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Overheating in buildings: performance and health risks

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Overheating in buildings: performance and health risks

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Declaration I am the author of this thesis, and the work described therein was carried out by myself personally, with the exceptions highlighted in the declaration of authorship preceeding each publication.

Signed on behalf of the Faculty of Engineering & Design:

Abstract

This thesis evaluates indoor overheating in buildings, focusing on the performance of design strategies, assessment criteria and forecasting at design stage. Given a warming climate, resilient and energy-efficient building design could mitigate carbon emissions while promoting occupant's health and wellbeing. However, these predicate on the robustness of compatible design strategies and methods to evaluate performance — aspects currently under scrutiny and here studied around three key questions.

How do passive design strategies influence overheating in free-running buildings? Firstly, unintended consequences of strategies for improved energy-efficiency were examined with regard to overheating, focusing on increased insulation as an important but controversial measure. A large computational parametric study was conducted and analysed through a novel framework based on data-mining techniques. Results show increased insulation plays a minor role in overheating and that it favours lower indoor temperatures if purge ventilation is available, exacerbating them otherwise. The underlying physical mechanism for these results was presented. These findings suggest energy policy should consider the compatibility of its recommended measures.

How can physiological models inform building design resilient to overheating? Secondly, the severely hot indoor environments of refugee shelters in the desert was examined through different overheating criteria to improve their design process. In agreement with empirical observations, results based on validated simulations show that shelters indeed develop excessive annual overheating as evaluated through comfort and heat strain models. Appraised passive strategies could eradicate the severest instances of overheating. Findings suggest physiology-based overheating criteria could be integrated in a cyclic design process where thermal assessments are routinely performed and acted upon until adequate indoor environments are guaranteed.

To what extent can high-fidelity annual building simulation predict indoor thermal conditions in free-running buildings at design stage? The last study compared predicted indoor temperatures through building simulation to those observed in prototyped shelters. Models based on design specifications and expert judgement loosely bound observations in unoccupied shelters, whilst model calibration improved goodness-of-fit metrics and qualitative agreement substantially. Findings suggest overheating predictions at design stage are fragile and that aid-agencies should adopt simulation and prototyping to assess and improve indoor thermal conditions in shelters.

Acknowledgements

Firstly, I would like to thank the supervisory team behind this work for their mentorship, constructive criticism and trust. In special, many thanks to Sukumar for the support, availability and shared enthusiasm to answer increasingly complex questions. I also thank him for the extraordinary negotiation skills he displayed to make my funders agree on the 4-year scholarship that, as time has proven, I very much needed. I thank David for the open invitations to get involved in his projects, the occasional kick up the backside and being actively involved in the supervision of my work. I would also like to take the opportunity to thank the examiners for the stimulating discussion during the *viva*, their recommendations and feedback to strengthen the thesis.

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A Cris y Miguel.

Contents

List of Figures

List of Tables

Abbreviations

ACDD Adaptive Comfort Degree-Days.

ACM Adaptive Comfort Model.

ASHRAE American Society of Heating Refrigerating and Air-Conditioning.

BPS Building Performance Simulation.

CAMS Copernicus Atmosphere Monitoring Service.

CDD Cooling Degree-Days.

CDH Cooling Degree-Hours.

CDT Centre for Doctoral Training.

CIBSE Chartered Institution of Building Services Engineers.

$\mathbf{CO_2}$ Carbon dioxide.

$\mathbf{CO_2e}$ Equivalent Carbon dioxide.

COLBE The creation of localized current and future weather for the built environment.

CREW Community Resilience to Extreme Weather.

CSH Code for Sustainable Homes.

CV(RMSE) Coefficient of Variation of the Root Mean Squared Error.

dCarb EPSRC CDT in the Decarbonisation of the Built Environment.

DHW Domestic Hot Water.

DISC Discomfort index.

DOE United States of America Department of Energy.

DSY Design Summer Year.

E+ EnergyPlus.

EBC IEA Energy in Buildings and Communities.

EPSRC Engineering and Physical Sciences Research Council.

EPW EnergyPlus Weather file.

FEES Fabric Energy Efficiency Standard.

GHG Greenhouse Gases.

HDD Heating Degree-Days.

HDH Heating Degree-Hours.

HHftD Healthy Housing for the Displaced.

HPC High Performance Computing.

HR Heat Recovery.

IBR Inverted Box Rib.

IDD EnergyPlus Data Dictionary File.

IDF EnergyPlus Input File.

IDP Internally Displaced People.

IEA International Energy Agency.

INGO International Non-Governmental Organisation.

IPCC Intergovernmental Panel on Climate Change.

ISO International Organization for Standardization.

IWEC International Weather for Energy Calculation.

LH Latin Hypercube.

LHS Latin Hypercube Sampling.

MBE Mean Bias Error.

MERRA Modern-Era Retrospective Analysis for Research and Applications.

MERRA-2 MERRA Version 2.

MIDAS Met Office Integrated Data Archive System.

MV Mechanical Ventilation.

NA Not Available.

NASA National Aeronautics and Space Administration.

NGO Non-Governmental Organisation.

NOAA National Oceanic and Atmospheric Administration.

NRC Norwegian Refugee Council.

NV Natural Ventilation.

PH Passivhaus.

PHI Passivhaus Institute.

PHIS Passivhaus Institute Standard.

PHPP Passivhaus Planning Package.

PHS Predicted Heat Strain.

PLEA Passive and Low Energy Architecture.

PMV Predicted Mean Vote.

PPD Predicted Percentage Dissatisfied.

PSUT Princess Sumaya University for Technology.

PVC Polyvinyl chloride.

ReaSat Reanalysis and Satellite weather file.

SAP Standard Assessment Procedure.

SCAT Smart Controls and Thermal Comfort.

TM Thermal Mass.

TRY Test Reference Year.

UK United Kingdom.

UN United Nations.

UNHCR United Nations High Commissioner for Refugees.

URSA University Research Studentships Account.

USA United States of America.

WGBT Wet bulb globe temperature.

WMO World Meteorological Organization.

XPS Extruded Polystyrene Insulation.

Note: Author abbreviations are shown in their corresponding reference entry.

Nomenclature

Term	**Description**	**Units**
A	Area	m^2
C_D	Discharge coefficient	—
K_m	Heat capacity per area of element	$\mathrm{kJ\,m^{-2}\,K^{-1}}$
M	Metabolic rate	$\mathrm{W\,m^{-2}}$ or *met*
T	Temperature	°C or K
V	Volume	m^3
$\dot{V}_{50}$	Flow rate at 50Pa	$\mathrm{m^3\,h^{-1}}$ or $\mathrm{m^3\,s^{-1}}$
$\dot{q}_{50}$	Air permeability at 50Pa	$\mathrm{m^3\,h^{-1}\,m^{-2}}$
λ	Conductivity	$\mathrm{W\,m^{-1}\,K^{-1}}$
μ	Mean	*as indicated*
U-value	Thermal transmittance	$\mathrm{W\,m^{-2}\,K^{-1}}$
g-value	Solar thermal transmittance through glazing	—
ρ	Density	$\mathrm{kg\,m^{-3}}$
σ	Standard deviation	*as indicated*
c	Flow coefficient	$\mathrm{m^3\,s^{-1}\,Pa^{-n}}$
c_p	Specific heat capacity	$\mathrm{J\,kg^{-1}\,K^{-1}}$
clo	Clothing	clo
d	Thickness	*as indicated*
n_{50}	Air changes per hour at 50Pa	$\mathrm{ach\,h^{-1}}$
p	Person	p
TMP	Thermal Mass Parameter	$\mathrm{kJ\,m^{-2}\,K^{-1}}$

Note: Other terms are introduced as they are presented in the studies.

Chapter 1

Introduction

As people spend increasing amounts of time indoors in a warming world, how can building design be informed to promote adequate thermal environments for its occupants, whilst not threating the mitigation of anthropogenic climate change? This is the central question this thesis addresses, leading to the study of overheating in buildings, passive design strategies, and the methods that allow forecasts of thermal performance.

This chapter introduces the overall topic and develops the key arguments that suggest this is an important yet underdeveloped area of research, requiring timely attention. First, the background outlines humans as a thermodynamic system whose careful thermoregulation is essential for survival. The motivation links to how people, buildings and climate are connected in overheating, through a discussion of thermal comfort, energy use in buildings and the impact of a changing climate. The research scope then introduces the knowledge gaps identified in the topic that this thesis addresses, and how these are then translated into aims and objectives. As overheating relates wide domains, the next section presents the context of the studies developed in this work. The chapter ends with an outline of the thesis, and the core and supplementary publications that inform it.

1.1 Background: human thermal response

Overheating in buildings refers conventionally to the study of excessive heat build-up in an indoor space primarily meant for human activity. In a wider sense, overheating may represent any heat build-up but, in the built environment, it is rooted in the need of having thermally safe, even comfortable conditions. This is what leads to defining what *excessive* means. Because it deals with heat, its understanding is amenable to a thermodynamics perspective that links people to an outdoor environment through the mediating influence of buildings. Indeed, buildings represent the most important means by which people have fostered thermally advantageous conditions not only to survive, but to thrive at locations with climates that do not always feature such conditions. The idea of human thermal response is first introduced as the background for this work.

Humans, like many other species, have developed a thermoregulatory system that maintains the bodily internal temperature at advantageous levels for their living processes. This system, and the mechanisms it governs, enable us to cope physiologically with a certain range of environments (Hardy et al. 1971). Not only are we a warm-blooded species but our internal temperature must be kept at 37 °C as well, making ours a homeotherm thermoregulatory system[1]. Regardless of the environmental conditions, the body will try to ensure that such temperature is maintained within an interval of approximately ±1 °C (Refinetti 2010).

The internal body temperature is constantly challenged by the environment and the activities performed. Gagge (1936) offered the first systematic study of the energy transfer involved in this process according to the first law of thermodynamics (the conservation of energy), whose results were summarised in the well-known heat balance equation. Although he used it to bound the extent to which physiological observations could be trusted in practice, the equation has been widely used since, undergoing changes according to conventions and constant refinements (Hardy et al. 1971; Auliciems and Szokolay 2007). As a result, the heat balance equation lacks a fixed expression. The most common one in physiology studies stresses meaningful and measurable components (eq. (1.1), as per Hardy et al. (1971)). It links the changes in the energy stored in the body (S) with the energy obtained by the body from nutrients (metabolic production; M), the energy invested in performing an activity (work; W), the losses through evaporation (skin and respiration, E) and the appropriate exchanges through convection (C) and radiation (R). Since the body is typically surrounded by air in an indoor environment, the small conduction between the body and the air is neglected (Auliciems and Szokolay 2007). Depending on the net exchange with the environment through radiation and convection, these components could be either positive (gain) or negative (loss):

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[1] Biological reasons for this particular value are not conclusive, but they point towards an optimal value for the average climatological temperature range and adequate preservation of proteins in the organism (Gisolfi and Mora 2000).

$$S = M - W - E \pm R \pm C. \tag{1.1}$$

The heat balance equation starts exposing the main avenues to keep the internal temperature constant. This can then be used to evaluate thermal conditions of subjects in various situations, a task known as “thermal audit” (Parsons 1992). However, this equation only captures necessary but not sufficient conditions. The thermoregulatory system controls which mechanism or mechanisms are activated to foster the thermal balance.

A human thermal environment can be simplified to four basic parameters according to the drivers of the energy exchanges described in the heat balance equation, namely the air temperature, the temperature of surrounding bodies (radiant temperature), humidity and air velocity. Similarly, the conditions of a subject can be expressed as a function of two parameters: the activity (heat production) and overall clothing level (insulation). Fixing these six parameters, the heat balance equation enables judgement of whether thermal balance is possible depending on the satisfaction of the equality.

For thermal exchange purposes, a person can be conceptualized as a layered system with a core (bones, organs, muscles) surrounded by fat and enclosed by skin (fig. 1.1). The fat layer provides a default thermal insulation layer since its heat transference is a third compared to that of other tissues and, together with the skin, favours a constant core temperature. The blood flow between the core and the skin bypasses the fat layer to dissipate to the environment the heat generated by our living processes through the skin. The thermoregulatory system monitors threats to the thermal balance in changes to the blood flow temperature, and activates the appropriate countermeasures if necessary to preserve the core temperature (Hall 2016).

