of the year, otherwise 5% |
| **Heating** | Applied when internal temperature < 20 °C for 07-18 every weekday of the year<br>12 °C for remainder of the year | |
| **Window** | Open 10 minutes at beginning of each hour, otherwise opens when internal temperature >23 °C 9-16 every weekday of the year, closed for remainder of year | |

Preceding research demonstrated the auto-generation of archetypes for all combinations of geographical region, era and ventilation combinations contained within the Property Data Survey Programme (PDSP) dataset (Schwartz, Korolija, Dong, et al., 2021). Python scripting (Python 3.9.2, 2021), utilising the EPPY set of libraries (EPPY 0.5.56, 2021) for creating and selectively altering EnergyPlus files, has been used to generate similar archetypes based on those present in the PDSP distinguished by:

- Phase (primary/secondary) – 70 W/student (primary) and 90 W/student (secondary) result in different internal gain and $CO_2$ output profiles within the classroom, as well as different occupancy patterns.
- Ventilation (natural/mechanical) – As discussed earlier, the vast majority (95%) of schools can be considered to be naturally ventilated, based on an analysis of the PDSP.
- Geographical regions – 13 regions across England and Wales have been defined based on different CIBSE degree-day regions (CIBSE, 2008) and have been allocated the following:
    - Hourly CIBSE weather files (CIBSE, 2016) used for simulating ventilation and heating loads for an entire simulation, discussed further in Section 3.3.
    - Hourly contaminant $NO_2$ and $PM_{2.5}$ concentrations from UK-wide monitoring sites (Department for Environment Food and Rural Affairs, 2021), collated and averaged over each geographical region
- Era of construction – Five different eras (Pre-1918, Inter-war, 1945-1967, 1967-1976 and Post-1976) have been allocated floor to ceiling height based upon the Department for Education's Resilient School Building Design (Department for Education (DfE), 2021) and differing wall constructions (Grassie, Schwartz, et al., 2022).

In order to examine through scenario modelling the consequences of various fabric and operational decisions, it is necessary to consolidate the number of archetypes under investigation. Hence naturally ventilated primary schools were selected for the following three regions and eras, given in Table 2, which covers a full range of construction eras and regions.

Table 2. Base case description of archetypes selected

| Primary school | Geographical Region | Construction era, U-value (W/m$^2$.K) | Floor to ceiling height (m) | Glazing (% Glazing ratio), U-value (W/m$^2$.K) |
|---|---|---|---|---|
| **P1** | London | Pre-1919, 1.92 | 4.5m | Single (25%), 5.8 |
| **P2** | West Midlands | 1945-1967, 1.37 | 2.7m | Single (25%), 5.8 |
| **P3** | NE England | Post-1976, 0.74 | 3.6m | Double with Air (27%), 3.1 |

### 3.2. Development of scenarios

Figure 2 shows 24 pair-wise combinations of retro-fit and operational scenarios, analysed longitudinally with three separate climatic scenarios. While Table 3 demonstrates the progressive implementation of external wall, glazing U-values and permeability or air tightness from base case through to EnerPHIt standard, each of the six operational scenarios can be considered in terms of four individual operational measures.

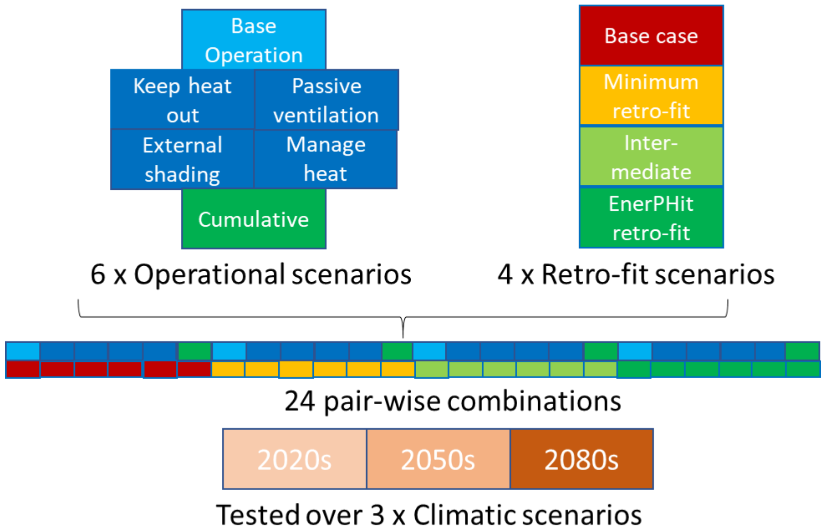


Figure 2. Combination of climatic, retro-fit and operational scenarios

Table 3. Description of energy efficiency retro-fit scenarios

| | **Base case** | **Minimum standard** | **Intermediate** | **EnerPHIt** |
|---|---|---|---|---|
| **Abbreviation** | **Base** | **MinR** | **IntR** | **EnPH** |
| **Description (based upon)** | As defined in previous section | Building regulations (HM Government, 2021) | Bespoke description used previously (Grassie, Schwartz, et al., 2022) | Criteria required for EnerPHit retro-fit (Institute, 2016) |
| **External wall U-value ($W/m^2.K$)** | Cavity wall (era-dependent) 0.74-1.92 | External expanded polystyrene added 0.34 | External expanded polystyrene added 0.34 | External 150mm of EPS insulation added 0.19 |
| **Permeability ($m^3/h.m^2$ @50Pa)** | 9 | 8 | 3 | 0.89 |
| **Glazing U-value ($W/m^2.K$)** | Single/double with air 5.80/3.09 | Double with air + low emissivity glass 1.79 | Double with argon + low emissivity glass 1.22 | Triple with argon + low emissivity glass 0.75 |

A description of the four individual operational measures which comprise the six operational scenarios is given below. The base operation (abbreviated to BaseOp) and cumulative (Cumtve) operational scenarios contain none and all of the below measures respectively.

- Keep heat out (KpHtOt): Wall albedo updated from 0.7 to 0.1 solar and visible absorbances. Internal window blinds with shading control added with setpoint of 120W.
- External shading (ExtSha): External overhang added above all windows at 90 degrees, 50mm thick (in vertical direction) and 800mm depth (projecting out from the wall), above the horizontal length of the window.
- Manage heat (Manage): 50mm thickness of cast concrete added to internal walls as thermal mass

- Passive ventilation (PasVen): Availability of school-day ventilation increased to 24 hours/day, and flow increased through ventilation by increasing the height factor of the opening from 0.1 to 0.3 and start height factor from 0.9 to 0.7

The climatic scenarios are derived from CIBSE weather files incorporating the UKCIP09 climate change scenarios (Mylona, 2012) for weather stations within the three separate geographical regions. For the 2020s, 2050s and 2080s climate scenarios, the weather files selected represent P50 conditions for an A1B medium emissions scenario (Intergovernmental Panel on Climate Change (IPCC), 2000). For each region and each climate scenario, a hybrid approach to account for both heating and cooling seasons has been utilised by merging weather data from October 1$^{st}$ to April 30$^{th}$ from Test Reference Year (TRY) files, with Design Summer Year (DSY1) files, representing a moderately warm summer from May 1$^{st}$ to September 30$^{th}$.

Ambient external $CO_2$, set as constant over a simulation year, has been updated across climatic scenarios to reflect projected trends. For 2020s, the figure of 435 ppm is based on 2021 measurement of 415 ppm (NASA, 2021) plus a 20 ppm urban uplift effect (Mitchell et al., 2018). For 2050s and 2080s, external $CO_2$ concentrations of 532 ppm and 649 ppm, based on the A1B projection (Intergovernmental Panel on Climate Change (IPCC), 2000), are also uplifted by 20 ppm to 552 ppm and 669 ppm. Although external $NO_2$ and $PM_{2.5}$ may be expected to decrease in line with the Clean Air Strategy (Department for Environment Food & Rural Affairs, 2019), they have conservatively been held constant.

### 3.3. Simulation and Post-processing

Each individual archetype and scenario combination has been simulated over a simulation year using UCL's Myriad high performance computing (HPC) cluster to simulate the large number of different models and weather file combinations. Since EnergyPlus calculates one contaminant at a time, separate runs are required to calculate internal $CO_2$ and Indoor/Outdoor ratios of $NO_2$ and $PM_{2.5}$ over a simulation year. Both $NO_2$ and $PM_{2.5}$, external hourly data was acquired for 2019 for all monitoring sites (Department for Environment Food and Rural Affairs, 2021) and multiplied at each time step by the Indoor/Outdoor ratio to give internal concentrations.

Metrics have been calculated for five separate criteria for occupied periods only, with Table 4 providing the linkage between model outputs via post-processing to each criterion, using Python and EPPY scripting.

Table 4. Description and derivation of health and attainment metrics used for evaluating performance.

| Criterion | Short label | Hourly data from annual EnergyPlus simulation | After processing |
|---|---|---|---|
| **Pupil learning performance** | Attainment | Internal temperature (t) | Annual average (%) by multiplying the following two factors (Dong et al., 2020; Wargocki et al., 2020) : $y = 0.2269*t^2 - 13.441*t + 277.84$ |
| | | Ventilation rate ($V_R$) | $y = 0.0086*V_R + 0.9368$ |
| **Pupil and staff sense of thermal comfort** | Overheating | Operative temperature | Total overheating hours based on "Annual hours of exceedance" metric from BB101 (Education and Skills Funding Agency (ESFA), 2018) |
| | | External temperature | |
| **Classroom air** | Stuffiness | $CO_2$ concentration | Annual average $CO_2$ concentration (ppm) |

| freshness | | | (occupied hours only) |
|---|---|---|---|
| **Cost savings to due to pupil/staff illness averted** | Health | $NO_2$ concentration | Annual averages of $NO_2$ and $PM_{2.5}$ (μg/m$^3$) (occupied periods only) |
| | | PM2.5 concentration | |
| **Cost savings from reduction in heating** | Heating | Energy use (J) of: baseboard heating | Annual total heating energy normalised by floorspace (kWh/m$^2$) |

## 4. Results

### 4.1. Performance of all possible different pair-wise combinations of scenarios

Table 5, Table 6 and Table 7 show the five criteria described in the previous section by column (omitting $PM_{2.5}$) for the three selected archetypes by row for South-facing classrooms in 2020s climate, South-facing classrooms in 2080s and North-facing classrooms in 2080s respectively. For each archetype and criterion, all 24 pair-wise combinations of retro-fit scenario (by column) and operational scenario (by row) are displayed, with green and red colour coding indicative of improved and reduced performance respectively.

Table 5: Performance criteria for archetypes based on a matrix of retro-fit and operational scenarios: South facing classrooms for 2020s climate scenario

| | | | |
|---|---|---|---|
| CO2 (ppm) | 801 | 1136 | 1999 |
| Overheating (h) | 79 | 581 | 763 |
| Attainment (%) | 82.7 | 79.5 | 75.9 |
| Heating (kWh/m2) | 0 | 0.46 | 16.3 |
| NO2 (ug/m) | 9.06 | 20.6 | 26.2 |

| | | Average CO2 (ppm) | | | | Annual overheating (h) | | | | Average attainment (%) | | | | Annual heating (kWh/m2) | | | | Average NO2 (ug/m3) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Base | MinR | IntR | EnPH | Base | MinR | IntR | EnPH | Base | MinR | IntR | EnPH | Base | MinR | IntR | EnPH | Base | MinR | IntR | EnPH |
| Archetype P1 | BaseOp | 935 | 838 | 811 | 802 | 482 | 593 | 680 | 686 | 81.8 | 80.4 | 80 | 79.7 | 11.3 | 1.78 | 0.78 | 0.47 | 22.9 | 24.6 | 25.2 | 25.6 |
| | ExtSha | 979 | 867 | 840 | 826 | 299 | 418 | 515 | 531 | 82.1 | 80.7 | 80.1 | 79.8 | 12.9 | 2.04 | 0.89 | 0.56 | 22.2 | 24 | 24.7 | 25.2 |
| | KpHtOt | 1009 | 859 | 834 | 807 | 262 | 469 | 572 | 659 | 82.5 | 80.6 | 80.1 | 79.8 | 16.2 | 2.4 | 0.96 | 0.52 | 21.7 | 24.1 | 24.7 | 25.5 |
| | Manage | 960 | 840 | 811 | 801 | 496 | 642 | 706 | 705 | 81.8 | 80.3 | 79.9 | 79.6 | 9.24 | 1.48 | 0.78 | 0.46 | 22.5 | 24.6 | 25.3 | 25.6 |
| | PasVen | 1271 | 1108 | 1106 | 1114 | 518 | 553 | 616 | 575 | 80.2 | 78.3 | 77.9 | 77.6 | 7.26 | 0.11 | 0.01 | 0 | 18.5 | 21.4 | 21.8 | 22 |
| | Cumtve | 1532 | 1162 | 1151 | 1145 | 79 | 192 | 268 | 319 | 81.5 | 78.5 | 77.8 | 77.4 | 10.7 | 0.12 | 0 | 0 | 15.8 | 20.7 | 21.3 | 21.9 |
| Archetype P2 | BaseOp | 1058 | 946 | 918 | 908 | 513 | 697 | 742 | 750 | 80.5 | 79.4 | 79 | 78.7 | 4.1 | 0.35 | 0.16 | 0.11 | 21.5 | 23.1 | 23.6 | 23.9 |
| | ExtSha | 1104 | 968 | 938 | 924 | 357 | 569 | 699 | 729 | 80.8 | 79.6 | 79.1 | 78.8 | 4.64 | 0.41 | 0.19 | 0.12 | 21.1 | 22.9 | 23.4 | 23.7 |
| | KpHtOt | 1147 | 967 | 937 | 912 | 316 | 593 | 705 | 743 | 81 | 79.7 | 79.2 | 78.7 | 6.12 | 0.47 | 0.21 | 0.11 | 20.6 | 22.9 | 23.3 | 23.8 |
| | Manage | 1082 | 946 | 916 | 907 | 536 | 718 | 759 | 763 | 80.5 | 79.4 | 78.9 | 78.6 | 2.11 | 0.31 | 0.16 | 0.1 | 21.4 | 23.2 | 23.6 | 23.9 |
| | PasVen | 1534 | 1430 | 1445 | 1460 | 547 | 617 | 663 | 644 | 78 | 76.6 | 76.4 | 76.2 | 1.93 | 0 | 0 | 0 | 17.8 | 19.6 | 19.7 | 19.7 |
| | Cumtve | 1726 | 1470 | 1484 | 1487 | 121 | 361 | 473 | 541 | 79 | 76.8 | 76.4 | 76.1 | 2.1 | 0 | 0 | 0 | 16.4 | 19.4 | 19.5 | 19.7 |
| Archetype P3 | BaseOp | 904 | 872 | 840 | 831 | 497 | 528 | 625 | 634 | 81 | 80.6 | 80 | 79.8 | 4.49 | 1.67 | 0.84 | 0.59 | 12.1 | 12.4 | 12.7 | 12.9 |
| | ExtSha | 947 | 901 | 866 | 851 | 318 | 383 | 496 | 513 | 81.6 | 81 | 80.3 | 80.1 | 4.78 | 1.87 | 0.97 | 0.67 | 11.8 | 12.2 | 12.5 | 12.7 |
| | KpHtOt | 949 | 895 | 862 | 837 | 317 | 417 | 530 | 599 | 81.5 | 80.9 | 80.3 | 79.8 | 6.73 | 2.26 | 1.03 | 0.64 | 11.7 | 12.2 | 12.5 | 12.8 |
| | Manage | 917 | 874 | 841 | 830 | 503 | 548 | 688 | 688 | 81 | 80.5 | 79.9 | 79.7 | 2.94 | 1.4 | 0.8 | 0.58 | 11.9 | 12.4 | 12.7 | 12.9 |
| | PasVen | 1225 | 1187 | 1185 | 1192 | 505 | 494 | 547 | 503 | 78.4 | 77.8 | 77.4 | 77.2 | 1.7 | 0.14 | 0 | 0 | 10.2 | 10.8 | 11 | 11 |
| | Cumtve | 1331 | 1229 | 1221 | 1218 | 115 | 171 | 249 | 278 | 79.3 | 78.3 | 77.7 | 77.3 | 1.79 | 0.05 | 0 | 0 | 9.53 | 10.5 | 10.8 | 11 |

Table 6: Performance criteria for archetypes based on a matrix of retro-fit and operational scenarios: South facing classrooms for 2080s climate scenario

| | | Average CO2 (ppm) | | | | Annual overheating (h) | | | | Average attainment (%) | | | | Annual heating (kWh/m2) | | | | Average NO2 (ug/m3) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Base | MinR | IntR | EnPH | Base | MinR | IntR | EnPH | Base | MinR | IntR | EnPH | Base | MinR | IntR | EnPH | Base | MinR | IntR | EnPH |
| Archetype P1 | BaseOp | 1133 | 1044 | 1021 | 1015 | 574 | 686 | 726 | 730 | 81.3 | 80.1 | 80 | 79.6 | 6.85 | 0.74 | 0.31 | 0.18 | 23.5 | 25.3 | 25.9 | 26.2 |
| | ExtSha | 1172 | 1071 | 1047 | 1037 | 433 | 554 | 663 | 671 | 81.1 | 79.9 | 79.5 | 79.3 | 7.79 | 0.93 | 0.36 | 0.2 | 22.8 | 24.8 | 25.4 | 25.8 |
| | KpHtOt | 1200 | 1064 | 1041 | 1019 | 391 | 599 | 686 | 714 | 81.4 | 80.1 | 79.8 | 79.6 | 10.4 | 1 | 0.39 | 0.19 | 22.3 | 24.8 | 25.4 | 26.1 |
| | Manage | 1146 | 1045 | 1020 | 1015 | 604 | 710 | 742 | 743 | 81.2 | 80 | 79.8 | 79.5 | 5.2 | 0.65 | 0.31 | 0.17 | 23.2 | 25.3 | 25.9 | 26.2 |
| | PasVen | 1451 | 1337 | 1344 | 1359 | 588 | 649 | 685 | 659 | 80.2 | 78.3 | 78.1 | 77.6 | 4.39 | 0.02 | 0 | 0 | 19.3 | 21.9 | 22.2 | 22.3 |
| | Cumtve | 1680 | 1386 | 1390 | 1391 | 206 | 375 | 466 | 508 | 80.2 | 77.8 | 77.4 | 77 | 6.31 | 0.02 | 0 | 0 | 16.7 | 21.3 | 21.7 | 22 |
| Archetype P2 | BaseOp | 1247 | 1158 | 1136 | 1131 | 621 | 745 | 763 | 763 | 79.9 | 78.9 | 78.7 | 78.4 | 2.43 | 0.14 | 0.06 | 0.03 | 22.1 | 23.5 | 23.9 | 24.1 |
| | ExtSha | 1286 | 1178 | 1155 | 1146 | 483 | 697 | 743 | 755 | 79.8 | 78.9 | 78.5 | 78.2 | 2.77 | 0.17 | 0.07 | 0.04 | 21.7 | 23.3 | 23.7 | 23.9 |
| | KpHtOt | 1320 | 1176 | 1153 | 1135 | 445 | 708 | 748 | 763 | 80.1 | 79 | 78.7 | 78.4 | 3.79 | 0.2 | 0.08 | 0.03 | 21.3 | 23.3 | 23.6 | 24 |
| | Manage | 1263 | 1156 | 1134 | 1130 | 663 | 757 | 763 | 763 | 79.8 | 78.8 | 78.6 | 78.3 | 1.01 | 0.13 | 0.06 | 0.03 | 21.9 | 23.6 | 23.9 | 24.1 |
| | PasVen | 1748 | 1680 | 1697 | 1715 | 637 | 685 | 716 | 707 | 77.8 | 76.5 | 76.4 | 76.1 | 1.14 | 0 | 0 | 0 | 18.3 | 19.7 | 19.7 | 19.7 |
| | Cumtve | 1897 | 1723 | 1740 | 1745 | 249 | 516 | 606 | 649 | 78.1 | 76.3 | 76 | 75.9 | 1.07 | 0 | 0 | 0 | 17.1 | 19.5 | 19.6 | 19.6 |
| Archetype P3 | BaseOp | 1108 | 1080 | 1052 | 1046 | 588 | 629 | 717 | 718 | 80.2 | 79.8 | 79.4 | 79.2 | 2.48 | 0.8 | 0.4 | 0.25 | 12.3 | 12.7 | 12.9 | 13.1 |
| | ExtSha | 1142 | 1103 | 1075 | 1065 | 443 | 505 | 614 | 647 | 80.4 | 79.9 | 79.4 | 79.2 | 2.98 | 0.95 | 0.45 | 0.29 | 12.1 | 12.5 | 12.8 | 13 |
| | KpHtOt | 1150 | 1099 | 1070 | 1051 | 446 | 532 | 645 | 698 | 80.5 | 80 | 79.5 | 79.2 | 4.03 | 1.12 | 0.49 | 0.28 | 12 | 12.5 | 12.8 | 13.1 |
| | Manage | 1115 | 1081 | 1051 | 1045 | 620 | 687 | 746 | 744 | 80.1 | 79.7 | 79.3 | 79 | 1.49 | 0.68 | 0.37 | 0.25 | 12.2 | 12.7 | 13 | 13.1 |
| | PasVen | 1445 | 1419 | 1424 | 1438 | 593 | 579 | 629 | 593 | 78 | 77.4 | 77.1 | 76.8 | 0.95 | 0.03 | 0 | 0 | 10.5 | 10.9 | 11.1 | 11.1 |
| | Cumtve | 1534 | 1460 | 1463 | 1466 | 224 | 296 | 378 | 411 | 78.4 | 77.5 | 77 | 76.7 | 0.85 | 0.01 | 0 | 0 | 9.93 | 10.8 | 11 | 11.1 |

Table 7: Performance criteria for archetypes based on a matrix of retro-fit and operational scenarios: North facing classrooms for 2080s climate scenario

| | | Average CO2 (ppm) | | | | Annual overheating (h) | | | | Average attainment (%) | | | | Annual heating (kWh/m2) | | | | Average NO2 (ug/m3) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Base | MinR | IntR | EnPH | Base | MinR | IntR | EnPH | Base | MinR | IntR | EnPH | Base | MinR | IntR | EnPH | Base | MinR | IntR | EnPH |
| Archetype P1 | BaseOp | 1263 | 1116 | 1092 | 1067 | 354 | 512 | 648 | 688 | 81.8 | 80.3 | 80 | 79.6 | 12.2 | 1.4 | 0.59 | 0.29 | 21.4 | 23.8 | 24.3 | 25.1 |
| | ExtSha | 1274 | 1126 | 1103 | 1074 | 314 | 455 | 583 | 650 | 81.9 | 80.4 | 80 | 79.6 | 13 | 1.51 | 0.62 | 0.31 | 21.2 | 23.6 | 24.1 | 24.9 |
| | KpHtOt | 1274 | 1121 | 1098 | 1067 | 256 | 439 | 566 | 671 | 81.9 | 80.3 | 80 | 79.6 | 13.1 | 1.52 | 0.62 | 0.3 | 21.2 | 23.6 | 24.2 | 25.1 |
| | Manage | 1297 | 1119 | 1093 | 1067 | 321 | 524 | 680 | 704 | 82.1 | 80.2 | 79.9 | 79.5 | 10.5 | 1.13 | 0.52 | 0.29 | 20.8 | 23.8 | 24.4 | 25.1 |
| | PasVen | 1634 | 1404 | 1403 | 1403 | 364 | 450 | 521 | 510 | 80.4 | 78.4 | 78 | 77.5 | 8.64 | 0.26 | 0 | 0 | 16.8 | 20.6 | 21 | 21.5 |
| | Cumtve | 1772 | 1425 | 1421 | 1415 | 186 | 308 | 389 | 433 | 81 | 78.4 | 77.9 | 77.5 | 8.55 | 0.05 | 0 | 0 | 15.7 | 20.5 | 20.9 | 21.5 |
| Archetype P2 | BaseOp | 1378 | 1216 | 1189 | 1167 | 427 | 708 | 752 | 763 | 80.3 | 79.3 | 79 | 78.6 | 4.75 | 0.32 | 0.15 | 0.08 | 20.5 | 22.7 | 23.2 | 23.6 |
| | ExtSha | 1397 | 1223 | 1196 | 1172 | 375 | 672 | 740 | 754 | 80.4 | 79.3 | 79 | 78.6 | 5.02 | 0.34 | 0.15 | 0.08 | 20.3 | 22.7 | 23.1 | 23.6 |
| | KpHtOt | 1399 | 1221 | 1195 | 1168 | 324 | 654 | 736 | 759 | 80.4 | 79.3 | 79 | 78.6 | 4.86 | 0.32 | 0.15 | 0.08 | 20.4 | 22.7 | 23.1 | 23.6 |
| | Manage | 1415 | 1215 | 1187 | 1166 | 431 | 728 | 762 | 763 | 80.4 | 79.2 | 78.9 | 78.6 | 3.16 | 0.25 | 0.13 | 0.07 | 20.2 | 22.8 | 23.2 | 23.6 |
| | PasVen | 1905 | 1727 | 1741 | 1751 | 436 | 581 | 631 | 633 | 78.4 | 76.7 | 76.5 | 76.2 | 2.66 | 0.01 | 0 | 0 | 16.7 | 19.2 | 19.3 | 19.4 |
| | Cumtve | 1999 | 1744 | 1760 | 1764 | 232 | 483 | 571 | 617 | 78.6 | 76.7 | 76.4 | 76.2 | 1.63 | 0 | 0 | 0 | 16.2 | 19.2 | 19.3 | 19.4 |
| Archetype P3 | BaseOp | 1215 | 1154 | 1122 | 1097 | 388 | 464 | 591 | 640 | 80.9 | 80.4 | 80 | 79.7 | 5.99 | 1.72 | 0.89 | 0.51 | 11.4 | 12 | 12.3 | 12.7 |
| | ExtSha | 1231 | 1163 | 1132 | 1104 | 324 | 417 | 539 | 598 | 81.1 | 80.5 | 80.1 | 79.7 | 6.33 | 1.8 | 0.92 | 0.53 | 11.4 | 11.9 | 12.2 | 12.6 |
| | KpHtOt | 1226 | 1160 | 1127 | 1097 | 294 | 410 | 533 | 620 | 81 | 80.5 | 80 | 79.7 | 6.16 | 1.74 | 0.92 | 0.52 | 11.4 | 12 | 12.3 | 12.7 |
| | Manage | 1244 | 1159 | 1125 | 1096 | 376 | 474 | 628 | 675 | 81 | 80.4 | 79.9 | 79.6 | 3.87 | 1.32 | 0.8 | 0.49 | 11.2 | 12 | 12.3 | 12.7 |
| | PasVen | 1572 | 1484 | 1480 | 1478 | 374 | 400 | 453 | 431 | 78.8 | 78 | 77.6 | 77.3 | 2.68 | 0.36 | 0.02 | 0 | 9.58 | 10.4 | 10.6 | 10.8 |
| | Cumtve | 1628 | 1502 | 1496 | 1491 | 193 | 254 | 326 | 349 | 79.1 | 78.1 | 77.6 | 77.3 | 1.7 | 0.04 | 0 | 0 | 9.27 | 10.4 | 10.6 | 10.9 |

The following observations persist across different orientations and climatic scenarios:

- In terms of IEQ, exposure to overheating and $NO_2$ concentrations are lowest and attainment highest for non-retrofitted classrooms due to the lower internal temperatures achieved through greater air and heat leakage during cooler nights. Consequently the heating requirements of base case retro-fit classrooms are highest, although more modern constructions (Archetypes P2 and P3) have considerably lower heating loads than Archetype P1. Figure 3 demonstrates the steeper night-time heat leakage of non-retrofitted cases and how during the warmest week, this functions in a similar manner to passive ventilation to reduce overheating (where operative temperature > dotted back BB101 threshold temperature line).

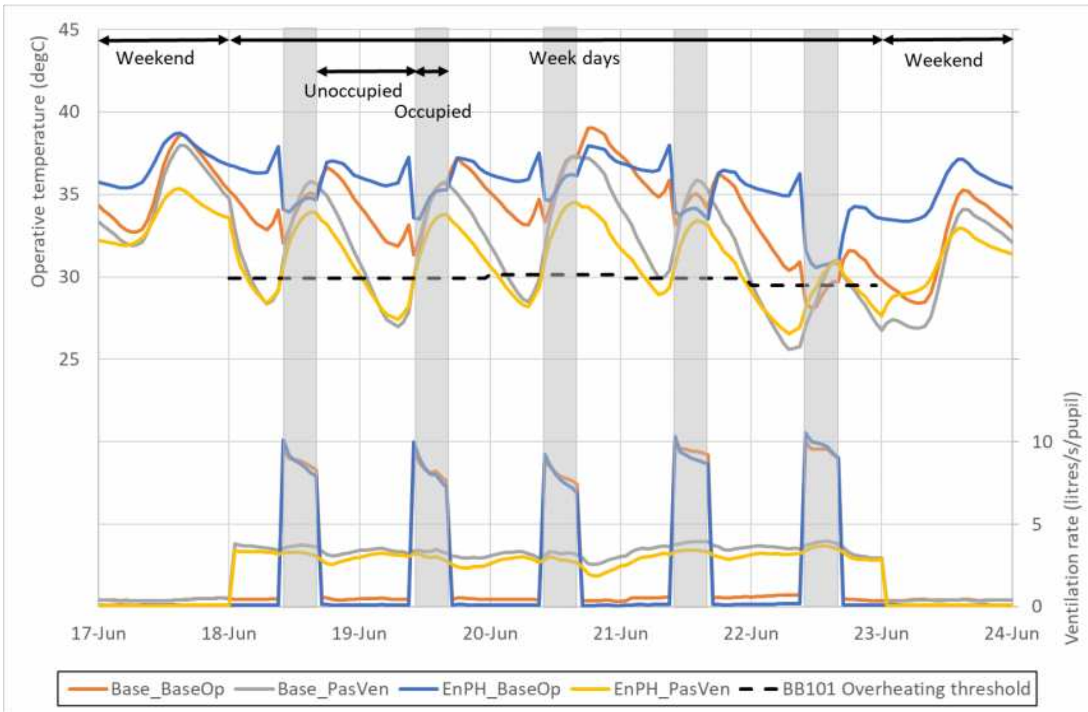


Figure 3: Internal temperatures and ventilation rates during hottest week of year for Archetype P1 base and EnerPHIt scenarios showing impact of night-time ventilation

- Although operational measures of keeping heat out through shading control and albedo are generally effective in mitigating overheating, other individual operational measures except external shading are not universally effective, dependent on the level of retro-fit, era of construction and orientation. For example, passive ventilation is most effective for any level of retro-fit, but not effective at all for base case scenarios, worsening for older, leakier fabric. Managing heat using thermal mass, while effective as a heating reduction, only improves overheating in a couple of North facing cases. However cumulatively, the combination of measures significantly reduces overheating in all cases, as shown in Figure 4, since the dotted threshold line representing overheating can be very sensitive to small changes in operative temperature.
- While $NO_2$ concentration is driven largely by location, passive ventilation is an effective measure, even in the more polluted London region (P1), due to more ventilation being shifted to less polluted night-time hours. An unintended consequence is that the lower required ventilation rates during occupied hours, shown in Figure 3, also lower the perceived attainment for passive ventilated and cumulative cases.
- P2 is most susceptible of the three archetypes to overheating and stuffiness; this is a function of both lower floor to ceiling heights of the 1945-1967 era and warmer West Midlands climate.

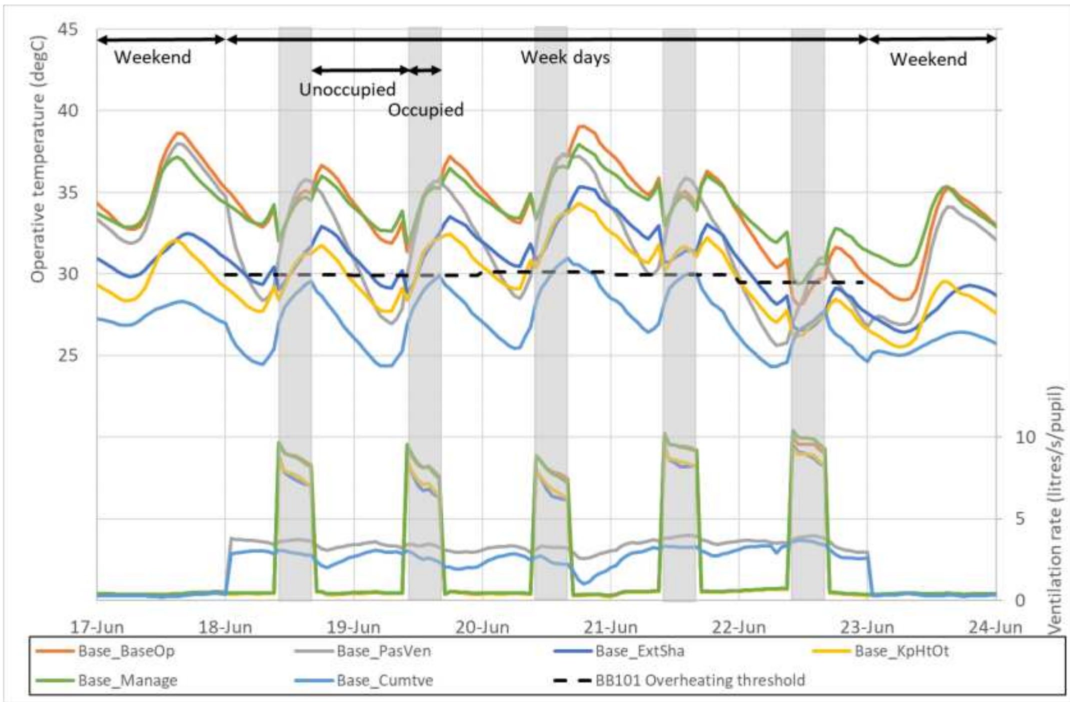


Figure 4: Internal temperatures and ventilation rates during hottest week of year for Archetype P1 base retro-fit showing individual and cumulative operational scenarios

Comparing the 2020s and warmer 2080s climatic scenario in Table 5 and Table 6, there is little change in attainment since higher internal temperatures are off-set by higher required ingress of air. However, these effects negatively impact overheating and contaminant ingress respectively, narrowing the ability of base operational cases to mitigate IEQ. With orientations, North-facing classrooms in Table 7, while decreasing overheating hours by around 30-40% for the Base-BaseOp case, have limited impact (<10%) for both greater retro-fitted cases and use of operational measures.

### 4.2. Summary of best performing pair-wise scenarios

Figure 5 shows the best performing pair-wise retro-fit and operational scenarios for the 5 metrics separately for a range of climate scenarios and orientations, with a couple of caveats:

- For heating demand, a number of combinations indicate zero annual demand (where internal gains are sufficient to maintain occupied temperature above 18 $^{o}$C), hence the least stringent retro-fit and operational scenarios to deliver these conditions are indicated.
- For stuffiness and attainment, across orientations and climates, there is little to differentiate between the three individual operational changes (Manage heat, Keeping heat out and External shading). All three individual measures offer an improvement over base operation and are not penalised by including night ventilation, which impacts stuffiness and attainment by bringing in a greater proportion of fresh air at night, resulting in lower required ventilation during occupied hours.

| | | | Stuffiness / CO2 | | Overheating | | Attainment | | Heating | | Health / NO2 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| P1 | N | 2020 | EnPH | Manage | Base | Cumtve | Base | Manage | EnPH | Cumtve | Base | Cumtve |
| | | 2050 | EnPH | BaseOp | Base | Cumtve | Base | Manage | EnPH | PasVen | Base | Cumtve |
| | | 2080 | EnPH | KpHtOt | Base | Cumtve | Base | Manage | IntR | PasVen | Base | Cumtve |
| | S | 2020 | EnPH | Manage | Base | Cumtve | Base | KpHtOt | EnPH | Cumtve | Base | Cumtve |
| | | 2050 | EnPH | BaseOp | Base | Cumtve | Base | KpHtOt | IntR | PasVen | Base | Cumtve |
| | | 2080 | EnPH | Manage | Base | Cumtve | Base | KpHtOt | IntR | PasVen | Base | Cumtve |
| P2 | N | 2020 | EnPH | Manage | Base | Cumtve | Base | KpHtOt | MinR | Cumtve | Base | Cumtve |
| | | 2050 | EnPH | Manage | Base | Cumtve | Base | ExtSha | MinR | Cumtve | Base | Cumtve |
| | | 2080 | EnPH | Manage | Base | Cumtve | Base | Manage | MinR | Cumtve | Base | Cumtve |
| | S | 2020 | EnPH | Manage | Base | Cumtve | Base | KpHtOt | MinR | Cumtve | Base | Cumtve |
| | | 2050 | EnPH | Manage | Base | Cumtve | Base | KpHtOt | MinR | Cumtve | Base | Cumtve |
| | | 2080 | EnPH | Manage | Base | Cumtve | Base | KpHtOt | MinR | PasVen | Base | Cumtve |
| P3 | N | 2020 | EnPH | BaseOp | Base | Cumtve | Base | KpHtOt | EnPH | Cumtve | Base | Cumtve |
| | | 2050 | EnPH | KpHtOt | Base | Cumtve | Base | Manage | EnPH | Cumtve | Base | Cumtve |
| | | 2080 | EnPH | Manage | Base | Cumtve | Base | ExtSha | EnPH | Cumtve | Base | Cumtve |
| | S | 2020 | EnPH | Manage | Base | Cumtve | Base | ExtSha | EnPH | Cumtve | Base | Cumtve |
| | | 2050 | EnPH | Manage | Base | Cumtve | Base | KpHtOt | IntR | PasVen | Base | Cumtve |
| | | 2080 | EnPH | Manage | Base | Cumtve | Base | KpHtOt | IntR | PasVen | Base | Cumtve |

Figure 5: Top performing pair-wise scenarios for 5 separate metrics and different orientations and climate scenarios for 3 archetypes

Figure 5 demonstrates that there are three/four different modes of operation which partially demonstrate degrees of optimal performance across the five metrics:

- For overheating and ingress of pollutants, a low-degree of retrofit, coupled with the cumulative scenario of operational measures is optimum for lowering exposure. Attainment would also be included within this set of metrics, were it not for night ventilation resulting in lower required occupied ventilation rates (as shown in Figure 4), hence impacting the attainment metric calculation.
- For stuffiness, the converse is true: a high-degree of retro-fit coupled with selective use of operational measures mitigates against high $CO_2$ levels.
- For heating, a high degree of retro-fit is highly desirable although EnerPHIt may not be essential for all scenarios. Some form of night-ventilation, most often as part of a cumulative strategy, minimises heating demand.

While a number of key caveats remain, the summarising of 24 pair-wise scenarios into three or four optimal groupings gives the potential to focus future research onto a smaller sub-set of models within the UK school stock.

## 5. Discussion

### 5.1. Implications and validity of results

While the previous section demonstrated a number of feasible pairwise scenarios in response to the research question, a remaining key question arising from Table 5 is around the degree to which it is necessary to retro-fit future buildings. While there is a current focus on provision of net zero carbon buildings (Department for Education (DfE), 2021), there is some indication that improvements towards minimum building regulation standard alone may provide around 60-80% of the required energy efficiency improvements, while preventing the worst of overheating and ingress of contaminants. However, a major issue with the models is the problem of applying rigid heating and ventilation rules, preventing the ad-hoc 'free-will' opening of windows to mitigate stuffiness which could give more retro-fitted models greater flexibility in the trade off between energy use and IEQ mitigation.

An interpretation of the acceptable ranges of each criterion is dependent on existing guidelines. BB101 (Education and Skills Funding Agency (ESFA), 2018) targets under 40 annual overheating hours of exceedance and 1500 ppm of annual $CO_2$ exposure, and World Health Organisation (WHO) annual mean targets for exposure to $NO_2$ and $PM_{2.5}$ are 10 and 5 µg/m$^3$ respectively, both of which are heavily exceeded for most cases. While entire-building heating energy use would generally be normalised and benchmarked against a typical school building through CIBSE TM46 (CIBSE, 2008), the classroom models represent a partial use of a school building and as such are only internally comparable between scenarios and archetypes. Similarly attainment percentages are useful for relative rather than absolute comparison outside the scope of this project.

### 5.2. Future work

Since the ultimate aim of this work is to inform the design of a modelling platform for IEQ in school classrooms across the UK stock to predict effectiveness of retro-fit decisions, considerable calibration of a baseline to monitored data will be required in the future to validate the dynamic trends demonstrated in this work. Additionally, the limitations of operating classroom stock models in isolation have been demonstrated, in terms of their inability to prioritise one output over another without further guidance. Hence, there is a need for modelling to feed into a further tool, which would combine the criterion investigated with weightings based on the priorities of various school sector stake-holders. A survey of over 150 such construction, educational and governmental stake-holders has therefore been carried out, to feed into a multi-criteria decision analysis (MCDA) tool. This would combine criterion with weighting to score individually different retro-fit, operational scenarios as well as different archetypes across the stock, based on the priorities of different groups.

In terms of additional simulation modelling, there may be a benefit in further analysis of some non-ideal cases to fully test resilience outside of future anticipated operating envelopes. Such cases could include archetypes with a lower floor to ceiling height than allowed for in proposed design, additional indoor sources of $PM_{2.5}$, extreme future climate scenarios, or extended school operating hours.

## 6. Conclusions

The simulation modelling presented in this paper in response to the research question clearly demonstrates that there are around three or four pair-wise retro-fit and operating strategies worthy of further detailed analysis. While, individually, the five criterion presented in the results section provide some indication of the degree to which various scenarios satisfy individual needs for energy demand reduction, IEQ mitigation and boosting attainment, to be an effective tool for policy makers this output should be coupled with weightings and priorities driven by stake-holders themselves.

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# Evaluation of the current indoor environment using physical measurement and a questionnaire in an educational space in a hot climate

**Fatema Al-Akhzami[1], Hanan Al-Khatri[1], Saleh Al-Saadi[1], and Hayder Khan[1]**

[1] Department of Civil and Architectural Engineering, College of Engineering, Sultan Qaboos University, Oman, khatri@squ.edu.om

**Abstract:** Indoor Environmental Quality (IEQ) can be considered an important indicator of the health and productivity of the occupants, especially in educational buildings where students spend the majority of their time indoors. Different studies highlighted the importance of studying IEQ in classrooms where the indoor environment can be linked to the student's academic performance. Although Oman is located in a region with extreme climatic conditions, there is no published research that addresses the evaluation of indoor environmental quality in educational institutions. In an attempt to fill this gap of knowledge, the paper at hand aims to evaluate IEQ in an educational space in Sultan Qaboos University (SQU), Oman, exploring the occupants' perception of the relative importance of the IEQ parameters for them. Physical measurements were conducted along with a questionnaire where the students were asked to evaluate their sensation, satisfaction, and preference regarding thermal, visual, acoustic, and air quality conditions. Different IEQ parameters were measured including air temperature, globe temperature, humidity, air velocity, $CO_2$ concentration, illuminance level, and sound level. The results show that students are satisfied with all IEQ aspects except visual conditions. Meanwhile, investigated studio shows comfortable internal conditions except for visual conditions. The findings of this study will be useful in enhancing the student's educational experience in SQU. Further, they can be used as a reference for further investigations of IEQ for educational buildings, especially in hot climates.

**Keywords:** IEQ, Occupant perception, Educational buildings, Comfort, Hot climate

## 1 Introduction

Indoor Environmental Quality (IEQ), especially its effect on the occupants, has become a topic that captured the interest of several researchers globally (Fantozzi and Rocca, 2020). Specifically, it is considered the main factor in defining indoor conditions due to its contribution to the health, well-being, and productivity of people (Salleh *et al.*, 2015; Coulby *et al.*, 2020). Based on the definition of the National Institute of Occupational Safety & Health (NIOSH), IEQ refers to how the building affects the well-being and health of people who occupy its spaces. In specific, it is defined as "the quality of buildings' environments related to the health of occupants within it determined by many factors including lighting, air quality, and damp conditions" (NIOSH, 2013). Indeed, IEQ is a term that indicates the combination of thermal conditions (TC), visual conditions (VC), acoustical conditions (AcC), and indoor air quality (IAQ) conditions (El-Salamouny, Abdou and Ghoneem, 2019). These conditions are the four main factors for defining an adequate indoor space (Wong, Mui and Hui, 2008).

The indoor environment is closely related to occupants' well-being and performance inside any type of building (Choi *et al.*, 2014). Thus, maintaining good indoor conditions in educational buildings is crucial (Yang and Mak, 2020), since students spend more than 30% of their time in educational facilities (De Giuli, Da Pos, and De Carli, 2012). It is worth mentioning that poor indoor comfort negatively influences the students' health, concentration, mental memory, and, thus, academic performance (Mendell and Heath, 2005; Lee *et al.*, 2012; Choi *et al.*, 2014; Ricciardi and Buratti, 2018).

Several studies were performed to evaluate IEQ in classrooms using subjective questionnaires and objective measurements (Astolfi and Pellerey, 2008; Zomorodian, 2018; Zuhaib *et al.*, 2018; Yang and Mak, 2020). The most evaluated parameters are air temperature ($T_a$), mean radiant temperature ($T_r$), globe temperature ($T_g$), relative humidity (RH), air velocity (VA), $CO_2$ concentration, sound level, and illuminance level. Their findings illustrated that IEQ is strongly correlated with the environmental parameters. Although thermal condition, IAQ, and visual condition are all important, the acoustical conditions have the greatest influence on students' concentration (Astolfi and Pellerey, 2008; Lee et al., 2012). In contrast, a study conducted in Hong Kong indicated that thermal comfort is the most critical factor, followed by acoustic comfort, visual condition, and IAQ. The results illustrated that lighting quality, temperature, and adjusting clothing have a strong association with users' acceptance, which may be the case due to the high temperature and high density in Hong Kong (Yang and Mak, 2020).

Moreover, the previous studies evaluating the IEQ in the classroom were mainly focused on the Mediterranean and subtropical climates and there is a gap in the literature on IEQ research in hot arid climates. Considering the gulf region, the studies on IEQ are limited and few studies can be mentioned (Fadeyi *et al.*, 2014; Abdul-Wahab, Salem and Ali, 2015; Al-Hubail and Al-Temeemi, 2015, 2019; Abdou, Ki Kim and Bande, 2020; Al-Khatri, Alwetaishi and Gadi, 2020; Al-Khatri, Etri and Gadi, 2022). Despite that most of these studies evaluated a single aspect of the indoor environment, (Fadeyi *et al.*, 2014; Al-Hubail and Al-Temeemi, 2019) and evaluated the effect of different parameters of IEQ in school classrooms. (Fadeyi *et al.*, 2014) conducted a study in elementary schools in the United Arab Emirates to evaluate IEQ parameters based on the standards of Dubai Municipality. The findings revealed that the students were exposed to poor conditions, especially those of indoor air quality. The other study conducted by (Al-Hubail and Al-Temeemi, 2019) examined IEQ conditions in secondary schools in Kuwait. The results showed that thermal conditions were below the standards' design limits because of ineffective air conditioning systems. The acoustical and visual conditions were adequate.

Although it has a hot arid climate, no published research addresses the evaluation of indoor environmental quality in educational institutions in Oman. Aiming to address this knowledge gap, the objective of this study is to evaluate IEQ in an educational space at Sultan Qaboos University (SQU) using field measurements along with subjective assessment. The environment of an architectural studio was evaluated in terms of thermal, visual, acoustic, and indoor air quality conditions.

## 2 Methodology

This study was conducted by subjective assessment and physical measurements to evaluate IEQ conditions in an architectural studio at Sultan Qaboos University (SQU), Oman. The studio was selected to represent a typical sample of architectural educational spaces. The measurements were taken during the morning and afternoon periods to represent the regular teaching hours. The studio is mechanically ventilated and the system was on during the measurements. Table 1 summarized the characteristics of the selected space.

Table 1. Characteristics of the studio

| | |
|---|---|
| **Wall construction** | Plaster, Concrete block, and plaster, 200 mm thickness |
| **Ceiling** | Acoustical tiles |
| **Length** | 17.8 m |
| **Width** | 12.2 m |

| | |
|---|---|
| **Height** | 2.7 m |
| **Area** | 156.2 $m^2$ |
| **No. of doors** | 4 |
| **No. of windows** | 2 clerestory |
| **HVAC type** | Ceiling mounted cassette |
| **No. of HVAC outlet** | 48 |
| **Electrical lighting type** | Fluorescent lamps |
| **No. of electrical lighting** | 48 |

The measurements were performed during the transitional season in Muscat, i.e. from the end of March to the beginning of April. Muscat is the capital city of Oman and it has a hot and arid climate. Air temperatures can reach 39.3 °C in summer while they reach 20.2 °C in winter (Betti, G., Tartarini, F., Schiavon, S., Nguyen, 2021). Figure 1 displays the mean, minimum, and maximum air temperatures. As observed, April to October is the hottest compared with the other months.

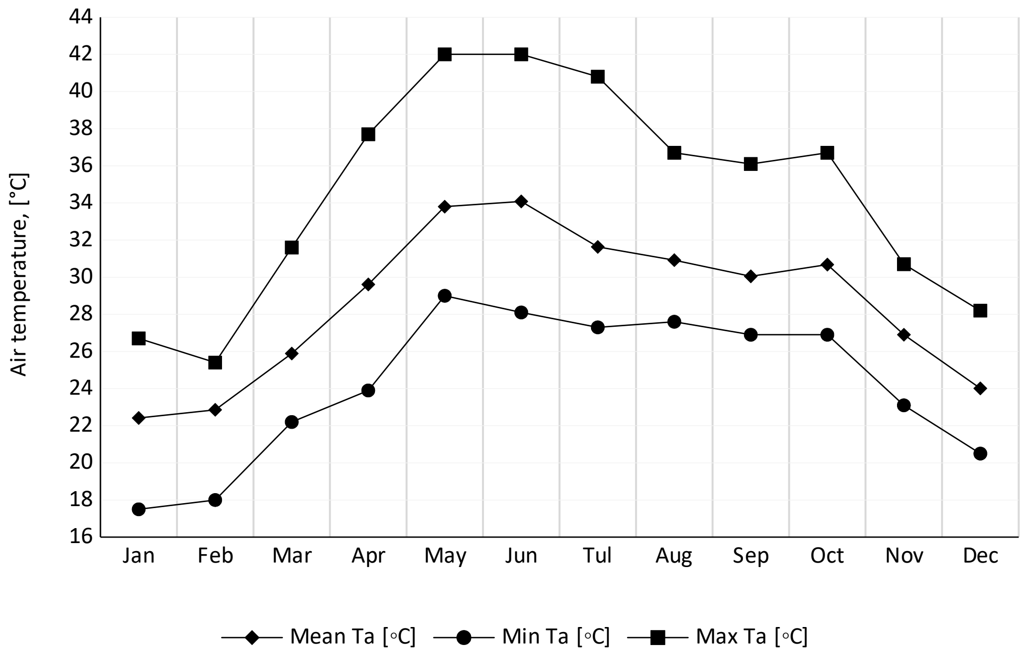


Figure 1. Mean, minimum, and maximum air temperatures in Muscat

## 2.1 Questionnaire

A subjective evaluation was conducted using a questionnaire that was developed based on previous literature (McCartney and Fergus Nicol, 2002). The objective of the questionnaire was to evaluate students' perceptions regarding IEQ aspects. A total of 60 questionnaires were distributed to the students after 15 minutes of sitting still in the studio to avoid the influence of previous activity on their perception of the investigated studio. The students were asked to express their perceptions in terms of sensation, preference, and satisfaction regarding the thermal, visual, acoustic, and air quality. Table 2 describes the questions distributed in this study. It is worth mentioning that the questionnaire contained two parts that were not analyzed in this paper.

Table 2: Description of questionnaire model

| Section | Description |
|---|---|
| Part 1: Demographic data | Gender, age, and health situation |
| Part 2: IEQ predictions | Sensation, satisfaction, and preference of the four IEQ parameters, using a 7-point scale for sensation, and a 5-point scale for satisfaction and preference |
| Part 3: Thermal comfort | Location of the participant in the classroom, sensation of air movement and humidity |
| Part 4: Visual comfort | Students' perception of lighting in the classroom |
| Part 5: Acoustic comfort | Student's perception of noise in the classroom |

## 2.2 Physical measurements

The indoor environment was evaluated by measuring air temperature ($T_a$), globe temperature ($T_g$), relative humidity (RH), air velocity (AV), illuminance level (lx), sound level (dB), and $CO_2$ concentration (ppm). Table 3 displays the accuracy of the used sensors. It is worth mentioning that the measurements of the parameters were conducted as specified in the guidelines of the international standards, namely (ISO 3382-1, 2009; BS EN 12464-1, 2011; EN 15251, 2012; ASHRAE-62.1, 2019;ASHRAE-55, 2021). The measurements were taken using a short-term approach at the center of the studio. The additional thermal sensors were distributed in the studio. Logging intervals were 3 minutes, 1 minute, and 5 minutes for thermal, acoustic, and $CO_2$ respectively. The visual measurements were taken using grid lines of 0.5 m x 0.5 m above deck level.

Table 3. Sensors used in this study

| Aspect | Parameters | No. of measuring points | Sensor | Picture | Accuracy |
|---|---|---|---|---|---|
| Thermal | $T_a$, $T_g$, RH, AV | Four points, 1.1 m | Heat shield |  | $T_a$, $T_g$ ± 0.3 °C<br>RH, 1.8%<br>AV, ± 10cm/s |
| Visual | Illuminance level | One point, desk level | ExTech HD 450: light meter/ datalogger |  | ±4% rdg |
| Acoustic | Sound level | One point, 1.2 m | Sound level meter |  | 33dB~136dB |
| Air quality | $CO_2$ | One point, 1.1 m | HOBO MX $CO_2$ data logger |  | ±50 ppm ±5% |

## 3 Results and Discussion

### 3.1 Students' perception of IEQ

Checking for inconsistent or incomplete answers resulted in rejecting 5% of the distributed questionnaires. With reference to the analysed 57 questionnaires, 24.6% of the participants were males and 75.4% were females and the majority were 20-24 years old. When asked about their behaviour to adjust or control the internal environment, the students reported 33.9% adjusting the doors, 33.9% adjusting window blinds, and 32.2% controlling air-conditioning units. This is an indication that the students are aware of their needs to control surrounding environments and adapt to their needs. The results from the TC, VC, AcC, and IAQ sections of the questionnaire are shown in the following sections.

#### 3.1.1 Thermal perceptions

The percentage of students who felt cold conditions (i.e. cold, cool, slightly cool) was 52.6%, whereas those who felt warm conditions were 21.1%. The percentage of students who felt neutral was 26.3%. Considering the preferences, around 35.1%, 22.8%, and 42.1% preferred cooler conditions, warmer conditions, and no change in their conditions, respectively. Moreover, around 36.8% of the students felt (slightly cool) and around 24% preferred (no change). It is worth noting that there were no votes in (cold) sensation or (much warmer) preference.

Figure 2 illustrates the relation between students' thermal sensations to preferences. As it is observed, students' sensations clustered mostly in the range between (neutral) and (cool). As well, the relation between thermal sensation and preference is linked, where, students who felt coldness preferred warmer conditions and students who felt warmness preferred colder conditions. For instance, 22.8% of the students who felt (cool) and (slightly cool) preferred (a bit warmer). Besides, 17.5% of students who felt (hot), (warm,) and (slightly warm) preferred to feel (a bit cooler) or (much cooler). Considering students with (neutral) sensation, they formed around 26.3% approximately. Out of them, around 60% and 40% preferred (no change) and (a bit cooler), consequently. Moreover, 42.1% of students who preferred (No change) had different thermal sensations, i.e. 8.3% for (cool), 45.8% for (slightly cool), 37.5% for (neutral), 4.2% for (slightly warm), and 4.2% for (warm). In addition, 22.8% of (cool) and (slightly cool) students preferred to keep their thermal conditions as they are, whereas 7% of them in the same sensation categories preferred (a bit cooler) conditions.

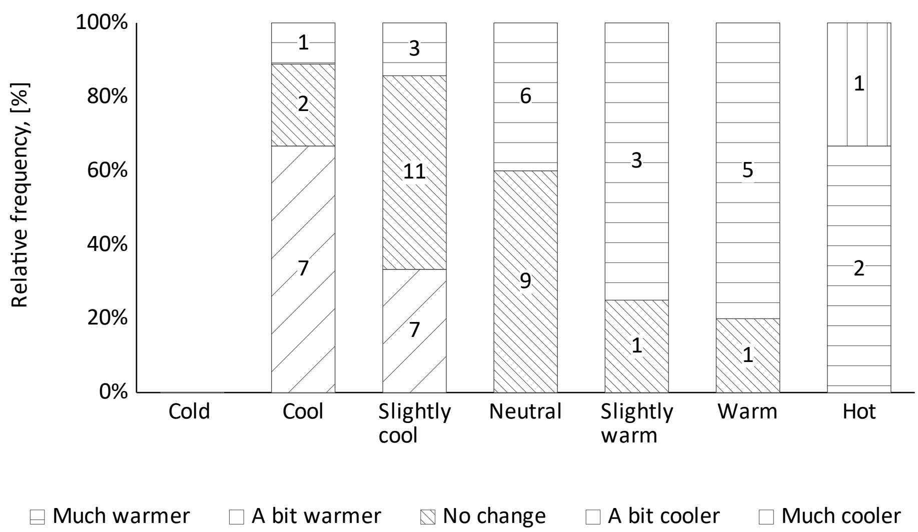


Figure 2. Relative frequency of thermal sensations and preferences (labels are number of students)

Furthermore, students were asked about their overall satisfaction with the thermal condition in the studio and the results are illustrated in Figure 3. It can be noticed that 57.9% of the students were satisfied with the thermal conditions (i.e. satisfied and very satisfied), whereas around 15.8% were dissatisfied. Considering those satisfied, (slightly cool) was reported by around 45.5%, whereas (warm) and (slightly warm) were reported by 6.1% and 6.1%, respectively. Additionally, 33.3% of the students who voted dissatisfied reported being (hot), whereas 11.1% and 11.1% were (slightly warm) and (warm) sensations, respectively.

It is noteworthy that these findings are in agreement with the findings of (Rasha W. AlNajjar, 2018; Al-Khatri, Alwetaishi and Gadi, 2020; Al-Khatri, Etri and Gadi, 2022) who investigated students' thermal perception under similar climate conditions and (Hwang *et al.*, 2009; Guevara, Soriano and Mino-Rodriguez, 2021) reported similar findings in other climatic conditions. It is obvious that the most preferable condition among the investigated students is the cold conditions despite the fact that the students were satisfied with internal conditions. This may be due to a cultural preference.

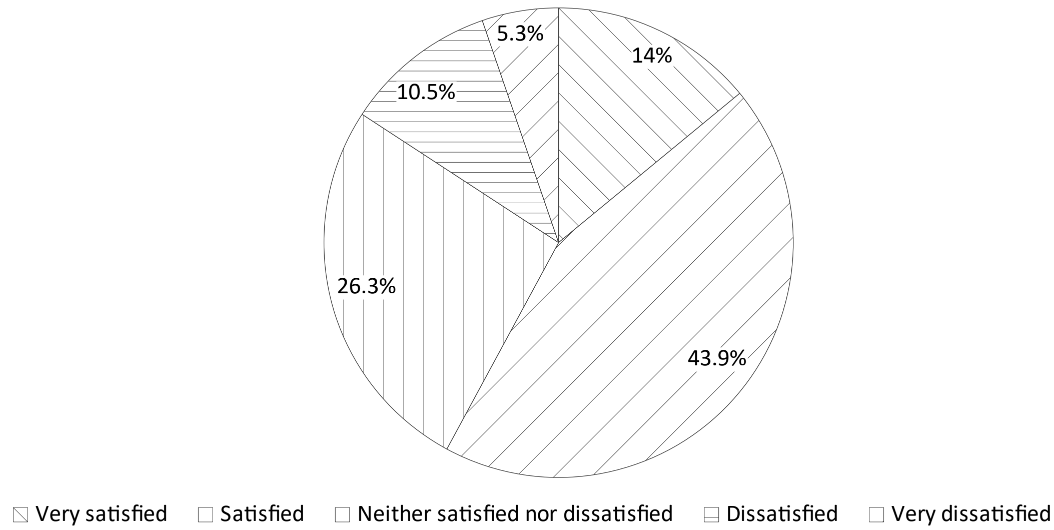


Figure 3. Students' thermal satisfaction levels

### 3.1.2 Visual perceptions

Based on the subjective assessment results, 63.2% of the students felt that the lighting in the studio had dim conditions (i.e. dim, slightly dim, and very dim). In contrast, 10.5% felt that the studio had a bright condition. Moreover, 26.3% of the students reported that they feel the lighting condition were (neither dim nor brighter). By considering the preferences votes, the majority of the students about 80.7% prefer brighter lighting conditions (i.e. a bit brighter and much brighter). Furthermore, 15.8% prefer to keep their condition. However, 3.5% of the students prefer to have (a bit dimmer lighting) conditions. It was noted that most of the sensation votes of the students around 40.4% selected (dim) whereas, (very bright condition) had the lowest percentage votes with 1.8%.

The relative frequency of students' sensations to the preference of lighting conditions is illustrated in Figure 4. The figure shows that most of the student's sensation votes were clustered between (neutral) and (dim). Indeed, it is noted that visual sensation votes followed preference votes. Whereas, students who felt dimmer conditions prefer brighter conditions. To illustrate, 61.4% of the students who felt (very dim), (dim), and (slightly dim) their preference votes is (much brighter) and (A bit brighter). As well, 1.8% of the students who felt (very bright), (bright), and (slightly bright) prefer to have (A bit dimmer) condition. Although 26.3% of the students reported that they feel (neutral), they have different preference votes where 13.4% of them prefer (much brighter), 40% prefer (a bit brighter), 40% prefer (no change) and 6.6% prefer (a bit dimmer). In consideration of the student who had preference votes of (no change), they have different sensation votes. For example, 11.1% (dim), 66.7% (neutral), 37.5% (Neutral), 11.1% (Slightly bright), and 11.1% (very bright) condition. Noteworthy is the fact that 5.3% of students feel bright conditions prefer to have the same conditions.

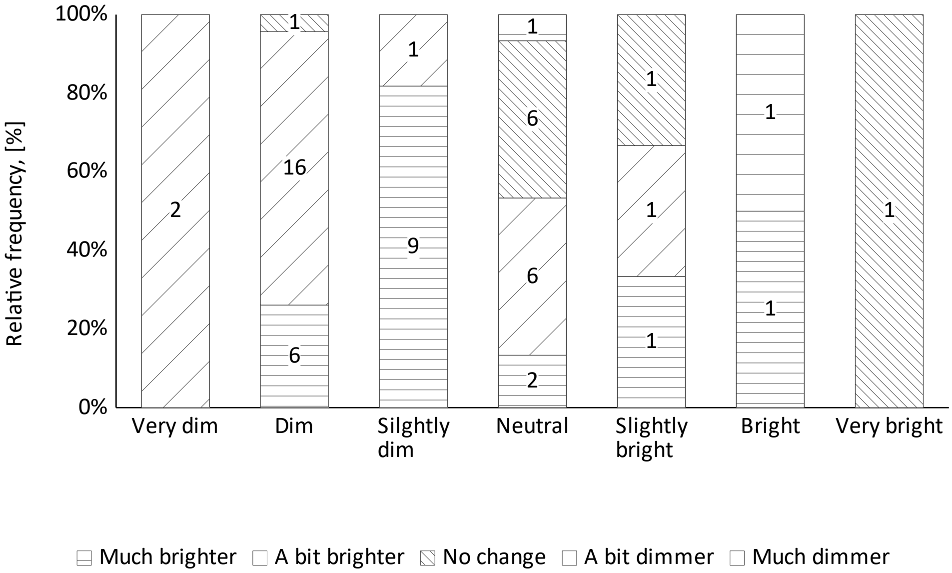


Figure 4. Relative frequency of visual sensations and preferences (labels are number of students)

To identify student satisfaction with lighting conditions in the studio, students were asked if they are satisfied or dissatisfied using a five-point scale. Figure 5 demonstrate the percentage of students' satisfaction level regarding visual condition. As shown, the majority of the students 43.9 % are dissatisfied whilst 26.3% only of the students were satisfied. Moreover, the majority of the students around 24.6% reported dissatisfaction to have a visual sensation of (dim) condition, and students with (neutral) and (slightly bright) represent the lowest percentage in dissatisfaction votes with an equal percentage of 1.8%. While the largest percentage of the students who were satisfied with their visual condition was around 15.8% had a visual sensation of (neutral), and the lowest percentage of the equal number fell in (slightly dim), (slightly bright), (bright) and (very bright) with a percentage of 1.8% each. In light of this, we can state that a brighter condition is the most preferable condition among the students.

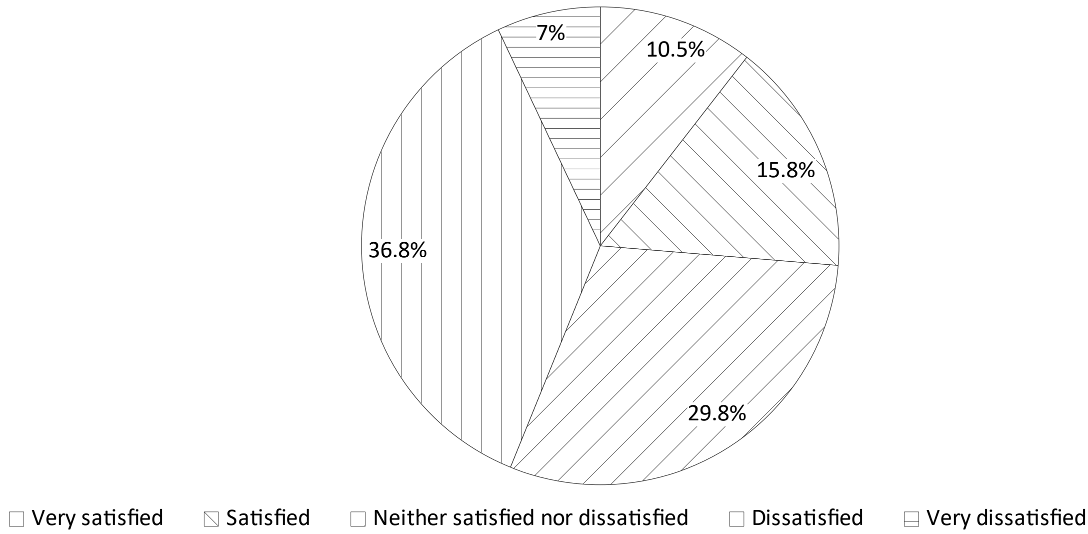


Figure 5. Students' visual satisfaction levels

### 3.1.3 Acoustics perception

Based on the questionnaire results, 42.1% of the students felt that the studio has noisy conditions while 10.5% feel it has quiet conditions. Moreover, most of the students approximately 47.4% felt that it has a neutral condition. Indeed, the largest percentage around 52.6% of the students prefer to have quieter sound conditions while 42.1% prefer to have the same condition as they feel in the studio. Reversing it, about 5.3% of the students prefer to have noisier conditions. In addition, the highest sensation votes were for neutrality with 47.4%. As well, the highest votes of preference were for (a bit quieter) and (no change), 24% each. However, no votes were for (a bit quieter), (no change), and (much noisier).

The results from the acoustics condition of sensation and preference votes are illustrated in Figure 6. As the figure observed, most of the student's sensation votes congregate between (neutral) and (slightly noisy). Based on the results, there is a direct relation between acoustic sensation and preference votes were both following each other. Whereas, the students who feel noisier prefer quiet conditions. To demonstrate, 38.6% of the students who felt (very noisy), (noisy), and (slightly noisy) their preference is (much quieter) and (a bit quieter). Moreover, 47.4% of students votes for (neutral) whereas 66.7% of students prefer (no change), 18.5% prefer (a bit quieter) and 7.4% prefer (much quieter) and (a bit noisier) each. Besides, 42.1% of students who prefer (no change) condition have different acoustic sensation were 75% (neutral), 16.7% (quiet), and 8.2% (slightly noisy). Based on the results it is noticeable that quiet condition is the most preferable condition among the students.

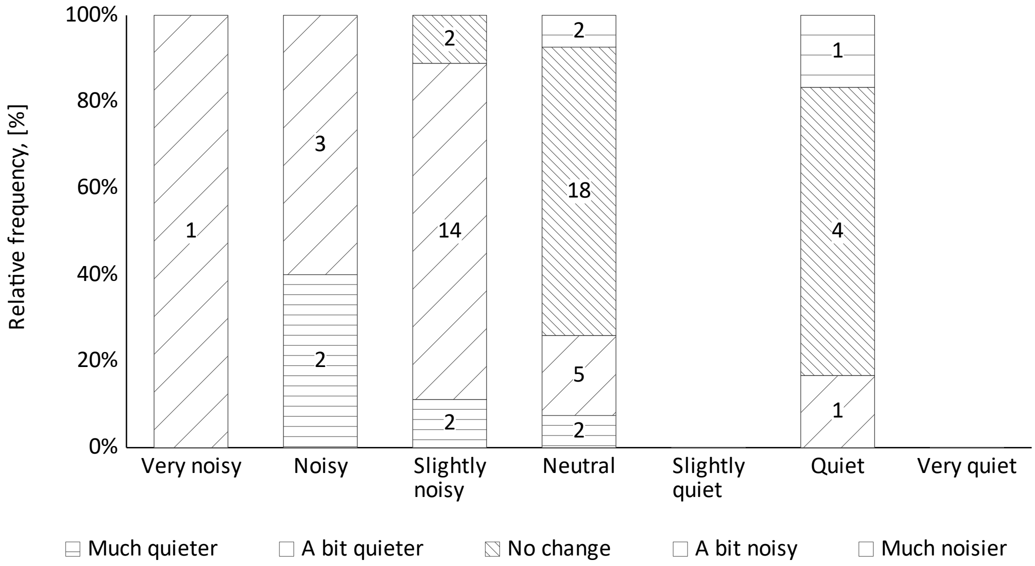


Figure 6. Relative frequency of acoustical sensations and preferences (labels are number of students)

Figure 7 presents students' satisfaction levels with acoustics conditions in the studio. As indicated, there are considerable differences between the students who are satisfied and dissatisfied where 50.9% of the students were satisfied while 15.8% of the students were dissatisfied with the acoustic condition in the studio. Indeed, 33.3% of the students were neither satisfied nor dissatisfied with the acoustic condition in the studio. In addition, the highest percentage of students who were satisfied with the acoustic condition is 38.6% and had an acoustic sensation of (neutral). On the other hand, the lowest percentage of satisfaction is for the (quiet) condition with 5.3%. Taking preferences votes into account, 35.1% of students who were satisfied with the acoustic condition had an acoustic preference of (no change) while 1.8% of students who were satisfied with the acoustic condition had a preference of (much quieter). According to the dissatisfaction votes, the highest percentage of students who were dissatisfied with the acoustic condition is 10.5%, and had the acoustic sensation of (being slightly noisy). In contrast, the lowest percentage of dissatisfaction is for a (very noisy) condition with 1.8%. While the highest percentage around 12.3% of students had an acoustic preference of (a bit quieter) and the lowest percentage about 3.5% of dissatisfied students had a preference of (much quieter). Although 42.4% of the students feel (Slightly noisy) (Noisy) (Very noisy) the majority of the students report that they are satisfied with this condition.

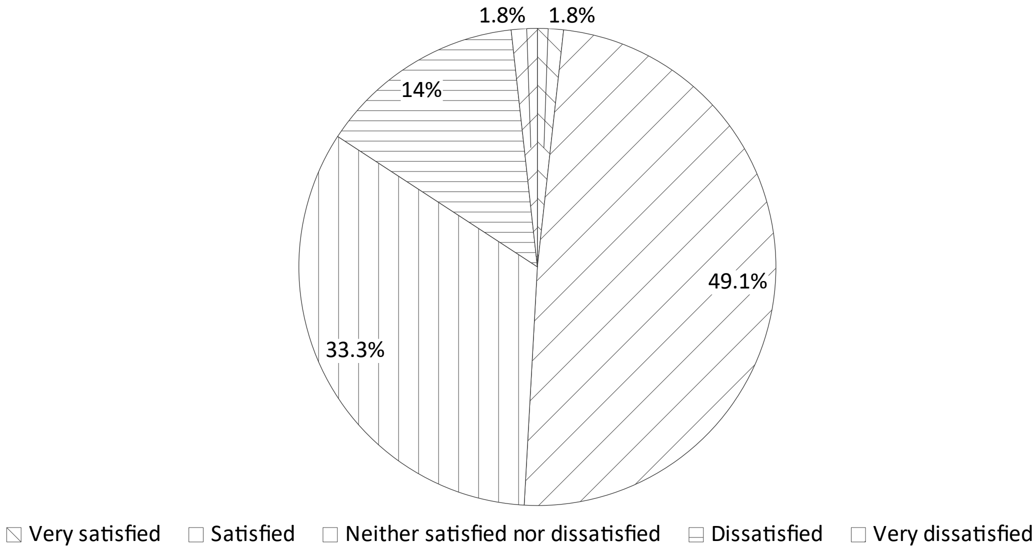


Figure 7. Students' acoustical satisfaction levels

### 3.1.4 Indoor Air perception

The analysis of the indoor air quality votes indicates that the majority of the students around 57.9% the studio has good indoor air condition and 22.8% and 19.3% felt that bad condition and neutral respectively. Meanwhile, 93% of the students reported that they preferred fresher condition and 7% prefer their condition as it is. Moreover, no one of the students voted for stuffy conditions as a preferable condition. The results show that students mostly voted for (good) conditions with about 45.6% whereas, (excellent) and (bad) conditions have the lowest votes with a percentage of 1.8% for each. On the other hand, the highest percentage in preference votes was for (much fresher) with approximately 49.1%. Indeed, (much stuffy) and (a bit stuffy) have no votes.

The relative frequency of students' sensation and preference votes are depicted in Figure 8. As the figure illustrates, the trends of students' votes are between (good) and (slightly bad). As well, the students clustered votes for (much fresher) and (a bit fresher). Where 57.9% of the students feel (excellent), (good), and (slightly good) their preference is (much fresher), (A bit fresher), and (no change). As well, 19.3% of votes were for (neutral) where, whereas 54.5% of students prefer (much fresher), 36.4% prefer (a bit fresher) and 9.1% prefer (no change). Furthermore, 7% of students who prefer (No change) conditions have different indoor air quality sensations 75% (good) and 25% (neutral). The results indicate that fresh condition is the most preferable condition among the students and they are aware of the importance of good air in the studio because all students votes for fresher conditions and no change and no one prefer to have stuffy conditions.

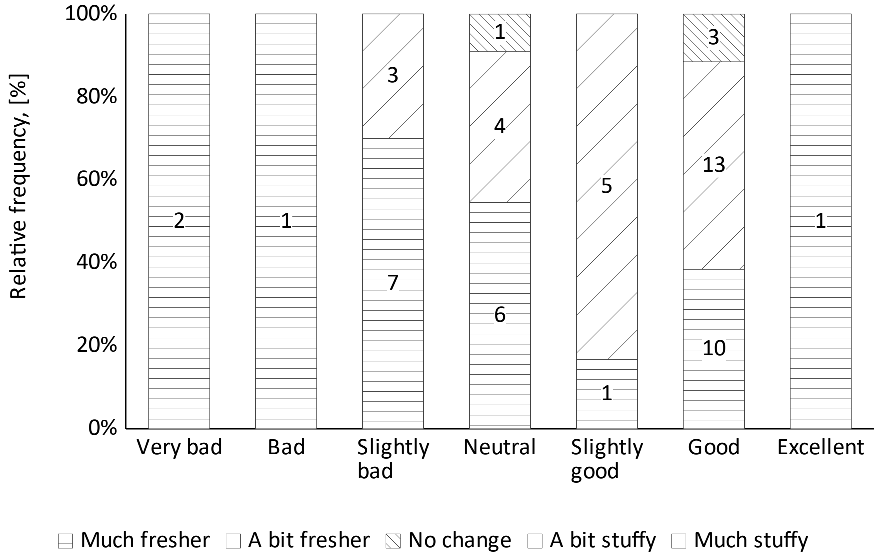


Figure 8. Relative frequency of indoor air quality sensations and preferences (labels are number of students')

The percentage of students' satisfaction and dissatisfaction with indoor air quality in the tested spaces illustrates in Figure 9. As the results indicate, 49.1 and 40.4% of the students were neither satisfied nor dissatisfied and satisfied sequentially. While 10.5% of the students vote about their dissatisfaction with indoor air quality in the studio. Consequently, 26 of .3% of the highest and lowest percentage of students who were satisfied with indoor air quality was 26.3 (good) and 1.8% (slightly bad), (excellent) conditions. Whereas, the maximum percentage of preference votes was for (a bit fresher) with 17.5%, and (no change) has the lowest votes with 7%. Taking dissatisfaction results into account, the highest votes for sensation and preference were 3.5% for (slightly bad), and (very bad) each and 8.8% (much fresher). The lowest percentage of dissatisfaction was for (neutral) and (good) conditions with 1.8%. Similarly, (a bit fresher) has the same percentage in preference votes.

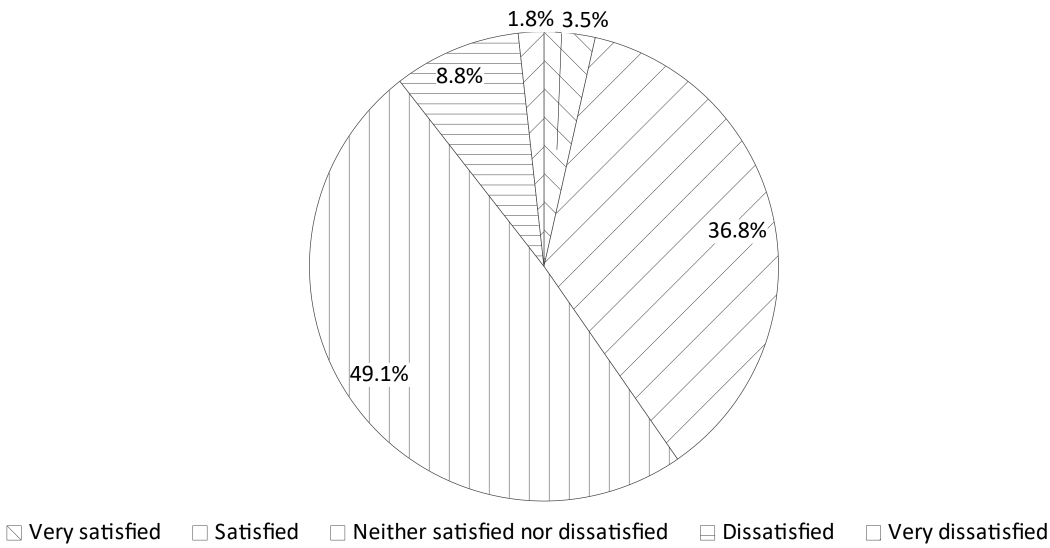


Figure 9. Students' indoor air quality satisfaction levels

## 3.2 Physical measurements

A total of 458 sets of data for air temperature, globe temperature, relative humidity, and air velocity were collected. Likewise, 672, 2251, and 69 sets of data were collected for the illuminance level, sound level, and $CO_2$ concentrations, respectively. The measurements were performed during the morning and afternoon for a period of three days.

### 3.2.1 Thermal Conditions

The measured air temperature ($T_a$), globe temperature ($T_g$), and relative humidity (RH) in the studio are depicted in Figure 10. As it is shown in Figure 10 (a), air temperature ranged between 16.8 °C and 24.4 °C. Considering morning sessions, the highest and lowest air temperatures were 16.3 °C and 21.3 °C, respectively. For the afternoon session, the maximum air temperature was 24.4 °C and the minimum value reached 20.7 °C. Meanwhile, the globe temperature Figure 10 (b) recorded an average of 21.3 °C and the highest and lowest during the two sessions were 20.4 °C and 17.2 °C, respectively. It is worth mentioning that air and globe temperatures were roughly similar with a strong correlation of 0.984 and 0.995 during morning and afternoon respectively. This indicated an absence of radiant sources in the investigated studio (Thapa, Bansal and Panda, 2016). During the morning session, the relative humidity ranged between 46.0% and 64.9% as Figure 10 (c) depicted. During the afternoon session, it was from 41.4% to 60.1%. The average RH for the whole measured period was 54.1%. On the other hand, the measured air velocity ranged from 0.0 m/s to 0.1 m/s.

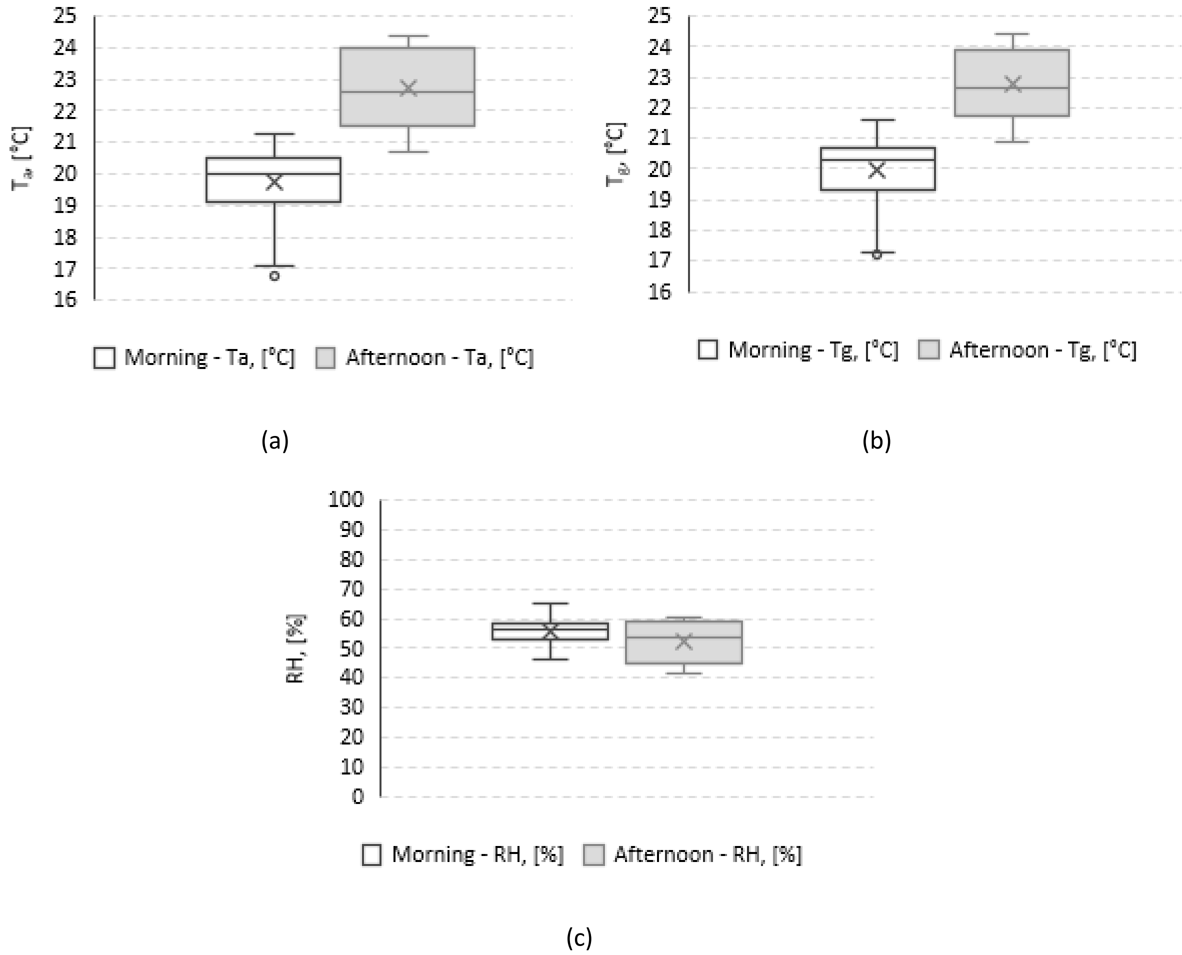


Figure 10. Box plots of: (a) $T_a$, (b) RH, and (c) $T_g$ of the studio

#### *3.2.1.1 Griffiths' method*

Further investigation was performed by using Griffiths' method to calculate the comfort temperature $T_c$ with reference to the students' thermal sensation. This method is used instead of the regression method and it is applied by different researchers using different Griffiths' slopes (Kumar *et al.*, 2016; Guevara, Soriano and Mino-Rodriguez, 2021; Al-Khatri, Etri and Gadi, 2022; Rupp *et al.*, 2022). Using Griffiths methods is recommended when the set of data is relatively small (Nicol, Humphreys and Roaf, 2012). Table 4 shows the comfort temperature calculated using different Griffiths' slopes. The comfort temperature ranged from 24.1 °C to 23.5 °C. It is noticed that by applying different Griffiths' slopes, the change in calculated comfort temperatures was minor and this is similarly observed by (Kumar *et al.*, 2016). As mentioned in (Haddad, Osmond and King, 2019; Guevara, Soriano and Mino-Rodriguez, 2021), taking a slop of 0.5 gave a more accurate prediction. Therefore, in line with these studies, the comfort temperature considered for this study took a slop of 0.5. The calculated comfort temperature using $T_a$, $T_g$, and $T_o$ is 23.5 °C. Considering previous studies with similar climatic conditions (Rasha W. AlNajjar, 2018), the estimated comfort temperature is in the same range as the estimates $T_c$ by this study. On the other hand, other studies in different climatic condition and using mechanical ventilation has approximately similar results (Guevara, Soriano and Mino-Rodriguez, 2021; Rupp *et al.*, 2022). As indicated in the table, the comfort temperature expressed as globe temperature using a slope of 0.39 was 23.7 °C. Interestingly, this temperature was recorded during the afternoon temperature when 19.3% of the students reported being (neutral).

Table 4. Comfort temperature by applying Griffiths' method

| **Griffiths' slope** | **$T_a$, [°C]** | **$T_g$, [°C]** | **$T_o$, [°C]** |
|---|---|---|---|
| 0.50 | 23.5 ± 3.01 | 23.5 ± 2.96 | 23.5 ± 2.99 |
| 0.49 | 23.5 ± 3.05 | 23.5 ± 3.01 | 23.5 ± 3.03 |
| 0.48 | 23.5 ± 3.1 | 23.5 ± 3.06 | 23.5 ± 3.08 |
| 0.47 | 23.5 ± 3.15 | 23.5 ± 3.11 | 23.5 ± 3.14 |
| 0.39 | 23.6 ± 3.67 | 23.7 ± 3.64 | 23.6 ± 3.65 |
| 0.33 | 23.8 ± 4.24 | 23.8 ± 4.22 | 23.8 ± 4.23 |
| 0.30 | 23.8 ± 4.62 | 23.9 ± 4.60 | 23.9 ± 4.61 |
| 0.25 | 24.0 ± 5.48 | 24.1 ± 5.46 | 24.0 ± 5.47 |

#### *3.2.1.2 Comfort temperature*

Figure 11 compares the measured operative temperatures in the studio with those calculated using those recommended by (ISO 7730, 2005; EN 15251, 2012) for three design categories as well as those calculated based on Griffiths' method. As the figure illustrates, the calculated $T_o$ fluctuates between 19.22°C and 23.7°C. This range extends beyond the range computed by Griffiths' method for the first category in both directions. Indeed, the latter category forms only 62.5% of the calculated temperatures. Considering $T_o$ comfort range recommended by EN 15251, the calculated $T_o$ is located totally within the category III range. Moreover, 82.6% of the measured $T_o$ is within the category II range with the remaining temperatures below the lower limit. It is worth mentioning that 84.2% of the students were (very satisfied), (satisfied), and (neither satisfied nor dissatisfied). Considering this and the general preference for cold conditions in the region, it is possible to consider the studio comfortable.

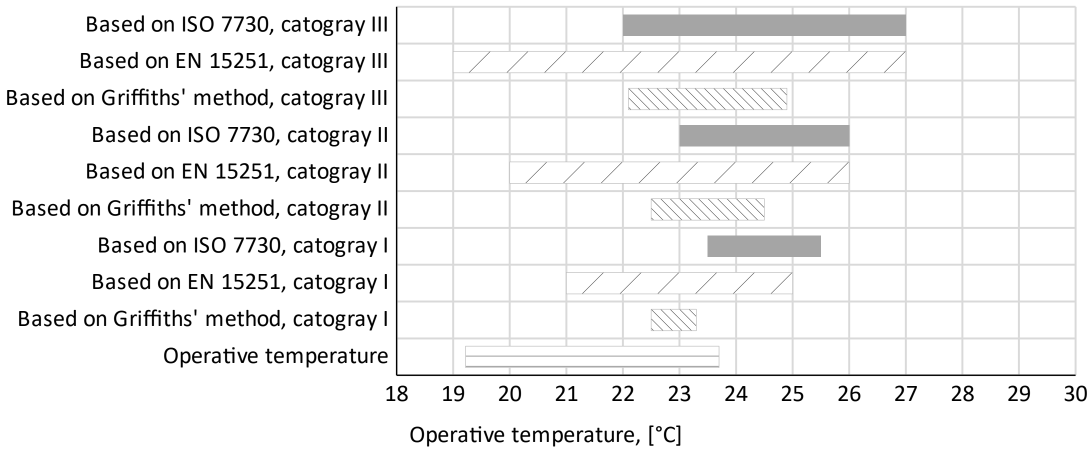


Figure 11. Summarized comfort temperature using Griffiths' method and recommended range in standards

### 3.2.2 Visual Conditions

Illuminance level was measured during the morning and afternoon periods at 11:00 AM and 14:00. It is important to denote that there was no intervention in the internal condition of the studio. The box plot represents the trends of illuminance level during the morning and afternoon periods as shown in Figure 12. The results show variety in illuminance level during the measurements where the effect of daylighting was considered since the windows were not shaded. As the figure indicates, the average illuminance level ranged between 338.4 lux and 315 lux. Morning measurements recorded the maximum illuminance level with 632 lux and the maximum value recorded during the afternoon period was 541 lux. On the other hand, the lowest illuminance level values for the morning and afternoon period were 128 lux and 154 lux respectively. Based on these results, the illuminance level in some areas is low and the main reason for this could be owing because the absence of daylighting in these areas, and there is no artificial lighting fixture placed above the measured points. Taking into account other studies in an educational building under a hot arid climate, (Al-Hubail and Al-Temeemi, 2019) measure illuminance levels in different schools in Kuwait, and the results indicate low lighting conditions. Where the minimum lighting level was 192.4 lux and considering recommended level mentioned in the study was 300 lux to 1000 lux. As well, (Ricciardi and Buratti, 2018) reported that one investigated university classroom suffers from lighting conditions where the lighting level does not exceed 49 lux and other classrooms have less than 200 lux.