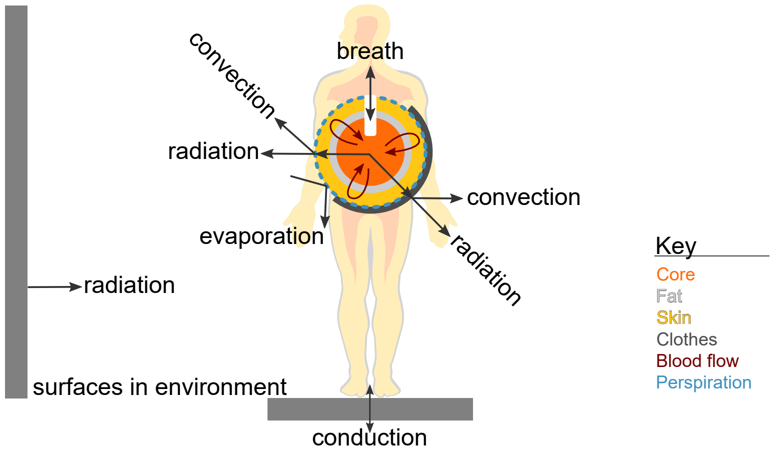

Figure 1.1: A possible conceptualisation of the body as a thermal model (under comfortable conditions, approximate temperatures are 37 °C for the core and 31–33 °C for the skin)

The first physiological response to thermal imbalance is an adjustment to the blood flow rate (Parsons 2015). If the environment is too cold for the subject's activity and clothing, the flow is minimised to lower the heat loss (vasoconstriction) and maximised if it is too hot (vasodilation). This is a versatile response that results in skin temperatures ranging 31–34 °C under comfortable conditions (Auliciems and Szokolay 2007). For larger imbalances, the equivalent conductance of the skin through this effect can vary nine-fold from that of neutral conditions (Hall 2016).

Changes to the blood flow rate is a first response, which is then supported by others after a certain degree of adjustment. The mechanisms that follows vasoconstriction in cold conditions are muscle tension (stiffness) and shivering, either voluntarily or involuntarily. These produce heat, which is reflected in an increment of the metabolic energy (thermogenesis). The response is directly proportional to the differences between cold temperatures and the reference ones for the skin and core (33.7 °C and 36.8 °C, respectively). It can boost, for instance, the metabolic energy five times (Parsons 2015). If these strategies cannot meet the excess in heat loss, the core temperature would decrease. Hypothermia would occur at a core temperature of 35 °C and risks of death starts at 25–30 °C (Auliciems and Szokolay 2007).

The second mechanism under hot conditions is sweating. The evaporation of sweat dissipates about $666\,\mathrm{Wh\,L^{-1}}$ (Auliciems and Szokolay 2007), the same energy required to boil six litres of water at 5 °C. Typical values found in the literature suggest sweating can be sustained at $1\,\mathrm{L\,h^{-1}}$ or up to $4\,\mathrm{L\,h^{-1}}$ for short periods of time by healthy young men (Belding and Hatch 1955). Nonetheless, it is not only a matter of sweating rate. The pioneering work of Gagge (1937) first found the evaporative potential of a person and its relation to the environmental parameters. He demonstrated that the body has a limited range where sweat is an effective cooling strategy, expressed by the product of the area of the body covered by sweat (skin wettedness), and air velocity and direction. Assuming steady air conditions, the maximum value is given by complete skin wettedness, not the amount of sweat. Subsequent work also demonstrated that its cooling efficiency diminishes with the amount of sweat (BSI 2004).

If these strategies do not dissipate enough heat, the core temperature would rise. Hyperthermia would occur at a core temperature of 40 °C and death due to heat stroke at 41–43 °C (Gisolfi and Mora 2000; Deng et al. 2018).

1.2 Motivation

1.2.1 People and thermal comfort

Two reflections follow from the background on human thermal response. The first is that, although the body can go to great lengths to sustain thermal balance, the mechanisms involved can become distressful to the person. The second is that the study of human thermal response is amenable to understanding and ultimately to modelling.

Together with the advances in the control of indoor thermal environments, and their subsequent widespread adoption in the 20th century, they fostered the study of thermal comfort. Its outcomes consequently inform the engineering of thermal environments by establishing the requirements that a designed solution — here a building — needs to fulfil.

The depiction of a person as a thermodynamic system contrasts with the fact that, in thermal comfort, acceptability is ultimately driven by the subjective evaluation of individuals rather than what the physical description of the system might suggest. This motivates the common definition of thermal comfort as “that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation” (ANSI/ASHRAE 2017b, p. 3). Put another way, whether certain environmental conditions are comfortable can only be determined by people expressing their satisfaction with them. Similarly, discomfort can be framed as an expressed dissatisfaction.

The potential problem this represents in a design context, where no prospective occupant can assess the thermal satisfaction with an environment not yet built, was avoided thanks to the development of comfort models. This is accomplished by analysing collected data for a range of environmental conditions and the expressed satisfaction of occupants performing an activity under potentially different levels of clothing (fig. 1.2). By the 1970s, the two main families of comfort models were already introduced through Fanger’s PMV-PPD (Predicted Mean Vote - Predicted Percentage Dissatisfied) model (Fanger 1970) and the adaptive model by Nicol and Humphreys (1973).

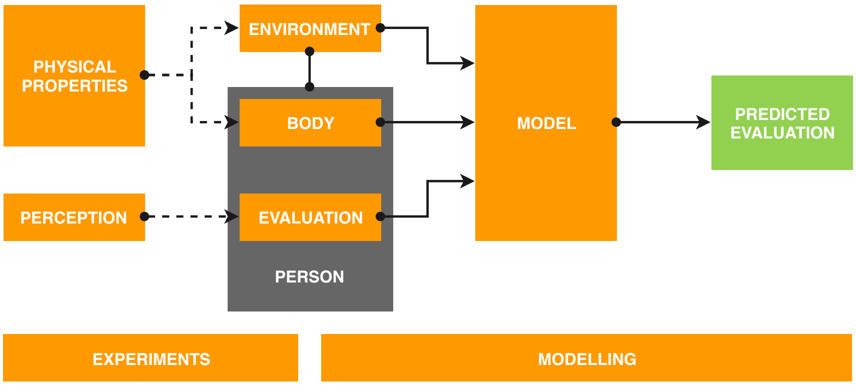

Figure 1.2: Conceptual workflow for measuring occupant satisfaction with the thermal environment and how it relates to mathematical modelling to predict responses in a design context

Fanger successfully related thermal comfort to the thermal balance of a person. From a minimal version of a complete thermodynamic model (termed here rational model), he derived a simplified one for steady-state conditions. This involved several assumptions, for instance that no changes to bodily thermal storage take place under comfortable conditions (Fanger 1970). Based on experimental observations of thermal satisfaction in controlled environments (climate chambers), he developed an empirical model that translated the heat exchange of his simplified rational model to a prediction of occupant satisfaction, the PMV model (eq. (1.2)). The PMV is expressed as a dimensionless integer index in a 7-point thermal sensation scale from -3 to $+3$, where -3 represents 'cold', 0 'neutral' and $+3$ 'hot'. As shown in eq. (1.2), it is a function of the thermal balance ($balance$, $\mathrm{W\,m^{-2}}$) and the metabolic rate (M, $\mathrm{W\,m^{-2}}$) of the occupant. A complementary empirical model related this PMV to the PPD that is, the average proportion of prospective occupants that are expected to judge the thermal environment inadequate (eq. (1.3)).

$$\mathrm{PMV} = balance \cdot (0.303 \cdot e^{-0.036 \cdot M} + 0.028) \tag{1.2}$$

$$\mathrm{PPD} = 100 - 95 \cdot e^{-0.03353 \cdot \mathrm{PMV}^4 - 0.2179 \cdot \mathrm{PMV}^2} \tag{1.3}$$

Nicol and Humphreys (1973) first presented the adaptive principle in thermal comfort. Analysing field-work data in free-running buildings, they noted that people adapted to remain comfortable in a wider range of environmental conditions than experiments in climate chambers and related rational models could explain. Whilst Fanger's PMV-PPD model was indeed successful in predicting comfort in buildings with mechanically controlled environments, it heavily underpredicted satisfaction in naturally ventilated ones. The implications of this finding underline the key influence aspects beyond mere thermodynamics play in this context, which gave rise to a more holistic and interdisciplinary understanding of thermal comfort. From the collected data, Humphreys (1975) and Humphreys (1978) derived an empirical model that associated a band of indoor temperatures within which occupants could be comfortable as a linear function of the outdoor temperature at the location. Although following studies further supported these findings (Auliciems 1981), it was not until the work by de Dear et al. (1997), and its subsequent inclusion in ASHRAE's thermal comfort standard (ANSI/ASHRAE 2004), that adaptive comfort models gained widespread acceptance in research and industry (fig. 1.3).

Focusing on a building design context, comfort models can be used to work out suitable thermal conditions for prospective occupants if model assumptions and limits are satisfied. Buildings that control indoor conditions through mechanical systems like heating or air-conditioning can be designed through the PMV-PPD model knowing the dress code and activity level of the occupants. In naturally ventilated buildings, adaptive models can be used to design thermally comfortable environments given records of external air temperature at the chosen location and promoting opportunities for adaptation such as openable windows, adjustments to clothing or operable shading devices.

Crucially for overheating in buildings, these models can be used to define uncomfortable conditions, that is, those in which comfort is unmet. Conventional overheating

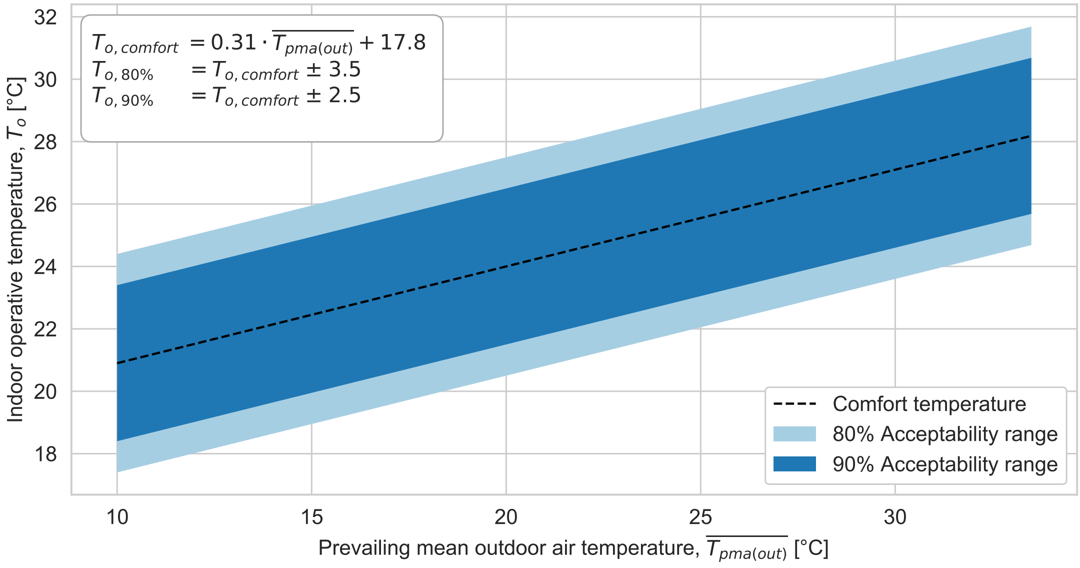

Figure 1.3: ASHRAE's adaptive thermal comfort ($10\,°C < \overline{T_{pma(out)}} < 33.5\,°C$, where $\overline{T_{pma(out)}}$ is the prevailing mean outdoor temperature calculated according to the standard ANSI/ASHRAE (2017b))

definitions express a notional upper temperature threshold according to a comfort model above which overheating is considered to happen (fig. 1.4). This in turn enables the definition of a series of overheating metrics to score the performance of an environment whose standards and guidelines could limit to consider a design as acceptable or not from this point of view. Such a framework is only backed up by evidence if overheating is defined as an instantaneous discomfort to thermal stimuli (instantaneous signifying a deviation from acceptable conditions at a certain point in time regardless of the thermal history leading to that moment). Everything else — overheating metrics, limits and overall acceptability — is based on educated estimates (see studies in chapter 3 and appendix A). Overall, the discussion about physiological principles of thermoregulation and comfort models can be used to define what are here considered different notions of overheating[2]:

- From a **physiological** perspective, two complementary concepts can be used to evaluate the system person-environment, namely heat stress and heat strain. Heat stress depicts the system according to the imposed thermal load, expressed as the energy transfer between the person and the environment. Heat strain depicts the system according to the resulting thermal response of the body. If thermal stress describes the stimuli, the thermal strain describes the response of the body to such stimuli. Here, overheating expresses excessive thermal stress or strain.

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[2] These are presented as fundamental approaches to overheating closely related to the underlying causing phenomena. Other points of view for overheating are also possible if the focus is placed on second-order consequences, such as productivity loss in a working environment.

– From a **thermal comfort** point of view, overheating expresses discomfort due to excessive heat.