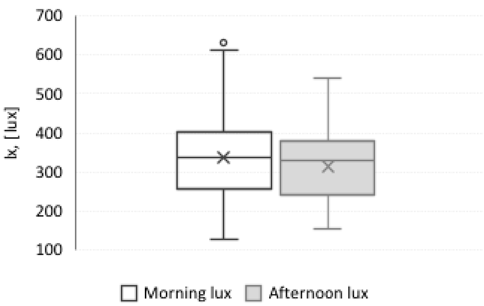


Figure 12. Box plot VC of the studio

### 3.2.3 Acoustic Conditions

The sound level was measured in the studio to evaluate acoustic conditions during lecture time. Figure 13 illustrates the measured values of sound level during the morning and afternoon periods. The sound level measured for the whole period ranged between 61.4 dB and 97.8 dB. Considering morning measurements, the highest value recorded was 94.8 dB whereas, the lowest value was 61.4 dB. For afternoon measurements, the maximum value achieved was 97.8 dB and the minimum value was 68.9 dB. The source of acoustic in the studio were students, the instructor, and air conditioning. Considering recorded values by previous studies, a study conducted in classrooms in Kuwait (Al-Hubail and Al-Temeemi, 2019), reported that measured sound levels in the investigated classrooms were recorded between 60 dB and 89.5 dB, and this is below recommended value by Occupational Safety and Health Administration (OSHA) standard 105 dBA. Another study conducted by (Lee *et al.*, 2012) measured sound levels in mechanical ventilated university classrooms in China and recorded lower values compared to this study with a range from 43.6 dB to 57.3 dB. Another study conducted by (Ricciardi and Buratti, 2018), measure sound levels and recorded the maximum in a classroom with 64.36 dB.

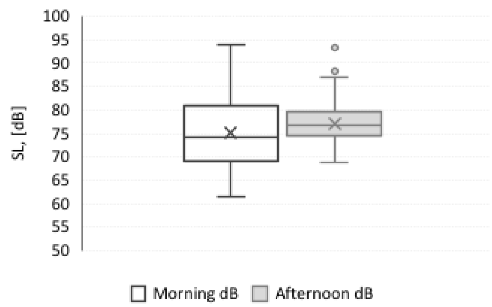


Figure 13. Box plots of AcC measurements of the studio

### 3.2.4 Indoor Air Quality conditions

Carbon dioxide $CO_2$ concentration was measured during the regular lecture period when the studio is occupied by the students to evaluate indoor air quality. From the observation of the studio, there are no sours that can affect indoor air quality in the space and the source of $CO_2$ was the students and instructors. Figure 14 indicates $CO_2$ consecration during in-field measurement. As the figure observed, the maximum concentration was achieved during afternoon measurements at about 2063 ppm while the lowest $CO_2$ concentration value recorded was in the same period around 1088 ppm. In light of morning measurements, the highest and lowest $CO_2$ concentration values recorded were 1578 ppm and 1206 ppm consecutively. Moreover, the average $CO_2$ concentration for the whole measurement period was 1491.8 ppm. The results indicate that the concentration of $CO_2$ in the studio varies depending on the students' density, where with increasing students' density, the range of measured values increased too.

Comparing these results with a study conducted in school classrooms in Kuwait under the same climate conditions (Al-Hubail and Al-Temeemi, 2015), the maximum $CO_2$ concentration was 3700 ppm. This value exceeds the limited recommended average of 1000 ppm as mentioned in the study as well as the classrooms have a concern regarding IAQ. On the other hand, it is observed that increasing students' density in the studio contributes to maximizing $CO_2$ concentration, where the peak of $CO_2$ was recorded during the afternoon session when the students' density increased. Findings similar to these have been reported in a study conducted in UAE to evaluate $CO_2$ conditions in classrooms (Fadeyi *et al.*, 2014).

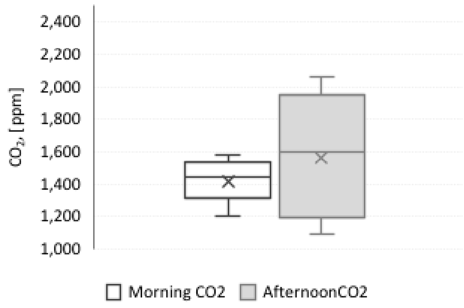


Figure 14. Box plot of $CO_2$ concentration during the measurement period

## 4 Conclusion

The present study evaluates the indoor environmental quality of an educational space at Sultan Qaboos University by using objective and subjective approaches. Thermal conditions, visual, acoustic, and indoor air quality were evaluated along with students' perception of indoor conditions to investigate their sensation and satisfaction. The subjective analysis illustrates that students were satisfied with thermal, acoustic, and indoor air quality except for visual conditions where the students complained of poor lighting conditions in the studio. Moreover, is noticed a direct relationship between sensation votes and preference votes where they followed each other. On the other hand, objective measurements illustrate a strong correlation between air temperature and globe temperature. Comparing the measured parameters with findings of other previous studies under similar climate and indoor conditions, the studio has comfortable conditions except for visual conditions in some areas, and this was reported by the students as well. Moreover, the average measurement of air temperature and relative humidity measured were 21.2 °C and 54.1% respectively. While the average illuminance level recorded was 326.7 lux. The average sound level measured was 76.6 dB. On the other hand, the $CO_2$ concentration average was 1491.8 ppm. As a result of this study, the SQU educational experience will be enhanced. Furthermore, these findings can also be used as a starting point for further research on IEQ for educational buildings, particularly in hot climates.

## 5 References


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# The Effect of Climatic Background on Users' Thermal Comfort in University Buildings

**Zehra Nur Disci, Steve Sharples and Ranald Lawrence**

School of Architecture, University of Liverpool, Liverpool, UK

**Abstract**

Long-term memory may influence people's thermal experience and expectations of their environment. Educational buildings, such as university libraries, are places where people from different cultural and climatic backgrounds come together. However, it is questionable whether the comfort standards and environmental management of these buildings offer equal comfort conditions to people from different climatic backgrounds. To explore this issue, a longitudinal study investigated the effect of cultural and climatic backgrounds on the thermal perception of users of the Sydney Jones Library at the University of Liverpool. Dataloggers in a study area recorded environmental factors such as temperature and relative humidity. Simultaneously, library users participated in an online survey that sort to understand factors affecting user thermal comfort and their views on the environmental conditions of the space. Statistical analysis of winter-time results from the survey suggested that the thermal perceptions and expectations of users varied depending on their different climatic backgrounds. In addition, the mechanical ventilation and cooling system in the study area negatively impacted upon the thermal comfort of users, while also causing unnecessary heat and energy losses. The average temperature of the study area was measured as 19°C. Although the recommended winter comfort temperature for computer rooms in CIBSE Guide A is 19-21°C, this temperature was found to be slightly cool for the majority of respondents.

**Keywords:** Thermal comfort, Climatic background, Education buildings, Comfort temperature

## 1. Introduction

According to a Carbon Trust report (2007), energy consumption in the UK's Further and Higher Education buildings was 62% for space heating (fossil fuels), 1% for space heating (electricity) and 1% for cooling and ventilation (electricity). If the energy consumed for heating educational buildings is high, but the building users feel uncomfortably cold, then that indicates a problem with the provided services. The important thing is to meet the expectations of the users whilst consuming less energy. Today, educational buildings, such as university libraries, are typically places where people from many different cultural and climatic backgrounds come together. However, it questionable whether the comfort standards and environmental management of these buildings, which are usually based on UK comfort criteria, offer equal comfort conditions to people from different climatic backgrounds. Since thermal environmental conditions affect the productivity and attendance of students, as well as their comfort and health (Mendell and Heath 2005, Wang et al. 2018), the thermal environments of university buildings are expected to provide students with as comfortable conditions as possible.

However, people can be comfortable in different situations (Nicol et al., 2012). ASHRAE Standard 55 and EN ISO 7730:2005 define thermal comfort as "*a condition of mind which expresses satisfaction with the thermal environment*". There are various environmental and individual factors that affect this mental state. In previous studies, these factors were discussed in detail under headings such as environmental (Olgyay,1992; De Dear and Brager,2002; Auliciems and Szokolay,2007); personal (De Dear and Brager,2002, Auliciems and Szokolay,2007) and contributing factors (Auliciems and Szokolay,2007). However, Parson (2003) mentioned the effect of cultural and climatic background on thermal comfort, which is also the subject of this study. In later studies, it was mentioned that the experiences of people living in different climatic regions were different (Nicol et al., 2012).

On the other hand, the temperature perception and experience of a person living in an air-conditioned building is different from people living in naturally ventilated buildings (Cândido et al., 2010). In the study conducted by Dear and Auliciems (1988), the fact that people who previously lived in naturally ventilated buildings preferred natural ventilation, while people who lived in air-conditioned environments preferred air conditioning, showed the effect of the climatic background. However, the intensive use of cooling systems in summer months reduces the adaptation of people to environmental conditions and their tolerance to temperature changes (Indraganti 2010). In addition, the fact that people who are accustomed to controlling the ambient temperature are in an environment beyond their control causes them to feel more vulnerable (Dear and Auliciems, 1988).

Knez et al. (2009) mentioned that long-term memory affects people's thermal experiences of and expectations from the environment, and they revealed that long-term thermal comfort memory varies according to the thermal history of people from different regions. In addition, Wang et al. (2017) showed that long-term thermal history has an impact on people's thermal comfort. Jowkar et al. (2020) researched the effect of long-term history and climatic background on thermal comfort in their study of students who had been in the UK for less than 3 years. According to this study, while the ideal acceptable temperature was 24°C for those coming from a hot climate zone, it was 22°C for those coming from a cold climate zone (i.e. a climate zone similar to that of the UK).

In this context, existing or newly designed educational buildings should be designed or renovated in accordance with multinational occupancy. In order to do this, it is necessary to better understand the impact of cultural and climatic background on thermal comfort. Therefore, this research aimed to investigate the effect of cultural and climatic backgrounds of users on thermal perception in buildings with multinational occupancy.

**2. Methodology**

This case study, which included an online survey and measurement of environmental data, was carried out in a study area of the Sydney Jones library at the University of Liverpool in Liverpool, England (Figure 1). Data were collected between 30th January 2022 and 31st March 2022. According to the University of Liverpool’s on site weather station data, the average air temperature in Liverpool was 7°C during the 2-month period when the study was conducted. All data were collected in the computer room located on the ground floor of the library. One of the most important features of this area is that it consists of two sections with natural ventilation and mechanical ventilation. The plan of the case study area is shown in Figure 2. While underfloor heating and mechanical ventilation are carried out in the area called section 1, radiators on the wall for heating and windows for natural ventilation are used in section 2. Since the heating and cooling of the library is remotely controlled, the current data determined for the computer room were obtained from University Facilities Management staff. According to this information, ventilation, heating and cooling systems operate 24/7, 365 days a year. Especially during the Covid period, the ventilation system worked at full capacity and without bypass, by direct transmission of fresh air by heating or cooling.

Figure 1. Case study area

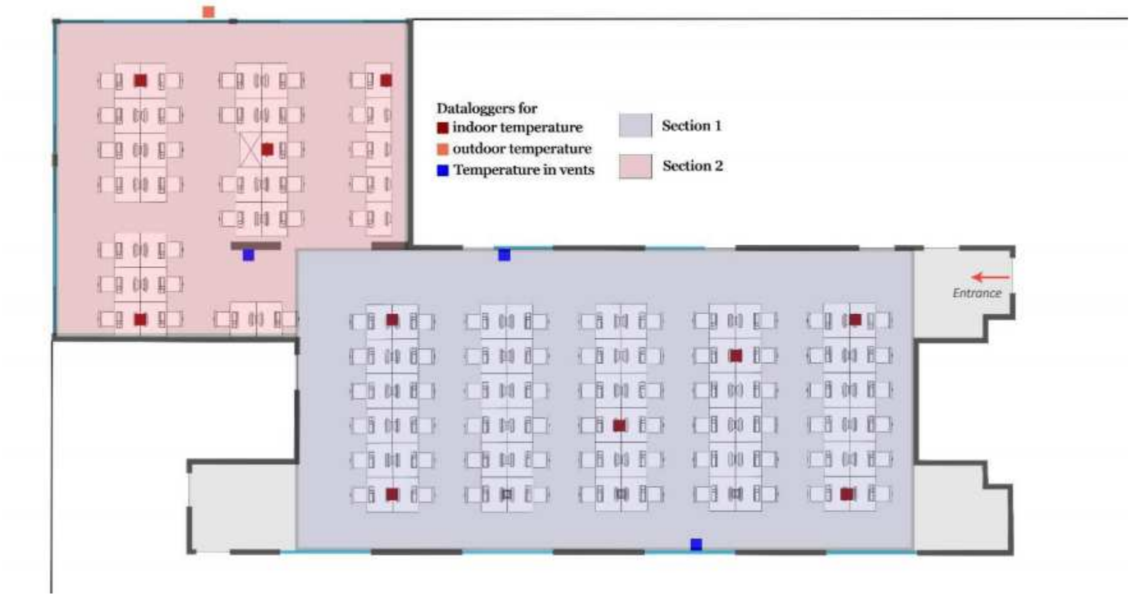


Figure 2. Plan of case study area

EasyLog EL-SIE-2+ dataloggers were set to measure the air temperature and relative humidity of the environment at 15-minute intervals and were placed on some tables in the area. In addition, a Lascar EL-GFX-2 datalogger was placed in a shaded location outside the library to measure the outdoor air temperature. To understand whether the ventilation was working, and to measure the temperature of the air coming from the ventilation, an iButton and a Kestrel DROP D2 datalogger were placed on the ventilation units. In addition, a Testo 405 thermal anemometer was used to manually measure the air velocity in the environment. Apart from these measurements, the weather data measured at 10-minute intervals was also collected monthly from the University's weather station, which is 300 metres away from the case study area.

Having obtained University ethical approval, an online survey was prepared, containing questions to understand the climatic history of the users and their thoughts on the thermal conditions of their environment. A 7-point scale was used to understand the thermal sensation and thermal preferences of the participants. To reduce contact during the Covid period, posters containing QR codes created a link to the survey and were placed on all desks in the case study area. The participants were asked to record their desk numbers in the area where they participated in the survey and in this way the indoor temperature data at the time they participated in the survey were obtained from the datalogger closest to the area they were in. A total of 135 people participated in the survey. All the data obtained afterwards were analysed using the IBM® SPSS® program (IBM®, 2022).

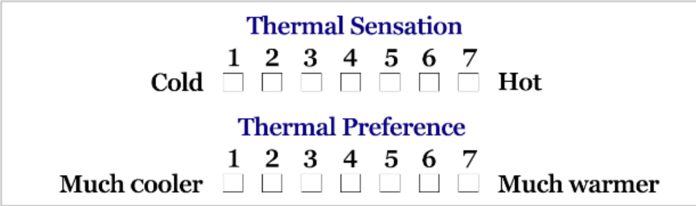


Figure 3. Thermal sensation and thermal preference scale

**3. Results**

Students from 24 different nationalities participated in the survey. Students were divided into three groups - warmer, similar and cooler backgrounds - and the results were analysed accordingly. As seen in Figure 4, the percentage of people who grew up in the UK and other countries with a similar climate was 63%, while the percentage of those who grew up in countries with climates warmer and cooler than the UK were 31.9% and 5.2%, respectively. In this study, 58% of the participants identified as female, 41% as male and 1% as non-binary. In addition, 60% of the participants were British students, and 40% were international students.

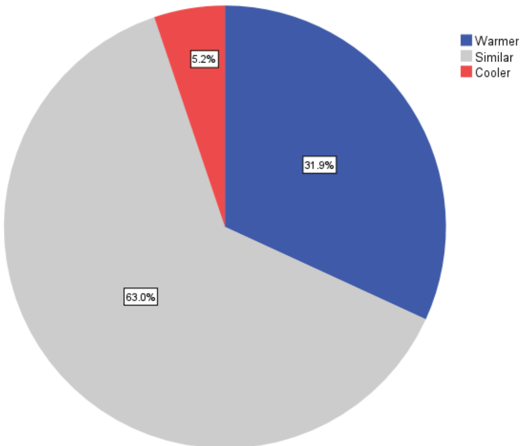


Figure 4. Percentage of climatic backgrounds of respondents

Figure 5 shows the mean indoor and outdoor temperatures when the students participated in the survey between 30th January 2022 and 31st March 2022. The minimum outdoor temperature was 4.5°C, while the maximum value was 16.9°C. The minimum and maximum values of the indoor temperatures were 18. 4°C and 23.0°C respectively. Figure 6 shows the comparison of the indoor temperature with the temperature coming from the ventilation system. In CIBSE Guide A (2015), the comfort temperature specified for computer rooms in winter is 19-21°C, while the comfort temperature specified for library reading rooms is 22-23°C. Although the area where the study was carried out is the library, 19-21°C will be considered for the comfort temperature, since computer use is intense. The indoor temperature was mostly within the specified comfort zone. However, the air temperature from the ventilation supply was below the comfort temperature. In addition, from the comments of the participants at the end of the survey, it was seen that they felt that the air conditioning was on and working in the environment and, therefore, the air was cold.


Figure 5. Mean indoor and outdoor temperatures during the survey

The engineering and contract support manager of the University stated that the fresh air is tempered at 20°C within the ductwork and then distributed to the room through the ceiling grills. He also stated that the fan coil unit tries to keep the room temperature at 21°C ± 2°C by performing both cooling and heating.

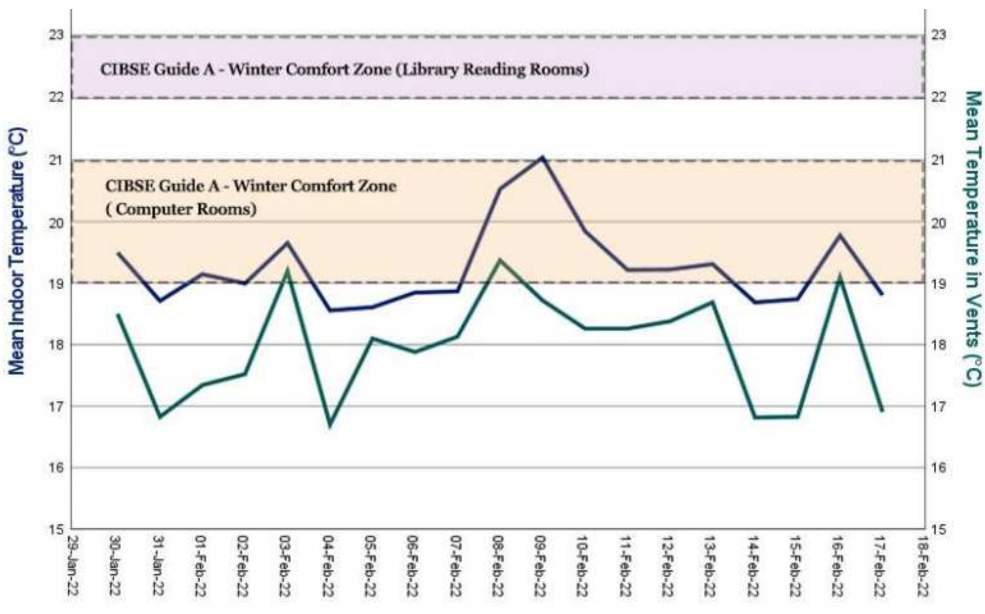


Figure 6. Mean indoor temperature and temperature in vents

Participants were asked to evaluate the air movement in the environment and their responses are compared in Figure 7. Although each group had different percentages within itself, the overall result shows that the majority of students felt *'insufficient'* air movement in the environment. Although the mechanical ventilation system worked at full capacity for 24 hours a day at full speed, and constantly provided fresh air to the environment, it is seen that the students found this situation unsatisfactory. The ventilation system may have been found to be insufficient since the windows were closed during the winter months and there was no ventilation in that part of the computer room.

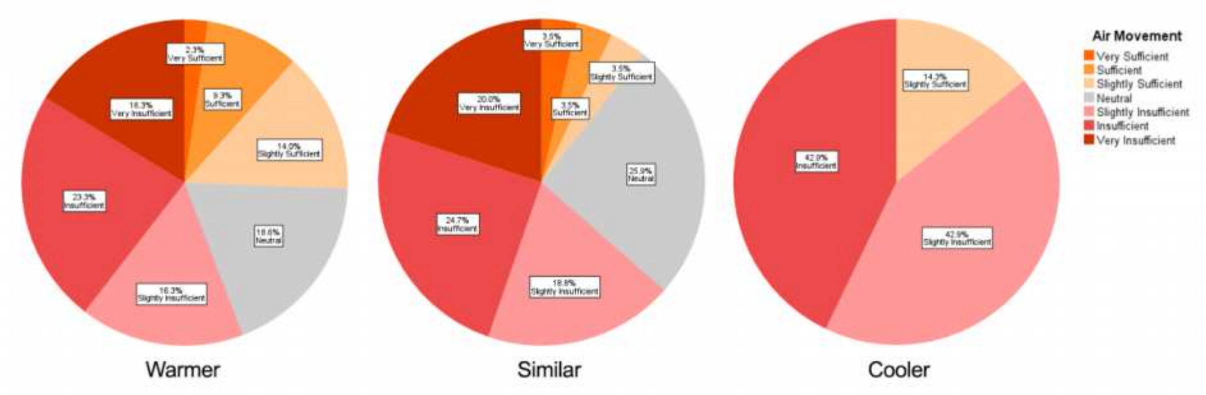


Figure 7. Air movement votes by climatic backgrounds

Figure 8 shows a comparison of the clothing insulation (clo) values of the participants. The mean value for students from a similar background was 1.2clo, while it was 1.4clo for students from a warmer background and 1.7clo for students from a cooler background. While the minimum value is 0.3clo for students from a similar background, it is 0.6clo for the other two groups. The clo value of students from a warmer and cooler background is higher than that of the students from a similar background. The reason for this situation is thought to be cultural differences. International students from 23 different nationalities have different climatic and cultural backgrounds, which may explain why they have different clothing levels.

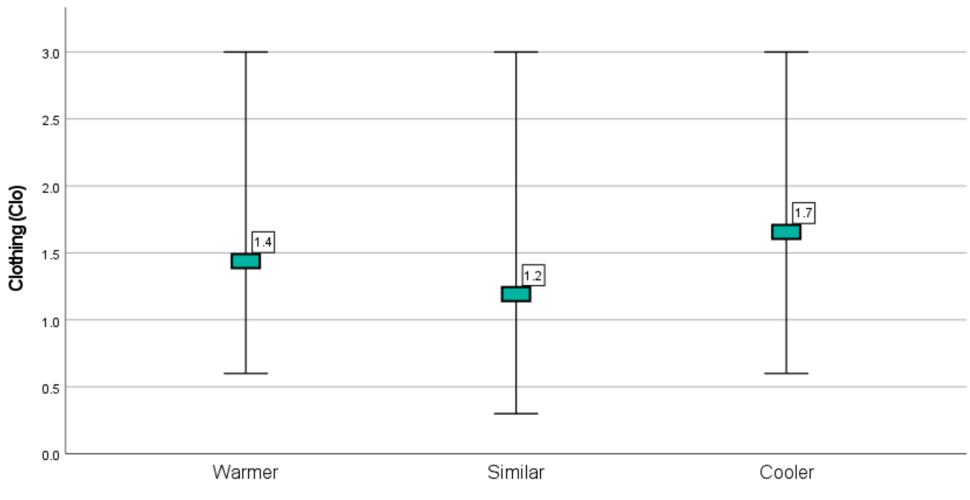


Figure 8. Clothing insulation value by climatic backgrounds

Predicted Mean Vote (PMV) is an index that predicts the mean response from a group of people scoring on a seven-point thermal comfort sensation scale. The CBE Thermal Comfort Tool (Tartarini et al., 2020) was used to calculate PMV for this study. Figure 9 shows the comparison of PMV sensation and thermal sensation by climatic backgrounds. For students from a warmer background, the highest percentage of thermal sensation was *'neutral'* and *'slightly cool'* with 23.3 percent, while the percentage of PMV sensation was *'slightly cool'* at 44.2 percent. Looking at the thermal sensation chart, students from a similar background mostly feel *'slightly cool'* with 28.2 percent, while it is seen that they should feel *'neutral'* with

41.2 percent in the PMV sensation chart. For students from a cooler background, the highest percentage of thermal sensation was *‘slightly cool’*, at 57.1 percent, while the percentage of PMV sensation was *‘neutral’* at 71.4 percent. It is thought that the difference in PMV values between the three groups was due to the difference in the clo value. As a result, the majority of the students in the three groups felt *‘slightly cool’* in terms of thermal sensation, but when the PMV sensation values are assessed, the students from a warmer background felt *‘slightly cool’*, while those in the other two groups felt *‘neutral’*. Figure 10 shows the comparison of thermal preference by climatic backgrounds. The students from a warmer background wanted to feel *‘warmer’*, while those in the other two groups wanted to feel *‘slightly warmer’*. Looking at Figure 9 and Figure 10, the relationship between thermal sensation and preference can be seen. Students who evaluated the environment as *‘slightly cool’* in general wanted it to be a *‘slightly warmer’*.

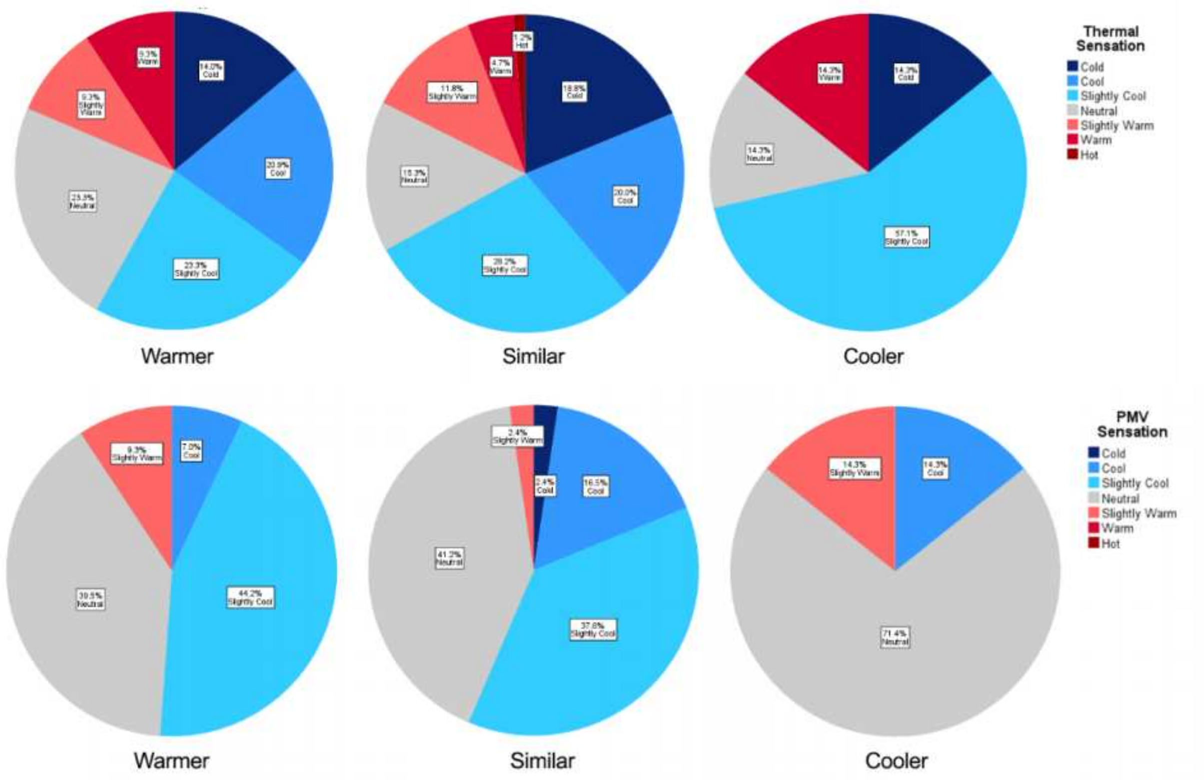


Figure 9. Thermal sensation and PMV sensation by climatic backgrounds

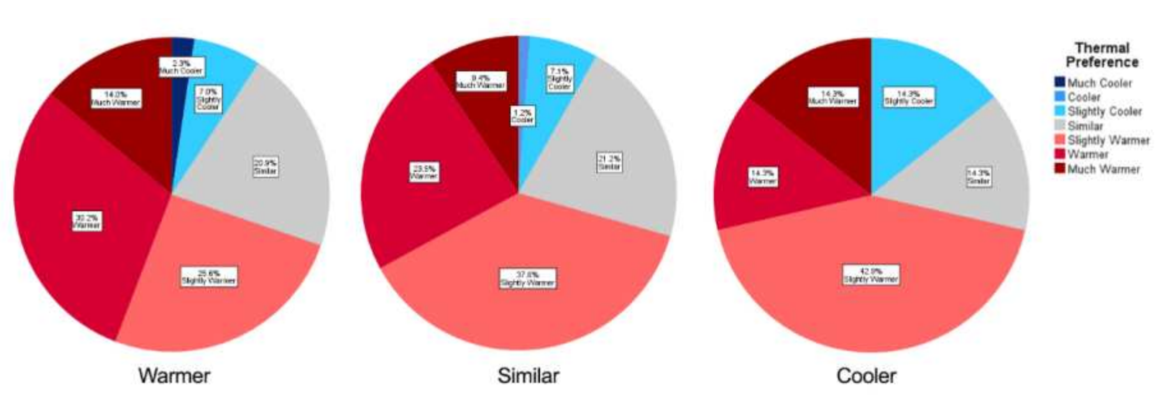


Figure 10. Thermal preference by climatic backgrounds

The overall thermal comfort comparison is given in Figure 11. The majority of students from a warmer background felt *‘comfortable’*, while the majority of students from a similar background felt *‘slightly uncomfortable’* and the majority of students from a colder background felt *‘slightly comfortable’* and *‘neutral’*.

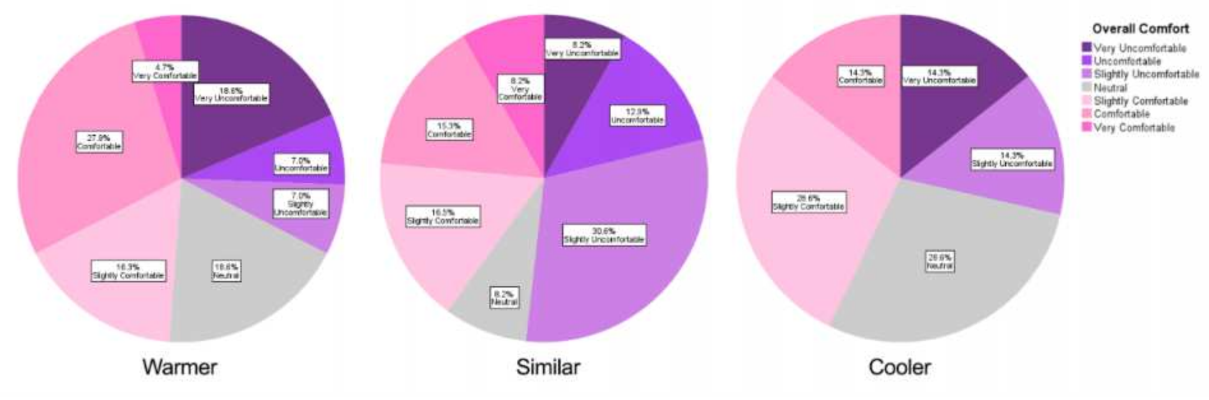


Figure 11. Thermal comfort by climatic backgrounds

## 4. Discussion and Conclusion

It is known that air temperature, ventilation, thermal sensation and level of clothing affect the overall thermal comfort of building users. In addition, other physical and psychological variables also affect comfort. When looking at the effect of cultural and climatic background on comfort examined in this study, the results of thermal sensation and thermal preference in the same environment were similar, while the thermal comfort results were different for students from three different climatic backgrounds. It is thought that this situation is due to the level of clothing. It has been observed that students from warmer and cooler backgrounds wore more clothes than students from a similar background in order to adapt to cultural influences or environmental conditions. However, this situation did not change the thermal sensation of the students about the environment, and the majority of the students in all three groups stated that the environment was slightly cool. Despite the fact that the mechanical ventilation system was working 24/7 at full capacity due to Covid, it is thought that the users' feeling that the ventilation was insufficient was due to the lack of natural ventilation. In addition, it is predicted that users' past experiences and habits regarding environmental control systems also affect their expectations (Auliciems, 1981).

According to HESA data (HESA, 2020), the University of Liverpool was ranked 10th among 131 universities in total energy consumption for the sector in 2019/20. The cooling of ventilation air during winter months for the library space investigated in this study is not an efficient use of energy and also does not consider the different comfort requirements of students from a range of cultural and climatic backgrounds. It is predicted that if the temperature the incoming air from the ventilation system was increased, the cold air effect felt by the students would decrease, and the heating energy required to balance the ambient temperature would also decrease. Such a situation could contribute to a reduction of energy consumption for the University of Liverpool as well as providing a more comfortable environment for students.

A limitation of this work is that the longitudinal study was only carried out using winter data collected between 30$^{th}$ January 2022 and 31$^{st}$ March 2022. It is planned to consider summer data in future studies.

## Acknowledgements

The authors would like to thank the Turkish government and the Republic of Turkey Ministry of National Education for supporting this study.

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# Investigating the effect of indoor environmental quality (IEQ) variables on comfort by a subjective assessment in university classrooms

**Fatema Al-Akhzami[1], Hanan Al-Khatri[1], Saleh Al-Saadi[1], and Hayder Khan[1]**

[1] Department of Civil and Architectural Engineering, College of Engineering, Sultan Qaboos University, Oman, khatri@squ.edu.om

**Abstract:** In buildings, the indoor environmental quality (IEQ) is determined by the collective influence of four factors, namely thermal conditions (TC), visual conditions (VC), acoustical conditions (AcC), and air quality conditions (IAQ). IEQ is an important aspect of the built environment that can positively or negatively affect the health, wellbeing, and productivity of buildings' occupants. Considering classrooms, the association between IEQ conditions and the students' health, comfort, and productivity is well documented. However, there is no clear conclusion regarding the weight of each of the four factors of IEQ on the overall indoor comfort level. The majority of the studies that investigated this issue were reported from the temperate climate. The paper at hand aims to investigate the individual effect of IEQ factors by conducting a subjective assessment in a hot dry climate region. The assessment investigates the opinion of the faculty members of the College of Engineering at Sultan Qaboos University, Oman, regarding the thermal, visual, acoustical, and air quality conditions of the university classrooms. The collected data were analysed using the Analytic Hierarchy Process (AHP) to quantify the weight of each factor on comfort level. The results indicated that TC is the most important factor with a weight of 0.286 followed by VC with a weight of 0.245. The weights of the IAQ and AcC were 0.242 and 0.226, respectively. On a larger scale, quantifying the weight of these four factors guides the architects and engineers to design comfortable and energy-efficient buildings.

**Keywords:** Indoor environmental quality, Weighting schemes, Occupant satisfaction, Analytic Hierarchy Process, Classroom

## 1. Introduction

Indoor environment quality (IEQ) is a holistic term for the combination of factors, namely thermal conditions (TC), visual conditions (VC), acoustical conditions (AcC), and indoor air quality (IAQ) (Yang and Mak, 2020). These factors have a combined effect on the overall comfort and energy consumed in buildings (Catalina and Iordache, 2012). With the increasing interest in IEQ and its influence on occupants' satisfaction and comfort inside buildings, a great focus was invested to allocate a weighting scheme for IEQ by identifying the relative importance of its individual factors (Rohde *et al.*, 2020). The appropriate use of IEQ weighting scheme assists the designers and architects to develop comfortable indoor environments and it enables them to identify the IEQ factors that need urgent interventions in the existing buildings (Leccese *et al.*, 2021). Several previous studies investigated occupants' perception and satisfaction regarding IEQ to propose an IEQ weight scheme for each factor in different buildings such as offices, schools, and residential buildings. Most of the studies were conducted using a questionnaire, which allowed the researchers to determine the occupants' perceptions of the indoor environments (Deme Belafi, Hong and Reith, 2018).

Reviewing the published literature on IEQ rating in educational buildings revealed nine papers that evaluated IEQ factors to propose a weighting scheme (Astolfi and Pellerey, 2008; Cao *et al.*, 2012; Catalina and Iordache, 2012; Lee *et al.*, 2012; Ghita and Catalina, 2015; Buratti *et al.*, 2018; Tahsildoost and Zomorodian, 2018; Yang and Mak, 2020; Leccese *et al.*, 2021). A study conducted by (Leccese *et al.*, 2021) reviewed the previous research on assessing IEQ using a weighting scheme comprehensively. Besides, it proposed a weighting scheme using three questionnaires distributed to university students to assess TC, VC, AcC, and IAQ. The results indicated that TC is the most important factor followed by AcC. IAQ was found to have the lowest relative importance. Another study was conducted by (Yang and Mak, 2020) to investigate the relation between IEQ and indoor factors in a university building in Hong Kong, China, using questionnaires and physical measurements. A weighting scheme was identified for TC, VC, AcC, and IAQ using a fuzzy comprehensive evaluation approach. The study concluded that TC has the highest relative importance, followed by AcC, VC, and IAQ. Buratti and co-workers (Buratti *et al.*, 2018) evaluated IEQ using a questionnaire survey and measurements in university classrooms in Italy. The authors proposed a new IEQ index by calculating three different weights for thermo-hygrometric, visual, and acoustical conditions and, then, combined these weights to identify a single IEQ index. The relative weight of the four factors of IEQ was obtained using a questionnaire created by the authors to investigate the effect of these factors on students' comfort. The results showed that AcC has the highest relative importance while VC is considered the lowest.

In Iran, Tahsildoost and Zomorodian (2018) evaluated IEQ in old, new, and retrofitted educational buildings using a questionnaire and physical measurements aiming to develop an IEQ weighting model. Using Person correlation, the results indicated that TC has the highest weight, followed by VC, AcC, and IAQ, respectively. Similarly, (Ghita and Catalina, 2015) highlighted the relation between IEQ and energy consumption in old, new, and renovated school buildings in Romania. Questionnaires were distributed to the students to evaluate their perceptions of IEQ, and physical measurements were conducted to calculate the IEQ weighting scheme. Then, a comparison between the IEQ weighting scheme and energy consumption in school buildings was conducted.

Using questionnaires and physical measurements, a study was carried out by (Lee *et al.*, 2012) to evaluate IEQ influence on students' performance in university classrooms that were ventilated mechanically. The weighting scheme was evaluated considering the students' acceptance of IEQ conditions. It was found that AcC has the highest relative importance followed by TC. The findings illustrated a strong relationship between IEQ factors and students' votes. Cao et al. (Cao *et al.*, 2012) investigated IEQ conditions in three buildings, including educational buildings, using physical measurements and questionnaires to propose an IEQ model. Another study was conducted by (Astolfi and Pellerey, 2008) to evaluate IEQ factors in an educational building using questionnaires and physical measurements. The weights of the IEQ factors were calculated using Pearson correlation, and the results indicated that TC was considered the highest important factor followed by AcC, whereas the VC was the least important.

Figure 1 summarises the weighting scheme proposed in the reviewed literature. As the figure depicts, thermal conditions receive the highest weight in most studies, followed by acoustical conditions. Although IAQ received little importance in general, it was an important element of IEQ in (Ghita and Catalina, 2015). This is an indication that the contribution of each factor in the indoor conditions is not similar for all climatic regions, and it may depend on the type of the building as well as the context (Tahsildoost and Zomorodian, 2018). Consequently, proposing a weighting scheme for IEQ factors in the hot climate region is required.

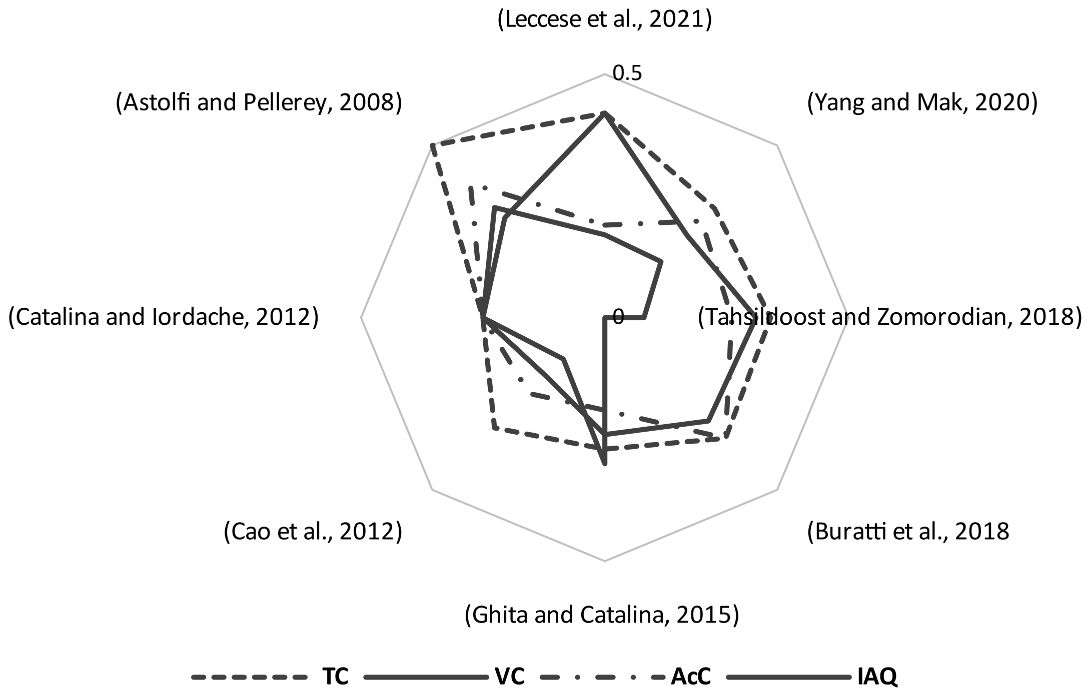


Figure 1. Summary of weighting scheme applied for educational building

Additionally, several papers assessed IEQ in office buildings. A study was conducted in four offices in the UK that evaluated IEQ conditions to identify the relative importance of IEQ parameters using subjective assessment. The weighting values obtained from the analysis indicated that TC has the highest value of 0.20, and VC has the second-highest weighting value of 0.159 (Middlehurst *et al.*, 2018). Frontczak *et al*. (Frontczak *et al.*, 2012) identified IEQ factors that affect occupants' satisfaction in office buildings in the US using a subjective assessment of 7-point scale answers for 15 parameters, including IEQ factors and other building characteristics. The results indicated that AcC is considered the most important among the IEQ factors. Furthermore, (Heinzerling *et al.*, 2013) proposed a new IEQ weighting scheme using subjective assessments of occupants' satisfaction in an office building. The analysis of multivariate linear regression indicated that VC and AcC are ranked as the most important factors compared with TC and IAQ.

Considering studies of IEQ assessment in residential buildings, (Frontczak, Andersen, and Wargocki, 2012) used a questionnaire to evaluate the parameters that affect indoor comfort in Denmark houses. The findings indicated that IAQ has the greatest importance compared to other factors, followed by VC and AcC. In Taiwan, 12 experts assessed the IEQ factors in a residential building to propose an IEQ index. It was found that IAQ ranked as the most important factor and VC had the lowest relative importance (Chiang and Lai, 2002).

The relative importance and rank for each IEQ factor vary in different types of buildings. For instance, the weighting scheme obtained by (Ncube and Riffat, 2012) for office buildings indicated that the weights of TC, VC, AcC, and IAQ were 0.29, 0.16, 0.18, and 0.36, respectively. While, (Chiang and Lai, 2002) computed the IEQ weight scheme for residential buildings. The relative weights were 0.21, 0.16, 0.20, and 0.30 for TC, VC, AcC, and IAQ, respectively. (Tahsildoost and Zomorodian, 2018) evaluated the weighting scheme in a school building. The results showed that the TC, VC, AcC, and IAQ were assigned 0.34, 0.31, 0.26, and 0.08 weighting scores, respectively. These differences emphasise the difficulty of adopting a common IEQ weighting scheme for all types of buildings (Heinzerling *et al.*, 2013; Ghita and Catalina, 2015; Tahsildoost and Zomorodian, 2018).

The research on the IEQ weighting scheme is significant and is still ongoing. Published recently, a comprehensive review of the IEQ weighting scheme included published papers from 2002 to 2018 that covered either three or four IEQ factors. Scopus, Science Direct, Web of Science, and Google Scholar databases were consulted using (Indoor Environmental Quality), (Thermal Environment), (Air Quality), (Acoustics), and (Lighting) keywords (Leccese *et al.*, 2021). To continue this effort, the published literature in the mentioned databases between 2018 and 2022 was reviewed using identical keywords. The search returned 14 studies of which four studies considered three or four factors of IEQ as listed in Table 1.

Table 1. Summary of published papers in IEQ weighting scheme from 2018 to 2022

| Reference | Period of administration | Countries of administration | No. of respondents | Type of building | Mathematical analysis |
|---|---|---|---|---|---|
| (Larsen *et al.*, 2020) | - | Denmark | 67 experts | Residential building | - |
| (Leccese *et al.*, 2021) | 2016 to 2019 | Italy | 945, 458, 65* | University building | Analytical Hierarchy Process (AHP) |
| (Li *et al.*, 2021) | - | China | 405 experts | university open-plan offices | fuzzy analytic hierarchy process (FAHP) method |
| (Yang and Mak, 2020) | 2018 to 2019 | China | 224 | University building | Combined fuzzy comprehensive evaluation (FCE) and AHP |

*For the first, second, and third questionnaires, respectively

A new tool for IEQ assessment in residential buildings was developed to evaluate the effect of IEQ conditions on occupants. The researchers evaluated 16 parameters of IEQ factors to find out that AcC was the most important factor followed by IAQ, whereas TC was found to be the least important factor (Larsen *et al.*, 2020). Additionally, 405 experts ranked IEQ factors in an open office in a university building in a cold climatic region. The analysis used to compute the weighting scheme is the fuzzy analytic hierarchy process (FAHP) approach. The results indicated that TC is the most important factor followed by AcC. Another phase of the assessment was carried out using physical measurements and subjective assessments. Then, a unified IEQ index was developed by calculating the average from the two obtained schemes (Li *et al.*, 2021).

The reviewed studies used different mathematical analysis approaches to determine the weighting scheme. Some of these studies adopted Analytical Hierarchy Process (AHP) to allocate relative importance for each factor and resulted in an overall IEQ index. Specifically, (Chiang and Lai, 2002; Lai and Yik, 2009; Kamaruzzaman *et al.*, 2018; Middlehurst *et al.*, 2018; Rohde *et al.*, 2020; Yang and Mak, 2020; Leccese *et al.*, 2021) adopted this approach. Besides, different studies involved experts as the decision-maker in the assessments with relatively small numbers, namely (Chiang and Lai, 2002; Rohde *et al.*, 2020).

It is noticeable that all reviewed papers were reported from a moderate climate and no published paper proposed an IEQ weighting scheme in a hot climate. Because of the climate conditions, building context, and cultural preference variation, it is important to propose a new IEQ index for buildings in hot climate regions, especially for educational buildings where the students spend most of their time in the classrooms. Currently, no regulation addresses the assessment of IEQ in classrooms in Oman despite the importance of this topic as well as its usefulness in enhancing the design of indoor buildings and assisting designers and architects in making decisions about building design. The present paper aims to investigate the relative importance of thermal, visual, acoustic, and indoor air quality in university classrooms in a hot climate depending on the opinion of a number of experts.

## 2. Methodology

The study used a questionnaire to propose a weighting scheme for thermal, visual, acoustical, and indoor air quality conditions in a hot climate region. The assessment of IEQ factors involved the judgement of 50 experts from Sultan Qaboos University (SQU), Oman. The experts were selected according to their specialisation in engineering and based on their teaching experience in SQU classrooms. The questionnaire was designed based on a previous study (Leccese *et al.*, 2021), and it was designed to be analysed using Analytical Hierarchy Process (AHP). AHP is an efficient technique for determining the priority of a number of criteria or factors (Middlehurst *et al.*, 2018). The questionnaire consisted of three sections. The first section contained a pairwise comparison matrix between thermal, visual, acoustic, and indoor air quality conditions inside SQU classrooms. In total, six pairwise comparisons were developed and the experts were asked to evaluate the relative importance of the compared factors using a nine-point scale.

In the second section of the questionnaire, the experts were asked to rank thermal, visual, acoustics, and indoor air quality conditions based on their importance in the classroom environment. The scale used for this question is a 1 to 4-point scale, where 1 indicates the highest importance and 4 indicates the lowest importance. Like the first section, the second section of the questionnaire was analysed using AHP. In the third section, the experts were asked about their general satisfaction levels with thermal, visual, acoustics, and indoor air quality conditions in the university classrooms. For this section, a 7 point-scale was adopted, ranging from very satisfied to very dissatisfied.

### 2.1. Mathematical analysis used to identify the IEQ weighting scheme

Analytical Hierarchy Process (AHP) method was developed by (Saaty, 1987) in order to allocate ratio or weighting scale for pairwise comparisons. The main advantage of using AHP is that it allows for effective analysis of complicated decisions and determines the relative importance of criteria as well as expedited decision making by identifying and analysing the collected data (Dalalah, Al-oqla, and Hayajneh, 2010). In addition, AHP divides large problems into smaller factors allowing for pair comparisons. Using AHP can demonstrate and quantify various factors for any problem and provide a framework for structuring and understanding complex problems (Ajay Guru Dev and Senthil Kumar, 2016).

The AHP analysis starts by identifying the goal and the criteria. Next, the pairwise comparison matrix is developed in the form of a questionnaire. The decision-maker assesses the importance of the compared factors according to a predefined scale. For factors with equal importance, the number 1 can be used. The collected data is analysed by calculating the consistency ratio (CR) of the comparison matrix as the ratio between the consistency index (CI) and a random index (RI). The consistency index (CI) is calculated using the equation $CI = (\lambda_{max} - n) / (n - 1)$, where $\lambda_{max}$ is the eigenvector or priority vector. Only matrices with consistency ratios of less than 10% are accepted for computing the relative weights (Moslem *et al.*, 2020; Ahmad and Pirzada, 2014).

For the study at hand, thermal, visual, acoustic, and indoor air quality form the criteria, and investigating the weight of each criterion based on the experts' judgments forms the main goal. The questionnaire was designed to be analysed using AHP. The comparison between the criteria was performed using the nine-point importance scale developed by Satty (2008) as presented in Table 1. This means that the weights allocated to the criteria are according to the qualitative evaluation by the decision-maker (Jung *et al.*, 2013). Besides, the consistency ratio was calculated for each questionnaire, and all questionnaires with CR less than 0.1 were included in the weighting scheme calculations.

Table 2. Importance scale developed by Saaty (Satty, 2008)

| Intensity of importance | Definition |
|---|---|
| 1 | Equal importance |
| 3 | Moderate importance |
| 5 | Strong importance |
| 7 | Very important |
| 9 | Extreme important |

A new flexible AHP analysis approach was proposed by (Alonso and Lamata, 2006) in order to simplify the acceptance and rejection of the pairwise comparison matrix according to its consistency. The approach estimates the random index (RI) value using an equation for acceptance or rejection, which is simpler than the Saaty approach. Considering the study at hand, the calculated random index (RI) was 6.7283.

## 3. Results and Discussion

### 3.1. Weighting scheme of section 1

A total of 75 questionnaires were distributed. The received questionnaires were 53, of which 94.3% were valid and included in the analysis. The experts involved in the study are familiar with the indoor conditions of SQU classrooms and their evaluations of the pairwise matrix are depicted in Figure 2. As observed, the majority of the experts considered each two compared factors as equal giving a score of 1.

Compared with the other factors, TC got the highest scores. For instance, 1, 7, 7, and 5 experts considered TC as (extreme important), (very important), (strong important), and (moderate important), respectively, compared with 2, 1, 4, and 2 votes for IAQ in the corresponding levels of importance. Likewise, 21 experts considered TC more important than VC compared with 13 for the opposite. Besides, it is noticed that AcC was ranked with lower importance levels compared with the other three parameters.

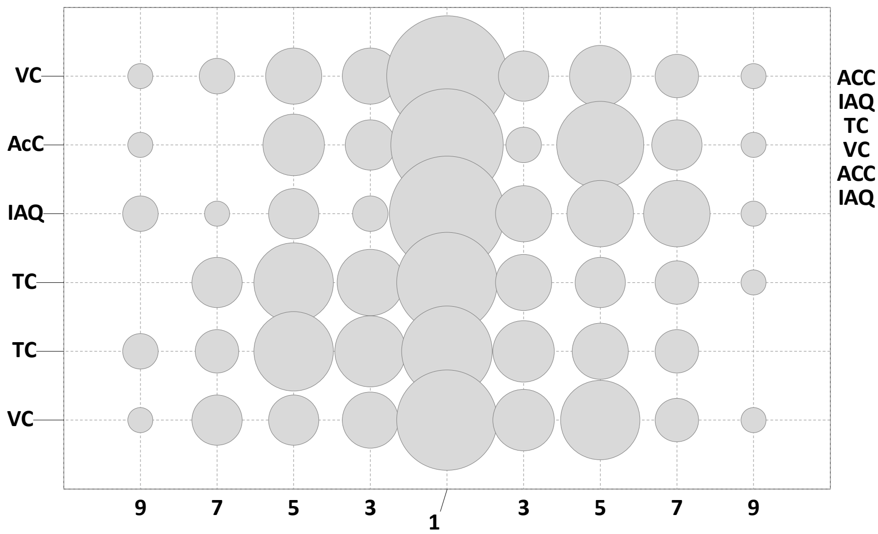


Figure 2. Matrix bubble chart of the expert's answers to question 1 (Labels are numbers of answers)

The AHP analysis method was carried out in order to rate and determine the weights of each parameter according to the pairwise comparison matrix. To ensure consistency, CR of each matrix was calculated and those that were lower than 0.1 were included in the analysis, as recommended by Saaty. Out of 53 questionnaires, 36% were valid for analysis. The relative weights of the IEQ factors are presented in Figure 3 (a). It is observed that TC has the highest relative weight of 0.277. The VC and AcC achieved 0.251 and 0.247, respectively, and IAQ has the lowest weight value of 0.225.

The AHP analysis was performed again using the relaxed approach of (Alonso and Lamata, 2006). In this approach, all questionnaires with an RI of less than 6.728 were included in the analysis. Accordingly, 94% of the returned 53 questionnaires were involved. The relative weights of each parameter were estimated as shown in Figure 3 (b). The weights obtained from the second method illustrated that TC was considered the highest relative important factor with a weight of 0.310, followed by IAQ with 0.260. VC and AcC ranked third and fourth with an inconsiderable difference in their weight values, which were 0.219 and 0.211, respectively.

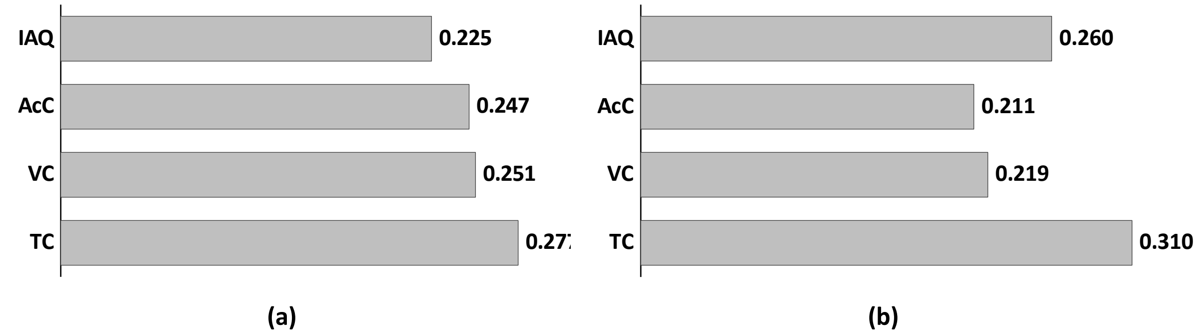


Figure 3. Relative importance of each parameter (a) Saaty method and (b) relaxed method

Based on the results of section 1, using different analysis approaches revealed differences in ranking and weights of the factors. Yet, both analysis approaches revealed that TC has the highest relative importance, which is in agreement with the findings of several studies conducted in educational buildings (Astolfi and Pellerey, 2008; Cao *et al.*, 2012; Buratti *et al.*, 2018; Tahsildoost and Zomorodian, 2018; Yang and Mak, 2020; Leccese *et al.*, 2021).

### 3.2. Weighting scheme of question 2

The data obtained from the questionnaire in section 2 were analysed using both approaches to determine the weight of each factor. Figure 4 presents the average relative weights of section 2 for TC, VC, AcC, and IAQ. For this section, the evaluations depended on ordering the factors from 1 to 4, where the lower sum score obtained from all questionnaires represents the most important factor. AHP was adopted to compute the relative importance of each factor using Saaty and relaxed analysis approaches. The consistency of the matrix was calculated, and the results showed that CR was less than 0.1. Accordingly, all questionnaires were included in the analysis. The results showed that TC ranked the highest relative importance with 0.271, followed by VC with a slightly lower weight of 0.265. IAQ is considered the third important factor with a weight value of 0.243 and AcC is considered the least important factor with a 0.221 value. It is worth mentioning that using the second approach for analysis resulted in identical weight values.

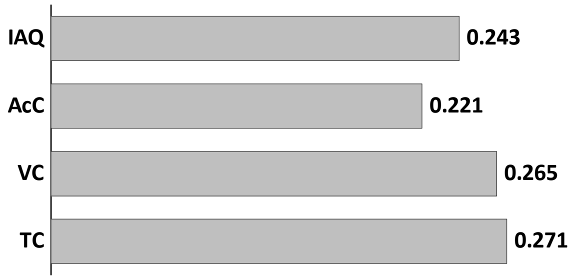


Figure 4. Weight scheme obtained from section 2 for Saaty and relaxed approaches

### 3.3. Comparing results obtained from the two sections

The previous discussion resulted in three IEQ weighting models using two questions and two analysis approaches as shown in Figure 5. It is observed that TC is the most important criterion in section 1 using Saaty approach and in section 2 with almost similar weights ranging between 0.277 and 0.271. VC ranks the second most important IEQ criteria with a slight variance of weighting value ranging from 0.251 to 0.265. A similar pattern of relative importance does not exist for AcC and IAQ. In section 1, AcC ranks as the third important criteria and ranks the fourth in section 2 with a considerable variance of weighting model fluctuating between 0.247 and 0.221. Moreover, IAQ in section 1 ranked as the least important criteria, while it was considered the third most important criterion in section 2, with weights fluctuating between 0.225 and 0.243.

Considering section 1 analysis using the relaxed approach and question 2, TC is still judged as the highest important factor. IAQ was considered the second and third important factor with relative weights of 0.260 and 0.243 based on the relaxed approach and question 2, respectively. VC weight values in both sections have considerable differences ranging from 0.219 to 0.265 and become the third important factor in question 1 while considered the second important factor in section 2. In both sections, AcC is considered the least important factor with the same weight value of 0.221.

A unified weighting model for IEQ in classrooms in the hot climate can be determined from the average of the two sections. Doing so resulted in the weighting values of 0.286 for TC, 0.245 for VC, 0.242 for IAQ, and 0.226 for AcC. From the results, it can be concluded that TC is has the comparatively strongest influence on IEQ in classrooms followed by VC.

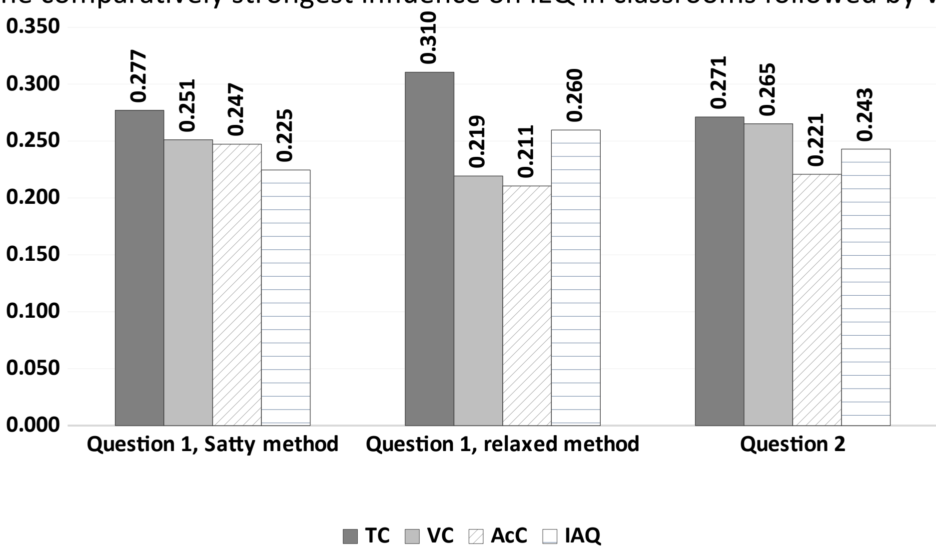


Figure 5. Weighting models obtained from the questionnaire

### 3.4. Comparing the judgement of Civil and architecture experts with other experts

Applying Saaty approach, a comparison between the judgments of 11 experts from the civil and architectural engineering department (CAED) and other engineering experts was conducted to investigate the relationship between their opinions in the first question. Figure 6 indicates the weighting schemes of (a) 11 experts from CAED and (b) other engineering experts using Saaty method. As observed, there is a slight difference between both groups. However, the two groups agreed that TC has the greatest relative importance and IAQ is considered the least important factor. CAED experts ranked VC to be slightly more important than AcC, with respective weights of 0.254 and 0.248, whereas other experts ranked VC and AcC to have the same relative importance with a weight of 0.246 for each one.

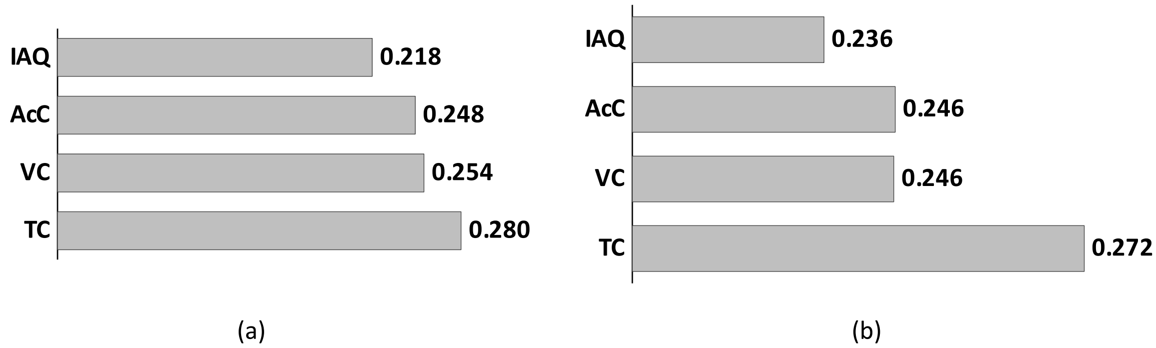


Figure 6. Weighting scheme using Saaty approach of (a) CAED experts and (b) engineering experts

Figure 7 presents the weights values of the two groups of experts considering the first question and using the relaxed approach. The figure illustrates that TC is still evaluated as the highest important factor for both groups. Unlike Saaty approach where it was the least important factor, IAQ is considered the second most important factor for both groups using the relaxed approach.

This variation may be attributed to the different number of experts' evaluations analysed in both approaches. It may also be related to the influence of COVID-19, where more people started to notice IAQ. Moreover, CAED experts ranked AcC to be slightly more important than VC. In contrast, engineering experts ranked VC to be more important than AcC. These results emphasise that the proportion of TC in determining indoor conditions in hot climate regions is higher compared with the other factors. Moreover, VC and IAQ rank to be the second most important factor considering Saaty and the relaxed approach, respectively.

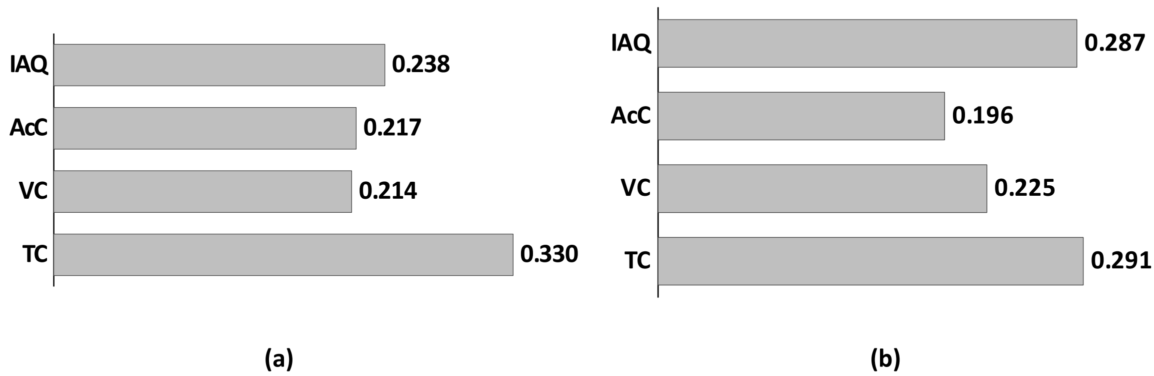


Figure 7. Weighting scheme using the relaxed approach (a) CAED experts (b) engineering experts

Considering the evaluation of question 2, the weighting scheme regarding CAED experts and other engineering experts is illustrated in Figure 8. Noteworthy, the evaluation of question 1 for both groups using both analysis methods reveal the same weighting scheme. Contrary to expectation, the analysis of CAED experts indicates VC ranks as the most important factor with 0.272. followed by TC, IAQ, and AcC with 0.262, 0.244, and 0.222 receptively. On the other hand, engineering experts rank TC as the highest important factor 0.280 followed by VC with 0.254. Whereas, IAQ ranked the third relatively important factor with 0.250 followed by AcC at 0.216. A possible explanation for weighting scheme variation of CAED experts is the limited number of the experts group. Furthermore, the method used for analysis may be attributed to the rank reversal that occurs when using AHP.

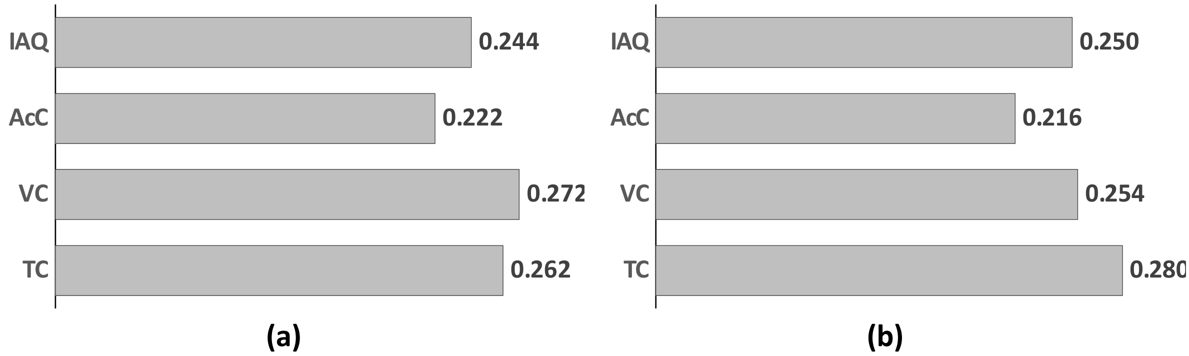


Figure 8. Weighting scheme of question 2 (a) CAED experts (b) engineering experts

### 3.5. Satisfaction of IEQ criteria

Considering their experience with SQU classrooms, the experts were asked to rate their satisfaction with the thermal, visual, acoustical, and indoor air quality conditions. From the results illustrated in Figure 9, most of the experts were satisfied with the indoor conditions of classrooms (i.e. very satisfied, satisfied, and slightly satisfied). Among the four factors, VC is the most satisfying condition in classrooms, with a total percentage of 92%. On the other hand, 8% were dissatisfied with VC in classrooms. For thermal conditions, 82% of the experts were satisfied, while 18% were dissatisfied. Considering AcC and IAQ, the percentages of dissatisfaction were 16% and 12%, respectively. Besides, 84% and 88% of the experts were satisfied with AcC and IAQ in classrooms, respectively. Overall, the IEQ conditions of SQU classrooms are satisfactory from the experts' point of view.

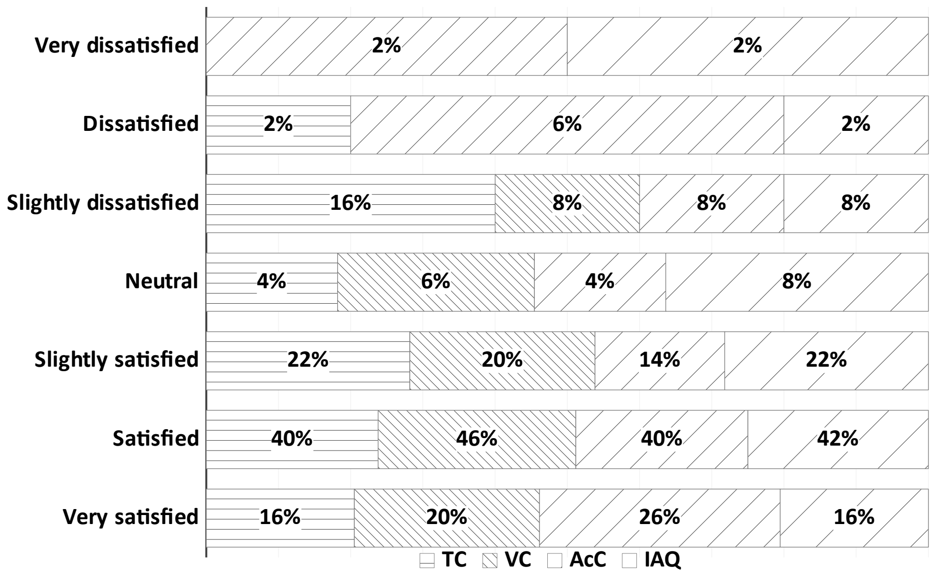


Figure 9. Relative frequency of experts' satisfaction levels regarding TC, VC, AcC, and IAQ

## 4. Conclusion

In general, indoor environmental quality (IEQ) is determined by four factors, namely thermal conditions (TC), visual conditions (VC), acoustical conditions (AcC), and indoor air quality (IAQ). Previous research proposed different weighting schemes for these four factors in different buildings under different climatic conditions except for hot climate regions. The present study proposed an original weighting scheme for university classrooms under hot climate conditions. More than fifty experts were involved in this study to rank the relative importance of IEQ factors. Applying AHP, the results indicated that TC ranks among the most important factors with 0.286, followed by VC with 0.245. IAQ and AcC weighted 0.242 and 0.226, respectively. Moreover, IEQ conditions in SQU classrooms were generally satisfactory for the experts. The highest level of satisfaction was achieved at 92% for VC followed by 88%, 84%, and 82% for IAQ, AcC, and TC, respectively. It is interesting to note that TC was the least satisfying factor for the experts despite the comparatively higher rank they gave it. This may be attributed to the harsh climatic conditions in Oman. This may call for further attention to the thermal conditions in SQU classrooms.

The importance of this study stems from the influence of IEQ on the health, well-being, and productivity of the occupants. Therefore, allocating an IEQ weighting scheme is extremely important, especially in hot dry climates because of the absence of such a scheme. It is hoped that the weighting of these four factors guides the architects and engineers when designing comfortable and energy-efficient buildings. Moreover, as a message for the designer, the results of this study imply that they should give priority to TC design since it is the dominant factor in IEQ according to experts' decisions. A further investigation involving students as decision-makers is recommended since students spend most of their time inside classrooms.

The selection of Saaty's Eigenvector method was based on its popularity among researchers despite the presence of more superior, yet not that popular, methods (Yuen, 2009). This selection subjects the findings to the possibility of rank reversal presence. Rank reversals is the possible reverse in the ranking due to adding or removing an alternative. Yet, it should be mentioned that this phenomenon is not limited to the applied method in this paper; rather, it is applicable to other decision-making approaches. Another limitation of the current study evolves from the fact that the consulted experts belong to one educational institution and, therefore, are subjected to similar climatic and cultural influences. Such influences possibly affected their evaluation of the four aspects of IEQ. Nevertheless, the findings of this study are useful considering the lack of similar studies from the hot dry climatic regions.

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# Comfort in Antarctic Bases: Design Lessons from the Extreme Cold

**Susan Roaf[1], Manuel Correia Gueddes[2], Gonçalo Araújo [2] and Paula Sassi[3]**

[1] Institute of Sustainable Building Design, Heriot Watt University, s.roaf@hw.ac.uk
[2] IST, Instituto Superior Técnico, University of Lisbon
[3] Sow Space Architects, Oxford

**Abstract:** In 2020 a short study was undertaken of the thermal performance of the Chilean research base, Julio Escudero, on King George Island, Antarctica. The aim of the study was to use a range of interrogation methods to understand how this building performed in an extremely cold climate. A walk-around and comfort survey recorded its use and functions, and perceived comfort in it. Measured temperatures shed light on the thermal interactions between climate, building and occupants. A thermal imaging survey highlighted the different ways in which cold penetrated the structures and spaces of the building. This study emphasised the need for designers from warmer climates to understand that the thermal pathways of heat and cold through the building in extreme climates can often produce counter-intuitive thermal landscapes indoors. A vernacular example of a 'cold building' is used to emphasise that design lessons for extreme climates may be in front of our faces, but due to lack of experience in such climates we do not absorb them. A re-design of the base is proposed. Further studies of Polar bases are needed to explore such lessons and to enable all designers to achieve maximum comfort, with minimum energy use both in extremely cold climates, and for emerging freak cold weather events elsewhere.

**Keywords:** Cold, Building, Design, Antarctica, Comfort, Thermal Landscapes

## 1. Introduction

Antarctica has the coldest climate on the planet with the lowest natural temperature ever recorded of −89.2 °C (−128.6 °F) was at the Vostok Station in Antarctica on 21 July 1983. In a world of ever more extreme weather trends and events, experience has taught us that a good way to understand how to design for unfamiliar climates is to understand how existing local buildings in those climates co-evolved with the local behavioural cultures of their occupants to provide acceptable indoor comfort. In 2019 ProPolar, the Portuguese Polar Programme (http://www.propolar.org/) supported a team of three architects to erect an experimental temporary shelter on King George Island, Antarctica in January 2019. Manuel Correia Guedes, Susan Roaf and Joao Pinelo Silva put together the Polar Lodge2 on site. It had been designed and built in the UK, based on the design of a traditional Mongolian Yurt (Roaf et al., 2019a), with innovative materials and triple skin envelope (Roaf et al., 2019b; Roaf et al., 2019c).

As well as the extremely cold winter temperatures, the tent site adjacent to the beach beneath Collins Glacier is exposed to very high wind speeds that resulted in the blowing over and away of a previous trial yurt in 2016 (Cantuária, et al., 2017). Many lessons were learnt through that experience and from subsequent simulation exercises on the impact of wind flow around the tent and site (Pinelo et al., 2019), the structure under duress (Guedes et al., 2019a) and the thermal performance of the tent (Guedes et al., 2019b). Lessons learnt were about the door orientation to avoid direct wind and leeward snow drifts, and the angle of the guy ropes that changed from the original $45^0$ angle from yurt shoulder to the ground, to being tied tight against the tent walls to avoid reverberations in high winds. The study of historic bases in Antarctica led the team to reinforce the structure with an external rock wall built to break the impact of the strong south easterly prevailing wind during extreme weather.

These three upgrades to the design were made in Escudero and on the site based on sense, science and experience. A team returned to the site in 2020 to find that the tent was largely as left the year before, showing that the mixed mode approach of theory and practice used in the design process had worked well in creating an extremely hardy temporary structure. It highlighted the importance of including locally appropriate vernacular understandings of design constraints when building at the extremes, as in Table 1. Simulation is only useful at certain stages of the process that involves a great deal of thoughtful design and expert advice.

| | **THE EXTREME DESIGN PROCESS** |
|---|---|
| 1 | Study the Site and its environs in great depth |
| 2 | Source and study appropriate vernacular archetypes and expertise for information |
| 3 | Design and simulate alternatives to the traditional structure for the proposed site |
| 4 | Explore and lab test innovative material solutions with advice from product experts |
| 5 | Field test structures and materials in an appropriate local test facility |
| 6 | Finalise structural and envelope design with tent makers |
| 7 | Transport and build final design on site and tailor structure to site conditions |
| 8 | Continually measure conditions on site and refine design for local conditions |
| 9 | Monitor structure for a year for strengths and weaknesses to inform next design |

*Table 1. The Extreme Design Process that evolved during the conception and construction of the Polar Lodge2 at Collins Bay on King George Island, Antarctica (Roaf et al. 2020a).*

The need to understand the performance of buildings more deeply in the extreme cold led the Polar Lodge 2 team in 2020 (Guedes, Roaf and Araújo), to append to their field season an in-situ study of the Professor Julio Escudero Base, operated by INACH, The Chilean Antarctic Institute, who hosted the ProPolar Polar Lodge 2 teams over two field seasons while erecting and testing the yurt on site. *The aim of the Escudero Base study was to learn what we did not know about building performance in a very cold climate using four different methods to explore those unknowns, in the spirit of the Extreme Design Process.*

2. **Escudero Base Thermal Performance Study Methodology involved:**
    - Recording the building by walking through, living in, photo'ing and mapping it
    - Logging temperatures in 12 areas to gauge the thermal personality of key areas
    - Thermal Imaging of the structure and occupants to show cold sources, sinks and flows
    - Thermal Comfort Survey to record clothing, activities and thermal perceptions indoors

Results were then analysed, discussed and conclusions drawn.

### 2.1. Recording the building

The Escudero main building is a three story building as shown in the sketch plan in Figure 1. The ground floor level consists of cold storage areas for equipment, outdoor clothing and food stuffs and a wet laboratory and aquarium. The first floor is raised to enable access during periods of extreme snow accumulation and drifting. The main entrance is via an external landing where snow and ice can be scraped off shoes and coats. The tightly fitting external doors lead to a lobby area with coat pegs, boot and shoe racks on three walls and three doors leading to the living room to the left, the sleeping quarters to the right and the stairs to the workspaces above accessed via a hall door. Dry laboratories, dining room and kitchen areas are accessed via the living room, which has a second stair to the top floor accessed via a door.

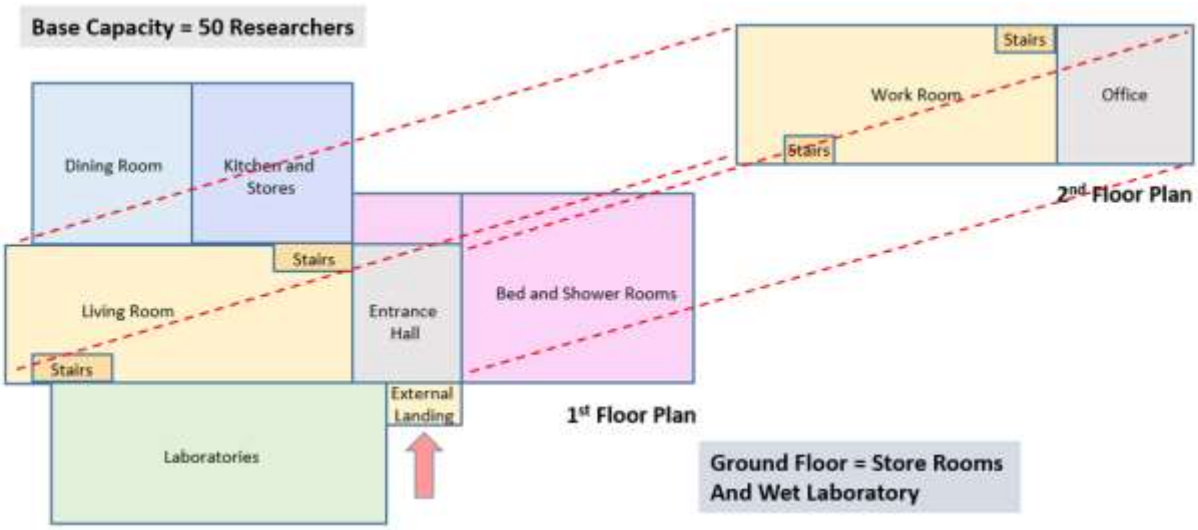
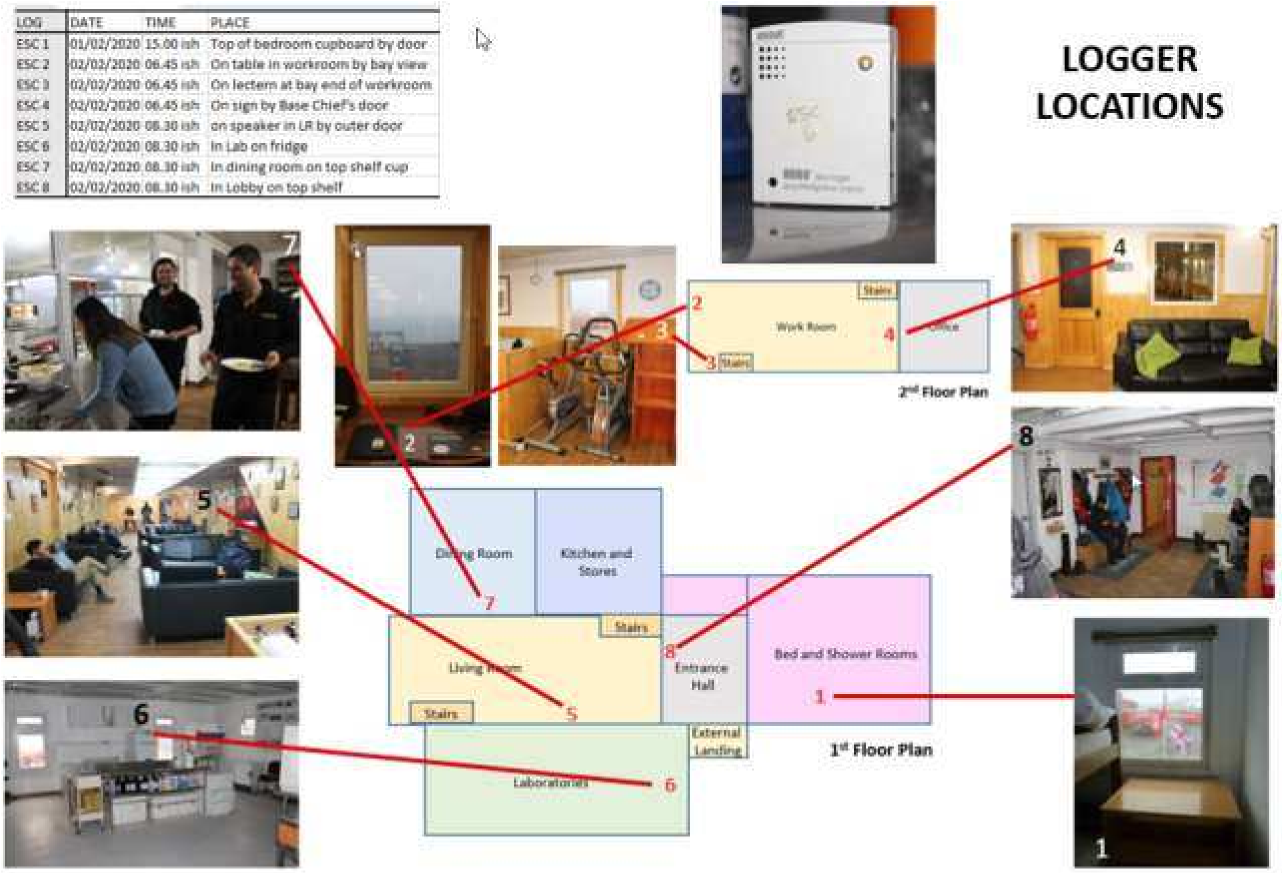



*Figure 1. Sketch floor plan of the first and second floors of the Julio Escudero Base.*

## 2.2. Temperature Logging Study

Eight Hobo data loggers were placed as shown in Figure 2. Logging local temperatures every five minutes over eleven days from the 2nd to the 12th February 2020.



| LOG | DATE | TIME | PLACE |
|---|---|---|---|
| ESC 1 | 01/02/2020 | 15.00 ish | Top of bedroom cupboard by door |
| ESC 2 | 02/02/2020 | 06.45 ish | On table in workroom by bay view |
| ESC 3 | 02/02/2020 | 06.45 ish | On lectern at bay end of workroom |
| ESC 4 | 02/02/2020 | 06.45 ish | On sign by Base Chief's door |
| ESC 5 | 02/02/2020 | 08.30 ish | on speaker in LR by outer door |
| ESC 6 | 02/02/2020 | 08.30 ish | In Lab on fridge |
| ESC 7 | 02/02/2020 | 08.30 ish | In dining room on top shelf cup |
| ESC 8 | 02/02/2020 | 08.30 ish | In Lobby on top shelf |



*Figure 2. Photos and plan of spaces in the base showing where loggers were located.*

## 2.3 Thermal Imaging Study

Thermal Imaging of the structure and occupants to show cold sources, sinks and flows using a SeeK RevealXR thermal imaging camera.

### 2.4 Thermal Comfort Study

A Transverse thermal comfort survey was filled out by 16 participants, roughly a third of the Escudero Base residents, 63% of them being between 20 and 40 years old, 31% between 40 and 60, and 6% over 60 years old. Additionally, 31% were female and 69% Male. 44% of those questioned were overweight while 56% were in the normal BMI range. The Questionnaire asked respondents about their perceptions of temperature, air movement, humidity, lighting, activity levels and use of controls. The clothing section of the usual comfort survey sheet was adjusted for the types of clothing worn on Polar Bases.

## 3. Results of the Escudero Base Study

### 3.2. Temperature Study (See Figures 3. and 4.)

**Bedrooms** with two or four bunk beds were generally unoccupied during the day as shown in Figure 3. High temperatures were recorded during the day of up to 28$^0$C days when small bedroom heaters were left on. Temperatures typically ranged between 15$^0$C and 28$^0$C, rising on getting up and going to bed when heaters were turned on. Humidities ranged between 35% and 70% inversely with room temperatures, peaking at noon with lowest temperatures.

The Logger on the **Workroom / Office Wall** displayed fairly stable temperatures between 15$^0$C-25$^0$C. Temperatures usually declined after midnight when the office and the workroom emptied. The Office has supplementary heating that is turned off when the office is not in use. Humidity was generally stable between 35% and 60%, unlinked to local temperatures, possible reflecting the nearness of a main access route downstairs to the Hall.

**Workroom temperatures** at the S.E. end of the space away from the office, that is normally always occupied after lunch, had temperatures generally within local comfort limits of 15$^0$C-25$^0$C indicating the space is constantly heated. Notably temperatures often drop just before lunch as people deposit equipment and finds there on returning from outdoor pursuits. Humidity ranges from 35%-60%, again with humidity and temperature less predictably linked here with people regularly moving through from the floor below.

The **Laboratory** was being re-furbished during the study with goods moving in and out and the heating turned on and off intermittently with temperatures falling from a high of 26$^0$C to 12$^0$C, indicating that temperatures fall fast and far when the heating is off.

The **Dining Room** is open to residents only during meal times during weekdays, and locked between them. Temperatures within local comfort limits (15$^0$C-25$^0$C) throughout, except during the day before the crew departure when it drops to 10$^0$C during a major cleaning exercise. It is the habit every few days for complete cleaning of the Dining, Living and Work rooms in sequence with workers moving from spaces where the floors were swept with all the windows thrown wide open to refresh the air in summer. Windows were shut after sweeping or when wiped floors dried and the cleaner moved onto the next space.

There is an abrupt dip in temperatures as people who have been outdoors return to queue by the Dining Room door in the Living Room that is unlocked to allow them in before lunch. They bring with them the considerable cold from outdoors still in and on their bodies despite leaving outdoor clothes hanging back in the Hall. They then shed this cold as they eat a hot lunch, in close proximity to each other over the half hour or so there. NB: This does not happen at supper time after people often work indoors in the afternoon before eating supper, nor at breakfast when they emerge warm from their sleeping quarters. We have coined the term *Carried Cold* for that brought in from outdoors before lunch.

Unfortunately, the **Hall** loggers was left behind so readings from there are missing.

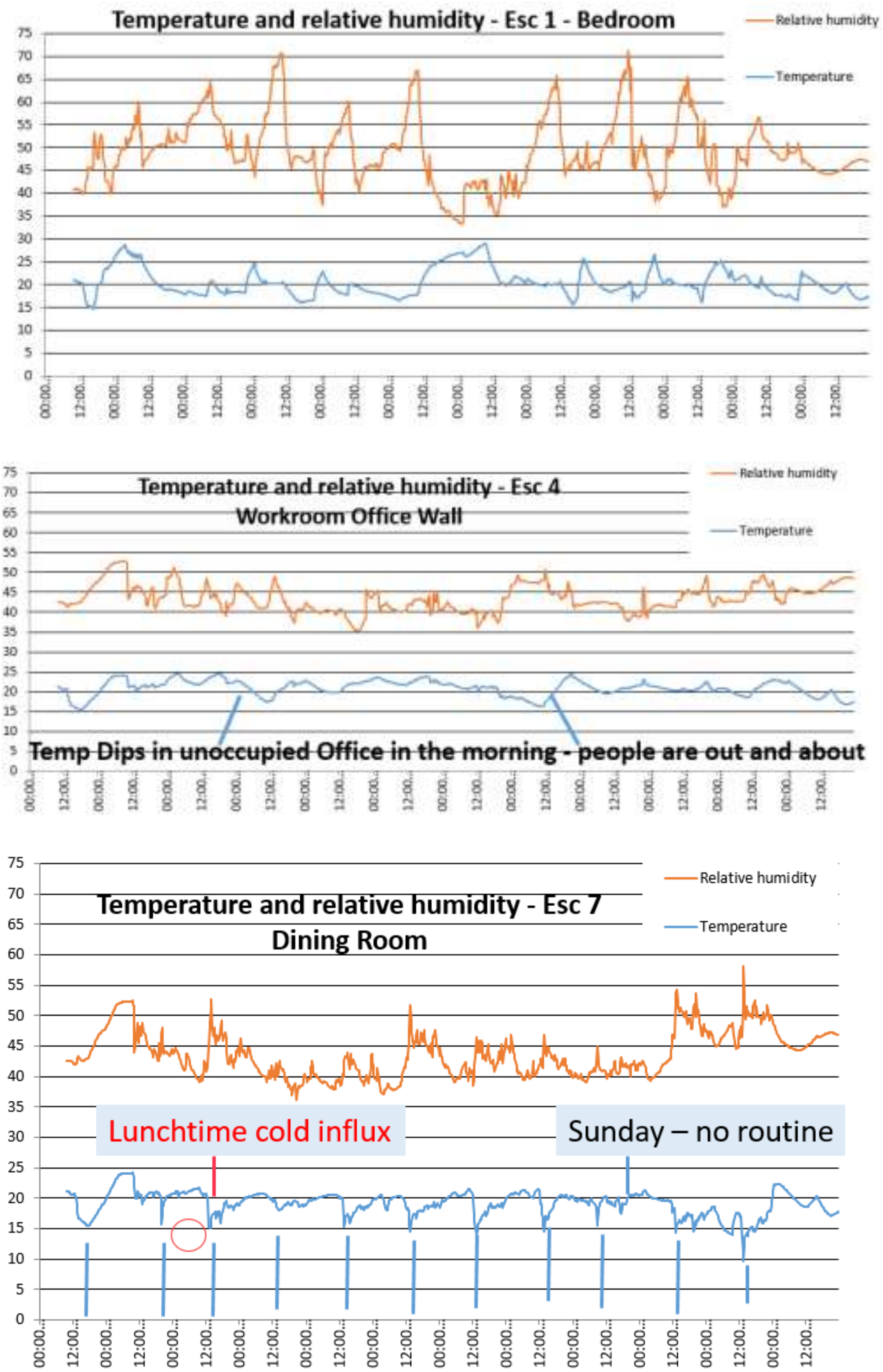



*Figure 3. Temperatures and Humidity data from loggers in a) a bedroom, b) the workspace / office wall and c) The dining room of Escudero Base from 2nd to the 12th February 2020 (Source: P.Sassi)*

Most noticeable is that regular pre-lunch drop in temperatures seen in the well-used Living Room where temperatures otherwise generally stay within local comfort limits ($13^0$C-$22^0$C). Humidity rises and falls inversely with the temperature between 36%-51% RH. Recreational parties also help raise the temperatures in the Living Room, as do ping-pong sessions.