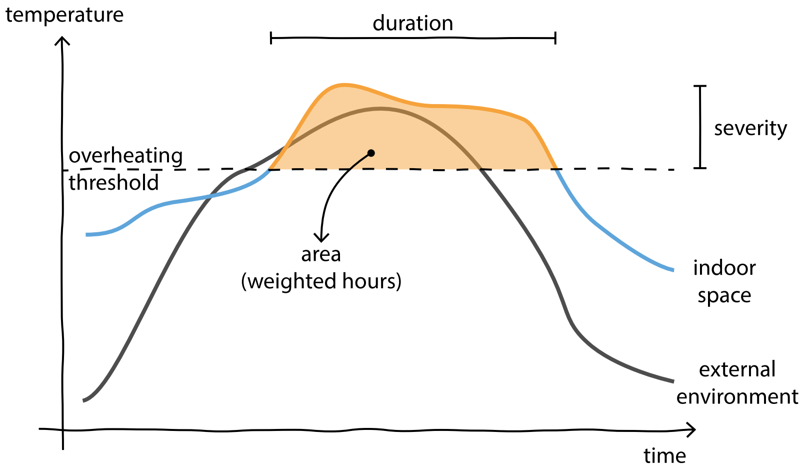

Figure 1.4: Notional definition of overheating as an instantaneous temperature exceedance above a maximum temperature threshold and related metrics

1.2.2 Building design and energy use

Buildings address the gap between the thermal environment that occupants seek and the one that the climate delivers. To this end, if the building design and operation favour strategies that take advantage of the climate at little or no energy cost (passive strategies), the related energy footprint is minimised. On the contrary, it is maximised if instead they favour heating, cooling and ventilation through mechanical systems (active strategies). The implications of thermal comfort here are important: passive buildings could leverage the adaptive approach to further minimise the energy footprint thanks to a wider range of comfortable conditions, as opposed to Fanger's for active buildings. At present, active strategies that foster adequate indoor thermal conditions entail an unsustainable toll on the environment. Over one third of the total energy consumed in the world is spent in buildings, a fraction that has hardly changed in the last forty years (IEA 2018). At 33 %, the energy consumption devoted to space heating and cooling leads the breakdown of energy use in buildings (fig. 1.5), followed by domestic hot water (22 %), cooking (20 %), other uses (18 %) and lighting (6 %) (IEA/OECD 2013).

As the largest energy-consuming sector, buildings play a key role in the economy. This was particularly evident in Europe as a result of the oil crises in the 1970s. In order to minimise the effects of such events on the economy, regulations began addressing the energy demand of buildings and, at the same time, the arrival of energy simulation as assessment and design tools (Clarke 2001; Kusuda 2001). Policy mainly focused on establishing a minimum thermal performance of the building envelope, since it was acknowledged that most of the energy in buildings was spent on space heating. Under

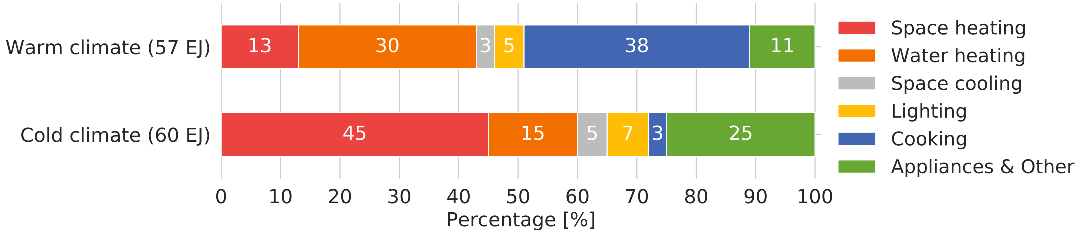

Figure 1.5: Breakdown of energy end-use in buildings according to prevailing climatic conditions in their respective countries (data from IEA/OECD (2013); n.b. overall energy difference between warm and cold climates; $1\,\mathrm{EJ} = 10^{18}\,\mathrm{J} \approx 277.78\,\mathrm{TW\,h}$)

this perspective, a low-energy built environment promotes energy security by reducing the energy demand, which further promotes associated savings in primary energy.

The relative importance of the energy end-uses and their associated greenhouse emissions further promoted initiatives in this direction in the advent of anthropogenic climate change. A key example is the goal of reducing 80 % the carbon emissions of buildings by 2050 from 1990 levels, where the Directives on the Energy Performance of Buildings constitute a fundamental instrument given the growing trends in energy consumption (European Commission 2018). These efforts have resulted in just an 8 % increase in the energy consumed by a residential sector that has grown 21 % between 1990 and 2013. Yet, space conditioning alone still represents more than 60 % of the energy demand in European buildings (Papadopoulos 2016). Under this perspective, it must be noted that this only represents an environmental problem inasmuch as active systems are fuelled by carbon-intensive technologies, as it is currently the case.

The main way regulations have improved the thermal performance of the building envelope has been through higher thermal resistance and airtightness. For example, new dwellings in the UK are now required to have thermal transmittances less than a third of those required in 1970 (ODPM 2013a). Likewise, air leakage is expected to be between a half to a quarter (CIBSE 2000; ODPM 2013b). Voluntary standards like that of the Passivhaus Institute (PHI) further increase these requirements. At $0.10\,\mathrm{W\,m^{-2}\,K^{-1}}$, their maximum allowed thermal transmittance is a quarter of what is currently required in many European countries (Papadopoulos 2016).

Even if regulations can have a transformative effect in the energy demand of new developments, some countries feature an old building stock. UK statistics show that 18 % of the dwellings is over a hundred years old and that 66 % were built between then and 1990 (Palmer and Cooper 2013). A number of retrofit schemes have been addressing the thermal performance of existing buildings, but there are still significant improvements to be made considering that space heating is still responsible for a third of the greenhouse gas emissions in the UK (DBEIS 2018).

A further complication is that these strategies for increased energy efficiency to promote energy-security and climate change mitigation have been associated with unintended consequences (Shrubsole et al. 2014). In the context of overheating, improvements to the building envelope aimed at reducing space heating demand have been linked with exacerbated indoor temperatures in both empirical and computational studies (Beizaee et al. 2013; Psomas et al. 2016; CCC 2016). This threatens the effectiveness of related policies because it could lead to a rebound effect in the adoption or increased use of cooling systems, especially if adaptation to climate change is taken into consideration (Mylona and Davies 2015). The lemma "[b]uildings don't use energy: people do" (Janda 2011, p. 15) is particularly evident in a space conditioning driven by the thermal comfort expectations of occupants. Whether the low-energy buildings adaptive comfort implies are a desirable pathway needs to be considered together with the adaptations to a changing climate.

1.2.3 A changing climate

The current climate emergency raises the concern that buildings might not be fit for purpose (IPCC 2015). The climate influences building design as it establishes the background conditions that buildings modify to foster adequate indoor conditions. Therefore, in the context of indoor thermal environments, what are the implications of a changing climate for buildings designed for historical weather and their occupants?

The availability of climate change projections and overheating criteria allows quantifying their potential effects in the built environment (CIBSE 2009). This includes the evaluation and classification of the thermal performance of existing buildings (Taylor et al. 2016), design strategies (Mavrogianni et al. 2012; Mulville and Stravoravdis 2016) and the potential consequences for discomfort and energy use (Collins et al. 2010; Goetzler et al. 2016). The findings of such studies, although not entirely consistent between them, point towards a likely rebound effect from energy-efficiency measures and an uptake of active cooling in buildings, with the associated losses in carbon savings. This conveys an image congruent with the expected impact on health by the IPCC: the exacerbation of hot conditions will outweigh any improvements during the cold season (Smith et al. 2014).

The impact of climate change is not homogeneous across the globe (Smith et al. 2014). The burden will be greatest for the densely populated range within the Tropics, a part that already features severe hot conditions. At the same time, countries in this range are expected to drive the world's economic and population growth in the next decades (UNDESA 2019). This represents both an opportunity and a risk considering that the reductions in carbon intensity per square meter achieved in buildings are being offset by the overall growth in the sector (IEA 2019).

Besides global warming, it is considered *virtually certain* that future climate will feature more frequent extreme weather events, specially more severe and longer heat waves (IPCC 2012). These events increase morbidity and mortality as seen in the European heat wave of 2003, where an excess of 70 000 deaths was recorded (Robine et al. 2008), including 2000 in the UK (Johnson et al. 2005), 4000 in Spain (Martiello and Giacchi 2010) and more than 14 000 deaths inside buildings in France (Vandentorren et al. 2006). Although it is not well-known what specific mechanisms trigger these numbers in indoor environments during a heat wave, it is clearly associated with the stress the body suffers to dissipate heat. For example, sustained high blood flow rates to the skin strains the heart, or the overall failure associated with excessive weight loss due to sweating. Even if these mechanisms successfully protect the deep body temperature, the pressure on the thermoregulatory system weakens the body, exacerbating pre-existing health conditions in vulnerable groups such as the elderly. Considering the health risks involved and the roles building have in modifying external conditions, this suggests that overheating in buildings should be taken as seriously as structural integrity, or earthquake resilience.

1.3 Research scope

Overheating in buildings is as a complex problem that relates occupants, buildings and climate. As a result, it has far-reaching implications for occupant's health, building design, energy use and climate change mitigation and adaptation. Taking these into consideration, this work focuses on the overall aim of a low-energy built environment resilient to overheating that is yet to be designed and implemented. In this regard, three key areas have been identified to underpin this goal.

Thermal performance of passive design strategies in overheating

The analysis of Vandentorren et al. (2006) of the European heat wave in Paris draws attention to how poorly insulated spaces exacerbated overheating, whereas those well insulated reduced it. This contrasts with the opposite effect found in the context of unintended consequences of energy-efficiency strategies and computational studies of thermal resilience. However, the field studies found in the literature that address this issue do not show a cause-effect relationship between individual passive strategies and exacerbated overheating. This is crucial for the case of increased insulation levels, where there is still little consensus on the role increased insulation has (see chapter 2).

Given the importance they have in enabling adaptive thermal comfort for successful climate change mitigation, *the first topic this work addresses is a quantification and understanding of how passive strategies, especially insulation, influence indoor thermal conditions in free-running buildings.*

Overheating quantification in the design process

Proposed overheating criteria have framed overheating as discomfort, and discomfort as the absence of comfort. True to their goals, thermal comfort models focus on understanding what the best conditions are. As a result, comfort-related metrics have a higher resolution to characterize environments that maximise comfort than for those that do not. This means that metrics characterising departures from the comfortable range do not scale congruently with heat strain. In addition, the use of current comfort models imply overheating happens instantaneously if comfort is unmet at any given moment, disregarding the accumulative effect of heat build-up overtime. Moreover, the more environments deviate from comfort the greater the physiological adjustment and strain on the body — and the less suitable is the subjective evaluation of comfort. It is precisely in such a domain where rational physiological models and their indices are arguably best placed to quantify the severity of overheating because they explicitly model the mechanisms that come at play in such circumstances and, in the case of dynamic models, account for the evolution of heat build-up.

Given that overheating evaluation in the built environment aims to appraise the impact of overheating on occupant health and wellbeing, *the second topic this thesis addresses is the way in which physiological models could inform overheating evaluation as part of the building design process.*

Forecasting thermal performance of passive buildings at design stage

An implicit idea in any overheating assessment at design stage is the ability to accurately predict the parameters that describe the thermal environment, like air temperature — the single most important parameter in every thermal comfort and physiological model. For instance, in standard overheating criteria, overheating quantification relies on establishing a temperature threshold above which overheating is considered to take place, with the implications that overheating metrics are non-negative quantities that can never decrease. This means that accurate and precise predictions of the absolute values of temperatures at design stage can be crucial. Even if different, more-robust overheating metrics are defined, the importance of absolute values in overheating are rooted in homeothermy; the baseline is a deep body temperature of 37 °C. This contrasts with the appraisals of energy demand that motivated high-fidelity simulations for building design. For space conditioning, Fanger's notion of comfort establishes the environment mechanical systems need to create. Rather than an unknown, it is a defining aspect for the design strategies under consideration. Even if predictions are not accurate, in many circumstances relative changes in energy performance could still be relied on.

Given that overheating influences the adoption of mechanical systems and the challenges of defining a model that reflects the as-built performance, *the third topic this thesis addresses is the extent to which thermal performance of naturally ventilated buildings could be forecasted at design stage assuming full knowledge of occupant behaviour and weather conditions.*

1.4 Aims and objectives

This thesis aims to establish a robust overheating evaluation framework to appraise the impact of building features at design stage. Addressing the knowledge gaps previously identified, it considers the performance of strategies that could help deliver passive low-energy buildings, overheating quantification metrics consistent with physiological effects and the validation of forecasts obtained through building performance simulation.

Research Question 1 How do passive design strategies influence overheating in free-running buildings?

Objective 1-A Quantify the impact of building features and passive strategies on overheating.

Objective 1-B Understand how increased insulation levels impact overheating risk.

Research Question 2 How can physiological models inform building design resilient to overheating?

Objective 2-A Evaluate heat strain in indoor overheating through well-known but hitherto unexploited physiological models.

Objective 2-B Demonstrate how such an evaluation could influence the design process to improve thermal safety in free-running conditions.

Research Question 3 To what extent can high-fidelity annual building simulation predict indoor thermal conditions in free-running buildings at design stage?

Objective 3-A Estimate the extent to which simulation models based on design specification and expert judgement can predict the as-built thermal performance.

Objective 3-B Appraise how prototyping and model calibration improves predictions of simulated thermal performance and the consequences for the appraisal of design variants.