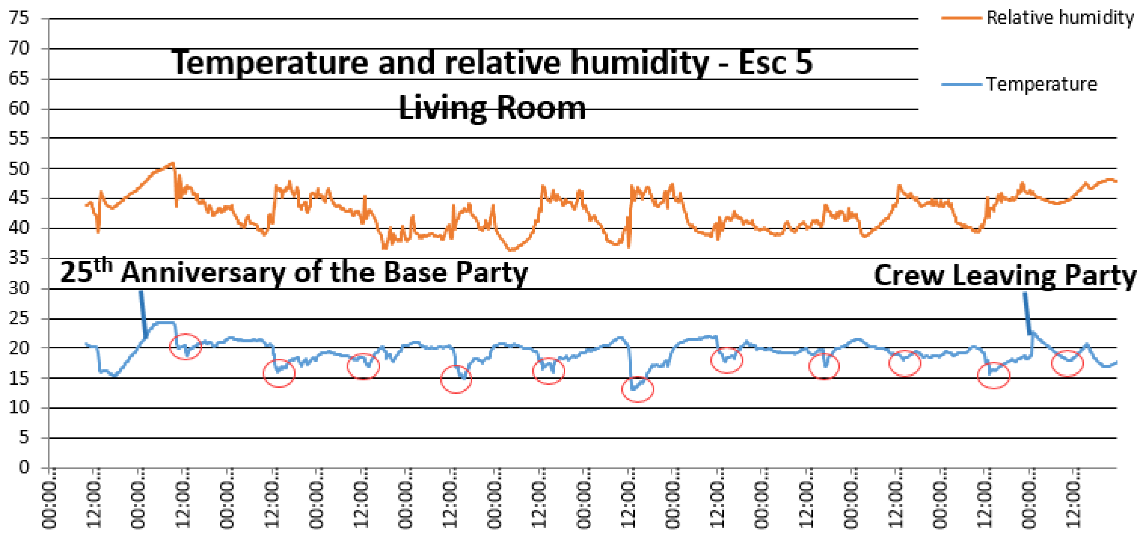



*Figure 4. Tell Tale Temperatures and Humidity data from the logger 5 in the Living Room that links the Entrance Hall to laboratory and the works space and office above.*

### 3.3 Thermal Imaging Study

Thermal imaging was useful to confirm a number of our assumptions and to identify other things we did not, until then know.  The obvious features involved cold bridging (b and d), heat from c) lights and a) waste of heat from rising hot air above heaters. The lights installed in the ceiling could be replaced by down lighters with more desktop work lamps provided.

What did become clear is e) the strength of the cold air inversion that develops at the foot of the stairs down from the workroom when the lower door is shut.  When that door is opened the cold spills down and the heat from the room below will rise into the workroom.

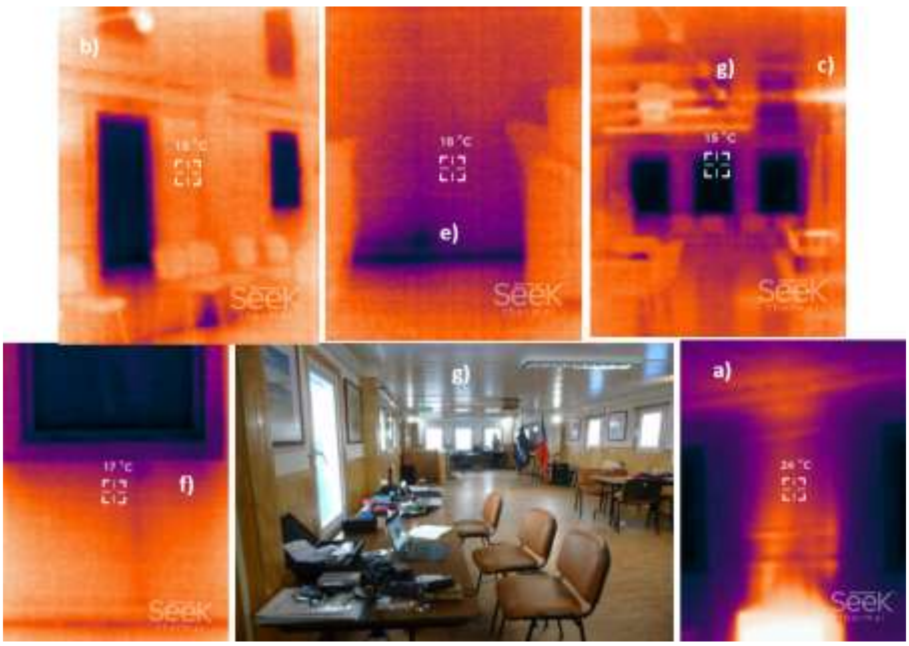



*Figure 5. Thermal images taken around the Workroom showing: a) Heat lost upwards and pools under ceiling; b) Cold leakage between Floors via vertical ducts behind the chairs; c) Lights also put heat into space; d) Cold bridging occurs around the windows in the outer walls; e) Strong cold air inversion accumulates at the base of the staircase when the lower door to the floor below is shut and f) Reflective ceilings bounce heat or cold radiation through the windows deep into the room.*

A number of innovative 'architectural' designs for other more modern Polar bases involve double, and even triple height spaces which might well cause real problems arising from the thermal stratification within those spaces with heat being lost upwards, cooling lower spaces. Another clear and unanticipated effect is that of the reflection of heat or cold radiation in through the windows, deep into the Workroom, as seen in the reflections of the metal ceiling (g). Cold external surfaces, eg. a metal roof below a window or white snow or ice surfaces beneath them can reflect cold indoors as well as direct heat from low angled sun in summer.

A number of recent polar bases even have whole walls of glass that must inevitably be the source of not only direct cold / heat gain but also radiated cold from adjacent outdoor surfaces. A simple, efficiency measure at Escudero is to put internal blinds on the windows to prevent unwanted radiation. With whole glass walls, especially curved ones, this is impossible.

Thermal images of seated people at an evening meeting in the workroom after supper show the huge range of thermal clothing preferences in residents. In Figure 6 shows one man in light trousers and a T-shirt and yet feeling warm as his posture is open. Another is in heavy trousers and a jumper and still feels cold as his closed posture indicates he is acting to conserve heat. These findings are born out in the following thermal Comfort Survey.


*Figure 6. Thermal images of residents at an evening meeting showing a warm splayed man in T-shirt and light trousers and a second in heavy clothing and crossed arms, and others indicating great thermal variety of experience and perception.*

### 3.3. Thermal Comfort Survey.

As might be expected at a remote research base where people in residence, either working a researchers or support staff, came from very different countries and climates, for differing lengths of time from two weeks to twelve months, people were thus **more or less adapted to the local climate and conditions**. Year round residents were noticeably more hardy.

The **level of activity** recorded for the participants right before taking the survey, showed that 50% of the participants have been *Sitting Passively* for at least half an hour, while 30% had been *Walking* outdoors.

The **air movement** in the living and work areas was characterised by 50% of people as having **Low Air Movement** by with the remaining 50% is split between *Slightly Low, Neutral*, and *Very Low*. 50% of those surveyed would have preferred slightly more air movement around them, 37% are neutral and 13% would have liked a little less ventilation. Draughts are the enemy of comfort in the cold. Next time such a study is done $CO_2$ must also be measured.

**Humidity** appeared to be an issue with 44% reporting no problems, 56% feeling the air to be *Slightly Dry, Dry, or Slightly Humid*. In the humidity preferences question 56% claimed to be *Neutral,* 19% still felt that it could be *Slightly Drier, and 25% Slightly More Humid.* Humidity is notoriously difficult to sense and evaluate by people.

Perception of **lighting levels** seemed also to divide people. 44% perceived illuminance *Neutrally* in their working environment, while 19% found it to be Bright, 19% found it *Slightly Bright*, and 12%, and 6% found it to be *Slightly Dim and Dim* respectively. This data indicates that either the lighting varied according with the participant's work environment or they are showing different sensitivity to lighting levels. 44% preferred *No Change* in lighting, 25% would prefer it *Slightly Brighter*, 25% *Slightly Dimmer* and 6% *Much Brighter.*

**Noise** again divided opinions. 25% found the noise in their work environment to be *Normal and Not Disruptive*. However, 25% found it *Very Noisy*, while 19% found it *Slightly Noisy.* The disparity increases with 25% of participants claiming their environments to be *Slightly Quiet, Quiet, and Very Quiet* (sum of parts). 56% of the participants were neutral in their preference, and 25% would have preferred their environment to be Slightly Quieter. Some work environments were quieter than others such as Labs and huts while occupation of all spaces varied considerably according to how many researchers were out in the field.

**Indoor air quality** divided participant's responses equally divided between *Neutral, Slightly Good, and Slightly Bad.* This disparity may relate to participant's working environments, or experiences during working hours the participants have. Some workers were involved in building construction where bad air quality response may have related to paints and materials being used etc. because the walls were being painted in the proximities.

**Thermal** responses also varied greatly. 69% found the indoor temperature to be *Warm.* There were outliers for both Cold and Hot situations. 37% claimed to prefer it to be *Slightly Warmer*, while 38% are *Neutral* and 25% would prefer it to be *Slightly Cooler*. No one felt *Extreme Discomfort* or preferred it to be *Much Warmer* or *Much Cooler*.

The **overall comfort** in the base figured well with most people (87%) claiming they were at least *Slightly Comfortable*, of those, 25% reported being *Very Comfortable*. 13% of the sample reported a *Slightly Uncomfortable stay*. Notions of overall comfort may be ambiguous as people's responses to other factors may or may not have affected their responses.

Overall **productivity** was reported to be Slightly Lower than normal, with 69% of the people claiming that they were less productive than in their usual work environment. 13% claimed their productivity was *Much Lower* than normal, while 12% claimed it to be *Normal*, understandable given the unique and exciting surroundings for many in Antarctica.

**In conclusion**, the results reflect a varied and active cohort, from diverse backgrounds.

## 4. Discussions

The Chilean Escudero Base is located on the coldest continent on earth, Antarctica. This short project was undertaken in search of the unknown thermal attributes of a building and its occupants in this extreme habitat.

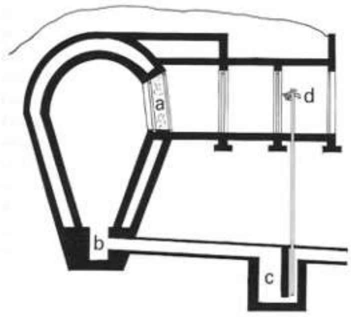
**Possibly predictable findings** from a transient summer population of researchers and support staff from many different backgrounds and climates:

1. People varied widely in their experiences of the thermal environment eg.in clothes worn and reported perceptions of indoor factors as expected from a highly active population.
2. People reported being are largely *Comfortable / Satisfied* with their thermal conditions.
3. The structure has some cold bridging –around windows and wall / floor / duct junctions.

4. Hot air from wall heaters and lights rises to pile up beneath the ceiling away from people.
5. Stairs between floors are associated with significant thermal stratification and movement of heat between floors driven by thermal buoyancy and cold air inversions.
6. Heating is used to heat people not 'the building' and routinely turned off in empty rooms.

**Surprising and Significant findings:**
1. The properties of internal finished make a big different in the distribution of externally sourced heat and cold from the sky and ground reflections. Reflective metal ceilings designed to re-radiate heat downwards also re-radiate cold from outside downwards.
2. People CARRY COLD with them indoors from outside when gathering for lunch at noon, travelling through the living to the dining room charging them with cold.
3. Cold indoors is: *Radiated, Convected, Conducted and Carried* by people through spaces.

**4.1 Learning from the Vernacular: Protecting Thermal Environments**
Ice-houses have been built for at least three millennia to store ice harvested from ponds and lakes in Winter for use in summer when the coolth is needed (Beamon and Roaf, 1989). In order to protect the stored cold over a year many design strategies were developed to keep the heat out. Structures were sunk underground, wrapped in cavity walls, ovoid or conical ice-wells built so ice formed an efficient ball as it shrunk, and sank inside in a ball with minimum surface area. Entrance lobbies or air-locks kept warm air away from the ice, sometimes in as many as four or five room entrances. Conversely, when cold is external and heat is needed indoors, core indoor micro-climates using the principal of successive buffer zones of increasing heat, can reduce them impact of cold people moving through them.




56 In this design of 1833 by Loudon, which supplies iced drinking water in summer, (a) is a vacuity between the inner two doors, which is filled with a cushion of barley straw; (b) is the sump; (c) is a trap in the drain; and (d) is a Siebe's rotary pump used to draw up the iced drinking water

*Figure 7. 1833 Ice-House with 4 doors form the heat outside (Beamon and Roaf, 1990).*

**7. Proposed Re-Design of Escudero Base to Thermally Buffer and Re-Educate**

Buildings in extremely cold climates must use of this powerful idea of *protected thermal environments* with cascading thermal buffer zones to protect more thermal spaces. If starting again at Escudero, a greater emphasis could be put on using spaces as cold dumps, en-route from the cold cloakroom to indoor warmer spaces. After routine dealing with cold bridging in the structure, new materials and finishes can be explored, applied and invented, such as cold absorbing surfaces and high or low emissivity finishes. The material internal blinds are made of could make an enormous difference. New materials at ceiling level might be used above heaters to redirect rising hot air back down radiantly to occupant levels, as they are at Escudero. Lighting could be lowered so heat associated with it is closer to occupants, and more local desk lamps used. Incoming transient research cohorts should be given introductory packs explaining the thermal culture of the Base, and advising them that doors must be kept closed to conserve heat, heaters used only when spaces are occupied, etc.

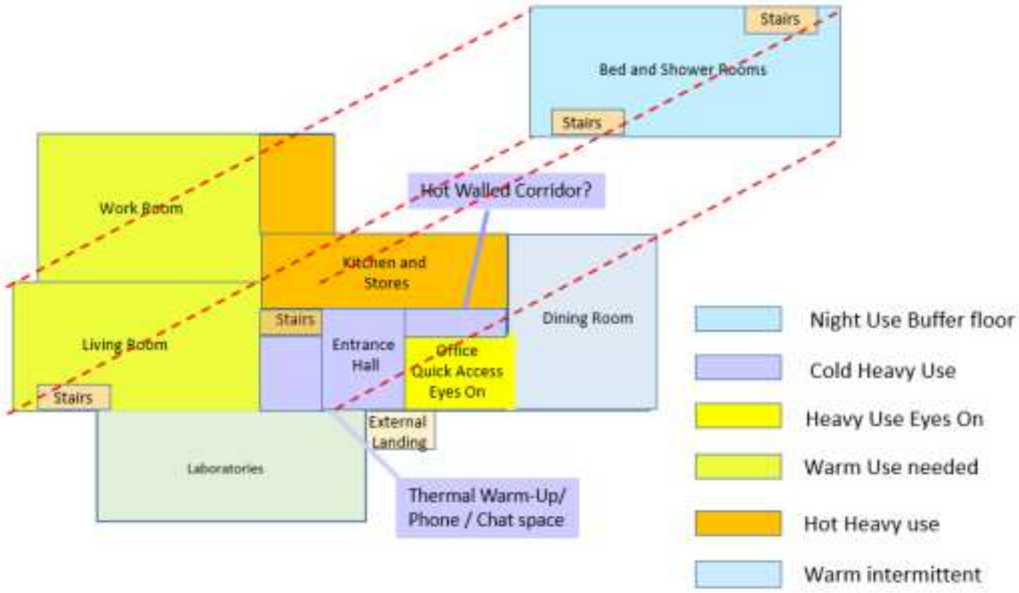



*Figure 8. Proposed redesign of the Escudero base to minimise discharge of heat from living and work area to cold carried by people passing through them from outdoors. Innovation can result eg in cold absorbing wall surface materials in the entrance hall and adjacent spaces.*


**Acknowledgements:**

Our thanks go to the Portuguese ProPolar organisation who facilitated and co-funded this work and to INACH the Chilean Antarctic Research organisation who hosted our team so well.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# Relaxing indoor climate control: lessons from the extreme

**Wouter D. van Marken Lichtenbelt[1], Adam Sellers[1] and Hannah Pallubinsky[1, 2],**

[1] Dept. of Nutrition and Human Movement Sciences, NUTRIM School of Nutrition and Translational Research on Metabolism, Maastricht University, the Netherlands, markenlichtenbelt@maastrichtuniversity.nl;
[2] Research and teaching area Healthy Living Spaces, Institute for Occupational, Social and Environmental Medicine, Faculty of Medicine, University Hospital RWTH Aachen, Germany;

**Abstract:** Research on heat and cold acclimation is more focused on thermo-physiological parameters and less on metabolic health and comfort. Here we summarize the importance of indoor exposure to temperature variations for our health and resilience to more extreme temperatures. Next, we discuss new studies that reveal that repeated exposure to extreme cold also improves our metabolic health.

**Keywords:** Extreme cold, acclimatization, dynamic indoor climate, metabolic health

## Thermal comfort and metabolic health

It is striking how long outdated insights into what constitutes thermal comfort continue to dominate design thinking and tools. In general, our indoor climate is still strictly controlled to those conditions deemed comfortable for a presumed average person. This paradigm stems from the predicted mean vote (PMV) model developed in the last century by Ole Fanger (Fanger, 1970) that can no longer be considered 'Fit for Purpose', and urgently needs to be updated. Ideas of a more adaptive control are not new. The Adaptive Comfort Model was established over forty years ago (Roaf and Nicol, 2022; Nicol and Humphreys, 2002; de Dear and Brager, 1998), and now forms the basis of the European Comfort Standard EN ISO 7730 and the US American ASHRAE standard 55.

Evidence from laboratory and field observations demonstrates clearly that people adapt to climatic, seasonal, and daily variations in temperature and adapted populations can tolerate a wide range of temperatures. The persistence of 20th Century steady model imposing strict control on indoor temperatures, despite these new insights, results from complex drivers. At least in part, it is based on the belief that such a thing as 'average' comfort exists regardless of the person, place or climate outdoors, in growing predominance of the use of technical climate systems to deliver comfort in buildings, and the conservative attitudes and/or lack of awareness of building owners, building managers, installation contractors, and end users themselves of the energy, cost, greenhouse gas emissions, health and discomfort impacts of using narrow temperatures bands indoors. Lack of awareness also of the alternative comfort approaches of the adaptive model that is based on the principal that people adapt to those conditions they normally occupy, and so people in different climates are comfortable at temperatures indoors that relate to the climate outdoors.

At Maastricht University, we focus our studies on the relationship between human physiology and comfort under controlled laboratory conditions. Our research observations and conclusions to date are aligned with the thermal comfort temperatures predicted by the adaptive comfort model. With respect to the PMV model, it should first be noted that the average person does not exist. In our lab and real life living lab (RLLL) studies, we observe again and again a huge variation in how different people experience similar environments, for instance under identical thermal conditions, reporting comfort experiences ranging from *uncomfortable* to *very comfortable,* and from *very uncomfortable* to *comfortable* (Jacquot et al., 2014). We also discovered that in a group of 16 females the neutral ambient temperature ranges (defined by PMV neutral temperature sensation votes from -0.5-0.5) are highly variable and dependent on the individual. The most extreme cases reveal neutral sensations being reported at a very wide range of temperatures from 20-30 °C and 17-25 °C on the one hand, and on the other to a narrow range of between 24-26 °C and 24.5-25.5 °C (Jacquot et al., 2014). These differences can be due to genetics, body composition, sex, age, cultural and habitual differences, and the amount of perceived control.

The level of acclimatization of a person or population depends on the hot and/or cold conditions they occupy and determines their comfort sensations and neutral temperature ranges to a large extent (van der Lans et al., 2013, Pallubinsky et al., 2017). In the past ten years, we mainly focused on mild cold and mild heat conditions and found that both in heat and cold acclimation, significant effects are observed with respect to physiological parameters, such as body temperatures, sweat capacity, metabolic adjustments, and cardio-vascular parameters. Generally, the physiological changes, both in heat and cold responses appeared to have positive effects on metabolic health, not least by keeping related systems active and functioning, avoiding their atrophication (Pallubinsky et al., 2020, Hanssen et al., 2015). Experiments have demonstrated that it is not necessary to be exposed to extreme temperatures: mildly cold and mildly hot environments can already elicit such beneficial health effects.

**Extreme cold**

But what about more extreme conditions? It should be noted that with global warming, not only are heat waves occurring more often, but there is also a marked increase in extreme cold climate phenomena such as snow and ice storms and freezing conditions (Johnson et al., 2018). Such extreme cold weather events have been attributed to Arctic warming in a recent study released in Nature Climate Change suggests (Cohen et al., 2020). These changes could be the cause of the major cold waves that hit North America, from Canada to Northern Mexico, in February 2021. The study also notes that cold spells can actually become more likely with global warming. Thus, while much work has been done on resilience to heat waves, studies linked to extreme cold conditions are also important.

Our studies on mild heat and cold acclimation make clear that the same physiological adjustments take place at both ends of the thermal spectrum, albeit are less pronounced than under more extreme conditions. This means that individuals and populations becoming accustomed to mild temperature variations is an important step to their becoming resilient to more extreme conditions. Though acclimation has been studied under more extreme conditions, not much is known about metabolic health effects of longer term and more extreme regular cold exposure. Most studies have focused on the health risks of acute cold rather than the physiological pathways and impacts of gradual cold acclimation (Mercer, 2003).

Recent studies in more extreme cold environments were conducted to explore issues around metabolic health under such conditions. One study compared the different physiological responses of Western Europeans to those of traditionally Tuvan pastoralists living in a yurt tent in wintertime in Siberia. These nomads provided a unique study opportunity since they live in a region with extreme temperature variation between summer and winter with wintertime environmental temperatures during our study ranging between 32°C to -15°C. Because indoor temperatures in the studied yurt reaching 20°C -30 °C, they are exposed to daily indoor to outdoor variations of temperatures of up to 50°C (Marken Lichtenbelt et al., 2020)!

During the daytime, the participants were exposed to temperatures below 0°C for on average 5 ± 2.2 hours/day. Preliminary results indicate that the Tuvan pastoralists have comparable resting metabolic rate to their matched European counterparts (Sellers et al., in prep.). Interestingly, it was shown for the first time that traditional pastoralists in an extreme cold environment have significantly higher daily metabolic rates than Western people. Their energy expenditure was on average 30 % higher than predicted by body composition, based on studies of Western populations. These high levels can partly be explained by the cold environmental conditions and secondly by their high physical activity level (Sellers et al., submitted). Of further notes was the fact that the Tuvans also show significant cardiovascular adjustments. During standardised cold tests they maintained higher skin temperatures on the fingers, indicating better blood perfusion at the finger.

In summary, the results of the fieldwork showed significant physiological adjustments, including increased metabolic health and resilience to extreme cold conditions in the cold-habituated Tuvan group. Interestingly and surprisingly, it was not possible to obtain relevant information about their thermal comfort. When using the translated standard VAS scales for thermal comfort, they reacted quite surprised and a little shy. They simply were unaware of comfort. Cold is just cold.

In a second series of tests, the effects of acclimation to shivering conditions were studied [publication in prep] in the laboratory and showed that mild cold acclimation improves insulin sensitivity and glucose handling. This is an important finding in view of the large prevalence in modern society of obesity and type 2 diabetes mellitus. Under laboratory conditions, volunteers were exposed to cold that made them shiver for 1 h/d for 10 consecutive days. Several metabolic measures were used such as the oral glucose tolerance test (OGTT), which is a standard test for glucose handling and diagnosing diabetes. The results reveal that repeated cold-induced shivering improved glucose tolerance in a group of overweight and middle-aged volunteers. Interestingly, also their blood pressure was substantially reduced. Thus, also this study supports that more extreme conditions can positively affect out metabolic health.

The conclusion can be drawn that keeping people exposed to a narrow range of temperatures, as is done in many buildings can make individuals more vulnerable, both from the viewpoint of health and in terms of their resilience to more extreme thermal conditions. Does this mean we can just quit controlling indoor temperature? Of course not, but a much more relaxed approach to the control of temperatures indoors, allowing them to drift with the outside conditions may considerably improve their physiological health. Importantly allowing  and enabling the drift of temperatures indoors can significantly reduce building energy consumption as related model calculations have revealed (van et al., 2022) *and* creates a healthier environment. Of course, there are limits. Humans, especially those who are not adapted and acclimatized, need to be protected against extreme cold (Daanen and Van Marken Lichtenbelt, 2016)  The same applies to the heat and measures have to be taken to protect populations against extreme heat waves such as those recently experienced in India, Australia and North America where temperatures in recently years have reached exceptionally over 50 °C.  Finally, in all our studies, the individual variation in both physiology and experience are highly variable. Ways to accommodate the differences between individuals in the same indoor environments also needs to be considered by ensuring that personal control is possible.

The main message from our work to date is that higher temperatures in summer and lower temperatures in winter may be(come) acceptable, a shift that will need to be strategically anticipated and enabled. Less strict control of indoor temperatures must happen from now on, not only to reduce energy consumption in, and emissions from buildings, but also to improve the longer-term resilience of populations. Although technically it is feasible to control indoor temperatures ever more closely our work has shown that so doing may well not improve the health of building occupants not their ability to acclimatize to the heating climate. Research done by the Maastricht team highlights that there in an urgent need to inform designers, architects, building managers, policy makers and users about the multiple benefits of relaxing control of thermal conditions as well as leaving more choice to the users about the comfort conditions they occupy.

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# Occupant Behaviours and Environmental Preferences in Home-Office Environments Versus Conventional Office Environments; Reflections from The Pandemic.

**Barah Rababa[1] and Eleni Ampatzi[2]**

[1] Cardiff University, Welsh School of Architecture, Wales, UK, baraah_hussein@hotmail.com
[2] Cardiff University, Welsh School of Architecture, Wales, UK, ampatzie@cardiff.ac.uk

**Abstract:** This pandemic has changed our work styles and our everyday interactions with the built environment. This paper focuses on differences in thermal comfort perceptions and behaviours between home-based and conventional office settings and discusses the consequences of its findings on domestic energy use in the UK in the context of extreme circumstances and beyond. Data were collected using a web-based questionnaire and online follow-up interviews. The 106 responses to the questionnaire captured the frequency of some adaptive behaviours. The in-depth interviews revealed a wide range and diverse adaptation strategies that people exercise when working from home, while these coping strategies were very limited in conventional offices. Moreover, discussions with energy and built environment experts shed light on the potential implications of working from home. These implications could contribute to raising awareness of people of energy-efficient houses, this could be buying new energy-efficient properties, refurbishing houses, and installing innovative energy-saving measures. The findings of this study indicate that occupants were satisfied with working from home, and the main elements they prefer for a future home office are energy-efficient airtight windows and good ventilation. Participants tended to apply low-cost strategies, related to the heating routine and practices. For example, reducing thermostat temperature or the heating duration. Further research could usefully propose an energy-efficient home office with the technological and personal behaviours and the upgraded standards revealed in this study

**Keywords:** Post-pandemic, built environment, home-office, working from home, energy consumption, thermal comfort, thermal adaptation, heating coping strategies

## 1. Introduction

In 2020, the COVID -19 crisis became a central issue for the world and the pandemic has since changed the way people live, work, and interact (Thapa et al., 2021) (D'alessandro et al., 2020) (Brown, 2020). In response to this pandemic, in March 2020, people in the UK were instructed to stay at home (Menneer et al., 2021), and many companies shifted to home working. According to (Chen et al., 2020), 30% of the population by 2020 had experienced lockdowns and quarantines. Research published in 2021 (Menneer et al., 2021), suggested that homeworking was to continue after the end of lockdowns. Moreover, it has been discussed (Chen et al., 2020) that this pandemic has a recurring risk, and that people might experience more epidemics due to the climate change impacts.

Spending more time indoors requires a higher need for heating, and consequently higher energy bills (Menneer et al., 2021). Therefore, significant changes in the energy and electricity consumption load profiles were observed during lockdowns. For instance, a 30% increase in midday consumption was shown in a study by (Chen et al., 2020) focusing on the UK domestic context.

This paper focuses on UK-based office workers and explores the differences in perceptions and behaviours influencing thermal comfort in their home-office and standard office environments. The specific objectives of this study are [to]:

- Review the impact of working from home on households' energy consumption and (space) heating load profiles.
- Evaluate the behaviours involved in coping with cold home-office spaces, and the potential implications of such behaviours on energy consumption.
- Explore the occupants' thermal preferences and willingness for adaptation that may underline these behaviours.

## 2. Literature Review

In the new global pandemic and confinement, housing has become a central issue in the research field. The outcomes of this pandemic lead to the reconsideration of new architectural and design archetypes, for example, the reconsideration of indoor space use, energy consumption, the perceived thermal, acoustic and light comfort and indoor air quality (Jaimes Torres et al., 2021). A global gap is detected in the studies that lack the analysis of residential behaviours and connect the daily thermal adaptations to energy consumption (Ambrose et al., 2021) and in understanding and documenting the coping strategies of fuel poverty households, during this time of the pandemic, where (Ambrose et al., 2021) describe it as – *"a critical period when it is more essential than before for homes to offer us safe, comfortable and healthy shelters"*. Moreover, research is needed to understand the occupants' satisfaction in their working spaces and how they interact with the environmental systems, needs, and demands (Yao and Yu, 2012). High priority research is needed to examine the occupants' thermal satisfaction in the living and office spaces in terms of, interaction with environmental systems and environmental needs and demands (Liu et al., 2014).

The combination of technological development and physical distancing imposed by the pandemic 'moved' typical work into the digital domain, a change described as 'digital migration' (Jaimes Torres et al., 2021). The need for physical distancing affected the work-life balance, as telecommuting was adopted by many workplaces to meet the social distancing instructions applied (Fabiani et al., 2021). Working from home and teleworking became the "new normal'' working style (Fukushima, 2021) with teleworking rising from 14% to 47% (TheCarbonTrust, 2021). Similarly, (Holliss, 2021) finds that by mid-2020, 37% of people in Europe were working remotely and the number of home-based employees increased to 50% in the UK. This makes people ask a question, is working from home a long-term response? A hybrid future for working is predicted, (Holliss, 2021) and (Frumkin, 2021) see working from home as a potential long-term implication of COVID-1.

A study by Vodafone, on the teleworking frequency in six countries for 2021 and 2022 scenarios in the pre-COVID, during-COVID, and post-COVID. The study found that the UK had the highest increase among the surveyed countries in the average number of teleworking days per week during the pandemic (TheCarbonTrust, 2021).

Due to the confinement regulations, and staying at home, changes occurred in people's activities and energy use, both for the standard workplace and for people's homes. The electricity consumption profile of weekdays was found to be similar to pre-pandemic weekend profiles, highlighting increased activity at times when homes would be typically little or not occupied (Bahmanyar et al., 2020).

(Lőrincz et al., 2021) captured the patterns of residential occupants' behaviour in 2014-2015 in the UK and examined their relationship to the energy consumption profiles and found that full-time workers have a higher possibility to reduce their energy consumption compared to part-time employees and that energy consumption profiles were significantly varied with work schedules. This heterogeneity in the work-energy relationship could be due to the impact of stricter work hours on the timing of energy-related activities, and further research is needed to examine the work-time-energy relationship (Lőrincz et al., 2021).

Significantly, working from home contributes to higher domestic utility usage and consequently to an increase of 10-30% in energy bills, and this impact could be stressful in socioeconomically disadvantaged areas (Menneer et al., 2021). For example, an estimation of an extra £16 per month of the average energy cost due to home confinements (Aimee et al., 2020). This is due to turning the heating on when it wouldn't necessarily be, and consuming extra gas and electricity for cooking and domestic services, and this cost could be higher for energy-poor houses (Aimee et al., 2020).

Spending longer periods inside the house and working from home have increased the interaction between occupants and the built environment. This interaction between people and the occupied environment is a reflection of self-adjustments behaviours or using environmental control measures (Liu et al., 2014). (Yang et al., 2014) cited by (Keyvanfar et al., 2014) that *"people are not passive recipients of their immediate environment, but constantly interacting with and adapting to it"*. This quote has been further explained by (Keyvanfar et al., 2014) who confirmed indoor environmental changes create discomfort and dissatisfaction among the occupants; this eventually contributes to physiological, psychological, and behavioural adaptation activities. This connection with the inhabited built environment and the behaviour of the occupants is vital for the building's performance, maintenance, and proper function (Jaimes Torres et al., 2021). A shortage of research evidence is observed on the broad subject of residential behaviours (i.e., their patterns and origins) and their relation to thermal adaptations that influence energy consumption (Ambrose et al., 2021). Moreover, research is needed to understand the occupants' satisfaction in their working spaces and how they interact with the environmental systems, needs, and demands (Yao and Yu, 2012).

Returning to the issue of working from home and staying indoors for longer periods have magnified some heating and housing quality issues. It is assumed that these issues forced the occupants to practice some coping strategies in their dwellings to keep themselves warm and comfortable. Several contextual factors affect our thermal comfort in residential buildings on how people adapt to the environment (receivers) and how occupants adapt the environment to their thermal needs (enablers): personal, local, building, and environmental systems factors, figure 1 illustrates these factors (Mora, 2019). Keep in mind, that there is a contextual difference between residential and non-residential built environments that leads to impact on the occupant's thermal acceptability and perception. For example, working from home, the occupant is more in control over the home office space than standard offices, consequently free to act upon their preferences. From the perspective of needs and expectations, (Mora, 2019) points out that productivity is not a matter at home. However, the conclusion of (Mora, 2019) study would have been different in the era of this pandemic and during the remote working period.

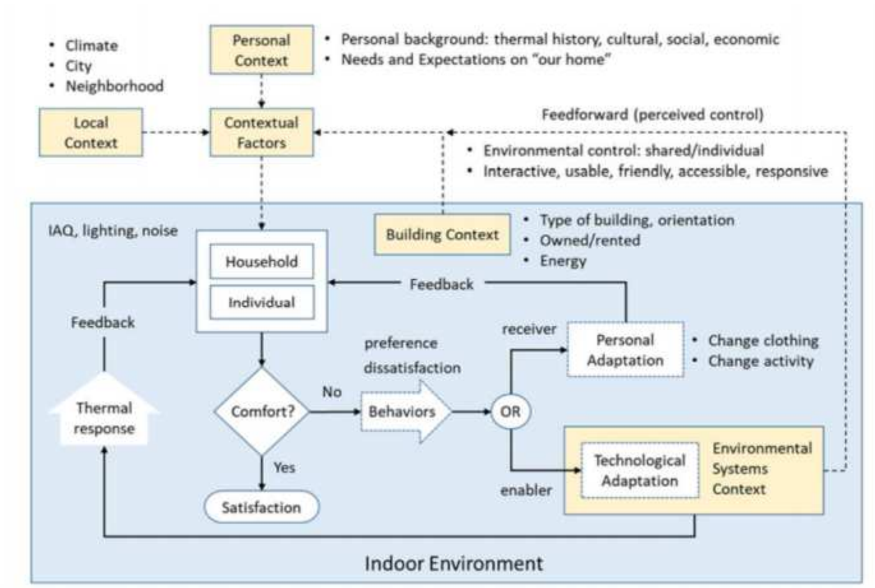



Figure 1: Contextual factors in residential thermal comfort, source: (Mora, 2019)

An interesting question was asked by (Hong et al., 2017); how does occupant behaviour influence building energy performance? A possible explanation for this is that since occupants are a proactive part of buildings (i.e.: perform energy-related tasks, they look for comfortable conditions, and they are the main consumers of energy (Hong et al., 2017). For example, the use of heating and ventilation systems, operating windows, and heat-generating appliances (Santín, 2010). People connect with the inhabited built environment, and the behaviour of the occupants is vital for the building's performance, maintenance, and proper function (Jaimes Torres et al., 2021). Thermal adaptations highly affect energy consumption, hence examining the occupants' interactions with the indoor environment and building is vital to obtaining and designing energy-efficient thermal comfort environments (Hong et al., 2017) (Liu et al., 2014). For example, in 2014, extensive research has shown that 40% of the total energy consumption in the UK is due to generating comfortable indoor environments for the occupants (Liu et al., 2014). Therefore, the main target of studying the occupant's behaviours is to use the energy-related occupants' behaviours as a basic feature of energy performance and to bridge the gap between the predicted and the actual energy consumption (Hong et al., 2017). The role of the occupants is getting more essential in the energy consumption variation due to the overall energy consumption correlated with the building characteristic is decreasing (Santín, 2010), but the extent of this influence is unknown. However, adaptive behaviours could have two different facets, an energy-saving lifestyle or according to Sorrell et al 'rebound effect' bad consumption habits, thermal dissatisfaction is a driving factor to higher energy consumption (Keyvanfar et al., 2014).

## 3. Methodology

The primary data for this study was collected through a web-based questionnaire and follow-up interviews. The secondary data is collected from energy experts' reports (Energyrev, Department of Energy and Climate Change of the UK, Department of Business, Energy and

Industrial Strategy, office of gas and electricity markets publications Ofgem), books, journal papers, and recent studies. The research framework is shown in figure 2.

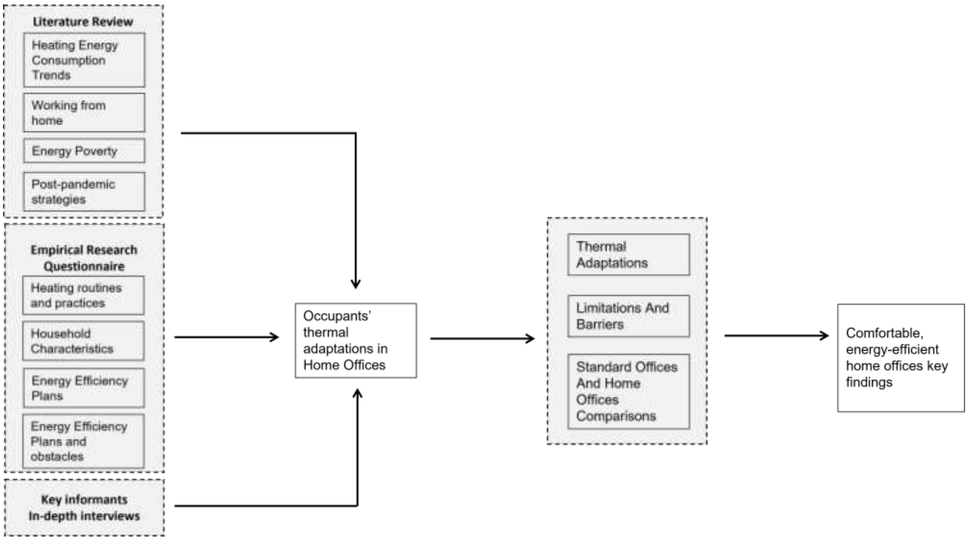



Figure 2 Research Framework

3.1. **Questionnaire:**

The questionnaire was built on previous research (Liu et al., 2014) (Ambrose et al., 2021) and was set up on the onlinesurveys platform. It consisted of five sections and included questions on the following: (The focus questions are the last two questions)

- Demographics of subjects.
- Overall house quality.
- Alterations and energy-saving improvements.
- Home office characteristics.
- Thermal adaptations strategies: conventional vs home office.

The link of the questionnaire was shared via LinkedIn and an email was also circulated to students and staff of the School of Architecture of Cardiff University. LinkedIn enabled the researcher to contact and target the participants who have shared interests or some shared identity, something in common expanding access to 'hard-to-find' research populations through a process of 'snowballing' (Denscombe, 2017).

3.2. **Interviews:**

The purpose of the interviews was to obtain information about the heating practices, adaptations and routines while working from home. Some interviews were with selected people who have extended knowledge of the topic, seen as "key informants" (Lazar, 2017). Eight experts in the industry of sustainable buildings and construction and four non-experts (software engineer, an architect, librarian, and surveyor) were interviewed. The key informants were members of CIBSE, working in academia or the industry, a senior building services engineer, a spatial planner, the associate director in a consulting firm and the head of a strategic lighting firm. 30-45 minutes of one-to-one Microsoft Teams interviews were performed, audio-recorded and transcribed (appropriate consents obtained). In addition, the researcher took notes on paper while interviewing. The interviews were semi-structured, with questions based on the study of (Barnes and McKnight, 2014) and (Ambrose et al., 2021).

After each interview, the researcher revised and updated the questions and added the questions that emerged as a result of the previous interview (Dawson and Dawson, 2009).

The interviews were recorded and transcribed on Teams calls, and analysis was carried out using NVivo qualitative analysis software, to code the transcriptions and highlight the thematic analysis of the research, the coding tree of the thematic analysis for the interviews is shown in Figure 3.

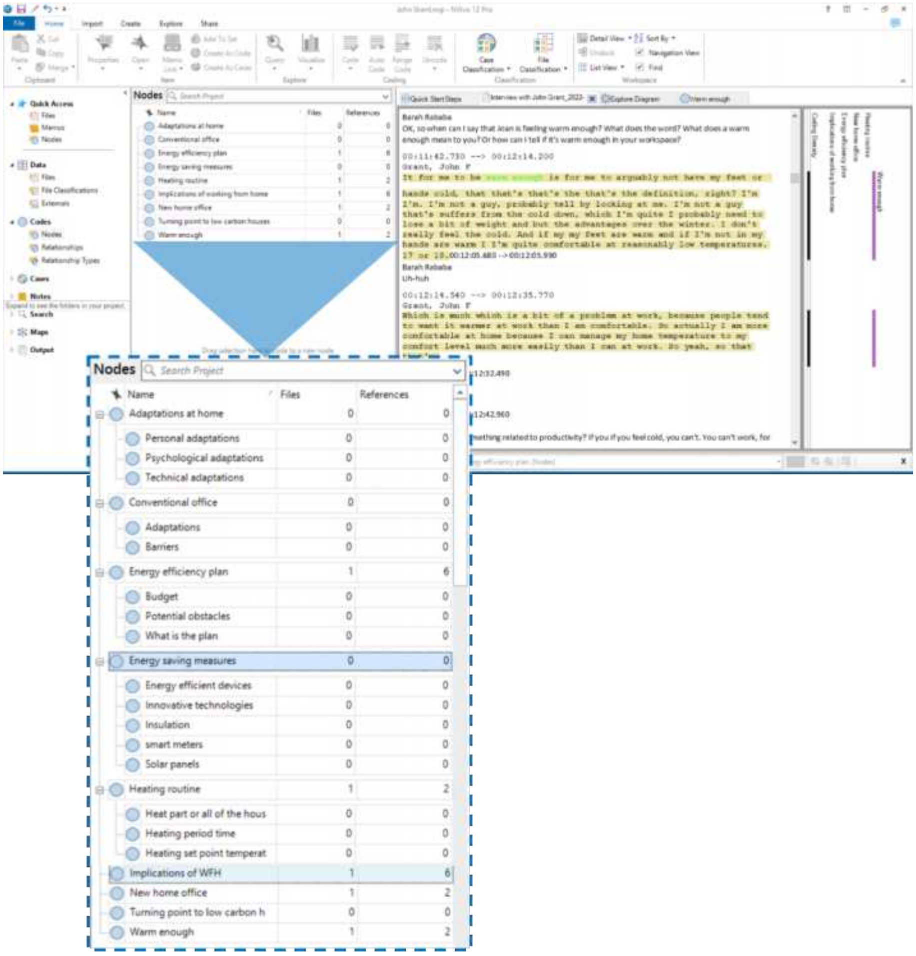



Figure 3 Coding tree using NVivo software

## 4. Data Analysis

### 4.1. Findings of the questionnaire

**Demographics of subjects**

The questionnaire was sent to a total of 729 people on LinkedIn and a total of 106 responses were received, with a proportion of 60% female and 40% male. The response rate was 14.5% and potentially impacted by the call being circulated during the holiday break (December 2021 – January 2022). Participants aged 30-49 years accounted for 57.6% of all respondents and almost 81.6% of those surveyed hold a postgraduate degree, mainly working in the building construction industry. Table 1 briefly outlines all the respondents' data. Most of the respondents work from home for more than 75% of their weekly working hours, Figure 4 provides the summary of key demographics and the percentage of working hours from home.

Table 1 Summary of respondents' data

**Respondents' data**

| | | |
|---|---|---|
| **Gender** | Female | 60% |
| | Male | 40% |
| **Age** | 18-29 | 19.2% |
| | 30-49 | 57.6% |
| | 50-64 | 19.2% |
| | >65 | 4% |
| | Prefer not to say | 0 |
| **Highest educational qualification** | Postgraduate degree (MSc, PhD, etc.) | 81.6% |
| | Undergraduate degree (BSc, BA) | 15.3% |
| | Higher Diploma | 1% |
| | Overseas qualification | 1% |
| | Vocational certificate | 1% |
| | O-levels, A-levels | 0 |
| | No qualification | 0 |

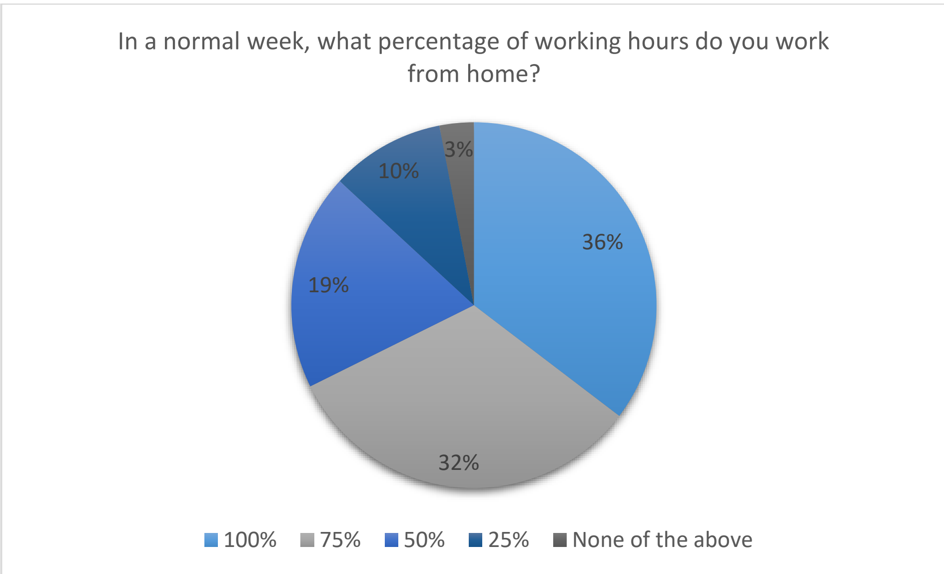



Figure 4 Percentage of working hours from home for the respondents

The responses were received from different locations in the UK; over a third of those who responded (36.1%) live in Wales, while 19.6% live in London. Figure 5 provides an overview of the distribution of the participants in the sample across all the regions of the UK.