1.5 Research context

The built environment is particularly varied and encompasses a diverse range of climates, buildings and occupants. Cases were selected for each of these aspects according to the foreseeable potential to exhibit measurable levels of overheating that could arguably be counteracted through passive, climate change mitigation strategies. The topics addressed in this thesis have led to the collaborations with the EPSRC-funded COLBE and HHftD projects, which have directed the attention to contexts most suited for the research questions of this work, and have supported this research with resources that would have been otherwise unattainable.

The COLBE project aims to devise a method for creating weather files for building simulation at 5-km resolution for the UK that represents current and future climate for typical and extreme weather events (EPSRC 2015). Research Question 1 is mainly addressed in this context, which comprises types of residential buildings in conventional urban settings. Further to the aspirations of generalisable conclusions about the performance of design strategies, other urban settings in selected capitals in the world are also considered in this thesis.

The HHftD projects aims to develop a systematic design process of shelter solutions through “a new science of shelter design” (EPSRC 2017). Among the camps studied in this project, the Syrian refugee camp of Azraq in Jordan is selected because shelters feature a well-known design consistently replicated throughout the camp and they are known to overheat to distressful levels for their dwellers. Research Question 2 and Research Question 3 are mainly addressed in this context because they feature a hot desert climate and shelters are free-running during the warm season.

Studies herein do not include extreme events and only one deal with climate change projections, although these are motivating aspects of this work. The reasons are that identified gaps focus on fundamental aspects of overheating evaluation, dealing not only with its definition but also with the capabilities to forecast thermal performance at design stage. Creation of weather files for overheating studies need to be informed by the characteristics of the building stock and impact on occupants to select weather records that would cause a pre-defined stress level to them. The topics addressed in this thesis represent underlying knowledge that informs such a process, and contributions to the creation of such weather files are deemed to fall beyond the scope of this work.

1.6 Thesis outline

The research addressing the objectives of this thesis has been developed through peer-reviewed journal publications, which constitute the main contributions presented in chapters 2 to 4. The content of these chapters is identical to the original manuscript albeit minor changes in style to deliver a consistent presentation. Although each paper stands alone, including its own literature review and methodology, a preamble and a postscript place them within the overall aims and narrative of the thesis, stressing the implications of the study to such extents. Similarly, supporting work published in international conferences is included in appendices A to D and referenced in the preambles with regard to the objectives they contribute to.

Chapter 1 (this chapter) presents the background and motivation for the study of overheating in buildings in relation to their implication and design, identifies the knowledge gaps in the topic, establishes the aim and objectives of the thesis and the context for studies herein.

Chapter 2 presents a comprehensive study on the impact of building features and strategies on overheating in selected dwelling types and cities in the world. An in-depth analysis of the role of increased insulation levels is given together with the reasons that could account for differences in reported performance in other studies.

Chapter 3 devises a cyclic design process for shelter design that leverages appraisals of overheating performance as quantified by adaptive comfort and 2-node physiological models, and related metrics.

Chapter 4 judges the extent to which thermal performance of a single-zone free-running shelter could be forecasted at design stage and what is the role of prototyping in informing forecasts of performance.

Chapter 5 summarizes the studies, draws conclusions with regard to the aim and objectives of the thesis, and recommends related areas for future work.

Appendix A examines the role standard overheating criteria could play in assessing the performance of passive strategies. This study supports chapter 2 and subsequent work by drawing the attention to the limits of such approaches.

Appendix B compares the extrapolated overheating performance of a shelter under comfort and selected physiological models given the limitations identified in the context of appendix A and chapter 2. This study constitutes the exploratory work behind chapter 3.

Appendix C explores how reanalyses datasets and satellite observations could be combined to produce weather files for locations far from accessible weather stations with suitable records. It introduces materials and methods that support the work of chapter 4 and that help studying under-represented areas of the world in sources until then unavailable.

Appendix D reflects on field-work findings regarding shelter adaptations by their dwellers from an interdisciplinary perspective. This study focuses on fundamental aspects for the context presented in chapters 3 and 4, which entails consequences for shelter design, and how they could inform the shelter provision process.

1.7 Thesis timeline

This thesis is the result of an evolving understanding of the topic by its author and it is structured around the three research questions presented in section 1.4. To put into perspective the choices made, the studies are here presented in chronological order according to their development rather than their final publication dates.

The study on the influence of overheating criteria (appendix A) was first developed to review the standard overheating criteria widely used in the literature. Developments in the methodology are the parametric simulation framework and non-parametric statistical analysis of summary overheating indicators. The interest lies in depicting the potential influence different criteria might have when evaluating the thermal performance of a given building design.

The study on the role of passive design strategies (chapter 2) fully develops the parametric simulation framework to understand through direct observation, the effect of selected parameters in overheating. The full factorial approach was favoured over alternatives like sensitivity analysis to screen influential parameters or the incremental generation of an overheating metamodel. The main reason is that there was a lack of consensus about the performance of certain passive design strategies and their overall role within a larger set of parameters. A parameter might have not been influential in the overall overheating response, but its behaviour might have been conditional on the wider parameter context. This type of insights might have been lost in favour of increasing a computational efficiency that was not needed at this time. In addition, initial analyses of overheating summary indicators could not successfully characterise the response in terms of metamodels such as generalised linear regression. For instance, the distribution of the response variable systematically violated the assumptions of this kind of models. Therefore, the combination of a full-factorial design with data mining techniques, whilst computationally onerous, provided a way forward to address the research objectives of the study.

The analysis of thermal performance of shelters (appendix B and chapter 3) provided the context to explore the application of physiological models given their severely hot monitored conditionsc. Although it is hoped that conventional buildings do not reach severe overheating in normal circumstances, the hypothesis tested in the study showed that this was indeed expected for these shelters. At the stage these studies were developed, initial surveys had been carried out in the camp the HHftD team, but only spot measurements of thermal conditions were allowed at this time by camp authorities. Weather data for this exact location was not available, for which weather files for surrounding sites at about 60 km were used.

To overcome the limitations of weather station availability in remote places, the study on weather files from reanalyses and satellite observations was then developed (appendix C). This helped with exploratory studies within the HHftD project because assessed refugee and internally displaced camps surveyed were often far from publicly available weather stations with suitable hourly records for all relevant parameters in a weather file.

The study on the importance of thermal modelling (chapter 4) was developed at the last stage. The work conducted as part of appendix B and chapter 3 was perceived useful to camp authorities, who welcomed on-site experiments to help inform improvements to the thermal performance of the shelters in place. The experiment was planned to last for a year, and it started a year and a half before the foreseeable end of the HHftD project. There was limited time to plan the experiment and the monitoring campaign and it was decided to follow an iterative approach based on subsequent visits to the camp, which was proven to be the best approach given on-site conditions (section 3.1). The study presented in chapter 4 reports on the thermal performance of a subset of seven shelters during the first monitoring period and data collection, which captured the end of the warm season in 2018. At this point, only key sensors could be fitted (see further details in section 4.13.2). Building simulation models for this study could therefore be studied in several stages to appraise the influence of increasing knowledge about these shelters and conduct a systematic model development that included calibration and validation for indoor air temperatures.

Appendix D was developed in parallel to chapter 4 to reflect on the ways surveyed camp dwellers live and alter their shelters. It was taken as an opportunity to discuss aspects that fall beyond the technical account of shelter performance presented in the thesis and that are often ignored both in the literature and in shelter design practices.

1.8 Dissemination

The research conducted during this thesis has been published in peer-reviewed journals. In addition, it has been presented in international conferences, recorded in publicly accessible databases, and reported to aid-agencies.

1.8.1 Peer-reviewed journal papers

Coley, D., M. Herrera, **D. Fosas**, C. Liu, and M. Vellei (2017b). “Probabilistic Adaptive Thermal Comfort for Resilient Design”. *Building and Environment* 123, pp. 109–118. DOI: `10.1016/j.buildenv.2017.06.050`.

Fosas, **D.**, D. Albadra, S. Natarajan, and D. A. Coley (2018b). “Refugee Housing through Cyclic Design”. *Architectural Science Review* 61 (5), pp. 327–337. DOI: `https://doi.org/10.1080/00038628.2018.1502155`.

Fosas, **D.**, D. A. Coley, S. Natarajan, M. Herrera, M. Fosas de Pando, and A. Ramallo-Gonzalez (2018c). “Mitigation versus Adaptation: Does Insulating Dwellings Increase Overheating Risk?” *Building and Environment* 143, pp. 740–759. DOI: `10.1016/j.buildenv.2018.07.033`.

Fosas, **D.**, F. Moran, S. Natarajan, J. Orr, and D. A. Coley (2020). “The Importance of Thermal Modelling and Prototyping in Shelter Design”. *Building Research & Information*. DOI: `10.1080/09613218.2019.1691489`.

Herrera, M., S. Natarajan, D. A. Coley, T. Kershaw, A. P. Ramallo-González, M. Eames, **D. Fosas**, and M. Wood (2017). “A Review of Current and Future Weather Data for Building Simulation”. *Building Services Engineering Research and Technology* 38 (5), pp. 602–627. DOI: `10.1177/0143624417705937`.

Liu, C., T. Kershaw, **D. Fosas**, A. P. Ramallo Gonzalez, S. Natarajan, and D. A. Coley (2017). “High Resolution Mapping of Overheating and Mortality Risk”. *Building and Environment* 122, pp. 1–14. DOI: `10.1016/j.buildenv.2017.05.028`.

Vellei, M., M. Herrera, **D. Fosas**, and S. Natarajan (2017). “The Influence of Relative Humidity on Adaptive Thermal Comfort”. *Building and Environment* 124, pp. 171–185. DOI: `10.1016/j.buildenv.2017.08.005`.

1.8.2 Proceedings of international conferences

Ferreira, A. A., M. Herrera, I. M. B. Rameh Barbosa, R. R. B. Aquino, S. Natarajan, **D. Fosas**, and D. Coley (2018). “Adaptive Piecewise and Symbolic Aggregate Approximation as an Improved Representation Method for Heat Waves Detection”. Computing Conference 2018. London, pp. 658–671.

Fosas, **D.**, S. Natarajan, D. Coley, A. Ramallo-González, and M. Fosas de Pando (2016). “Influence of Overheating Criteria in the Appraisal of Building Fabric Performance”. *Making Comfort Relevant Proceedings 9th Windsor Conference.* Windsor Conference 2016: Making Comfort Relevant. Windsor: NCEUB 2016, pp. 1078–1098.

Fosas, **D.**, D. Albadra, S. Natarajan, and D. Coley (2017). “Overheating and Health Risks in Refugee Shelters: Assessment and Relative Importance of Design Parameters”. *Proceedings of the 33rd PLEA International Conference: Design to Thrive.* PLEA International Conference: Design to Thrive. Ed. by L. Brotas, S. Roaf, and F. Nicol. Vol. 3. Edinburgh: NCEUB 2017, pp. 3746–3753.

Fosas, **D.**, M. Herrera, S. Natarajan, and D. A. Coley (2018e). “Weather Files for Remote Places: Leveraging Reanalyses and Satellite Datasets”. *1st International Conference on Data for Low Energy Buildings.* 1st International Conference on Data for Low Energy Buildings. Murcia: Diego Marín, Murcia, pp. 14–19.

Herrera, M., **D. Fosas**, B. M. Beltran, and D. A. Coley (2018). “Enhancing Predictive Models for Short-Term Forecasting Electricity Consumption in Smart Buildings”. *1st International Conference on Data for Low Energy Buildings.* 1st International Conference on Data for Low Energy Buildings. Murcia: Diego Marín, Murcia, pp. 26–30.

Paszkiewicz, N. and **D. Fosas** (2019). “Reclaiming Refugee Agency and Its Implications for Shelter Design in Refugee Camps”. *Proceedings of the 1st International Conference on: Comfort at the Extremes: Energy, Economy and Climate.* International Conference on: Comfort at the Extremes: Energy, Economy and Climate. Dubai: Ecohouse Initiative Ltd, pp. 584–594.

1.8.3 Datasets

Coley, D., A. M. Herrera Fernandez, **D. Fosas**, C. Liu, and M. Vellei (2017a). *Probabilistic Adaptive Thermal Comfort for Resilient Design.* In collab. with University Of Bath. DOI: `10.15125/bath-00369`.

Fosas, **D.**, D. Coley, S. Natarajan, M. Herrera Fernandez, M. Fosas de Pando, and A. Ramallo-Gonzalez (2018d). *Dataset for "Mitigation versus Adaptation: Does Insulating Buildings Increase Overheating Risk?"* DOI: `10.15125/bath-00390`.

Fosas, **D.**, F. Moran, S. Natarajan, J. Orr, and D. Coley (2019). *Dataset for "The Importance of Thermal Modelling and Prototyping in Transitional Shelter Design".* DOI: `10.15125/BATH-00668`.

1.8.4 Other

Fosas, **D.**, D. Albadra, S. Natarajan, and D. A. Coley (2018a). *Improving The Thermal Comfort In New Shelters.* Bath: University of Bath. DOI: `10.6084/m9.figshare.8977556`.

Chapter 2

Mitigation versus adaptation: Does insulating dwellings increase overheating risk?

2.1 Preamble

This chapter addresses the performance of passive strategies to reduce overheating in buildings (Research Question 1). In reference to the three fundamental components of overheating — people, building and climate —, this chapter stresses the role of the building design parameters (fig. 2.1) in the context of standardized individuals and a range of climates (fig. 2.2).

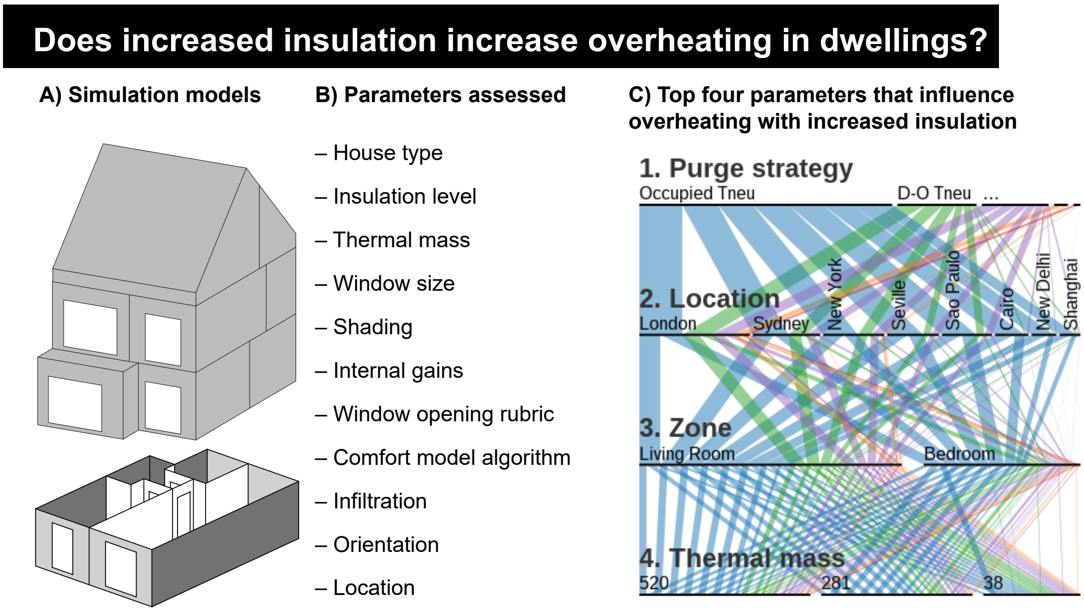

Figure 2.1: Graphical abstract of the study (License CC BY 4.0, Fosas et al. (2018c))

Although a wide range of strategies are studied, the analysis focuses on increased insulation levels. As depicted in the state of the art, there is little consensus on the role increased insulation has. On the one hand, there is emerging evidence from field studies of a correlation between increased indoor temperatures and improved building fabric, but no evidence that identifies increased insulation as the cause of unwanted increased temperatures. Therefore, the study focuses on a computational approach that allows for pairwise comparisons to isolate the influence of individual parameters. In particular, the experiment develops a full-factorial design in which every parameter and case is combined with others in every possible way. As reasoned in the study, parameters and cases are established to bound the problem given that their underlying distribution is unknown. To bound the problem, low and high estimates are selected together with in-between cases according to their perceived importance in the literature. Current weather has been preferred over climate change projections as the time signature in the latter is unknown[1]. As a result, the study is developed for selected locations in the world that span prevailing cold conditions (e.g. New York and London) to hot ones (e.g. Cairo and New Delhi).

At the same time, it establishes the fundamentals of the methodology followed throughout this thesis to model buildings and forecast thermal performance. This comprises two interlinked aspects, the modelling and the evaluation of overheating performance. The first is discussed at length in this paper. The second is explored in a conference paper (appendix A), which examines standard overheating criteria as means to evaluate the performance of passive strategies. Every guideline and standard to evaluate overheating are closely based on the notion of comfort and regard overheating as discomfort due to warm temperatures. As a result, standard overheating criteria are currently defined based on the two main ways of understanding comfort: Fanger's PMV-PPD and adaptive comfort models. However, there is limited evidence in thermal comfort to establish limits of discomfort, and the criteria are resultingly based on expert judgement. This preliminary work showed how these criteria, although reasonable to an extent, can influence the qualitative outcome of a study. Given the limitations of their definition, overheating is here based on the fundamental metrics conventionally agreed upon: duration and severity of overheating. It must be stressed that this is indeed a convention rooted in classical metrics in building services for unmet load hours, hours in which the system is not able to maintain the set-point temperature. Duration and severity of overheating are just metrics that translate unmet hours in familiar terms. No study reviewed has yet established empirically-based widely accepted metrics to measure the long-term occupant tolerance to environments that overheat (see section 3.1).

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[1] To study the impact of climate change in the thermal performance of buildings, weather files are typically morphed. This technique can be applied to any location, but it assumes weather patterns remain essentially unaltered. An alternative approach is to use weather generators that simulate the climate to obtain prevailing conditions in the future, but such generators are not generally available (Herrera et al. 2017).

This chapter is based on the journal publication “Mitigation versus Adaptation: Does Insulating Dwellings Increase Overheating Risk?” published in the journal Building and Environment in 2018 (Gold Open Access paper) together with its associated dataset (Fosas et al. 2018d). This study was conducted as part of the COLBE project [grant number EP/M021890/1] to advance the understanding of the role building features have intermediating between climate and occupants. Details about the authorship of this paper are provided in table 2.1.

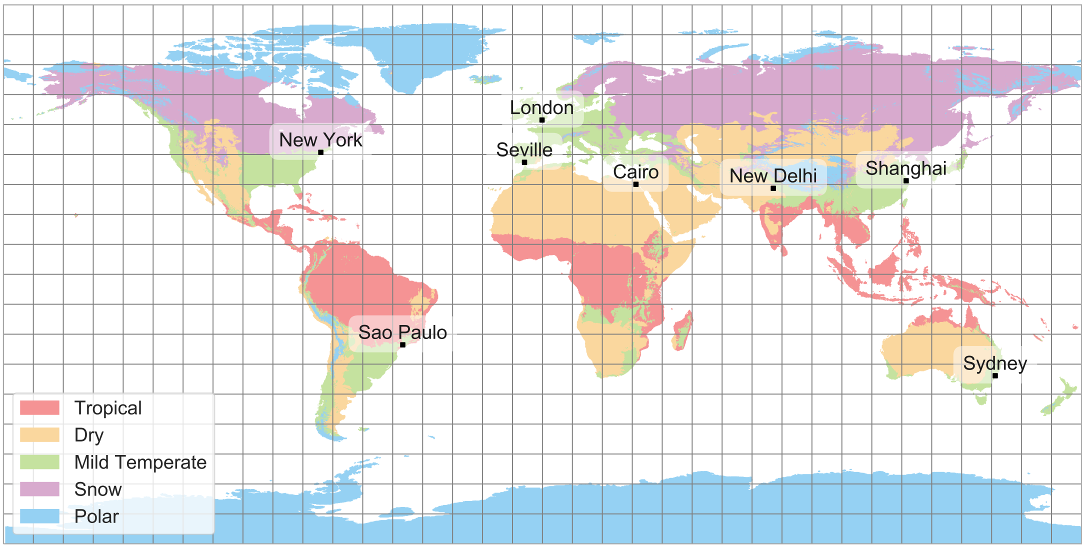

Figure 2.2: Locations considered in the study (background: Köppen-Geiger climate classification simplified from Kottek et al. (2006))

2.2 Declaration of authorship

Table 2.1: Declaration of authorship

This declaration concerns the article entitled:
Mitigation versus Adaptation: Does Insulating Dwellings Increase Overheating Risk?

Publication status:
Published

Publication details:
D. Fosas, D. A. Coley, S. Natarajan, M. Herrera, M. Fosas de Pando, and A. Ramallo-Gonzalez (Oct. 2018c). “Mitigation versus Adaptation: Does Insulating Dwellings Increase Overheating Risk?” *Building and Environment* 143, pp. 740–759. DOI: `10.1016/j.buildenv.2018.07.033`.

Copyright status:
I hold the copyright for this material.

Candidate’s contribution to the paper:
The author of this thesis has predominantly contributed to the publication (84 %). The contributions by each author are as follows:

- Formulation of ideas: D. Fosas (80 %), D. A. Coley and S. Natarajan (20 %).
- Background: D. Fosas (90 %) and A. Ramallo-Gonzalez (10 %).
- Design of methodology: D. Fosas (80 %), M. Herrera (10 %) and M. Fosas de Pando (10 %).
- Experimental work: D. Fosas (90 %) and M. Fosas de Pando (10 %).
- Analysis: D. Fosas (90 %) and M. Herrera (10 %).
- Preparation of manuscript: D. Fosas (90 %) and D. A. Coley (10 %).
- Editing drafts of manuscript: D. Fosas (70 %), D. A. Coley (20 %), S. Natarajan and M. Fosas de Pando (10 %).

Statement from Candidate:
This paper reports on original research I conducted during the period of my Higher Degree by Research candidature.

Signed **Date** 20 December 2019

2.3 Abstract

Given climate change predictions of a warmer world, there is growing concern that insulation-led improvements in building fabric aimed at reducing carbon emissions will exacerbate overheating. If true, this would seriously affect building regulations all over the world which have moved towards increased insulation regimes. Despite extensive research, the literature has failed to resolve the controversy of insulation performance, primarily due to varied scope and limited comparability of results.

We approach this problem through carefully constructed pairwise comparisons designed to isolate the effect of insulation on overheating. We encompass the complete range of relevant variables: latitude, climate, insulation, thermal mass, glazing ratio, shading, occupancy, infiltration, ventilation, orientation, and thermal comfort models — creating 576 000 building variants. Data mining techniques are implemented in a novel framework to analyse this large dataset. To provide confidence, the modelling was validated against data collected from well-insulated dwellings.

Our results demonstrate that all parameters have a significant impact on overheating risk. Although insulation is seen to both decrease and increase overheating, depending on the influence of other parameters, parameter ranking shows that insulation only accounts for up to 5 % of overall overheating response. Indeed, in cases that are not already overheating through poor design, there is a strong overall tendency for increased insulation to reduce overheating. These results suggest that, in cases with acceptable overheating levels (below 3.7 %), the use of improved insulation levels as part of a national climate change mitigation policy is not only sensible, but also helps deliver better indoor thermal environments.

2.4 Introduction

The buildings sector accounts for 25 % of global fossil fuel related greenhouse gas emissions (Lucon et al. 2014). These emissions arise primarily from the demand for space heating and cooling (IEA 2015), hence, improved building insulation lies at the heart of energy reduction policies (European Commission 2002; Papadopoulos 2016; Saheb et al. 2013; Janda and Busch 1994; Janda 2009; Iwaro and Mwasha 2010; Li and Shui 2015; Chandel et al. 2016). Taking the UK as an example, buildings represent the sector with the single greatest emissions, accounting for 37 % of total CO_2e emissions ($210.9\,\mathrm{Mt\,CO_2e\,a^{-1}}$) (CCC 2013) and, in order to meet the planned national trajectory of emission cuts, considerable reductions are expected from the sector. Increased wall insulation is expected to provide 42 % of this reduction, heating-related measures 27 %, other measures (such as increased energy efficiency of appliances or lighting) 24 %, and building fabric measures other than wall insulation 6 % (CCC 2013). Consequently, at 48 %, improved insulation/fabric will be the largest contributor and therefore critical in meeting the trajectory.

As seen in the European heat wave of 2003, where over 14 000 died inside buildings in Paris alone (Vandentorren et al. 2006), excessive temperatures (termed overheating) in buildings can lead to a severe loss of life. Several studies (see table 2.2) have suggested that improved insulation might exacerbate overheating, implying a direct conflict between mitigation and adaptation for this key policy. If correct, these studies suggest alternative routes to mitigation will have to be found, or carbon trajectories rethought with much greater cuts from other sectors such as transport or electricity generation (Lucon et al. 2014; DCLG 2012a; CCC 2016). However other studies have found the opposite. For example, the empirical evidence collected during the Paris heat wave shows higher internal temperatures in rooms without insulation (Vandentorren et al. 2006). Given that improved insulation in buildings is one of the central planks of climate change policy in many countries, and a belief that this might exacerbate temperatures would be a serious challenge. These contradictions therefore need to be resolved.