Figure 5 Questionnaire's participants' locations on the UK map

Approximately half of the respondents (53.6%) live in privately owned properties and 39.2% of them live in rented houses, 5.2% live in a house owned by extended family or friends, and only 2 respondents live in a house provided by a housing association or a local council, shown in figure 6.

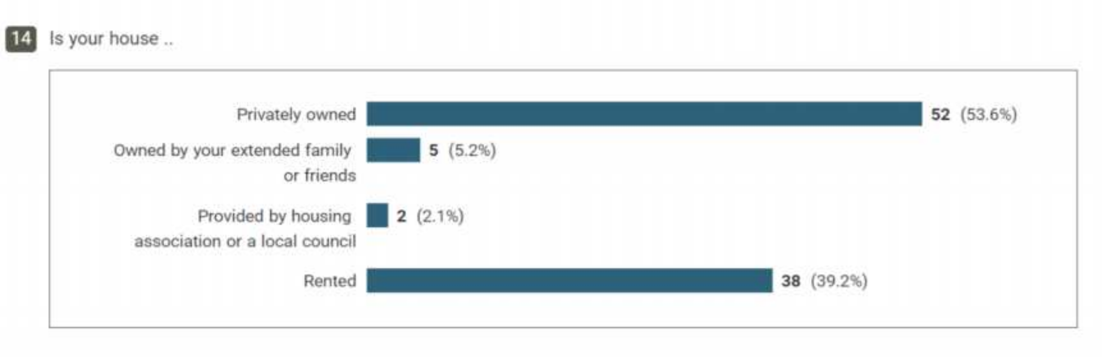



Figure 6 Ownership percentage of houses

- **Overall house quality**

In general, more than half of the respondents (69.4%) find their house's size too small. The participants also had to indicate any house quality issues and rate the performance of their windows. Some questions discussed other quality issues, with figure 7 showing that the majority of respondents live in conventional (non-low energy) houses (78.3%) with 55.3% finding these to consume a lot of energy, 43.9% being poorly insulated and 33.7% experiencing damp and mould issues.

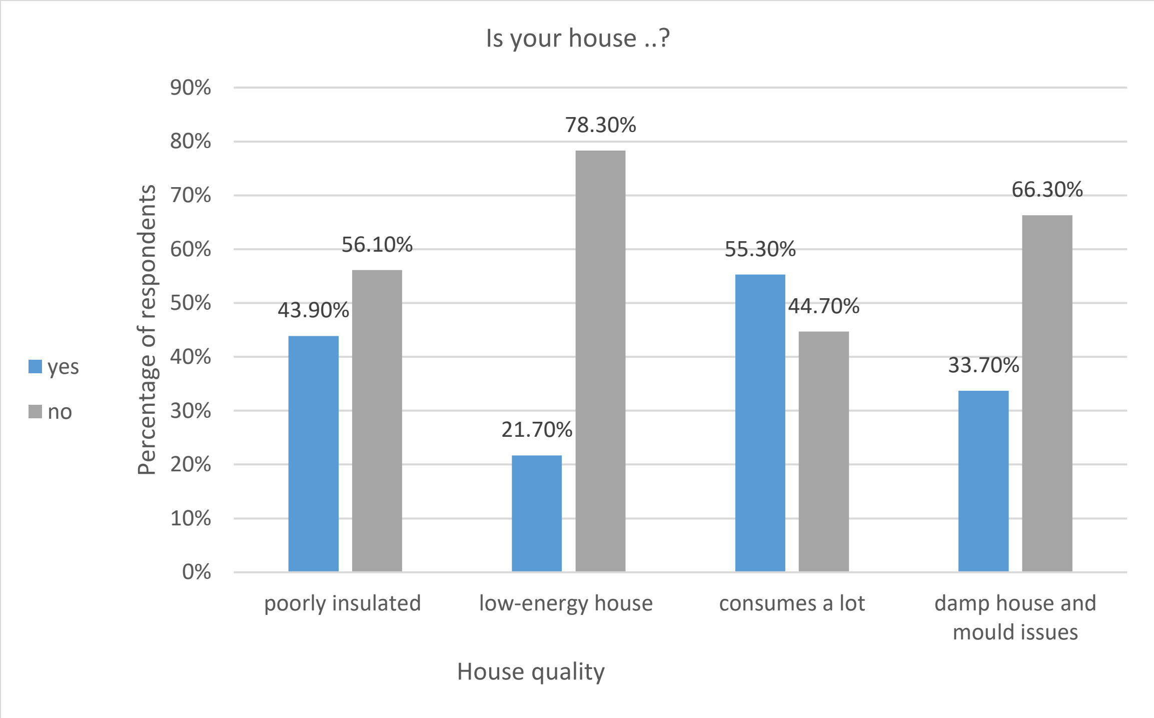



Figure 7 House's quality and issues

The surveyed households were asked about the performance of their windows and 61.2% reported this to be "average" whereas only 18.4% reported it as "bad" (see figure 8).

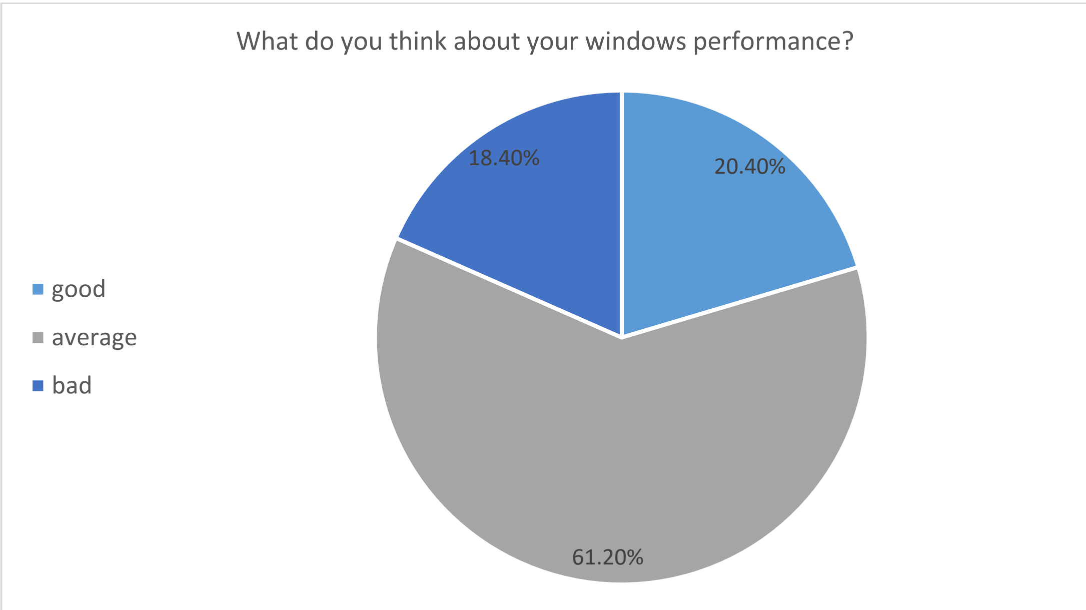



Figure 8 Windows performance

- **Alterations and energy-saving improvements:**

Respondents were asked if they have done any changes to their current house. The majority (75%) have switched to LED bulbs, and nearly half of the respondents (47.2%) have installed smart meters. More than a third of the respondents (36.1%) have insulated their houses, and 31.9% have changed or upgraded heating systems. 23.6% of respondents have changed or upgraded windows and installed energy-efficient boilers, while (9.7%) have installed solar panels (see figure 9). In response to other changes (9.7%), the detail provided by respondents indicated the following:

- "Installed Tesla battery storage"
- "The house has been already fully refurbished (i.e., Insulated, upgraded windows) by the previous owner some years ago."
- "Installed dMEV fans, installed smart car charger, installer PV hot water diverter, replaced gas hob with induction hob, removed gas meter, installed air source heat pump"
- "Smart heating controls, low energy appliances

'

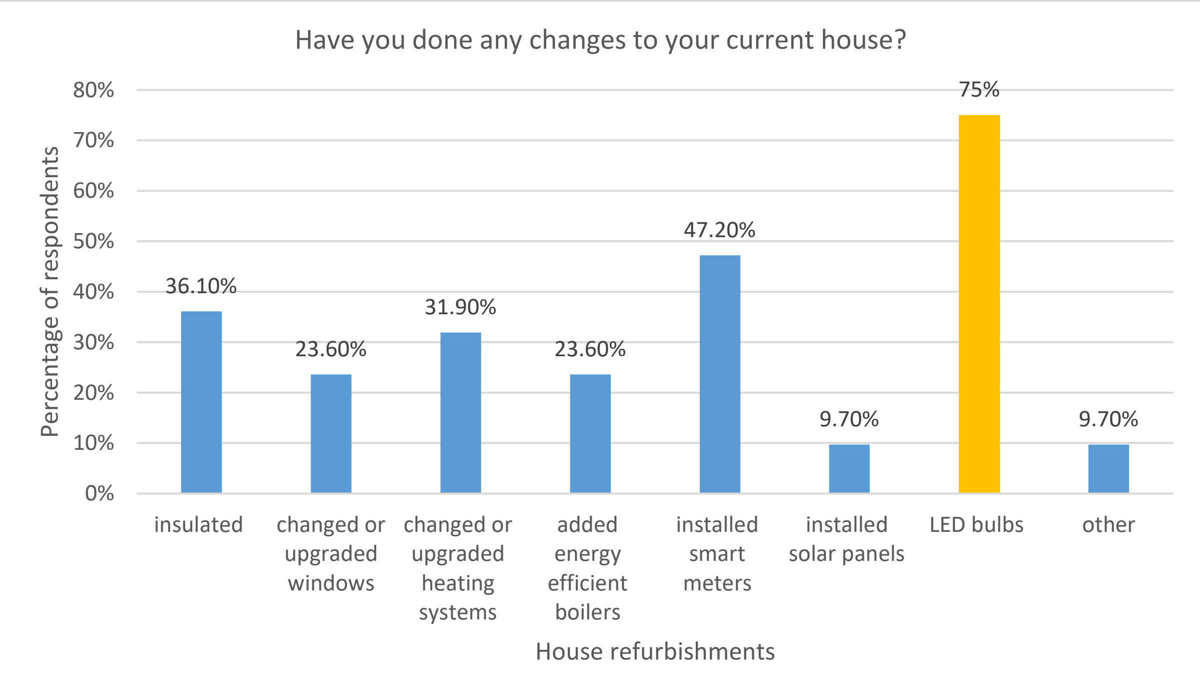



Figure 9 House refurbishments

A specific question was asked to examine if they had installed energy-saving measures during the pandemic. Figure 10 reveals that most of the respondents (84%) have not applied any saving measures during that period and only 15 respondents who did provided the following details on measures:

- "Add weatherproofing strips to doors"
- ''Reduced heating (how long it is on)"
- ''Sat in the cold or only heated one room"
- ''installed a 2nd PV array and 13.5kWh battery storage''
- ''Checked and re-laid loft insulation''
- ''Reduce household thermostat settings from 22°C to 20° C. Increase CLO value of indoor clothing.''
- ''Changed energy supplier; had a smart meter installed; monitor energy use''

- ''I have insulated my loft spaces.''
- ''Plastic secondary glazing on windows''
- ''Heat pump was installed during pandemic''
- ''Reduced flow temperature of condensing boiler''
- ''Instead of heating the entire house, a small electric heater is used for the study.''
- ''I don't own it, so I have only done small, removable solutions, such as foil behind radiators, insulating film on windows, curtains over external doors, insulating pipes coming from outside, insulating tape on external door''
- ''Added draft exclusion''
- ''Draft excluders on doors''

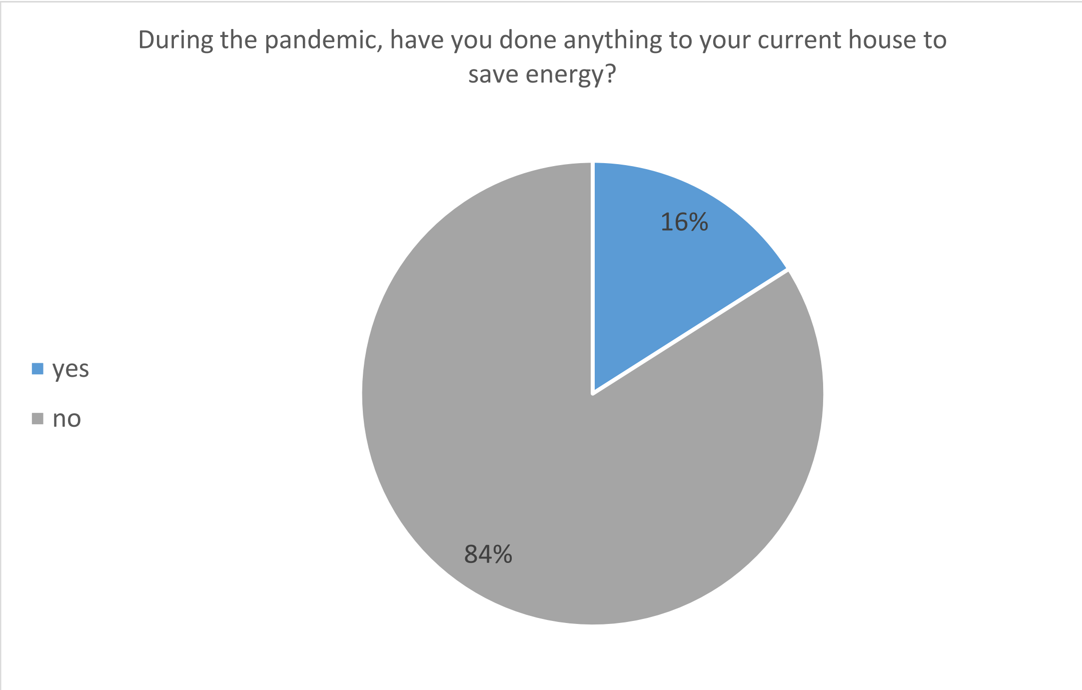



Figure 10 Saving energy measures during the pandemic

- **Home office characteristics:**

43.3% of participants have a study space in a corner of their bedroom whereas 40.2% have a dedicated home-office room (figure 11). Most of these office spaces are naturally ventilated (72.7%), 45.5% are centrally heated and 17.2% use non-centralised heating systems. The free-text responses provided further detail: One respondent uses *"Electric radiator heating" "[Study is] on North side of house for constant indirect light, wisteria grown on South face to reduce summer heat gain."*, figure 12.

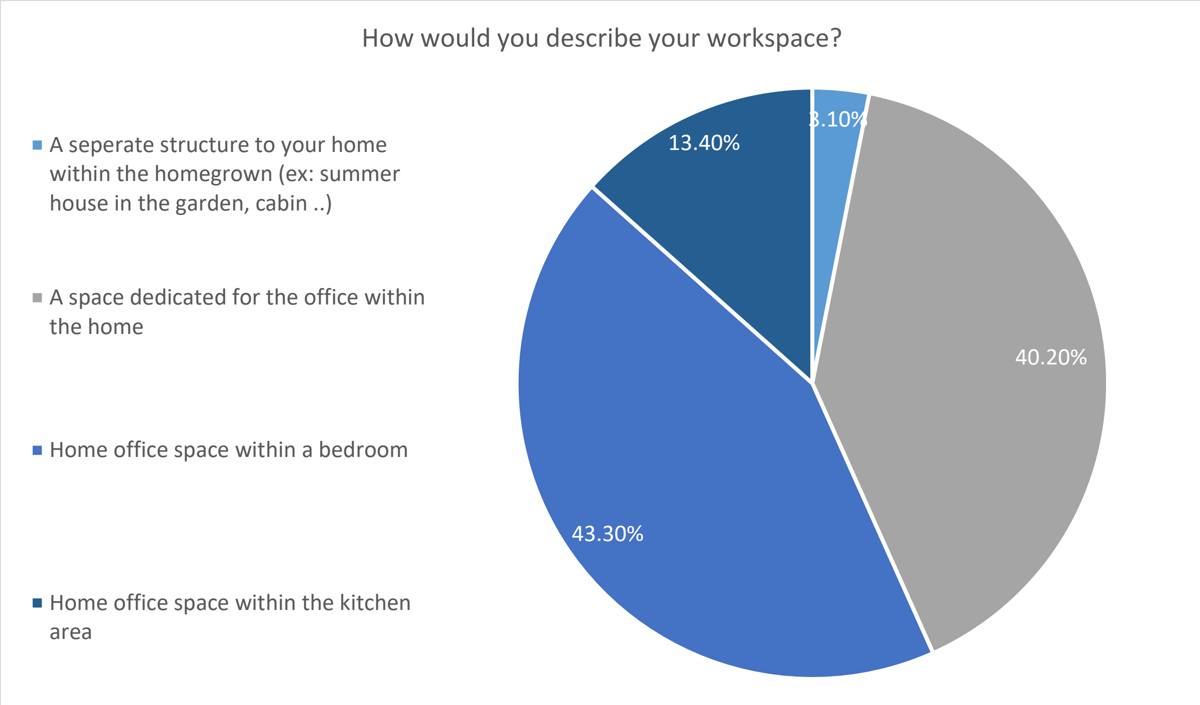



Figure 11 Home office space

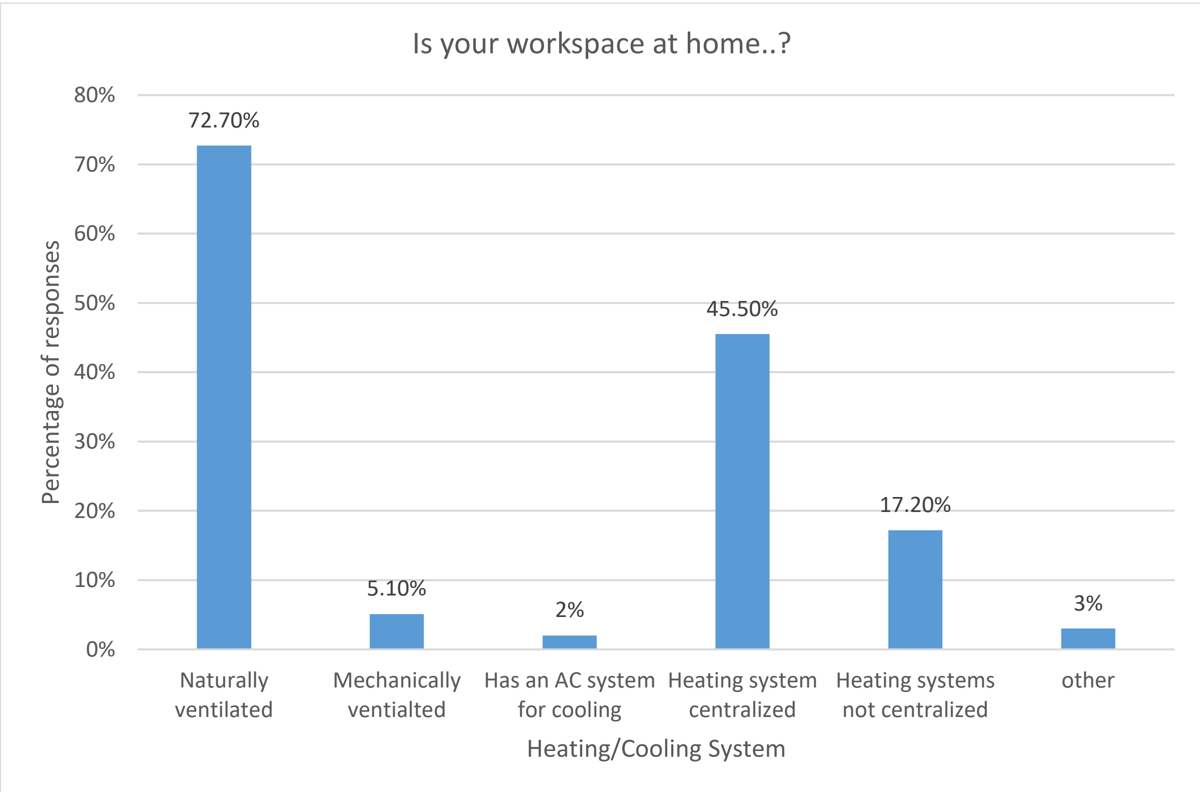
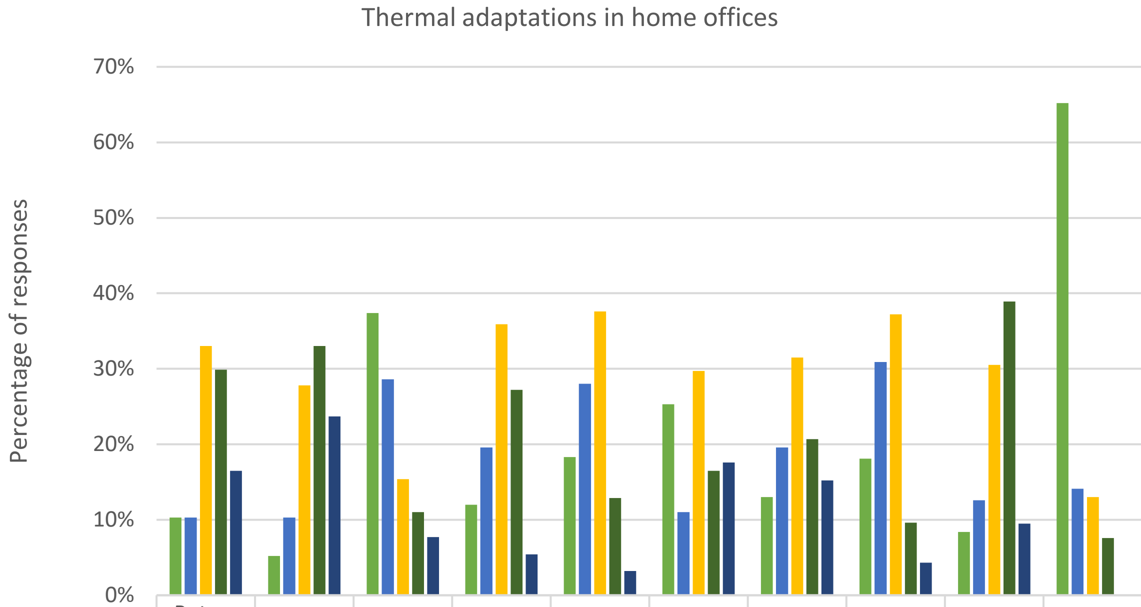



Figure 12 Heating/cooling system in the workspace

## Thermal adaptations strategies: conventional vs home office

The findings of the key question "How regularly do you adopt these behaviours to keep yourself warm in the home office/standard office environment?" provided insights into the differences in types of thermal adaptations and frequency of use between the two office environments. The most adopted (highest 33% for 'often' and 23.7% 'always') action in home offices is “have a hot drink”, followed by “open internal blinds” 16.5% for often and 17.6% for always and 15.2% “open/close windows”. However, 38.9% of the respondents tend to often “turn on heating units” 29.9% “put on a jacket, blanket or slippers” and 27.2% “change posture”, figure 13.

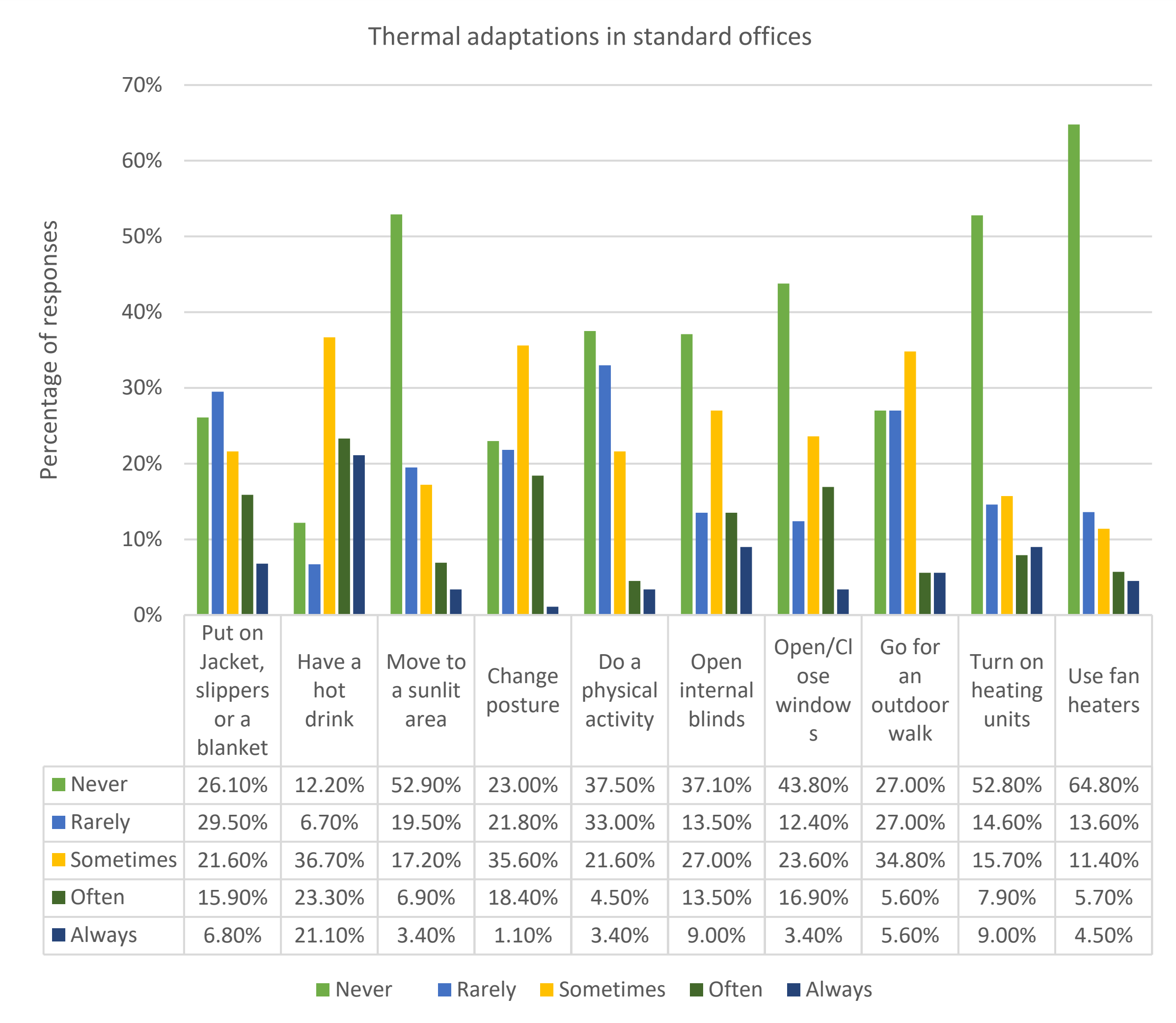



| | Put on Jacket, slippers or a blanket | Have a hot drink | Move to a sunlit area | Change posture | Do a physical activity | Open internal blinds | Open/Close windows | Go for an outdoor walk | Turn on heating units | Use fan heaters |
|---|---|---|---|---|---|---|---|---|---|---|
| Never | 10.30% | 5.20% | 37.40% | 12% | 18.30% | 25.30% | 13% | 18.10% | 8.40% | 65.20% |
| Rarely | 10.30% | 10.30% | 28.60% | 19.60% | 28% | 11% | 19.60% | 30.90% | 12.60% | 14.10% |
| Sometimes | 33% | 27.80% | 15.40% | 35.90% | 37.60% | 29.70% | 31.50% | 37.20% | 30.50% | 13% |
| Often | 29.90% | 33% | 11% | 27.20% | 12.90% | 16.50% | 20.70% | 9.60% | 38.90% | 7.60% |
| Always | 16.50% | 23.70% | 7.70% | 5.40% | 3.20% | 17.60% | 15.20% | 4.30% | 9.50% | 0% |

Never Rarely Sometimes Often Always

Figure 13 Thermal adaptations in home offices

In contrast, in the standard workplace environments, respondents tend to adopt mostly personal adjustments, for example, 21.1% always have a hot drink. Sometimes 35.6% change posture and 34.8% sometimes go for an outdoor walk. What stands out in the standard office behaviours responses is that the frequency of choosing “never” as answer is higher than in the home office. For example, 64.8% never use fan heaters, 52.9% never “move to the sunlit area”, 52.8% never turn on heating, and around half 43.8% never open or close windows (details seen in figure 14).




| | Put on Jacket, slippers or a blanket | Have a hot drink | Move to a sunlit area | Change posture | Do a physical activity | Open internal blinds | Open/Close windows | Go for an outdoor walk | Turn on heating units | Use fan heaters |
|---|---|---|---|---|---|---|---|---|---|---|
| Never | 26.10% | 12.20% | 52.90% | 23.00% | 37.50% | 37.10% | 43.80% | 27.00% | 52.80% | 64.80% |
| Rarely | 29.50% | 6.70% | 19.50% | 21.80% | 33.00% | 13.50% | 12.40% | 27.00% | 14.60% | 13.60% |
| Sometimes | 21.60% | 36.70% | 17.20% | 35.60% | 21.60% | 27.00% | 23.60% | 34.80% | 15.70% | 11.40% |
| Often | 15.90% | 23.30% | 6.90% | 18.40% | 4.50% | 13.50% | 16.90% | 5.60% | 7.90% | 5.70% |
| Always | 6.80% | 21.10% | 3.40% | 1.10% | 3.40% | 9.00% | 3.40% | 5.60% | 9.00% | 4.50% |

Figure 14 Thermal adaptations in standard offices

In a follow-up question, this point was examined further for both of working environments by enquiring “what would be the barrier to stop you from adopting the heating behaviour at your home [or standard] office?”

For the home-office environments, around two-fifths, (43.7%) of participants find the cost to be the main barrier, followed by (20.7%) those who find the radiator’s location as a reason (see figure 15). Some respondents encountered other barriers and reported:

- “No barriers for the home office as I control the environment. But several in the standard office as I do not.”
- “Environmental impact”
- “I choose not to use central heating for the whole house while only using study space. I have a small heating mat (60W) and wear extra clothes.”
- “No option given for my heating system, which is underfloor electric, on-site PV. Also, solar gain in early afternoons is difficult to regulate in winter - the only option is to manually open windows or door.”
- “Air source heat pump heating controls are slow to respond to any changes in thermostat setting”
- “Lack of localized controls”
- “There are no sunlit areas at home, faces north. I don't have fan heaters”

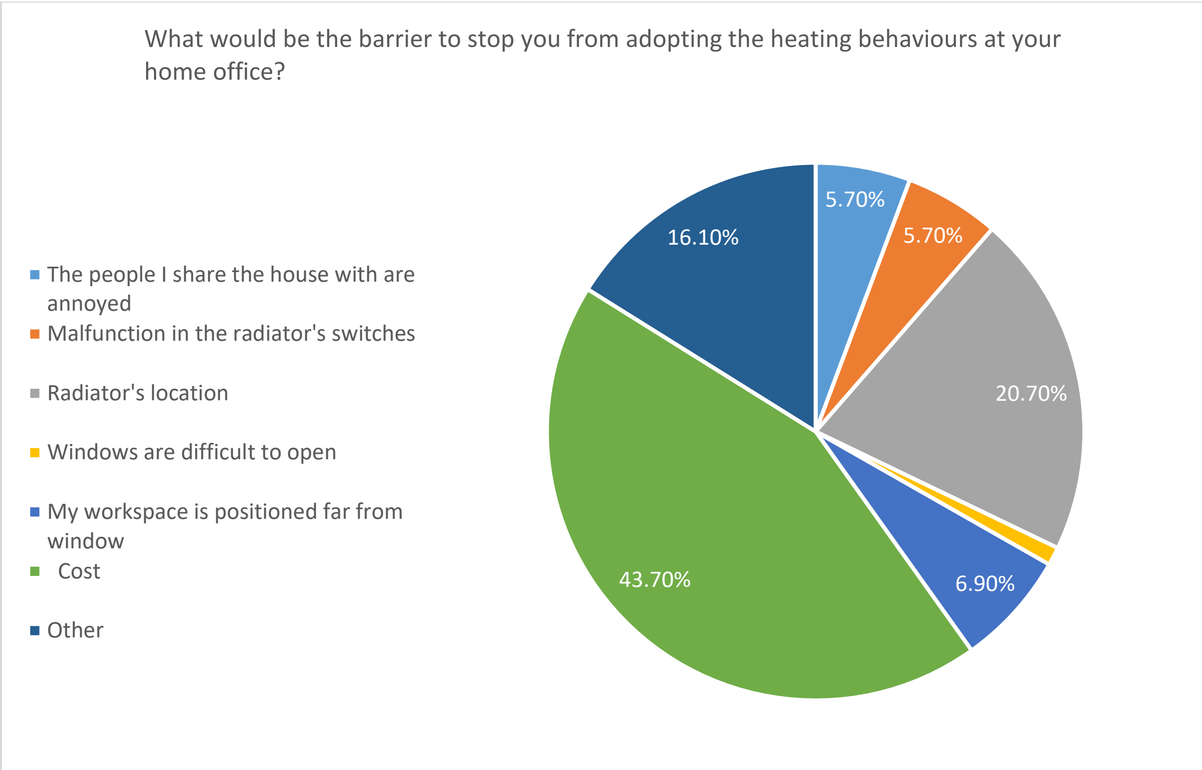



Figure 15 Barriers of adopting heating behaviours at home offices

In standard offices, central heating systems with no individual controls seem to be the main barrier (34.5%), and the barrier behind the "control over space" made up around a third of the responses (29.9%). Figure 16 illustrates some issues that were explained further by some respondents in the free text questions, for instance:

- "Office has a huge single glazed window. The heating system doesn't activate until after 8 am, but I get in earlier. We're not allowed supplementary heating''
- "No separate thermostat''
- "Poor responsiveness of individual control, solar gain, poor fabric efficiency and unsuitable HVAC''
- "Poorly insulated office with external draughts with certain wind directions.''
- "I can only turn up and down the radiator, but if the central heating is off there is nothing, I can do about it. I share the office with other two colleagues and we might disagree''

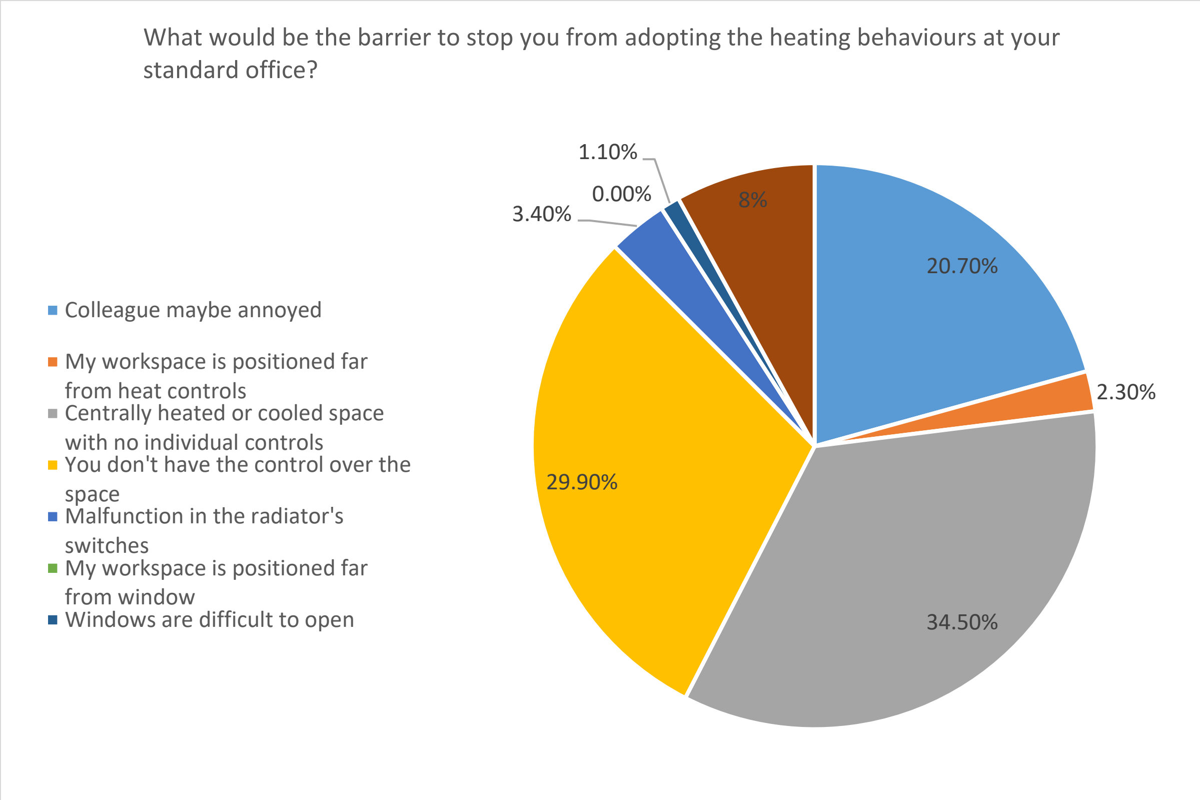



Figure 16 Barriers of adopting heating behaviours at standard offices

## 4.2. Findings of the Interview

This section outlines the thematic key findings that emerged from the interviews, as follows:

- **Warm enough:**

Respondents were asked, "what does 'warm enough' mean to you?" This question was derived from (Department for business, 2017) and its purpose was to underline the ideal scenarios of a comfortable workplace and if it is related to environmental parameters or controls and to detail the conditions and implications of thermally un/comfortable environments. Opinions expressed during interviews differed largely in defining "warm enough" or "I'm feeling warm", with three perspectives emerging from the analysis:

1. **Clothing insulation:** Respondents reported that clothing is an indicator of feeling warm or not. *"I'm just wearing my shirt. If I was too cold, I would put the fleece on." MWE30*
2. **Distraction and productivity:**

   Four interviewees indicated that being warm enough is attributed to their productivity level and distraction while working, e.g., *"I [am] supposed to be able to undertake tasks that you need to do, without feeling discomfort." MPM60*

   An explanation for this is given in the work of (Wargocki and Wyon, 2017) reproduced in figure 17, which shows the extent of the temperature impact on office workers' performance. It is obvious that a decrement in performance is shown when the temperature gets below 18 C, and consequently, attention is distracted due to thermal discomfort (ibid).

3. **Manual dexterity and performance:**

Four interviewees mentioned that the sensation of fingers and hands are their indicators of being “warm enough”. One respondent expressed that, cold hands and feet are a reason for distraction in cold conditions cold: *“My hands are cold, and when I get really cold, I start shaking, and the other way is my hands get red and my nose, that is one way of telling… and I won’t concentrate and I start moaning, basically I can’t work, it is distracting” FCF20*

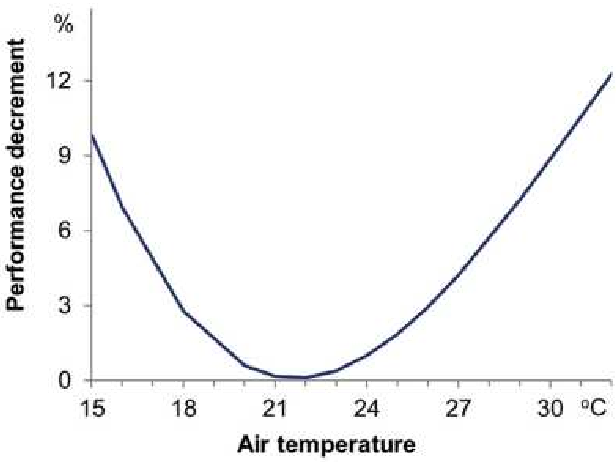



Figure 17: Temperature-performance relationship in offices. Source: (Wargocki and Wyon, 2017)

- **Has working from home shed light on house’s quality issues:**

The long periods inside the house, made some people realize the issues of their houses. Draughts, cold rooms, glazing issues and extended hours of space heating system being ON, were the main issues noticed.

*“Yes. I've been aware of draughts more that are coming through my double glazing. Needs replacing badly. I think the longer I've worked here, the more I've realized that it needs replacing” FSR60*

*“Yeah, yeah, of course. As I told you the lack of double glazing in where I like to work there's …a lot of condensation,” FCF60*

- **Home office vs. conventional office:**

Similarly, with the results coming out of the questionnaire analysis, the results from the interviews indicate a difference between the home office and conventional office, on types of thermal adaptations exercised. The result summary is presented in table 2 categorised according to the classification presented by (Liu et al., 2014).

Table 2 Categorization of thermal adaptations reported in the interviews

| | Conventional office | Home office |
|---|---|---|
| **Technological responses** | • Rolling down internal blinds<br>• Electric heating mat<br>• Opening window<br>• Electric heater<br>• Turn on heating | • Heating mat<br>• Electric heater<br>• Reduce heating temperature<br>• Reduce heating duration<br>• Heat the house partially |
| **Personal adjustments** | • Wear cardigan<br>• Changing position<br>• Thermal underwear | • Wear a cardigan<br>• Put a blanket on legs<br>• Clothes<br>• Socks<br>• Woolly jumper and scarf<br>• Standing desk<br>• Physical activity<br>• Hot drink |

As can be seen from table 2, some occupants adopt a range of thermal adaptive actions to obtain thermal satisfaction. Interviewees reported both behaviours to adjust the environment to their needs and behaviours to adapt themselves to the environment (Hong et al., 2017). Interviewees also reported effective approaches to feel warm while working from home that would allow them to lower their temperature heating setpoint or decrease the number of hours when heating runs on a working day. These approaches are likely to be related to economic consequences since lower heating temperatures will result in lower energy bills (Luo et al., 2014).

Within the sample, one of the interviewees uses a 60-Watt heating mat to heat up her study space to the required comfort level and reduce the heating of the entire house which sits under her desk (figure 18). The participant also reported that if she feels her knees, ankles, or chin cold, she will add an extra layer on the top part of her body.

Figure 18 Electric heating mat under a desk of the interviewees

Another interviewee switched from the sitting down position while working to a standing position using a special harmoni desk (Harmoni, 2021) as shown in figure 19. This standing desk increased his physical activity while working, thus allowing him to stay warm at a wider range of temperatures. Interestingly, this participant also discussed another adaptive action, that of doing work-life balance. In other words, he managed to break his day up more than in the standard office. He turns the heating on in the early morning and starts doing the cognitive work while the heating is turned on for 3-4 hours. After that, he would take a break for an hour or two and do a physical activity (go for a walk, or gardening), then work another 4 hours.


Figure 19 Standing desk used by one of the interviewees

Increasing clothing insulation was the most commonly reported coping strategy among the interviewees (7 out of 12). Figure 20 is from the home office of an interviewee who mentioned the presence of a collection of jumpers in her study space.

Figure 20 A study space for one of the interviewees, and a jumper shown

Another interviewee, whose study space is shown in figure 21, discussed how the fact that both the window and the radiator are in the same wall, makes her feel cold and leads her to turn the radiator ‘ON’ during the entire day. She also discussed other adaptation strategies for staying warm: *“And also, I got this blanket... so, the heater is off now, I use it to cover me”*

Figure 21 Blanket used by one of the interviewees in her home office

- **New home office image**

All the respondents revealed a general satisfaction with the home-office environment. However, respondents were asked, “If you had the chance to have a new home office, what would be the considerations that you take into account, to have a warm and comfortable home office?”. Using NVivo software, a word cloud was generated from the transcripts of the answers to this question at interview. As shown in figure 22, it is notable that windows and light are the most frequent words and were widely reported in conversations by the interviewees.