Table 2.2: Comparative analysis of selected studies regarding overheating and their findings regarding insulation[2]

Research	Year	Scope			Method			Assessment			Findings related to overheating and insulation
		Building type	Location	Weather	Field-study	Simulation	Thermal Comfort	Time over threshold	Severity	Energy demand	
Chvatal & Corvacho	2009	Dwellings, Offices	Portugal (3) + Italy (1) + Greece (1)	P	—	✓	A	C	✓	H+C	The performance of improved insulation was twofold. It could increase or decrease overheating depending on the solar gains.
Mavrogianni et al.	2012	Dwellings (various)	UK (1) (London)	P+F	—	✓	*	—	✓	—	Under certain cases, adding or increasing internal solid wall insulation could increase indoor temperatures.
Porrit et al.	2012	Dwellings (Terrace)	UK (1) (London)	P*	—	✓	F	W	—	—	Overall, adding insulation helped in reducing internal temperatures. In some circumstances, adding it to the internal layer increased them.
Beizaee et al.	2013	Dwellings (various)	UK (nationwide)	P	✓	—	F+A	C+W	✓	—	Houses built after 1990 or with cavity walls were significantly warmer than the rest despite the mild summer conditions.
Lomas & Kane	2013	Dwellings (various)	UK (1) (Leicester)	P	✓	—	F+A	C+W	✓	—	Houses built before 1919, or those that had solid walls were colder than the rest. Houses built after 1980 were significantly warmer.
McLeod et al.	2013	Dwellings (end-terrace)	UK (1) (London)	P+F	—	✓	F	C	✓	H	The performance of the lower U-values of the Passivhaus was a function of solar heat gains. Overheating would start in 2050.

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Research	Year	Scope			Method			Assessment			Findings related to overheating and insulation
		Building type	Location	Weather	Field-study	Simulation	Thermal Comfort	Time over threshold	Severity	Energy demand	
Mavrogianni et al.	2014	Dwellings (various)	UK (1) (London)	P	—	✓	F	C	✓	—	Occupant patterns and behaviour greatly influence overheating (assessed for retrofit packages).
Taylor et al.	2014	Dwellings (various)	UK (6)	P+F	—	✓	*	—	✓	—	The external climate influences how buildings overheat and the effectiveness of different dwelling retrofit strategies.
van Hoof et al.	2014	Dwellings (various)	Netherlands (1) (de Bilt)	P	—	✓	A	C+W	—	—	Improving insulation exacerbated the duration of overheating when U-values are reduced from $0.20\,\mathrm{W\,m^{-2}\,K^{-1}}$ to $0.15\,\mathrm{W\,m^{-2}\,K^{-1}}$.
Gupta & Kapsali	2015	Dwellings (various)	UK (not specified)	P	✓	—	F+A	C+W	✓	—	Energy efficient dwellings overheated, but the cause pointed to faulty building services, not to the characteristics of the building.
Makantasi & Mavrogianni	2015	Dwellings (flats)	UK (1) (London)	P+F	—	✓	F+A	C	—	H+C	The way wall insulation affected indoor temperatures was a function of the other building characteristics retrofitted.
Sameni et al.	2015	Dwellings (flats)	UK (1) (Coventry)	P	✓	—	A	C+W	✓	—	Passivhaus dwellings overheated, but underlying causes reviewed do not mention issues with improved building fabric.
Mulville & Stravoravdis	2016	Dwellings (semidetached)	UK (2) (London, Edinburgh)	P+F	—	✓	F+A	C+W	✓	—	Improving building fabric (increased insulation and reduced airtightness) increases overheating risk.

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[2] *Weather:* *P*resent, *F*uture. *Comfort Model:* *A*daptive, *F*ixed (absolute values), * Statistical description. *Time over threshold:* *C*ounted, *W*eighted. *Energy demand:* *H*eating, *C*ooling. —: not performed/assessed.

2.4.1 Overheating in dwellings

Increasing insulation could be regarded as a measure that will reduce the ability of a building to dissipate heat, and hence exacerbate overheating. However, this will only be the case when the external temperature is lower than the internal, and is further complicated by fabric elements that receive direct sunlight reaching much higher temperatures, and therefore additional insulation reducing external heat gains. There is also the need to consider the size of the internal/external temperature difference. In winter this might be 20 K or more, in summer in much of the world it will be considerably smaller. In naturally ventilated buildings in winter, air ingress is likely to be low and fabric heat exchange will play an important role. In summer, however, much larger air flows will be the norm to alleviate high internal temperatures, making air ingress the likely dominant heat path — and more so in well insulated buildings. The situation is also expected to vary over the day as the internal/external temperature difference changes sign. It might also potentially differ with occupant willingness to open and close windows and the internal heat gains. Moreover, other effects such as the dynamic influence of thermal mass or shading further obscures an intuitive characterization of the role of increased insulation in overheating.

Several studies have addressed these concerns (see table 2.2). Chvatal and Corvacho (2009) studied the relationship between overheating and insulation. They altered thermal transmittances (U-values), shading and night ventilation for a free-running dwelling in various locations, showing that trends in discomfort hours shifted in sign according to shading conditions in certain circumstances: it could either increase or decrease the duration of overheating. They also found that additional insulation was detrimental in cases with extremely high, and probably unrealistic, levels of overheating (i.e. overheating hours 40–100 % of occupied hours during summer); whereas it was not for lower, and more realistic, levels of overheating (i.e. fewer than 40 % overheating hours). This shift in the sign of the effect was found for solar energy transmittances ranging from 0.32 to 0.61, but the low summertime purge ventilation rates considered in most of the work (sometimes as low as $0.60\,\mathrm{ach\,h^{-1}}$) suggest these results do not correctly account for occupant behaviour (such as opening of windows), that would result in much higher ventilation rates.

Porritt et al. (2011) and Porritt et al. (2012) performed several studies regarding measures to lessen overheating during heat waves as part of the Community Resilience to Extreme Weather (CREW) project. Focusing on retrofits and mid-2000 dwellings, they also assessed orientations, wall coatings, glazing types and occupancy profiles, showing that all parameters had an impact on overheating. The research concluded that the control of solar gains was the most effective action to reduce overheating, and that insulation was also beneficial except when placed in the layers closest to the occupied space. Mavrogianni et al. (2012) arrived at similar conclusions about insulation when characterising London dwellings and retrofit measures. Gupta and Gregg (2013) further supported these findings but stressed that overheating depends highly on how measures are combined.

McLeod et al. (2013) considered the performance of Passivhaus Institute Standard (PHIS) and Fabric Energy Efficiency Standard (FEES) compliant dwellings under a changing UK climate. It was shown that the slightly better building envelope of the PHIS case outperformed the FEES variant (i.e. led to less overheating). The study also included a sensitivity analysis that ranked parameters according to the increase in overheating risk they posed, as follows: glazing ratio > thermal mass > shading device > airtightness. Unfortunately, the study did not include natural ventilation, a key measure against overheating. However, van Hooff et al. (2014) found exactly the opposite when looking into changes in U-values from $0.20\,\mathrm{W\,m^{-2}\,K^{-1}}$ to $0.15\,\mathrm{W\,m^{-2}\,K^{-1}}$ with increasing insulation significantly increasing overheating. Besides the potential influence of overheating criteria, it is not clear if the differences in impact are caused by different choices of locations, parameters or assumptions, as there is not enough information in the publications to compare them.

Taylor et al. (2014), building on the studies of Mavrogianni et al. (2012) and Mavrogianni et al. (2014), focused on the influence of different locations, obtaining significant changes in overheating patterns within the UK. Yet, the performance of each measure remained qualitatively similar for most parameters (e.g. retrofitting windows decreased overheating everywhere). Additionally, the study correlated wall retrofits to internal temperature increases of 0.1–3.5 K, a greater effect than the ±1 K variation obtained in the previous study (Mavrogianni et al. 2012) but similar to the combined reduction due to roof and windows retrofits. A further publication, based on the findings from CREW, investigated how overheating changes for different occupancy patterns (pensioners, always home; and working family, away from 9 h to 18 h) and considered different levels of engagement with the operation of windows and shading devices (Mavrogianni et al. 2014). As expected, overheating increased significantly for cases with higher internal gains and lower occupant engagement in the operation of openings, in particular for the pensioners. The work clearly quantified the extent to which occupant behaviour alters overheating, and the implications this can have for people not able to operate the house as advised. Unfortunately, highly insulated dwellings were outside of the scope of these studies, as was the impact of different levels of insulation.

Identifying the most influential parameters

Overall, the findings reviewed in the previous section show a tendency towards a holistic characterization of the problem, arriving at the idea that every parameter is equally critical. In addition, some authors have suggested, sensibly, that the combined performance of building elements is not the sum of individual ones (e.g. Gupta and Gregg (2013) and Makantasi and Mavrogianni (2015)). Few studies, however, have characterised the contributions of each parameter concurrently with the changes in others.

Taylor et al. (2014) specifically focused on the relationship between overheating and the characteristics of London dwellings. Overall, they found similar trends as other studies did, although the ranking of the influence of parameters varied by location in the UK. Unfortunately, this work does not specifically cover the impact of insulation because the aim was to characterize the building stock. Another study focused on the performance of retrofit packages, but it only covered a limited number of variables and it did not include low U-values (Makantasi and Mavrogianni 2015). On the other hand, McLeod et al. (2013) performed a sensitivity analysis of thermal mass, glazing ratio, shading, airtightness and internal gains for the previously mentioned PHIS and FEES variants. They found that the most important factors were glazing ratio, followed by thermal mass, shading devices and airtightness. Although this ranking should be contextualized within the range of the variables under consideration, it provides a good starting point to evaluate the importance of different parameters on overheating. Unfortunately, different purge ventilation strategies were not included in the sensitivity analysis.

Field studies of super insulated dwellings

It has been pointed out that real, rather than modelled, modern buildings might overheat significantly more than older ones (DCLG 2012b; Dengel and Swainson 2012; Lomas and Kane 2013; Beizaee et al. 2013; Taylor 2014). However, increased levels of insulation are only one of the many differences between older and newer buildings, making it hard to connect cause with effect. Pairwise comparisons with different building fabrics do not exist, but there have been several monitoring studies reporting the performance of highly insulated dwellings (Gupta and Kapsali 2015; Sameni et al. 2015; Fletcher et al. 2017). Dwellings in these studies developed high indoor temperatures, but the causes pointed to other driving forces, particularly issues with building services, e.g. gaps in pipe insulation, poor commissioning or heating on during summer, rather than improved building fabric. On the contrary, during the European heat wave of 2003, it was found that older houses and those lacking thermal insulation were at a higher risk (Vandentorren et al. 2006).

A further point is that thermal comfort research highlights that indoor conditions should be evaluated by occupants themselves whenever possible (de Dear et al. 2013). The above-mentioned field studies monitored indoor air properties without the associated occupant's thermal satisfaction, for which they compared results with standard overheating criteria. Therefore, they do not indicate whether occupants wanted to be at a lower temperature. In fact, Baborska-Narożny et al. (2016) showed that occupants might not take actions to reduce temperatures. Fletcher et al. (2017) suggested that familiarity with the mechanical systems, its configuration and perceived security can play a significant role in these groups, although they also acknowledged the need to further link assessed overheating with actual occupant perception. In this sense, Vellei et al. (2016) analysed the differences in indoor conditions between vulnerable and non-vulnerable groups. They showed that the dwellings of vulnerable people were statistically warmer than the non-vulnerable, but also that vulnerable people indeed preferred warmer conditions when questioned.

2.4.2 Objectives

The aim of our work is to clarify whether additional insulation exacerbates overheating. Given the challenges arising in previous research, this covers a complete, realistic and consistent range of building parameters, occupant behaviours, locations across the world and definitions of overheating. Unfortunately, this cannot be achieved via a meta-study due to wide differences in methodology, scope and building parameters used in previous work. Key to doing this, we will present enough information for the results to be reproduced by others, and to cover enough variants of the situation to be comprehensive. In particular, the objectives are:

1. To quantify the combined impact of building features on overheating.
2. To understand the impact of increased insulation on overheating risk.
3. Point to why previous studies have been contradictory.

The paper is organised as follows. Firstly, we propose a methodological approach that combines time-resolved simulations of indoor conditions in parametrically-designed dwellings to encompass a wide range of conditions and scenarios. Next, the influence of insulation and every other parameter is analysed and discussed. To this end, techniques such as regression and classification trees as well as classical hypothesis testing techniques will be applied to express the results in a meaningful way and to draw generally-applicable conclusions. The results will allow us to determine the role of increased insulation, with key findings summarised in the last section.

2.5 Methods

Like almost all work on the topic, we calculate overheating performance using mathematical models of buildings because this allows for pairwise comparisons to isolate the influence of changing a particular parameter. In our case, the simulations are based on validated models that replicate the performance of real monitored dwellings (see fig. 2.3). In total 576 000 cases were modelled. Each case comprises specific combinations of the following building parameters: insulation level, location, building type, thermal mass, windows size, shading, natural ventilation rate and control, internal gains, infiltration and orientation. We purposely avoid attempting to weight these samples with their true distributions, as these are unknown. Instead, every possible combination is considered, regardless of its propensity to exist. This ensures all possibilities are covered and no bias is introduced. Although overheating is important in all buildings, naturally ventilated buildings and their occupants are at far greater risk due to a lack of any air conditioning or mechanical ventilation system to provide cooling. In addition, due to the greater impact of overheating in vulnerable groups, particularly the elderly, and the greater time spent at home, dwellings are of more concern than commercial buildings. Hence, we concentrate on naturally ventilated domestic properties.

In the following the parameter space is described, followed by a description of the overheating metrics, monitoring and validation.

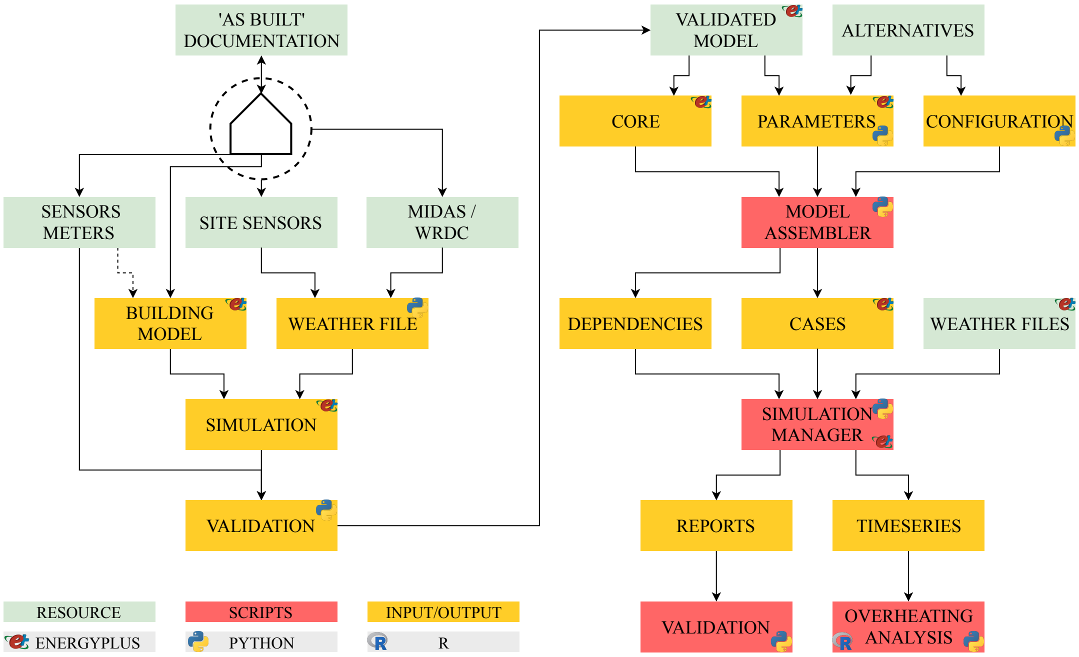


Figure 2.3: Overview of the methods (Crawley et al. 2001; PSF 2017; R Core Team 2017); the left-hand area shows the generation of the model for the validation using monitored data for both house types in the study; the right-hand one shows how design alternatives are generated and simulated based on the validated model together with the post processing of the results)

Table 2.3: Parameters in the study (total: 576 000 cases, see section 2.5.1 for definitions)

Parameter	**Cases per parameter**							
House	Apartment	Detached						
Insulation [$\mathrm{W\,m^{-2}\,K^{-1}}$]	0.60	0.45	0.35	0.18	0.10			
Thermal mass [$\mathrm{kJ\,m^{-2}\,K^{-1}}$]	38	281	520					
Windows size [%]	8	11	14					
Shading	None	Full						
Internal gains	Home	Away						
Window opening rubric	None	Day-O T_{max}	Day-O T_{neu}	Day-A T_{max}	Occupied T_{neu}			
Algorithm	Fixed	Adaptive						
Infiltration [$\mathrm{m^3_{air}\,m^{-2}_{envelope}\,h^{-1}}$]	20	10	5	2.5	0.2			
Orientation	South	West	North	East				
Location	Cairo	London	New Delhi	New York	Shanghai	Seville	Sydney	Sao Paulo

2.5.1 Parameters

There are an infinite number of possible buildings, hence we explore this large parameter space via combinations of fundamental architectural parameters (see fig. 2.3 and table 2.3). In total, 576 000 cases, i.e. specific combinations of building parameters and occupant behaviour, have been chosen to span the space, and importantly, have enough variety to cover a greater range than previous work, hence answering some of the criticisms of such work; such as too narrow a range of: ventilation, insulation (U-value), or shading. This approach aims to clarify how fundamental parameters affect overheating by studying every combination of the parameters involved. Therefore, the models are conceived to bound plausible ranges for the relevant building physics parameters involved in overheating, and do not necessarily reflect the expected prevalence in the real building stock.

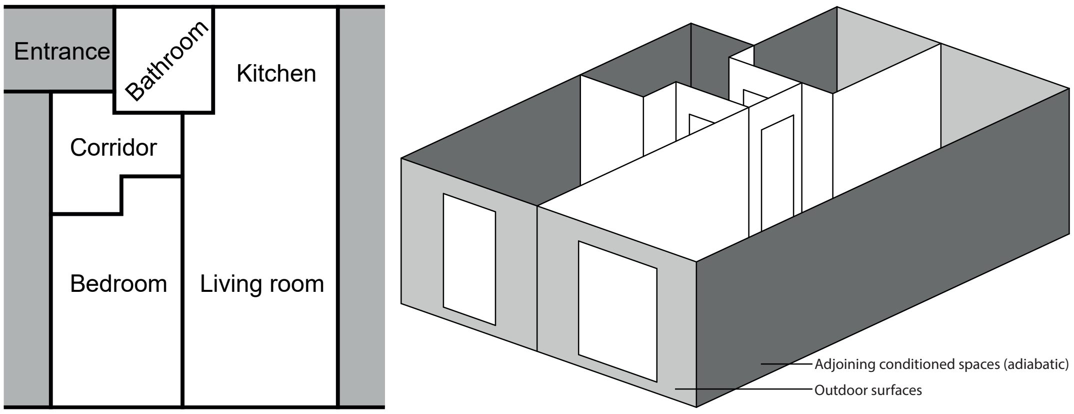
The buildings were simulated over one year using EnergyPlus (E+) v8.8 (NREL 2017) within a computer cluster. E+ is an open source building simulation engine that integrates the three fundamental domains in building physics: surface heat balance (sky, shading, daylighting, window glass and conduction transfer functions), air heat balance (airflow networks) and building systems (heating, ventilation, air conditioning and renewable energy). These domains are coupled and solved at the defined timestep ranging from 1 min to 60 min.

Basic architectural form

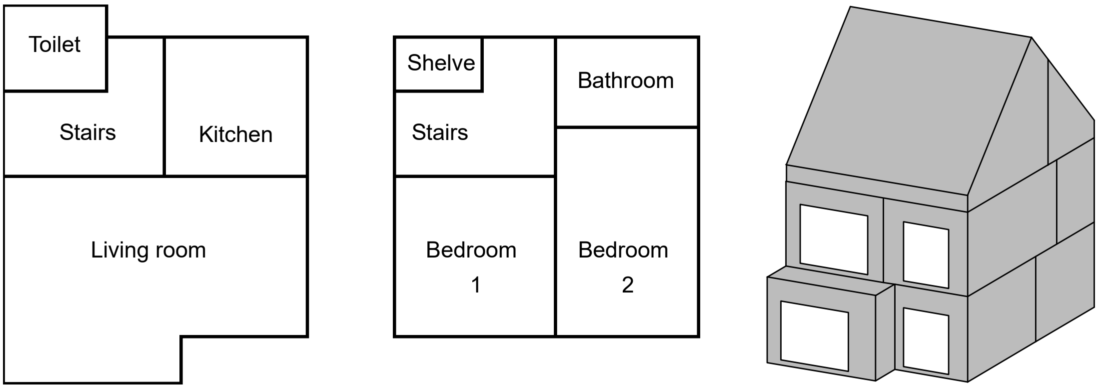
The study was based on a worst-case scenario to bound one side of the parameter space and a best-case one to bound the other. An apartment with ventilation from windows on only one façade is selected as the worst case because this form of building is most prone to overheating (ZCH 2015) and because it is a common typology in the various, worldwide, locations considered in this study. It corresponds to a real apartment built in the UK in the late 2000s (fig. 2.4(a)). A top floor unit was selected due to the greater exposure to solar gains, thereby further exacerbating overheating (roof directly exposed to solar gains without intermediate buffer space). A detached house was then used as a best-case scenario, i.e. least likely to overheat, as heat losses are maximised due to external exposure on all four façades, and maximised natural ventilation due to cross-ventilation (fig. 2.4(b)).

The apartment is surrounded by identical units on either side with the other two faces exposed to the external environment; only the main façade, that with the living spaces, has windows. The model is considered to be in an urban low-rise environment and the conditions for the elements defining each zone are the following:

1. Façades: exposed to wind and sun.
2. Party walls and floor: The adjoined units develop the same temperatures as the apartment, i.e. with no net heat transfer across the separating walls or



(a) Apartment: plan (left) and building model (right; maximum dimensions 6.4×9.5×2.6 m)



(b) Detached house: ground floor (left), first floor (centre) and building model (right; maximum dimensions 6 m×9.7 m×9.4 m)

Figure 2.4: Base models description (apartment and detached house, best and worst-case dwelling types for overheating risk, respectively)

floors (adiabatically). This simplifies the analysis, is again the worst case and is consistent with other studies. Nevertheless, the thermal mass of these elements is still considered.

3. Internal walls: Energy exchanges through these elements are modelled to capture the effects of higher gains in some rooms passing to other rooms.

4. The building is modelled out to the external side of the thermal envelope (IBO 2009) (except for the internal walls, which are defined by their midpoint). Each room constitutes a thermal zone to obtain individual temperature readings and to have complete control over the definition of heat gains (e.g. the solar distribution model assigns the solar gain to each room (NREL 2017)).

5. The ventilation model is an airflow network. Here, air exchanges are driven by wind and stack ventilation. The external environment and the internal zones are represented as a set of nodes linked with the windows and other elements

> such as doors. The chosen window type is sliding and only the upper half of the opening is considered openable and up to 5 % of the room area. The system is then solved for pressure and airflow to give temperature, humidity and the resulting thermal loads. This evaluates input parameters and runtime conditions to decide whether windows should be opened or not and, if so, to what extent (NREL 2017). External conditions are derived from the weather files and adjusted for height and building context through wind profiles and wind pressure coefficient models. For the latter, the building form-dependent pressure coefficients after Swami and Chandra's low-rise model with rectangular obstructions is used (Swami and Chandra 1987). The overall effect of all these conditions can be observed in fig. 2.13.

The detached house follows the same approach, but every external surface is fully exposed to outdoors conditions. Additionally, there are windows in the main façade and the opposite one to allow cross-ventilation, consistent with a best-case scenario. The wind pressure coefficients are modelled after Grosso[3], since it was applicable for the building and urban characteristics at hand (e.g. urban density, building aspect ratios) (Grosso 1992). Thus, the particular wind pressure coefficient values at the precise opening location within the façade is accounted for. Like in the apartment, the overall effect of the ventilation parameters can be observed in fig. 2.13.

The predicted annual heating energy demand and temperature time series provides data for the validation of the parametric models (fig. 2.6). The heating is the same in every case, although schedules and values vary according to the occupancy under consideration (table 2.10 and 2.11). Heating is provided through an ideal loads system to control the energy demand without explicit modelling of building services, to generalize results. Background ventilation is provided to control CO_2 concentrations (table 2.10 and 2.11). Overheating is appraised in the living room and the main bedroom separately.

Insulation

Five cases are considered with wall transmittances between $0.60\,\mathrm{W\,m^{-2}\,K^{-1}}$ and $0.10\,\mathrm{W\,m^{-2}\,K^{-1}}$. The thermal resistance of elements was based on both Building Regulations and best practice standards in the UK to ensure consistency and future relevance of the results. Table 2.4 defines U-values and glazing properties for each building element present in the models. The U-values of the walls give the names of U-value cases, although the performance of other elements varies consistently with construction practices.

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[3] N.B. This is *not* the built-in model in E+. The coefficients are calculated separately and fed into the simulation via custom wind pressure coefficient objects to account for the particular settings of the model.