Figure 22 Word-cloud generated of the elements and considerations the interviewees have identified to have a new home office

The vast majority of the participants had expectations of a new space with energy-efficient windows,

*"I think that view, -what I look out- on is very important to me. I would want windows that provided me with a good view, and which were energy efficient would be a consideration." (FCF60)*

For another participant, solar gains through windows are an issue of his current study space:

*"Well, I'm actually quite happy with it as it is, there's no need for change. The only thing I perhaps would do is I need to get a blind on the window to stop solar gain during the summer." (MWE30)*

Several participants described a future image of their home office with lots of natural light. (MDm60) and (FCF60) were both satisfied with their current home office and would not change anything; because of the big window and the daylit workplace:

*"Because it's warm enough, it's light enough. The lighting turned on because I have a big window next to me" (MDm60)*

(FCF60) describes the comfort of working from her home office, shown in figure 20:

*"Well, I'm very lucky, because I've got a lovely room already and it's very warm in this attic. Lovely window and a fantastic view. This suits me fine I wouldn't make a better run than this is. I love coming up here. It's a pleasure. I've got three windows in this room. Well, from the South, this is the big southern window here. And then there are two windows on this side facing north, and so it's full of light, which I think light is the most important thing ... I think*

*light is more important than heat. And I think it's good for your mental health to have light and air. it's just it's lovely to be in a light space. So have white walls and the sun coming in and just the windows on both sides." (FCF60)*

Interestingly, FSR60 proposed a comprehensive lighting and windows system for her space:

*"Obviously, I would want lots of natural light... I think it's also very important to one's health and well-being, so it would have to have a lot of light. Therefore, if I'm going to have lots of Windows, I want good double glazing, maybe even triple glazing. To stop me from overheating in the summer, I would then also want some sort of blind mechanism, maybe also automatic lighting controls, so that when the sunlight coming into the space is high enough my lights go out automatically without me having to remember to do... I'd relocate my office space to the ground floor if I could... because in the summer it gets really hot and in the winter it's much colder up here." (FSR60)*

In addition to natural light, two respondents expressed their interest in natural ventilation as a vital element for a comfortable and efficient study space:

*"So, I would have to convert the loft or the roof space. Would have to insulate it, and put some natural light in there so some skylights. Uh, I [would] just put some radiators in there and I would also like [a] bright area space. So natural ventilation would for me personally ... be important." (MBG30)*

*"I think the combination of comfort and fresh air. I like to be comfortable but have decent ventilation and quite a sealed space. And there's not an awful lot of flow of air through, or if you do have airflow, you lose the energy efficiency to an extent... So that would be nice, [i.e.,] fresh air, but still warm." (MPM60)*

One respondent only (FCA40), reported the acoustic issue:

*"I think we've already got most of the thermal efficient office elements. A well-insulated house. We have a double-glazed window. We have curtains over the window so if it's a bit chilly when it gets dark, we pull down the blinds. We shut the curtains so that reduce the chill of the window. The big issue would be acoustic, which would probably involve us having separate study spaces."*

The findings of this question have emphasized that light and windows are the main elements for a future home office, followed by natural ventilation.

Overall, participants showed a range of adaptive and coping strategies while working from home. These strategies varied from sewing thick curtains to installing heat pumps and PV cells. Low-cost measures revealed in this study are illustrated in figure 55. Our results are reflected and supported by (Shreedhar et al., 2021), who believe that there is no evidence to suggest that people work from home sustainably. Sustainable key behaviours are diverse and range from "one-off choices e.g., switching energy providers) to, habitual behaviours (e.g., diets, driving to work, heat and temperature settings at home, or showering)" (Shreedhar et al., 2021).

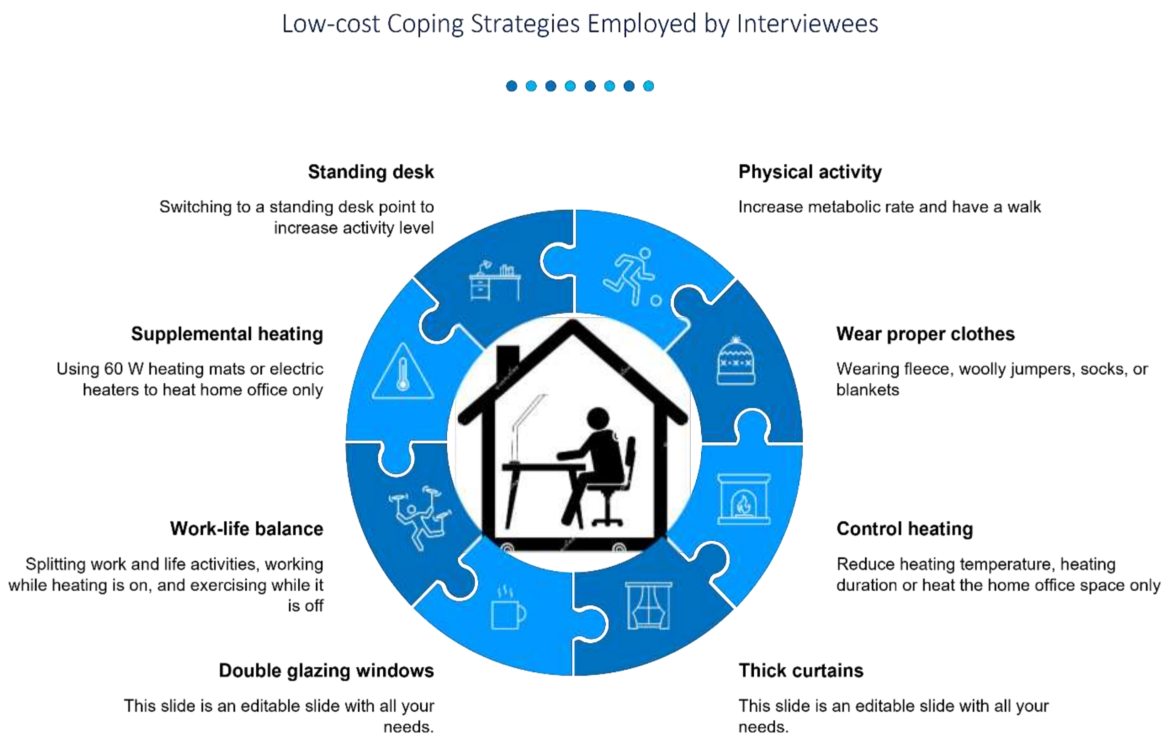



Figure 23 low-cost coping strategies revealed by the interviewees of this study

## 4. Conclusion

The overall aim of this research was to examine the impact of working from home on thermal adaptations and household energy consumption. Spending more time at houses has caused changes in the residential sector, in terms of energy consumption, thermal comfort and occupants' behaviours (Jaimes Torres et al., 2021). The literature review identified the consequences of working from home on energy heating load patterns, namely a 20% increase in gas usage and a shift to midday peaks in the morning electricity usage (Menneer et al., 2021), more distributed energy use throughout the day and no morning peaks (Chen et al., 2020) (Santiago et al., 2021).

This study has identified the coping strategies of occupants in winter while working from home. The empirical research has shown that most of the respondents (84%) have not applied any energy-saving measures during the pandemic, such as fabric or building services upgrades. For those who applied measures, they tended to apply low-cost strategies, related to the heating routine and control practices. For example, reducing thermostat temperature or the duration of heating staying ON during a typical working day. The main barrier behind adopting thermal adaptations is cost, followed by the radiator's location in the space and in relation to windows and the desk positioning.

The questionnaire provided insights into the most adopted coping strategy in home offices. The highest adopted action that respondents 33 % 'often' adopt is "have a hot drink" followed by "open internal blinds" and "open/close windows". On the other hand, in the conventional work offices, respondents favour adopting personal adjustments. Surprisingly, the frequency of choosing "never' as an option is higher in standard offices than in home offices.

This study generally has found that participants relate “warm enough” to three main attributes: Clothing insulation, productivity and distraction and manual dexterity and performance. In general, the interviewees were satisfied from working from home. One of the more significant findings to emerge from this study is that the future image for the interviewees for new home offices is daylit spaces with energy-efficient sealed windows and good ventilation. The implications of working from home could contribute to raise the awareness of people of energy-efficient houses, this could be buying new energy efficient properties, or refurbishing houses and installing innovative energy-saving measures. There is one other, unexpected, conclusion that this research work has uncovered, the concerns shared amongst these interviewees on the upcoming energy price rise [that has been implemented at the time of writing this paper but was merely a news item at the time of data collection].

A key limitation of this study is the small sample size and the fact that most of the participants are from Wales and postgraduates. It is unfortunate that the study does not seem to have received data from energy-poor households as one would expect a set of different viewpoints expressed by that group to the questions asked. Notwithstanding these limitations, the findings of this research provide insights into the interaction of teleworkers with their home office’s environments and revealed the preferred adaptations.

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# The use of Setpoint temperatures based on local adaptive comfort models as an energy conservation measure: the case of Japan.

**Daniel Sánchez-García[1], David Bienvenido-Huertas[2], Carlos Rubio-Bellido[3] and Jesús Alberto Pulido-Arcas[4]**

[1] Department of Electrical Engineering, University Carlos III of Madrid. Leganés, Spain; dsgarcia@ing.uc3m.es
[2] Department of Building Construction, University of Granada. Granada, Spain.
[3] Department of Building Construction II, University of Seville. Seville, Spain
[4] Graduate School of Arts and Sciences, The University of Tokyo. Tokyo, Japan

**Abstract:** Utilizing adaptive setpoint temperatures, which are setpoint temperatures dependent on adaptive thermal comfort models, has been recently considered and ended up being an energy conservation measure (ECM) with a significant energy saving potential. However, the only method to perform building energy simulations with adaptive setpoint temperatures was manually, and it was very time-consuming and error-prone. To address these inefficiencies, a computational approach, called Adaptive-Comfort-Control-Implementation Script (ACCIS) was developed and nested in an easy-of-use Python package called 'accim', which allows to automate most of the process. Up to now, only international adaptive comfort models have been included in ACCIS and accim, namely ASHRAE Standard 55 and EN 16798-1. However, local adaptive comfort models seem to be more accurate than international models. Therefore, this research presents the application of setpoint temperatures based on a local Japanese adaptive comfort model, and compares the energy consumption resulting from the application of static setpoints and the local Japanese model. The results show significant energy savings ranging between 25 and 52% for cooling, between 30 and 62% for heating, and between 30 and 52% for total energy demand, depending on the climate zone, although the higher energy savings take place at the extreme climates.

**Keywords:** Adaptive thermal comfort, Energy efficiency, Heating and cooling setpoint temperatures, Computational approach, Adaptive local comfort model

## 1. Introduction

Buildings account for over 30% of worldwide energy consumption (The United Nations Environment Programme, 2012), resulting in 40% of greenhouse gas (GHG) emissions. As a result, by 2050, the target is to have reduced GHG emissions by at least 80%. To achieve this, the construction industry must reduce GHG emissions by almost 90%, among other things. These assertive initiatives occur at the same time as a pandemic and rising energy bills. As a result, energy management to ensure good health is becoming increasingly holistic, taking into account the increase in time spent by households owing to intermittent confinement periods.

Six assessment reports (IPCC, n.d.) have been issued since the Intergovernmental Panel on Climate Change (IPCC) was founded in 1988, and numerous research have focused on climate change, increased GHG emissions, and natural resource scarcity (Kalvelage *et al.*, 2014, Wang and Chen, 2014, Rubio-Bellido *et al.*, 2016). Climate change has the potential to alter energy consumption projections and users' climate adaptability.

Adaptive comfort models have previously been presented for incorporating users' climate adaptation into reduced energy consumption. The main international standards EN 16798-

1:2019 (European committee for standardization, 2019) and ASHRAE 55-2020 (ANSI/ASHRAE, 2020), which consider user interaction with the environment, include such models. Both standards are based on two worldwide projects: SCATs (Smart Control and Thermal Comfort) (conducted in Europe) and RP-884 (conducted in various world locations). Such initiatives' outcomes revealed a link between the interior operative temperature and the external temperature in terms of user comfort.

Field investigations revealed that occupants' temperature responses are somewhat influenced by the external climate and differ from those of buildings with centralized HVAC systems, owing to differences in thermal experience, control availability, and occupant expectations (de Dear and G.S. Brager, 2002).

Specific adaptive thermal comfort models have been developed in recent years to I overcome the constraints of international models, (ii) comprehend the uniqueness of each country, and (iii) address specific living or building usage conditions:

(i) The limits of the two international adaptive comfort models are primarily based on the case studies analyzed. According to the EN 16798-1:2019 standard, which is the result of the SCATs project, the comfort standard is based on a limited database for outdoor temperatures greater than 25°C because data for such conditions is only available for two buildings in Greece, and the majority of the sample comes from countries with colder climates (e.g., United Kingdom and France). In other words, by applying this model to warm regions, the results are limited, and its applicability is reduced, especially when addressing climate change research. Even though the ASHRAE 55-2020 cases studies database includes instances from all around the world, many of them are mixed-mode and centralized HVAC buildings. As a result, specific examples may differ depending on the criteria evaluated.

(ii) In recent years, other national standards have been produced, such as ISSO 74 (Instituut Voor Studie En Stimulering Van Onderzoek, 2004, 2014) from the Netherlands and GB/T50785 (Ministry of Housing and Urban-Rural Development (China), 2012) from China. The first, in its second version from 2014 (Boerstra *et al.*, 2015), focuses on creating interior spaces with four levels of acceptability based on international databases and local studies with varying upper and lower limits. Two separate models are set according to the cold, warm, and moderate climate zones in the Chinese standard. Each model also creates two distinct groups, with the boundaries differing from international standards. Furthermore, customized models for distinct locations were developed in China (Yang *et al.*, 2020).

(iii) The most recent global trend is to conduct specific research for various building applications or to have a better understanding of actual living scenarios. In this regard, a research for office buildings (Manu *et al.*, 2016) was conducted in India, with two different models (natural ventilation or mixed-mode) and three percentages of approval. Other examples include the Chilean model for social housing (Pérez-Fargallo *et al.*, 2018), an adaptive comfort model for the elderly in Shangai (Jiao *et al.*, 2020), and two particular models for residential models in Australia (Williamson and Daniel, 2020) and natural ventilation buildings in Bucharest (Udrea *et al.*, 2018).

Another example is the local adaptive comfort model for Japanese residential spaces developed by Rijal et al (Rijal *et al.*, 2019), which was utilized as the local model in this work for comparison with the setpoint temperatures provided by the local Japanese government. This model was developed to quantify seasonal fluctuations in comfort temperature and to produce a domestic adaptation model for Japanese houses. It is based on a four-year thermal field survey that included 36,114 thermal comfort votes from 244 people of 120 dwellings in the Kanto area of Japan.

Adaptive comfort models' incorporation into buildings has a considerable impact on energy consumption (Ren and Chen, 2018). Some research have used this method to minimize energy usage by varying setpoint temperatures (Wan *et al.*, 2011, Hoyt *et al.*, 2014). The majority of them, on the other hand, employ setpoint temperatures based on the Predictive Mean Vote index (PMV). In recent years, a number of research papers have examined how adaptive setpoint temperatures affect energy usage by comparing their benefits and drawbacks to models based on the PMV. The following are some examples of such research: (i) Sánchez-García et al. (Sánchez-García, Rubio-Bellido, *et al.*, 2019) investigated the application of adaptive setpoint temperatures in future climate scenarios with the goal of lowering office building energy demand. Depending on the climatic scenario studied by the authors, daily setpoint temperature adjustments lowered demand and total HVAC consumption by 63 to 52 % and 61 to 51%, respectively. (ii) Holmes and Hacker (Holmes and Hacker, 2007) investigated the use of the adaptive thermal comfort strategy in several administrative buildings in the United Kingdom, both in the present and in the future scenarios; (iii) lastly, Kramer et al. (Kramer *et al.*, 2015) applied the lower limit of the comfort zone of the model produced by Van der Linden et al. (van der Linden *et al.*, 2006) (defined in the ISSO 74 standard (Instituut Voor Studie En Stimulering Van Onderzoek, 2004, 2014)) to the museum's heating setpoint temperature, resulting in a 74% reduction in energy usage. Although adaptive comfort models were initially designed for naturally ventilated rooms, Parkinson et al. (Parkinson *et al.*, 2020) recently published evidence that occupants tend to adapt to the interior environment independently of the technology used to provide it.

Given the potential for adaptive setpoint temperatures to save energy, research comparing adaptive setpoint temperatures to PMV-based setpoint temperatures have grown in popularity in recent years. However, because the technique for performing building energy simulations with adaptive setpoint temperatures was manual, it took a long time to complete these studies because it entailed repetitive and error-prone procedures. To overcome this flaw, the Adaptive-Comfort-Control-Implementation-Script (ACCIS) (Sánchez-García *et al.*, 2021) computational approach was created, which was then nested in the Python package 'accim' (Sánchez-García, 2021a), which stands for Adaptive-Comfort-Control-Implemented Model. This program not only automates the procedure, but also allows the user to develop numerous building energy models depending on user-specified parameters and run an unlimited number of simulations.

The utilization of setpoint temperatures based on adaptive thermal comfort models is investigated in this work. The research is unique in that it focuses on local comfort models rather than the previously utilized international comfort models. The methodology developed for this study is presented in Section 2, which includes an analysis of the different climate zones in Japan, a description of the study building, an update of the Python package accim to include the Japanese local adaptive model, and finally the use of accim. The results and discussion in Section 3 are based on the comparison of static or PMV-based and local adaptive setpoint temperatures. The conclusions are presented in Section 4.

## 2. Methodology

### 2.1. Climate zones in Japan

According to the Japanese Building Technical Code, Japan's area is split into eight climatic zones based on heating degree-day requirements at a setpoint temperature of 18°C (Fig. 1). As a result, climate data (i.e. EnergyPlus Weather, EPW) for one city in each climatic zone was utilized in this study to offer an overall picture of the possibilities of adopting local adaptive setpoint temperatures across Japan's territory. Wen et al (Wen *et al.*, 2017) conducted a research that looked at the different climatic zones in Japan, thus the same sites were employed in this study for consistency with the surrounding literature. Given the diversity of Japan's climates, this study and the chosen area allowed determining the feasibility of adaptive local setpoint temperatures for various climates, as well as the potential for energy savings. The yearly average outdoor dry-bulb air temperature ranges from 7.1 to 23.6°C, varying from cooler (Asahikawa, climatic zone 1) to warmer (Naha, climate zone 8). (Figure 1, Table 1).

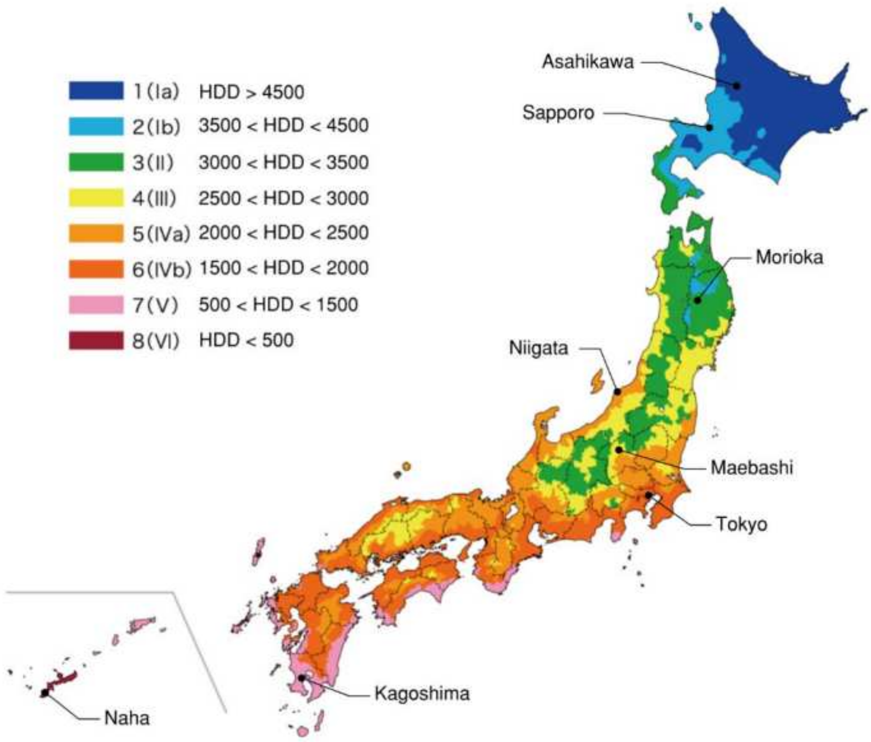


Fig. 1. Climate zones according to Japanese Building Technical Code based on the heating degree-days thresholds.

Table 1. Basic information of the selected locations.

| City | Climate Zone (Koppen-Geiger) | Outdoor Dry-bulb Temperature (°C) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Months | | | | | | | | | | | | Year |
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | |
| Asahikawa | 1 (Dfb) | -7.7 | -6.7 | -1.3 | 5.5 | 12.6 | 16.9 | 21.0 | 21.4 | 16.3 | 9.4 | 2.1 | -4.6 | 7.1 |
| Sapporo | 2 (Dfa) | -5.6 | -5.0 | -0.3 | 6.0 | 12.3 | 16.3 | 20.4 | 21.7 | 17.3 | 10.7 | 3.6 | -3.0 | 7.9 |
| Morioka | 3 (Dfa) | -1.8 | -1.3 | 2.9 | 9.1 | 15.4 | 19.2 | 23.0 | 24.1 | 19.5 | 13.1 | 6.4 | 0.7 | 10.9 |
| Niigata | 4 (Dfa) | 2.8 | 3.1 | 6.4 | 11.6 | 17.3 | 21.0 | 25.2 | 26.9 | 22.7 | 17.0 | 10.7 | 5.5 | 14.2 |
| Maebashi | 5 (Cfa) | 3.2 | 4.0 | 7.9 | 13.3 | 19.0 | 22.2 | 26.7 | 27.6 | 22.9 | 17.1 | 11.0 | 5.8 | 15.1 |
| Tokyo | 6 (Cfa) | 5.4 | 6.2 | 10.3 | 15.4 | 20.3 | 23.1 | 27.1 | 28.0 | 23.7 | 18.6 | 13.0 | 7.9 | 16.6 |
| Kagoshima | 7 (Cfa) | 7.5 | 9.1 | 12.2 | 16.7 | 20.8 | 23.4 | 28.1 | 28.7 | 25.1 | 20.6 | 14.7 | 9.6 | 18.0 |
| Naha | 8 (Cfa) | 17.7 | 18.2 | 19.4 | 21.4 | 24.5 | 26.9 | 29.4 | 29.3 | 27.8 | 26.0 | 22.7 | 19.5 | 23.6 |

## 2.2. Case study

In terms of envelope characteristics, the façade is constituted of painted concrete walls with internal insulation and plywood boards with painted paper interior finishes (1.0267 W/m2K), while the roof is made up of concrete floor tiles and a concrete slab with rigid insulation (1.2238 W/m2K). The windows have a wooden frame and 3mm single glazing. Table 2 has detailed information. All of these designs have been included in the building energy model made for this study since they are often utilized in social building flats.

Table 2. Characteristics of the building case of study.

| Element | Layers (outside to inside) | U-value (W/m²K) |
|---|---|---|
| Envelope | Coat of paint | 1.0267 |
| | 15cm Concrete structural wall | |
| | 3cm Rigid insulation (0.03 W/mK) | |
| | Plywood board | |
| | Painted paper | |
| Roof | 5 cm Concrete floor tiles | 1.2238 |
| | 3cm Rigid insulation | |
| | Waterproofing sheet | |
| | 15cm Structural concrete slab | |
| Internal partitions | Painted paper | 1.4733 |
| | 2cm Plywood board | |
| | 6cm Timber studs substructure | |
| | 2cm Plywood board | |
| | Painted paper | |
| Ground floor slab | 15cm Structural concrete slab | 0.5699 |
| | Vinyl flooring | |
| Windows | 3mm Clear Single glazing | 5.8940 |
| | Painted wooden frame | 3.6330 |

Table 3 shows the consumption profile for the building under study. This profile represents the residential building usage and takes into account three types of loads: occupancy, equipment, and illumination. The load profiles of equipment and lighting systems were the same regardless of the day of the week, while occupancy loads were different in weekdays and weekends.

Table 3. Use profile of rooms at the building case of study.

| Type of load | Days | Hours and load (W/m²) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 0:00-6:59 | 07:00-14:59 | 15:00-17:59 | 18:00-18:59 | 19:00-22:59 | 23:00-23:59 |
| Occupancy (sensible) | Mon., Tue., Wed., Thu., Fri. | 2.15 | 0.54 | 1.08 | 1.08 | 1.08 | 2.15 |
| | Sat., Sun. | 2.15 | 2.15 | 2.15 | 2.15 | 2.15 | 2.15 |
| Occupancy (latent) | Mon., Tue., Wed., Thu., Fri. | 1.36 | 0.34 | 0.68 | 0.68 | 0.68 | 1.36 |
| | Sat., Sun. | 1.36 | 1.36 | 1.36 | 1.36 | 1.36 | 1.36 |
| Lighting | Week | 0.44 | 1.32 | 1.32 | 2.2 | 4.4 | 2.2 |
| Equipment | Week | 0.44 | 1.32 | 1.32 | 2.2 | 4.4 | 2.2 |

The 51C, one of the most popular public housing types in Japan, is the subject of this research. It was called after the year when a group of Japanese researchers on public housing originally designed it (1951) (Ozawa and Mizunuma, 2006). It is constituted of a 2DK (Dining-Kitchen) apartment with an open layout (Fig. X). The entryway leads to a dining-kitchen area that links immediately to the two bedrooms, which are measured in tatami mats. The largest bedroom contains 6 tatami mats (about 10 sqm), while the smallest has 5 tatami mats (circa 8 sqm). Those rooms were not meant to feature beds, but rather sleeping mats (futons) that would be folded and stored within the closet during the day, then spread out on the tatami before bedtime. With the exception of the bathroom and the toilet, all rooms are connected through sliding doors. Because public housing complexes are often vast, each block is separated from its neighbours and surrounded by shared green spaces. The flats are structured into long 4-story blocks, with two units per level accessible through one stairway. Each apartment includes a large balcony that faces south and windows that face north, allowing for cross ventilation in all rooms.

This background information defines the scope of our study, which focuses on a model of Japanese social housing that represents an elderly residential stock with low-income residents.

### 2.3. Inclusion of Japanese local adaptive model in accim

Only the Spanish standard for energy calculations provided in the Building Technical Code (CTE by its initials in Spanish) and two international thermal comfort standards (EN 16798-1 and ASHRAE 55), were previously included in the Python program accim. However, a Japanese local adaptive model has been introduced to identify changes in energy usage. Given the large number of thermal comfort votes obtained, this model, created by Rijal et al. (Rijal *et al.*, 2019), was chosen for its excellent reliability.

The weighted mean outside temperature, whose nomenclature varies depending on the adaptive standard, is used to develop adaptive comfort models. Because ASHRAE 55 is the only world-wide adaptive comfort model, Prevailing Mean Outdoor Temperature (PMOT) will be employed in this situation, as per the ASHRAE 55 framework (Eq. 1). The comfort temperature equation (Fig. 3, free-running (FR) graph) is derived using linear regression and uses PMOT as an input (Eq. 2)

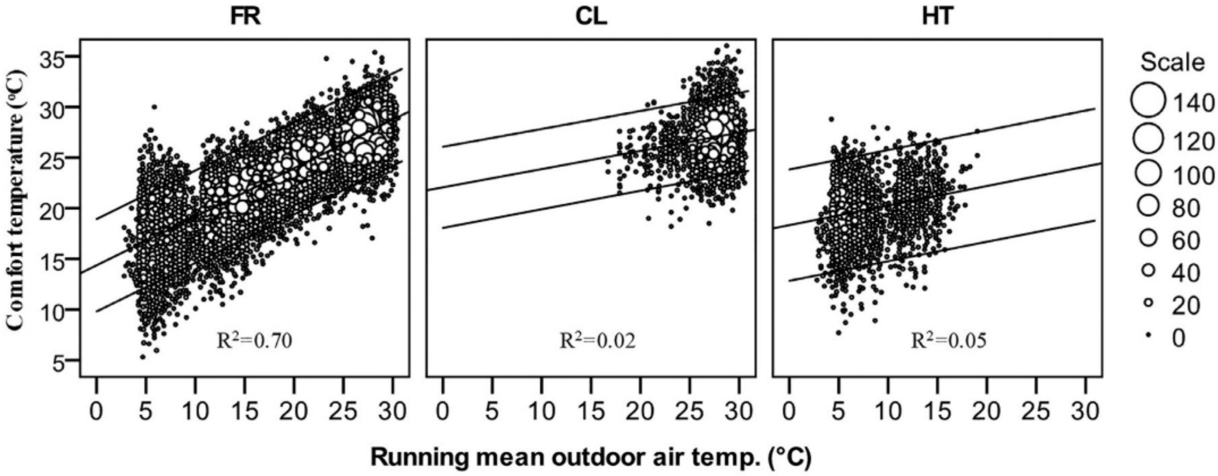


Figure 3: Linear regression of the Japanese local adaptive comfort model by Rijal et al. (Rijal et al., 2019) for free-running (left), cooling (center) and heating (right) modes.

$$\text{PMOT} = (1-\alpha)\cdot\sum_{d=1}^{n}\left(\alpha^{(i-1)}\cdot T_{ext,d}\right)\quad [°C] \tag{1}$$

$$Comfort\ temperature = 0.48\cdot\text{PMOT} + 14.4\quad [°C] \tag{2}$$

Because some information needed for implementation was not provided in the research article, some assumptions were made: applicability limits were set at 5°C and 30°C for both upper and lower comfort limits, and offsets from comfort temperature for comfort limits were set at 3.5°C and 2.5°C for 80 percent and 90 percent acceptability levels, respectively, for consistency. The formulae for upper and lower comfort limits are derived using these assumptions (Eqs. 3-6).

$$Upper\ limit\ (80\%\ acceptability) = 0.48\cdot\text{PMOT} + 14.4 + 3.5\ [°C]\quad (5°C \leq \text{PMOT} \leq 30°C) \tag{3}$$

$$Lower\ limit\ (80\%\ acceptability) = 0.48\cdot\text{PMOT} + 14.4 - 3.5\ [°C]\quad (5°C \leq \text{PMOT} \leq 30°C) \tag{4}$$

$$Upper\ limit\ (90\%\ acceptability) = 0.48\cdot\text{PMOT} + 14.4 + 2.5\ [°C]\quad (5°C \leq \text{PMOT} \leq 30°C) \tag{5}$$

$$Lower\ limit\ (90\%\ acceptability) = 0.48\cdot\text{PMOT} + 14.4 - 2.5\ [°C]\quad (5°C \leq \text{PMOT} \leq 30°C) \tag{6}$$

Adaptive setpoint temperatures are applied by an EnergyManagementSystem:Program object called ‘SetAST’ (which stands for Set Adaptive Setpoint Temperatures). This object contains different if-statements which allows to customise the assignment of setpoint temperatures depending on some parameters specified by the user, namely ‘AdapStand’, ‘CAT’ and ‘ComfMod’, which has been previously studied in (Sánchez-García, Bienvenido-Huertas, *et al.*, 2019, Bienvenido-Huertas *et al.*, 2020, Sánchez-García *et al.*, 2020).

All data related to the Japanese local adaptive model is listed in Table 4. AdapStand stands for Adaptive Standard, and refers to the adaptive comfort model to be applied. In this study, only the Japanese adaptive comfort model has been considered, therefore AdapStand is always 3. CAT stands for acceptability levels (i.e. occupant expectations) and overrides the comfort zone width (increases and decreases 1°C the cooling and heating setpoint temperatures respectively, changing from 2.5 to 3.5 and -2.5 to -3.5 for cooling and heating setpoint temperatures respectively). In this study, only 80% acceptability levels are considered, therefore CAT is always 80. Lastly, ComfMod stands for Comfort mode (determines the behaviour of the setpoint temperatures when adaptive applicability limits are not met, i.e PMOT < 5°C or 30°C < PMOT), and therefore will determine if the applied setpoint temperatures are based on the PMV-index or local adaptive Japanese model. Static or PMV-based setpoint temperatures are utilized when ComfMod = 0. The static model in this case is based on the Japanese Local Government's specified setpoint temperatures. In the case of the heating setpoint temperature, 18°C is the baseline used in the Japanese Building Technical Code for calculating heating degree-days, while in the case of the cooling setpoint temperature, 28°C is the temperature that the Japanese Government suggested using in summer after the Fukushima nuclear plant incident for energy-saving purposes, considering that office workers would be allowed to wear casual clothes instead of suit and tie (COOL BIZ campaign (Tanabe *et al.*, 2013)). As a result, the cooling setpoint temperature has been set at 28°C, not only because occupants are expected to dress casually, but also to be consistent with other relevant research publications (Yuan *et al.*, 2017). There are other ComfMod behaviours related to values 1 and 2, however these have not been included in Table 4 for clarity purposes, since these are out of the scope of research.

Table 4. Setpoint temperatures values as a function of parameters AdapStand, CAT and ComfMod, and applicability limits.

| AdapStand | CAT | Mode | ComfMod | Setpoint temperatures | | |
|---|---|---|---|---|---|---|
| | | | | PMOT < 5°C | 5°C < PMOT < 30°C | 30°C < PMOT |
| 3 | 80 | Cooling setpoint temperature | 0 | | 28 | |
| | | | 3 | 5*0.48+14.4+3.5 | PMOT*0.48+14.4+3.5 | 30*0.48+14.4+3.5 |
| | | Heating setpoint temperature | 0 | | 18 | |
| | | | 3 | 5*0.48+14.4-3.5 | PMOT*0.48+14.4-3.5 | 30*0.48+14.4-3.5 |

PMOT: Prevailing mean outdoor temperature

### 2.4. Use of accim

The tool has been updated to preserve its convenience of use while adhering to the concepts and standards stated in accim. After installing Python, do ‘pip install accim’ to install the accim Python package. The user must then open the command prompt in that folder and execute Python, given there is at least one IDF file (which is the EnergyPlus building energy model itself). Finally, it just needs 2 lines of code to apply adaptive setpoint temperatures:

```
from accim.sim import accis
accis.addAccis()
```

The tool will then ask the user for some information about the parameters for the output IDF files it will generate. The desired parameters can also be specified when calling the function, as detailed in the available documentation (Sánchez-García, 2021b). For instance, the following code was used in this study:

```
from accim.sim import accis
accis.addAccis(
    ScriptType='vrf',
    TempCtrl='temp',
    Outputs='standard',
```

```
    EnergyPlus_version='ep96',
    AdapStand=[3],
    CAT=[80],
    ComfMod=[0, 3],
    HVACmode=[0],
    VentCtrl=[0],
    VSToffset=[0],
    MinOToffset=[50],
    MaxWindSpeed=[50],
    ASTtol_start=0.1,
    ASTtol_end_input=0.1,
    ASTtol_steps=0.1
    )
```

## 3. Results and discussion

The results obtained show the energy saving potential of using adaptive setpoint temperatures based on local adaptive comfort models (shown in the figures as CM_3, which stands for Comfort mode or 'ComfMod' 3) against static or PMV-based setpoint temperatures (shown in the figures as CM_0, which stands for Comfort mode or 'ComfMod' 0). As stated above, Comfort mode 3 corresponds to the application of the local adaptive comfort model, and when applicability limits are exceeded, the comfort limits are extended horizontally, while Comfort mode 0 corresponds to the static temperatures based on the COOLBIZ Campaign (18°C for heating and 28°C for cooling throughout the year).

The results show that the highest total energy consumption takes place in Asahikawa climate (1067 kWh/m² in Comfort mode 0 and 743 kWh/m² in Comfort mode 3), which is the coldest climate, and it gradually decreases towards warmer climates. However, this tendency changes after Tokyo (395 kWh/m² in Comfort mode 0 and 193 kWh/m² in Comfort mode 3) for the climates of Kagoshima and Naha (605 kWh/m² in Comfort mode 0 and 290 kWh/m² in Comfort mode 3), where temperatures exceed acceptable limits and therefore energy demand increases because of cooling systems start to work.

The percentage of reduction in energy demand ranges depending on the climate between 25 and 52% for cooling, between 30 and 62% for heating, and between 30 and 52% for total energy demand, while the average reduction is 41% and 43% for cooling and heating, and 43% for the total energy demand (Table 5).

In terms of absolute values, the reduction in energy demand ranges between 20 and 315 kWh/m² for cooling, between 20 and 300 kWh/m² for heating, and between 191 and 324 kWh/m² for total energy demand, while the average reduction is 118 kWh/m² and 136 kWh/m² for cooling and heating, and 253 kWh/m² for the total energy demand (Table 5). Therefore, although the highest percentages of reduction take place in mild and warm climates (from Niigata to Naha), the highest absolute reductions (in terms of kWh/m²) takes place at the extreme climates (Asahikawa and Naha).

In order to maximise the comfort hours, HVAC systems have been allowed to work at any time, any day of the week. Therefore, Fig. 4 shows that indoor operative temperature has been within adaptive comfort limits at all hours, both in Comfort mode 0 and Comfort mode 3, for all climates. This figure also shows the drastic change in the range of temperatures, which varies between roughly -10°C and 23°C in Asahikawa, where setpoint temperatures need to be horizontally extended below 5°C in the PMOT, to 17°C and 30°C in Naha, where setpoint temperatures do not need to be horizontally extended, since 30°C in the PMOT are not exceeded.

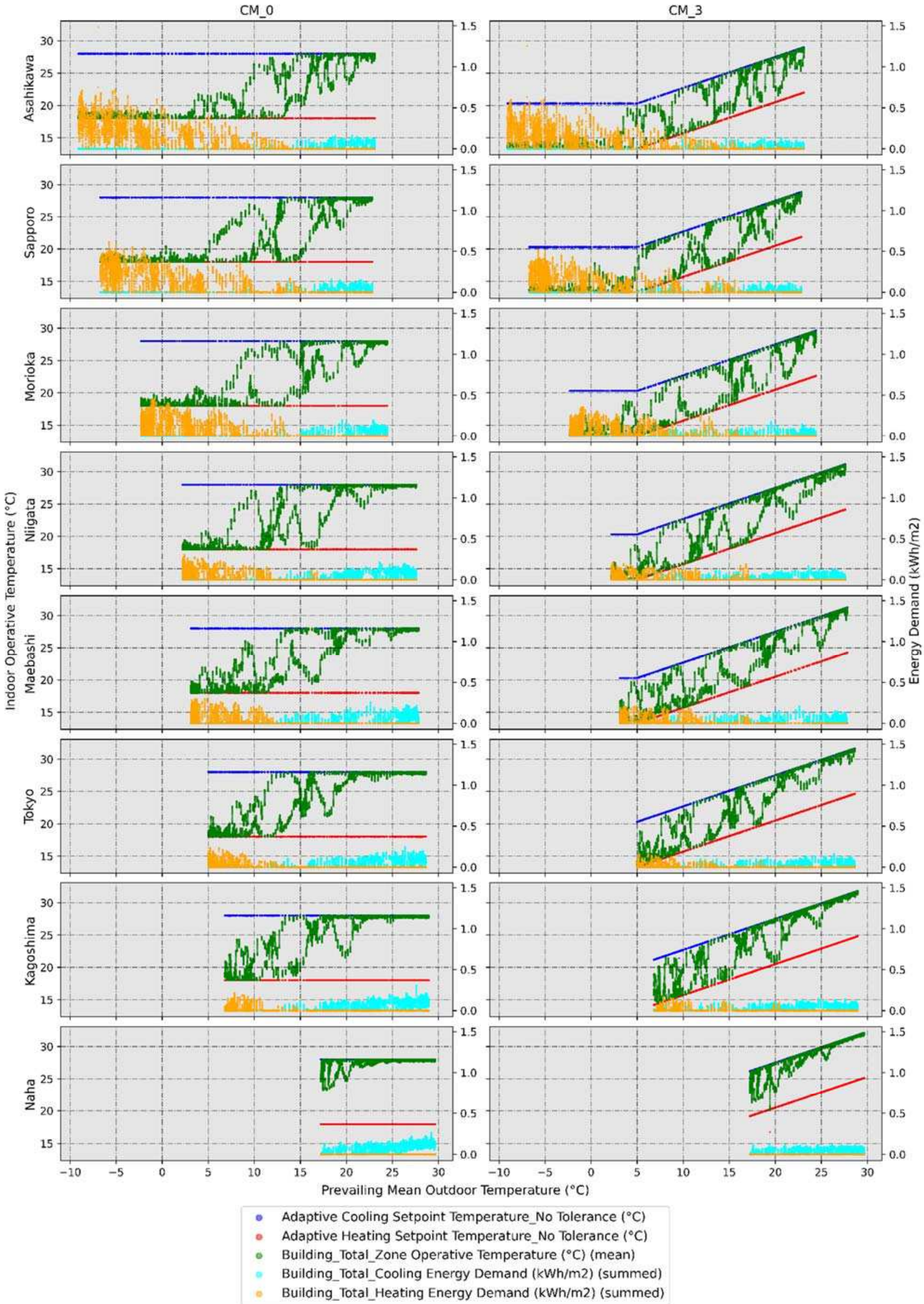


Figure 4. Indoor operative temperature and energy demand as a function of the PMOT.

Table 5. Energy demand depending on the operation mode, Comfort mode and climate zones.

| Operation mode | Comfort mode | Energy Demand (kWh/m²) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Asahikawa | Sapporo | Morioka | Niigata | Maebashi | Tokyo | Kagoshima | Naha | Average |
| Cooling | CM_0 | 82 | 79 | 145 | 229 | 265 | 295 | 357 | 605 | 257 |
| | CM_3 | 58 | 59 | 92 | 127 | 148 | 155 | 187 | 290 | 140 |
| Heating | CM_0 | 985 | 824 | 529 | 277 | 194 | 100 | 52 | 0 | 370 |
| | CM_3 | 685 | 562 | 318 | 143 | 98 | 38 | 32 | 0 | 235 |
| Total | CM_0 | 1067 | 903 | 674 | 505 | 458 | 395 | 410 | 605 | 627 |
| | CM_3 | 743 | 621 | 411 | 270 | 246 | 193 | 219 | 290 | 374 |
| Cooling | 1-(CM_3/CM_0) | 29% | 25% | 36% | 45% | 44% | 47% | 48% | 52% | 41% |
| | CM_0 - CM_3 | 24 | 20 | 53 | 102 | 116 | 140 | 171 | 315 | 118 |
| Heating | 1-(CM_3/CM_0) | 30% | 32% | 40% | 48% | 50% | 62% | 39% | -inf | 43% |
| | CM_0 - CM_3 | 300 | 262 | 211 | 133 | 96 | 62 | 20 | 0 | 136 |
| Total | 1-(CM_3/CM_0) | 30% | 31% | 39% | 47% | 46% | 51% | 47% | 52% | 43% |
| | CM_0 - CM_3 | 324 | 282 | 264 | 235 | 213 | 202 | 191 | 315 | 253 |

## 4. Conclusions

The use of setpoint temperatures based on adaptive thermal comfort models has been recently studied and considered an energy conservation measure with a high energy saving potential, mostly dependant on the climate. Also, an open-source computational method called ACCIS has been recently developed and nested in a Python package called 'accim', which allows to automate most of the entire process of performing building energy simulations considering adaptive setpoint temperatures. This computational method only allowed to apply adaptive setpoint temperatures based on international standards ASHRAE 55 and EN 16798-1, however, functions have been extended by considering the application of setpoint temperatures based on a local adaptive comfort model, namely a comfort model developed by Rijal et al for residential spaces in Japan. Therefore, in order to study the energy saving potential of the local adaptive setpoint temperatures, a representative building case of study has been selected, considered one of the most popular public housing types in Japan (the 51C), and it has been studied in the different climates considered in Japanese Building Technical Code.

The energy saving potential of local adaptive setpoint temperatures has been studied by means of the comparison with static setpoint temperatures, relevant to the Japanese area and culture. With that purpose, static setpoint temperatures based on the COOLBIZ campaign has been chosen (18°C and 28°C for heating and cooling respectively), while for the local adaptive setpoints, the adaptive comfort limits has been horizontally extended beyond applicability limits.

The results show significant savings in energy demand, which range depending on the climate between 25 and 52% for cooling, between 30 and 62% for heating, and between 30 and 52% for total energy demand, while the average energy saving is 41% and 43% for cooling and heating, and 43% for the total energy demand. Also, it is remarkable that these savings are achieved by only adjusting the HVAC system thermostat, with no retrofit of the building envelope or renovation of HVAC system.

Also, this computational approach can be widely applied to any heating and cooling control system in any location (i.e. with any EPW file), since adaptive setpoint temperatures can be applied to the existing HVAC systems in the building energy model, and the values of these are calculated 'on the go' by EnergyPlus as the simulation runs. Also, its high customization attributes allow to perform a wide range of simulations varying the settings of the output IDFs.

Although this study sheds light on the application of setpoint temperatures based on local adaptive comfort models, further research is needed to fully understand the energy saving potential, and therefore it must be understood as the first step to future studies such as the inclusion of local adaptive models for other countries, and the comparison with international standards.

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# PAVEMENTS AND MICROCLIMATIC COMFORT IN REQUALIFICATION DESIGNS OF URBAN PUBLIC SPACES: CASE STUDY OF THE SOUTH LOCAL HOSPITAL SECTOR – BRASILIA/DF

**Juliana Linder de Oliveira Lahn[1], Gustavo A. C. Cantuaria[2] Manuel Correia Guedes[3]**

[1] CEUB Centro Universitário de Brasília, Brazil, juliana.lahn@sempreceub.com
[2] CEUB Centro Universitário de Brasília, Brazil, gustavo.cantuaria@ceub.edu.br
[3] IST Instituto Superior Técnico de Lisboa, Portugal, manuel.guedes@tecnico.ulisboa.pt

**Abstract:** Thermal comfort in public spaces is one of the main indicators that provides for its enjoyment, and habitability. Considering that the thermal and permeability properties of pavement materials are strongly related to heat intensity perceived in public spaces, the objective of this research is to investigate thermal behavior of different pavement materials for the thermal comfort of its users, by means of microclimatic studies for the requalification of the South Hospital Sector of Brasilia, in both the dry and rainy season. The methodological procedures for this work are: literature review; analysis of environmental surface variables; and analysis of superficial temperature of selected spaces. For data corroboration, simulated scenarios with ENVI-met 5.0 software were analyzed. Results show that material temperatures in the rainy season have a different behavior in relation to the dry period, and a constant relation to the increase in temperature according to the material used, and if exposed to sun or sheltered by shade. During the dry season, "cold" materials performed better in a sun exposed space. Significant differences of up to 22°C were recorded. The simulations corroborated with the fieldwork investigation.

## Introduction

On the constructive scale, projects for public spaces must be carefully designed, ensuring that people walk, cycle, and socialize. As for the pavements, the combination of the materials that cover it should facilitate the routes, bring safety, comfort, and accessibility, and also alleviate the thermal sensations. However, in the process of materialization of public space, building materials have a high capacity to absorb and re-radiate heat, in addition to favoring the decline of evaporation, as they are impermeable.

The use of suitable materials in urban planning contributes to reducing surface temperatures that affect thermal exchanges with the air. As for this adaptation, the choice of the type of pavement covering in urbanization projects should be conditioned to the characteristics of the environment, in addition, to take advantage of the surface qualities of the constituent materials.

The bioclimatic conception of the public space adopts objective criteria regarding the choice of the types of materials that compose it. According to Doulos et al (2004), the role of construction materials is decisive for the reduction of thermal gains and overheating. In Brazil, the performance characteristics of pavement materials as part of the heat mitigation strategy in urban areas are still poorly explored. Therefore, it becomes important to expand knowledge in the area, to subsidize urbanization projects to improve thermal comfort and health conditions in urban spaces.

Thus, this research investigates the contribution of pavement treatment regarding thermal comfort through microclimatic studies, in requalification projects of urban public spaces. The choice of the city of Brasília as the study area is mainly due to the moment in which several projects for the revitalization of public spaces are carried out, which include the treatment of the pavements in these spaces.

**Pavements and its microclimatic implications**

The material's performance is decisive in the thermal gain, and they are determined by the radiative and thermal characteristics, being the albedo (reflectance coefficient) and the emissivity the most significant (DOULOS; SANTAMOURIS; LIVADA, 2004). The percentage of reflective energy back to the atmosphere depends on the characteristics of the material and surface coverage, so more radiation will be absorbed, and more heat emitted by the surface depending on the pavement used.

In public spaces, the construction materials used have a lower albedo, higher heat capacity and a high value of thermal conductivity in relation to natural soil. Such characteristics result in the modification of the radiation balance, influencing, above all, the increase in temperature and air humidity, which impairs the bioclimatic quality of the space.

Doulos, Santamouris and Livada (2004) compared the thermal performance of 93 paving materials commonly used in open spaces. For the same material, temperatures ranged from 33.4ºC to 54ºC, where the minimum value was observed for the white colour and the maximum for black colour. As for texture, smoother surfaces had lower temperatures than rough surfaces. High temperatures were observed on black and gray pebble surfaces, in the order of 45ºC. As for the type of material marble, stones and mosaics were cooler than other materials.

Thus, 'cold' materials can be characterized as those that have a smooth and light-colored surface with materials made of marble, stone, and mosaics (natural raw material). In the same way that hot materials can be defined by those that have a rough surface and dark color, and with materials made of pebble and paving stone.

Dimoudi et al. (2014) monitored the thermal fluctuation of the city of Serres in Greece, where traditional construction materials are used. The simulations of substitution by 'cold' materials accompanied by other mitigating techniques resulted in the reduction of the average surface temperature of the streets by up to 6º C.

Thus, the use of 'cold' materials contributes to the reduction of air temperature due to heat transfer phenomena. However, 'warm' materials are used for urban structures rather than 'cold', both for aesthetic, comfort, and economic reasons, as well as poor planning.

In addition to thermal and radiative properties, the permeability properties of pavement materials also influence human thermal discomfort in spaces. The replacement of natural soil and vegetation with impermeable surfaces, such as asphalt and concrete, reduces the cooling effect of the air by evaporation, further increasing the surface temperature. The impermeability of pavements reduces the possibility of heat release by evapotranspiration. The part absorbed by a surface is used as latent heat to evaporate the water contained therein, while the remaining energy is conducted to its interior (ROMERO, 2011).

As a mitigating proposal, permeable coating materials are considered an effective technology. Research on permeable pavements is aimed at increasing capillarity, since its thermal response depends on the availability of water for evaporation, cooling the pavements (SANTAMOURIS, 2013).

Studies carried out in China have shown the effectiveness of permeable pavements in urban thermal comfort through evaporative cooling (WANG et al., 2018). After testing two types of permeable materials (permeable concrete and draining ceramic blocks), the results indicated that floors with high capillary strength can improve thermal comfort above the pavements by up to 3°C.

In view of this, it is possible to highlight the direct influence on the urban microclimate of the materials incorporated into the urban infrastructure. In urban public spaces, the use of appropriate materials, such as 'cold' and permeable materials, associated with the intensive use of vegetation, can generate comfort conditions, especially in cities with a hot and dry climate such as Brasília.

**Bioclimatic design for public spaces**

In the current urban context of intense transformation of the natural space, the relationship between the dynamics of life and the environment has taken more and more opposite directions, especially in large city centres. Hence the appearance of the bioclimatic conception of public spaces.

The term refers to the harmonious relationship between the built environment and the natural site and consists of an architectural design aimed at controlling climatic conditions to satisfy human comfort requirements (OLGYAY, 1963). The bioclimatic conception of public space aims at comfort and health through guidelines, strategies, and sustainable techniques to control the physical-natural agents of each urban site (ROMERO, 2015). Choosing the right pavement is part of these strategies for thermal comfort.

In recent research on the influence of pavement materials on air heating, DJEKIC et al. (2018) highlights different mitigation and adaptation strategies such as: solar control that include shading systems such as pergolas and tents; the shading of trees that reduce the radiant temperature of the materials; and the cooler, more permeable materials.

Thus, the bioclimatic design considers the thermal comfort of the users as an important element in the urban design proposal, as it seeks to avoid situations in which people do not spend time in these spaces, due to inadequate weather conditions.

**The context of Brasilia**

Brasília, capital of Brazil, is in the middle of the country, at 1070 meters above sea level. According to the Köppen climate classification, the climate of the Federal District is tropical of altitude and its rainfall is characterized by marked seasonality. About 90% of precipitation occurs in the rainy season (October to March), while in the dry season (April to September) it rarely rains more than 9mm/month. (BRASILIA, 2020).

Average annual temperatures vary between 19°C and 23°C. The hottest period occurs in September and October, in which the historical average of the highest temperatures reaches 30°C. The coldest period occurs in June and July, months when the lowest temperatures reach 13°C.

As for the urban context, the city was inaugurated in 1960, becoming a landmark in the history of urban planning. Lucio Costa's project became known by the name of Plano Piloto and was openly conceived under the urban principles prescribed by the International Congresses of Modern Architecture - CIAM. These principles were translated into four urban scales: the monumental, the residential, the bucolic and the gregarious. The urban scales, together with the other principles already enshrined in the urban design of Brasília, are fundamental pillars and constitute its uniqueness and exceptionality (BOTELHO, 2009).

After 60 years of its inauguration, today it is necessary to make some corrections and adaptation to the current demand, especially the streets and sidewalks, because it is on them that people move. However, the modern heritage of the city of Brasília must be considered.

In this sense, the PPCUB - Plan for the Preservation of the Urban Complex of Brasília, provides for the urban qualification of public spaces in cities to intensify the urban dynamics and promote the continuous conservation of these spaces according to urban scales; and landscape, through strategies that promote bioclimatic comfort.

The South Hospital Sector Requalification Project (SHLS), object of study of this work, was executed and inaugurated in 2020. With the objective of requalifying the sector and promoting the use of public transport and pedestrians, the project reduced the size of the car lanes, limited the parking lots, changed the texture of the pavements, installed pergolas, planted trees, among other changes. As for the pavements, more permeable and 'cooler' materials were proposed, as shown in Figure 1.

Fig 1.  Before and after pavement change

**Methodology**

To reach the research objective, which relates pavement treatments in public spaces with the urban microclimate, an investigation was developed within the qualitative perspective with technical procedures of a case study and based on the theoretical conception.

Measurements were taken in public spaces adjacent to hospitals in the South Hospital Sector of Brasilia, which were covered by the proposed new pavements in its lanes, sidewalks, parking lots and squares.

Three measurement points were selected in these spaces (Figure 2). The definition of points was based on the type of surface, seeking to include the following types in the areas under study: asphalt; concrete floor; natural soil; lawn; Interlocked concrete blocks; perforated blocks with grass (pisograma), and washed granite pavement  (fulget), composed of small natural stones and cement, which allows its surface to remain porous and rough, which makes it non-slip.

Fig 2. Measurement spots

The chosen spots points were also representative of Romero's classification (2015): A- Shaded zones during the day and open at night; B – Shade during the day and covered during the night; and C – Open zones.

To characterize the spaces in terms of pavement covering, an area of influence of approximately 4,000m² was marked to determine the percentage of covering surface material at each measurement point.

**Definition of climate variables; of measurement periods and equipment**

Based on the literature review, the following climatic variables were chosen to be measured: air temperature (ºC) – Ta; relative air humidity (%) - %RH; Surface Temperature (ºC) – Ts.

Measurements were carried out for three consecutive days, in the dry season (September/October), and rainy season (January). Measurements were taken at 9 am, 3 pm and 9 pm.

To carry out the research, a thermo-hygrometer was used to measure Ta and %RH; and a thermographic camera, to measure the surface temperatures at selected points. Furthermore, the INMET meteorological station provided additional climatic data for comparative analysis.

**Envi-met simulations**

The ENVI-met software is a three-dimensional model that simulates the urban microclimate. The program provides interactions between surface-vegetation-atmosphere, calculating the energy balance through the variables: radiation, reflection and shading of buildings and vegetation, air flow, humidity and the thermal exchange of water and heat within the soil.

The simulation stage was divided into three sequential phases: preparatory phase, modeling phase and simulation phase. In the preparatory phase, the necessary information was gathered for the delimitation of the study area and the main characteristics of the climate in Brasilia. The meteorological data was organized to build an input simulation file for the next step.

Due to the limitation of simulation of permeable pavements, and for its performance to be evidenced in the rainy season, it was decided to enter only climatological data from the dry season. Since it is also the most critical time of the year, as it registers high temperatures with low humidity, which brings great discomfort to pedestrians. Thus, the months of September and early October were incorporated as representative months for investigating the dry period.

In the modeling phase, three-dimensional models were created corresponding to the selected locations and the areas occupied by buildings and the types of pavements that cover the ground were identified.

During the last phase, the original scenario was simulated, prior to the intervention, and the current scenario (Modified Scenario) with the intervention already carried out. The construction of these scenarios aims to fill the gap of the impossibility of collecting data before the SHLS intervention and to estimate the bioclimatic strategies through the treatment of pavement coverings. In addition to these scenarios, the Green Scenario was also simulated, which includes the inclusion of urban vegetation as proposed by the projects.

For a comparative analysis, two parameters were extracted to evaluate the effect of each strategy: Air temperature and Surface temperature. The surface temperature parameter is discussed as a function of the albedo and emittance changes of cold materials and the surface permeability. Air temperature was chosen because it is a parameter that influences human thermal comfort.

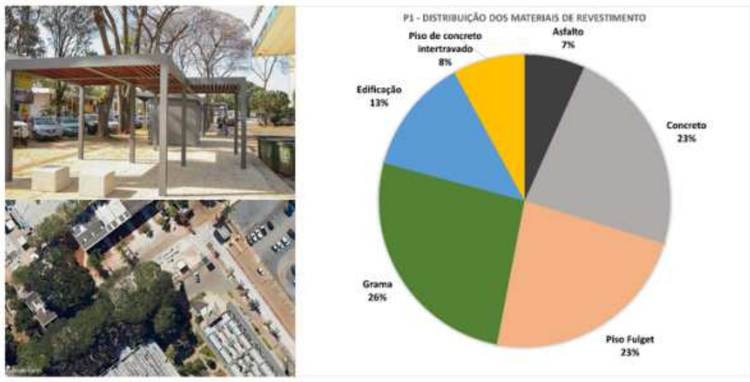
**Study case results analysis and discussion**

**Physical variables**

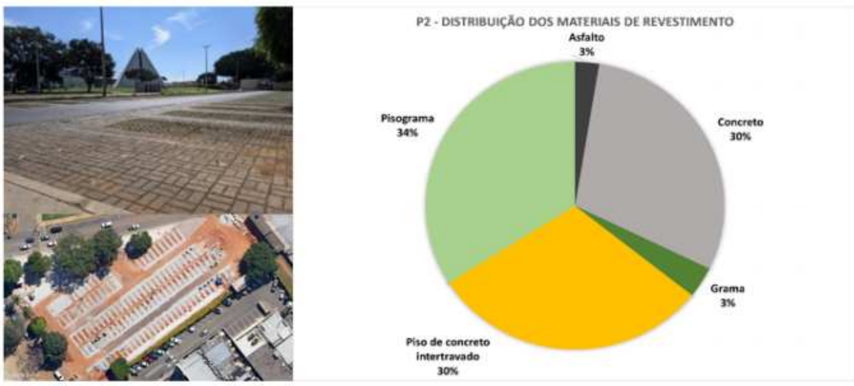
Once the area of influence was traced, the floor covering materials were classified according to the impact of solar radiation incidence near the surface and the effects of cooling the air by evaporation.

Fig 3. Images below present an aerial photograph, a location, and the floor distribution chart at each collection point.

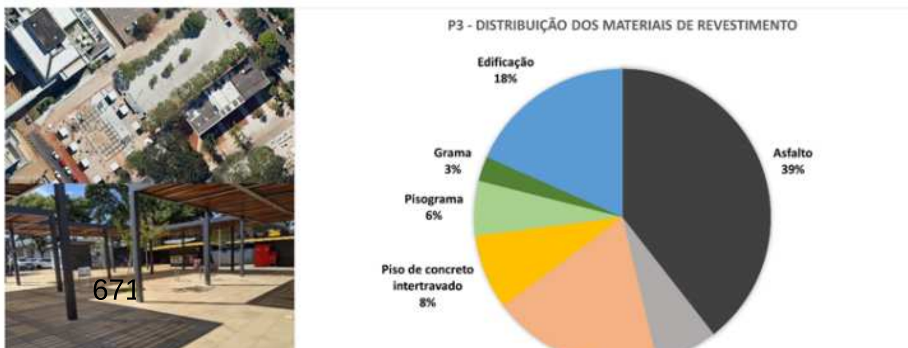
POINT 1




POINT 2




POINT 3



**Climate variables**

In the process of surveying the climatic variables and their relationship with the existing pavement, in terms of air temperature, it was not possible to estimate the microclimatic cooling potential, primarily due to the impossibility of collecting data before and after interventions in the same sector; and, as the points are open spaces very close together, the air "mixes", so the temperature difference between the points was mainly due to the passage of time, in which the temperature was raised. On the other hand, surface temperature measurements showed satisfactory results.

The research also demonstrated the potential for cooling with vegetation. In both the dry and rainy seasons, PS1, a point shaded by trees with high leaf density, recorded a temperature 3.8°C lower than PS3 at 3 pm, and also registered higher relative humidity. This cooling is attributed to the process of evapotranspiration, the major mechanism by which trees contribute to reducing urban temperature, in addition to the shading mechanism, which intercepts part of the radiation in the process of photosynthesis and reflectance.

As shown in Figures 4, 5 and 6, the temperature of the materials in the rainy season has a different behavior in relation to the dry season and a constant relationship with the increase in temperature according to the material and the situation of sun or shade.

**Fig 4.** – Comparative graph of the average temperature of the materials at 9h at SHLS

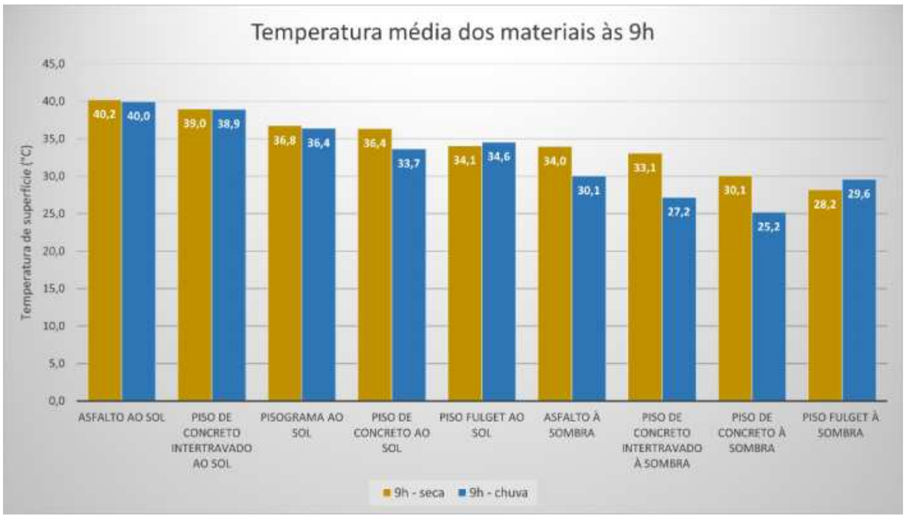



**Fig 5.** – Comparative graph of the average temperature of the materials at 15:00h at SHLS

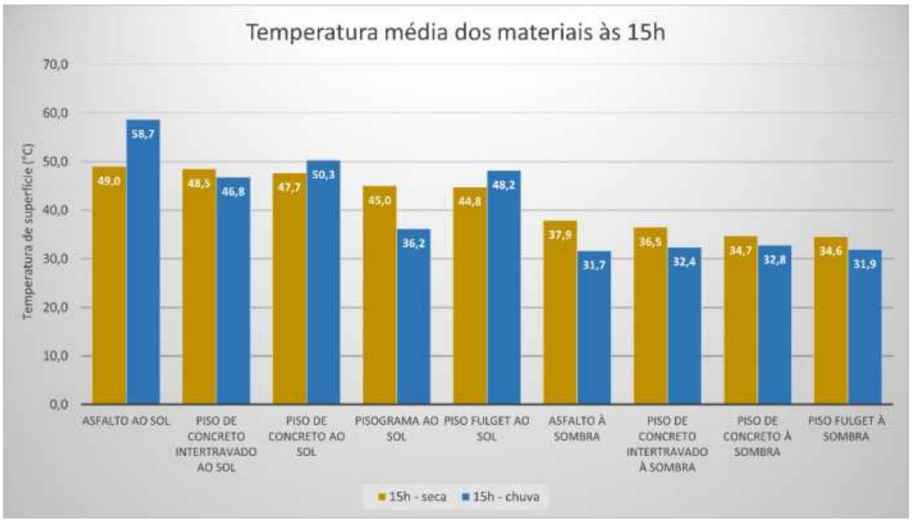
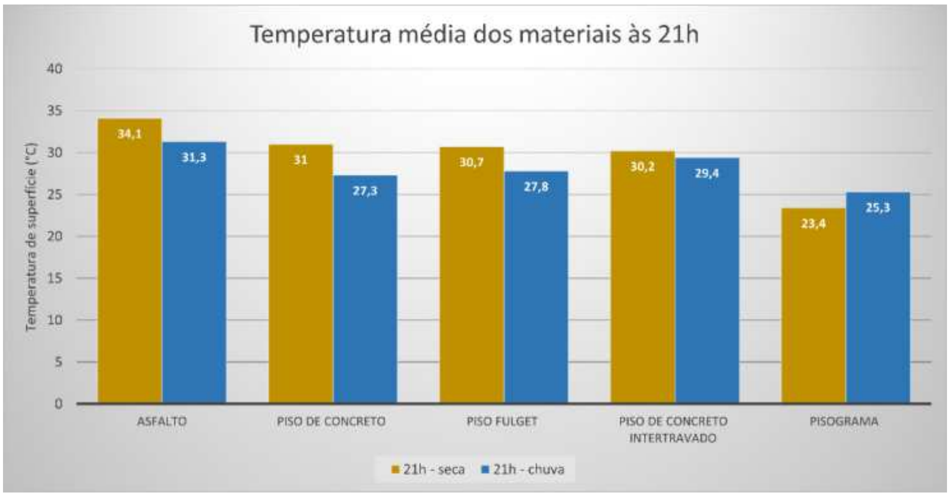



**Fig 6.** – Comparative graph of the average temperature of the materials at 21:00h at SHLS




Among the 'cold' materials, the washed granite (Fulget) pavement performed better when exposed to the sun, being 5°C cooler than asphalt at 3:00 pm, the most critical time for pedestrians. Among the permeable materials, the perforated concrete block with grass (Pisograma), recorded average temperature average of 36.2°C at 3:00pm, 22°C cooler than Asphalt. Also noteworthy is the Interlocked Concrete Floor, which was 12°C cooler than the Asphalt. It is noteworthy that in both periods, the Pisograma presented lower temperature at 9 pm, revealing that its natural part of soil and grass can contribute to the urban heat island mitigation.

The pavement analysis in situations of sun exposure and shade, showed the cooling potential caused by the shading of the treetops and pergolas, in which the pavements were warmer when exposed to the sun. Shading reduces the absorption of solar radiation from the surface and decreases the transfer of sensible heat to the air. The washed granite pavement, when shaded by trees, recorded a temperature of 27.15°C, and when shaded by the pergolas, 36.15°C, this demonstrates that the treetops have a greater potential for blocking sunlight.

**Simulation analysis and discussion**

For the simulation process, Point 2 was selected for its major modification of surface materials and Point 3, for the proposed use modification, from parking to square, and coverage of the area with pergolas. The scenarios are based on the requalification project, as detailed in tables below.

| Sector | Point | Scenario | Scenario Identification |
|---|---|---|---|
| **SHLS** | Ponto 2 | PS2CO | Ponto 2 do SHLS – Original |
| | | PS2CM | Ponto 2 do SHLS – Modified |
| | | PS2CV | Ponto 2 do SHLS – Green |
| | Ponto 3 | PS3CO | Ponto 3 do SHLS – Original |
| | | PS3CM | Ponto 3 do SHLS – Modified |
| | | PS3CV | Ponto 3 do SHLS – Green |

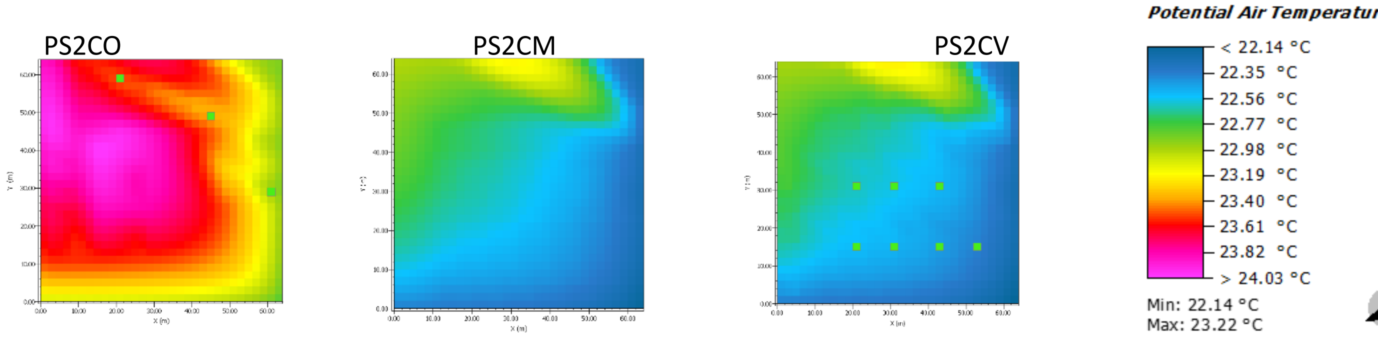
| Scenario | **Bioclimatic Proposal** | Cooling Mechanism |
|---|---|---|
| **PS2CM** | Modification of the thermal properties of materials and permeability: increase in albedo and green cover. | Increased solar radiation reflection; evapotranspiration. |
| **PS2CV** | Technique Combination: PS2CM plus shading of the pavement with trees in the parking lot. | Solar radiation reduction; evapotranspiration. |
| **PS3CM** | Modificationof the termal properties of materials. | Increased solar radiation reflection. |
| **PS3CV** | Technique Combination: PS3CM plus shading of the pavement with trees and pergolas. | Reduction of solar radiation absorption; evapotranspiration. |

Thus, the original scenario was built with the original features before the interventions. In general, the roads and parking lots were paved, with concrete sidewalks, some grassy areas with exposed soil and scarce greenery. The modified scenario was built with cold (higher albedo) and permeable pavements. The proposed new greenery was disregarded, so that it was possible to estimate the potential of the pavements in the cooling of the microclimate. The green scenario was designed to study the combination of techniques of the most reflective pavement of the Modified Scenario with the shading of the surfaces by means of vegetation and pergolas.

The simulations generated maps of Air Temperature (°C) and Surface Temperature (°C), were organized by time, and point for each scenario. As for the air temperature, the simulations revealed zones up to 1.5°C cooler depending on the type of pavement. Areas covered by Asphalt and Concrete were warmer than those covered by washed granite (Fulget),and concrete perforated block with grass (Pisograma) and Interlocked Concrete Floor, as shown in figures 7 and 8.

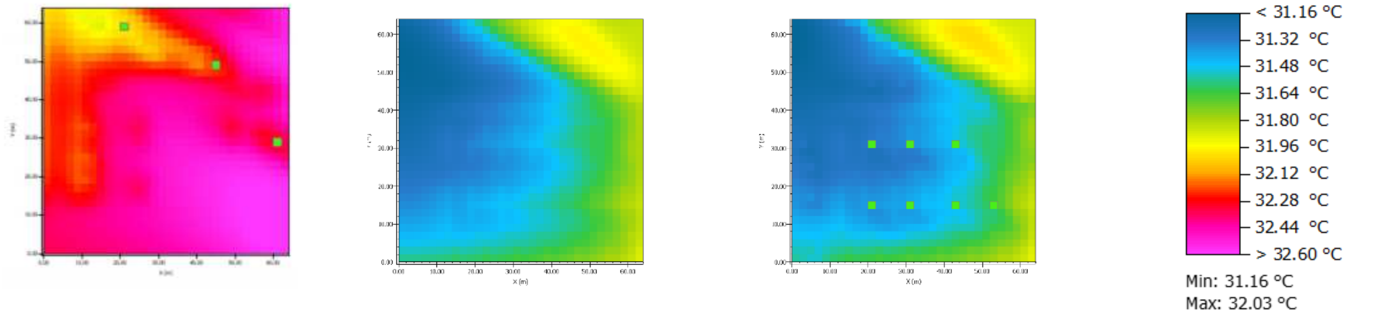
**Fig 7.** Air temperature distribution maps for simulated PS2 scenarios at the level of 1.50 m above ground for the dry period

a. 9h



b. 15h

PS2CO PS2CM PS2CV




c. 21h

PS2CO PS2CM PS2CV

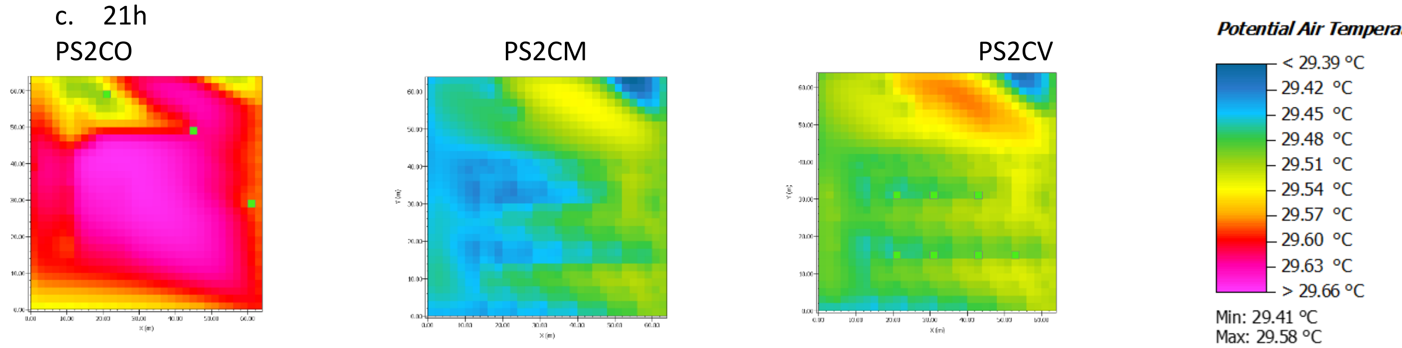
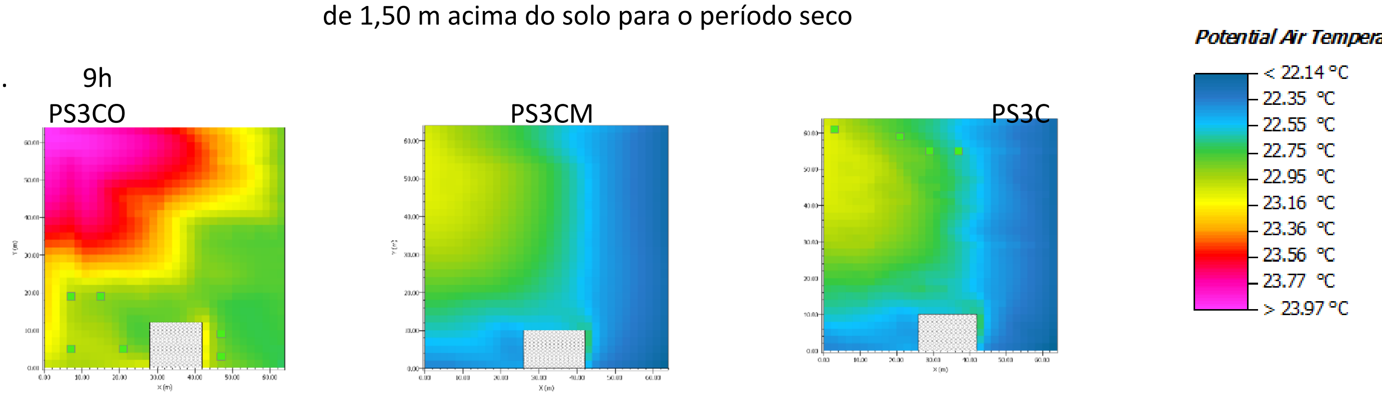



**Fig 8.** - Air temperature distribution maps to simulate PS3 scenarios at 1.50 m above ground level for the dry period. Mapas de distribuição de temperatura do ar aos cenários de PS3 simulados no nível de 1,50 m acima do solo para o período seco

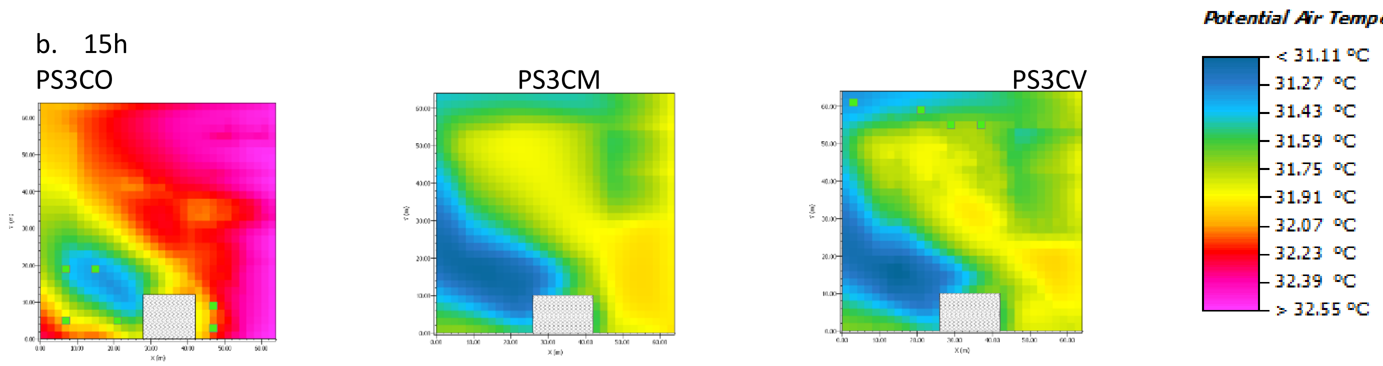
a. 9h

PS3CO PS3CM PS3C

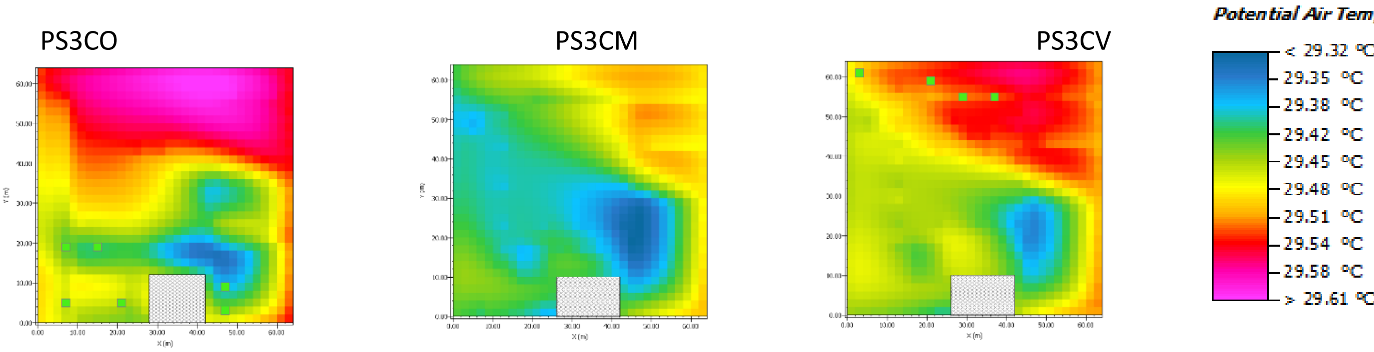



b. 15h

PS3CO PS3CM PS3CV




c. 21h




**Surface temperature**

The results of surface temperature reduction were superior when compared to air temperature reduction, proving to be the parameter with the greatest impact. These reductions were expected since the thermal properties of the pavements changed, with the replacement of conventional materials (Asphalt and Concrete) for cold materials and permeable materials (Wahed granite and interlocked concrete blocks).

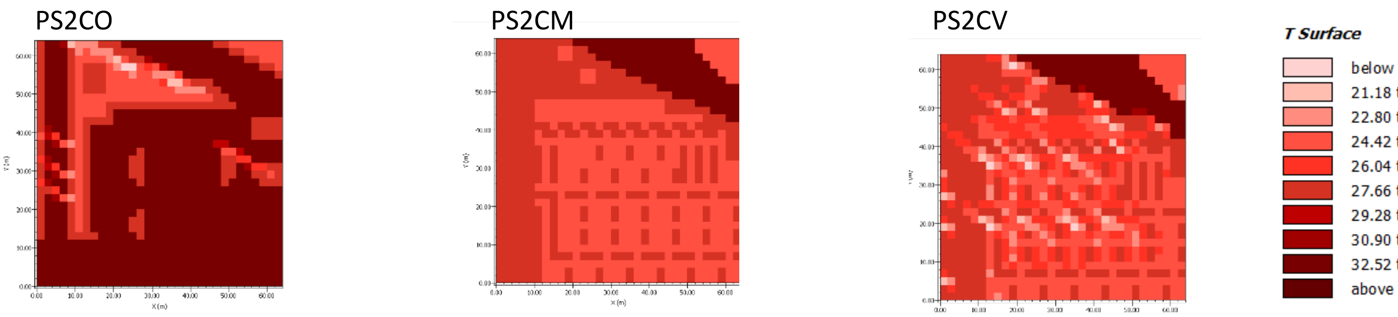
For Point 2, this change covered almost the entire parking lot. As shown in Figure 9, the highest temperatures were found in the Asphalt, represented by the wine color, and the lowest under the perforated blocks (Pisograma) and areas shaded by trees. When compared to the Original Scenario, at 15:00, the Modified Scenario showed a temperature reduction of up to 10.2°C, and in the Green Scenario up to 17.7°C.

As shown in Figure 10, for Point 3, in the morning, the pavements proposed to replace the Asphalt, namely washed granite, (Fulget), Concrete, and Interlocked Concrete, had lower temperatures, in the order of 10°C.

In both points, the punctual effect of the shading of the trees stands out, which reduces the solar absorption of the surface and reduces the transfer of sensible heat to the air. Also, the vegetation potential was observed for the night period, because with the same pavement as the modified Scenario, the temperature of these was lower, mitigating the formation of heat islands.

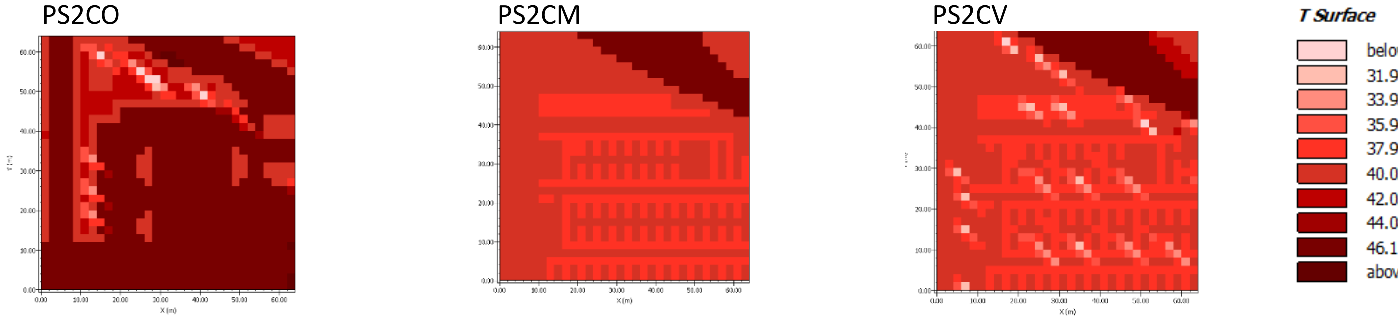
Figure 9 - Surface temperature distribution maps referring to the simulated PS2 scenarios for the dry period

a. 9h



b. 15h

PS2CO PS2CM PS2CV




c. 21h

PS2CO PS2CM PS2CV

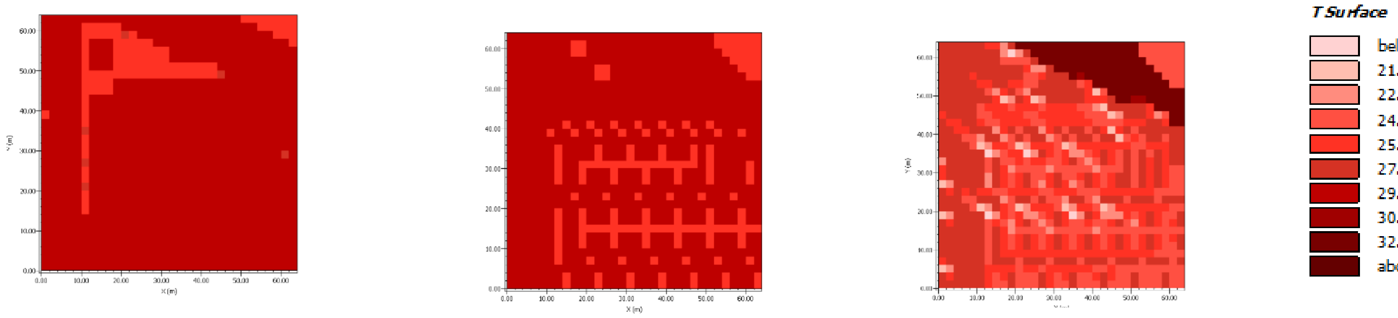
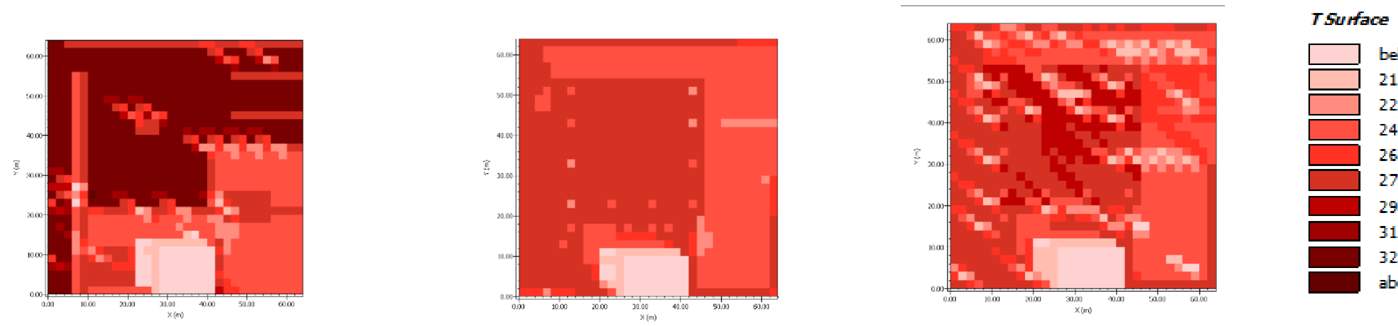



**Figura 10** - Mapas de distribuição da temperatura de superfície referente aos cenários de PS3 simulados para o período seco

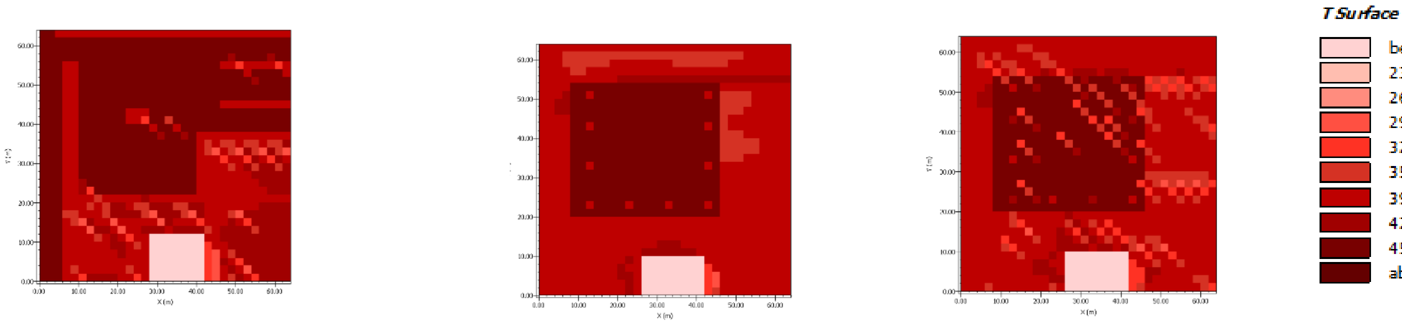
a. 9h

PS3CO PS3CM PS3CV



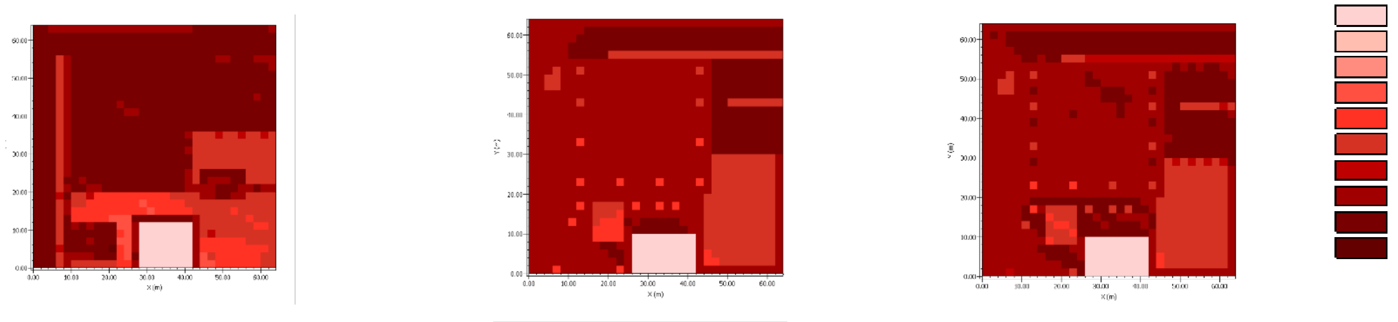

b. 15h

PS3CO PS3CM PS3CV




c. 21h

PS3CO PS3CM PS3CV



Thus, for this research, the simulation corroborated the experimental field work investigation, as it made it possible to estimate the bioclimatic proposals as a cooling mechanism for public spaces, since it was possible to simulate each point before and after the intervention, for the same day, at the same time.

**Final considerations**

Through data collection, it was possible to highlight, on a microclimatic scale, the influence of the two characteristic annual periods, one dry and the other rainy, on the microclimatic scale, given the different behavior of the pavement materials when dry and wet.

The results showed that the temperature of the materials in the rainy period has a different behavior in relation to the dry period and a constant relationship with the increase in temperature according to the material and the situation of sun or shade. In the dry period, materials with lower albedo presented higher temperature when exposed to the sun, and materials with higher albedo were cooler. In the rainy season, permeable and natural materials performed better, because the retained water is available for evaporation and pavement cooling.

As for the simulation process, results corroborated the experimental investigation, as it made it possible to estimate the bioclimatic proposals as a cooling mechanism for public spaces, since it was possible to simulate each point before and after the intervention, for the same day, at the same time. From the simulation results, only with the change of pavement material there is already a cooling effect on the air temperature, however, associated with vegetation, the mitigation of heat can be potentialized.

The results on the use of cold and permeable pavements confirm, regarding the reduction of surface temperature, what has already been raised by research on the subject in other climatic contexts. Therefore, the implementation of these pavements, from the point of view of reducing air temperature and surface temperature, can be adopted. In addition to surface materials, shading should be proposed by means of greenery and installation of pergolas, since their implementation provided an even greater punctual reduction in temperature.

From what has been exposed, it is reinforced that the thermal, radiative and permeability characteristics of the materials that make up the floor coverings used in public spaces must be designed to benefit the thermal environment of the pedestrian. The Surface Temperature (Ts) parameter was the most suitable for this type of analysis, in addition to the thermal comfort indices (not estimated in this research). Actions that promote the use of vegetation in the studied context are indicated because they reduce heat gain and thus heat exchange between the human body and the environment. In this sense, the projects for the requalification of public spaces, which adopt a combined strategy of cold and permeable pavement and medium-density urban greenery, deliver better conditions than just cold and permeable pavements. Even with slightly lower air temperatures due to pavement material replacement, with additional greenery to maximize the potential for heat mitigation at the microclimatic level is more promising.

Finally, the results of this research must be translated into viable urban planning actions, aiming for the best microclimatic thermal performance  for the users of urban spaces.

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