Table 2.4: Detached dwelling: occupancy, gains and ventilation according to "internal gains" profiles

Parameter / Case	**0.60**	**0.45**	**0.35**	**0.18**	**0.10**	**Unit**
U-value$_{\text{Wall}}$	0.60	0.45	0.35	0.18	0.10	$\mathrm{W\,m^{-2}\,K^{-1}}$
U-value$_{\text{Roof}}$	0.35	0.25	0.25	0.13	0.10	$\mathrm{W\,m^{-2}\,K^{-1}}$
U-value$_{\text{Ground}}$	0.60	0.45	0.25	0.18	0.10	$\mathrm{W\,m^{-2}\,K^{-1}}$
U-value$_{\text{Door}}$	5.70	3.30	2.20	1.40	0.85	$\mathrm{W\,m^{-2}\,K^{-1}}$
U-value$_{\text{Window,limit}}$	5.70	3.30	2.20	1.40	0.85	$\mathrm{W\,m^{-2}\,K^{-1}}$
U-value$_{\text{Window,BSI (2011)}}$	5.66	3.30	2.20	1.30	0.76	$\mathrm{W\,m^{-2}\,K^{-1}}$
g-value	0.80	0.74	0.70	0.60	0.59	—
Light transmission	0.88	0.80	0.76	0.76	0.69	—
Windows composition	3	4+6+4	4+8+4	4+16+4	5+12+4+12+5	mm

Thermal mass

Thermal mass has been identified as a potentially important parameter in previous work. Consequently, three cases were established based on the TMP, a metric that takes into account the thermally-active depth of a construction. Following the ISO-13790 method, a thermally lightweight construction is taken as having a TMP of $38\,\mathrm{kJ\,m^{-2}\,K^{-1}}$, with medium and heavyweight ones at $281\,\mathrm{kJ\,m^{-2}\,K^{-1}}$ and $520\,\mathrm{kJ\,m^{-2}\,K^{-1}}$, respectively. Short timestep dynamics are accounted for by setting the simulation timestep to 10 min.

Construction assemblies were serialized in groups according to their thermal mass. Lightweight construction requires internal insulation whereas it is externally located for the medium and heavyweight cases. Internal blocks of different properties achieve target TMP values (table 2.8 and table 2.9). The insulation thickness conforms with the thermal resistance of these layers. Internal partitions are based on a standard drywall assembly. Lastly, the real internal areas and volumes for each of the fifteen combinations were implemented in the model rather than assuming they correspond to the space enclosed by outdoor surfaces. Thus, energy exchanges are invested in the real enclosed air, accounting for changes in building volumes associated with different construction thicknesses.

Window area

Three different window areas were considered ensuring that solar gains remained constant across other modifications that could influence them. All windows are rectangular and are kept in their original location (fig. 2.4). For the double-sided detached house, cases at 15 %, 20 % and 25 % window area to floor area ratio were explored. For the single-sided apartment this means three cases at 9 %, 12 % and 14 % wall-to-floor ratio each. Frame thicknesses were set consistently with window U-values (5 cm frames in U-value = 0.60–$0.35\,\mathrm{W\,m^{-2}\,K^{-1}}$ and 10 cm in U-value = 0.18–$0.10\,\mathrm{W\,m^{-2}\,K^{-1}}$). Finally, since different wall thicknesses can affect solar heat gain through different depths of reveals, they were adjusted to remain constant at 5 cm for all simulations.

Shading

The shading strategies considered were ‘none’ and ‘full’. In the first case, windows are completely exposed to solar radiation, accounting for the worst case. In the second case, openings are shaded via fixed horizontal overhangs and vertical fins to realistically capture the physics of the heat transfer while minimizing model complexity (e.g. different occupant behaviours or the impact blinds and shades have on conduction and convection). These were based on the latitude and designed to fully shade windows at the summer solstice (overhangs at noon and fins at sunrise/sunset, table 2.5). The overall effectiveness of this ‘full’ shading strategy is a median reduction of direct solar radiation of 45 % compared to the ‘none’ case.

Table 2.5 summarizes key characteristics for the locations under study and the properties of the shading devices as a function of the opening characteristics.

Table 2.5: Locations and shading used

Location	**Köppen-Geiger Climatic Zone**	**Latitude**	**Overhang ratio**[a b]	**Fin ratio**[b c]
Cairo	Arid (BWh)	+30.13	0.12	1.93
London	Warm temperate (Cfb)	+51.15	0.53	1.22
New Delhi	Arid / Warm temperate (BSh/Cwa)	+28.58	0.09	1.97
New York	Warm temperate (Cfa)	+40.78	0.31	1.62
Sao Paulo	Warm temperate (Cfa)	−23.61	0.05	2.08
Seville	Warm temperate (Csa)	+37.42	0.25	1.73
Shanghai	Warm temperate (Cfa)	+31.17	0.14	1.91
Sydney	Warm temperate (Cfa-Cfb)	−33.95	0.19	1.83

[a] Depth over opening height. [b] Depth over opening width.

[c] The overall median solar gains reduction of these shading devices is 45 % compared to the ‘none’ case.

Internal gains

In line with previous studies (e.g. Taylor et al. (2014) and Mavrogianni et al. (2014)), two cases were examined to cover different types of behaviour: a working couple ‘away’ from 9:00 to 17:00 and another ‘home’ all-day-long. The former concentrates internal gains early in the morning and evenings, and the latter induces lower but sustained internal gains throughout the day.

Occupancy was modelled as discrete individuals (with metabolic outputs) in specific rooms. Lighting and other gains were based on the current state of the art (Richardson et al. 2010; McLeod et al. 2013; Palmer and Cooper 2013). These establish a power ‘budget’ spent according to occupancy, but consider residual loads and specific appliances in the kitchen. Resulting average gains were 2.84 $\mathrm{W\,m^{-2}}$ (evening total: 1670 W) and 3.38 $\mathrm{W\,m^{-2}}$ (evening total: 1209 W) for the ‘away’ and ‘home’ scenarios, respectively (tables 2.10 and 2.11).

Comfort algorithm and window opening rubric

As this is a study of naturally ventilated buildings, a model/algorithm for window opening is needed. Such models are based on the thermal comfort of the occupants, and assume people will, or will not, open windows to restore comfort. Unfortunately, differences in the way this has been accounted for and reported in previous studies precludes a meta-analysis that would shed light on the role of insulation in overheating (table 2.7). We use the two standard thermal comfort models: (**F**[4]) Fanger's model (Fanger 1970), which assumes that the majority of occupants are comfortable at a fixed temperature (T_{neu}), and uncomfortable at a higher fixed temperature (T_{max}), and (**A**) the adaptive comfort model (de Dear and Brager 1998; Nicol and Humphreys 2010), which assumes T_{neu} and T_{max} vary based on the historic time series of external temperature. As it is unknown just how responsive occupants are, we assume occupants might start to use purge ventilation once the temperature of the room is above T_{neu}, or only once T_{max} is reached. We are agnostic to **F** and **A** — since both are considered valid representations of the physiology and psychology of occupants — and we allow occupants to adopt either. They can also not react to the temperature in the room at all, leaving the windows only open enough to ensure reasonable air quality. In addition, it is possible that occupants might behave differently at different times of day. The final requirement is that windows are only opened to provide additional cooling if the external temperature is lower than the internal temperature.

The 'algorithm' parameter captures the influence of these thermal comfort models. Fanger's model (**F**) is accounted for through fixed set points, $T_{neu} = 25\,°\mathrm{C}$ in the living room and 23 °C in the bedroom (CIBSE 2005), with the operative temperature taken as the average of air and radiative temperatures (CIBSE 2017a). T_{max} is then $T_{neu} + 3\,\mathrm{K}$. Underpinning these thresholds and values is the assumption of air speeds below $0.1\,\mathrm{m\,s^{-1}}$, a conservative estimate for naturally ventilated buildings. For **A**, T_{neu} is calculated for European (BSI 2007) and other locations (ANSI/ASHRAE 2017) from:

$$\begin{cases} \text{Location in Europe:} \quad T_{neu} = 0.33 \cdot T_{rm} + 18.8; \quad T_{max} = T_{neu} + 3 \\ \text{Location elsewhere:} \quad T_{neu} = 0.31 \cdot T_{rm} + 17.8; \quad T_{max} = T_{neu} + 3.5 \end{cases} \tag{2.1}$$

with

$$T_{rm} = (1 - \alpha) \cdot \{T_{od-1} + T_{od-2} + T_{od-3} + \dots\} \tag{2.2}$$

where T_{rm} is the outdoor running mean, α is a constant in the interval $[0, 1)$ and T_{od} is the 24 h mean outdoor temperature. α controls the rate at which T_{od}

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[4] We use the term "fixed" (**F**) to refer to Fanger's model in this manuscript. This just indicates that, in this model, temperature thresholds do not depend on the past thermal experiences of occupants in the previous days as it does in the adaptive comfort models (**A**).

influences T_{rm} and is set to 0.8 in this study as recommended in standards (CIBSE 2013; ANSI/ASHRAE 2017). Whenever T_{rm} falls outside the applicability range of the adaptive model, temperatures are taken according to **F**. Overall, these values for **F** and **A** consider occupants can adjust one or more values of clothing, activity and relative air speed, among others, to remain comfortable. When operative temperatures exceed the comfortable temperature by more than 3 K or 3.5 K, such adjustments can no longer be relied upon and overheating is considered to be taking place. Note that the use of fans was not considered in this study, since any result that does not increase overheating without fans will also not increase overheating with them.

Windows are opened to provide purge ventilation based on a set of rules. This provides a transparent approach based on first principles that is coherent with the thermal comfort models mentioned above. This allows us to account for a wide range of scenarios, in light of the known epistemic limitations in window occupant behaviour (Yan et al. 2017), while retaining the ability to perform pairwise comparisons across building variants. In the model, windows are opened for purge ventilation if the following conditions are all met simultaneously:

1. A trigger internal temperature is surpassed. This accounts for the natural tendency for occupants to open windows to provide cooling.
2. The external temperature is lower than the internal. In very hot climates the cultural norm is for windows to be left closed during periods of peak external temperature.
3. A rule based on time of the day and occupancy. To stop windows being opened when the building is unoccupied, or if occupants feel nervous about leaving windows open when they are asleep. These rules are:
    a) (Cases 1F and 1A) None: Purge ventilation is never available. This constitutes a worst-case scenario and assumes occupants never open windows in response to overheating.
    b) (Cases 2F and 2A) Day-O-T_{max}: Purge ventilation is available during the day (but not at night) if there are occupants in the dwelling. The trigger temperature is T_{max} calculated under the fixed or adaptive model. This represents a minimal reaction to temperatures above the acceptable threshold at times occupants are awake and adaptation is possible.
    c) (Cases 3F and 3A) Day-O-T_{neu}: Same as Day-O-T_{max}, but the trigger temperature is T_{neu} calculated under the fixed or adaptive model. This represents occupants that aim for optimal comfort conditions, as suggested by the standard thermal comfort models.
    d) (Cases 4F and 4A) Day-A-T_{max}: Same as Day-O-T_{max}, but purge ventilation is always allowed during daytime regardless of the occupancy. This increases

its availability during the hottest periods of the day i.e. windows can be left open, or open via electronic sensors.

e) (Cases 5F and 5A) Occupied-$\mathrm{T_{neu}}$: Purge ventilation is available day or night if there are occupants in the dwelling. The ventilation set point is the comfort temperature. This represents traditional natural ventilation strategies in hot countries aimed at taking advantage of colder night-time temperatures (constraints such as security or noise ingress are not considered) (La Roche et al. 2001).

Altogether, the combination of the 'Comfort Algorithm' and 'Purge ventilation' parameters result in ten ways windows can be opened ('rubrics') to deliver purge ventilation.

Infiltration

Infiltration describes uncontrolled exchanges of air, for example through cracks in the construction, the use of porous materials or imperfect window seals. Infiltration air flow rates of between $20\,\mathrm{m^3_{air}\,m^{-2}_{envelope}\,h^{-1}}$ and $0.2\,\mathrm{m^3_{air}\,m^{-2}_{envelope}\,h^{-1}}$ (table 2.3) at a pressure difference of $50\,\mathrm{Pa}$ (denoted as $\dot{q}_{50}$) are covered. Actual infiltration due to wind pressure and temperature differences is then modelled dynamically. Since infiltration was modelled as a separate parameter from insulation, it is possible to assess its contribution to overheating risk independently.

Orientations

Four cases, one per cardinal point, were considered.

Locations

Eight locations across the world were selected to assess overheating risk for different climates and latitudes, i.e. solar paths and timings (table 2.5). Within those, we selected reference capitals for representativeness and weather data availability. The weather files used represent a typical year based on historical weather data.

2.5.2 Overheating performance

For this study, metrics for overheating are based on discomfort, as suggested in international standards (BSI 2007; ANSI/ASHRAE 2017) and the previous literature (table 2.2). As individual occupants might be more, or less, vulnerable to overheating, a room is assumed to be overheated if there are occupants in it and it is above T_{max}. The hours above are then summed to find the duration of discomfort, $D\,[\%]$, as

$$D(x) = \frac{\sum_{i=1}^{8760}[T_{max}(x) < T_i]}{H}100 \quad \forall \quad x \in \{\text{fixed, adaptive}\} \tag{2.3}$$

where T_i is the room's average of the dry bulb air temperature and radiative temperature over hour i, T_{max} is the maximum temperature allowed, which is a function of the comfort model considered x, and H is the total occupied hours in a year.

Likewise, we define the severity of overheating, S [K], as

$$S(x) = \frac{\sum_{i=1}^{8760}(T_i - T_{max}(x)) \cdot [T_{max}(x) < T_i]}{H} \quad \forall \quad x \in \{\text{fixed, adaptive}\} \tag{2.4}$$

since the level of overheating might be as important as the number of hours (CIBSE 2017a; CIBSE 2013).

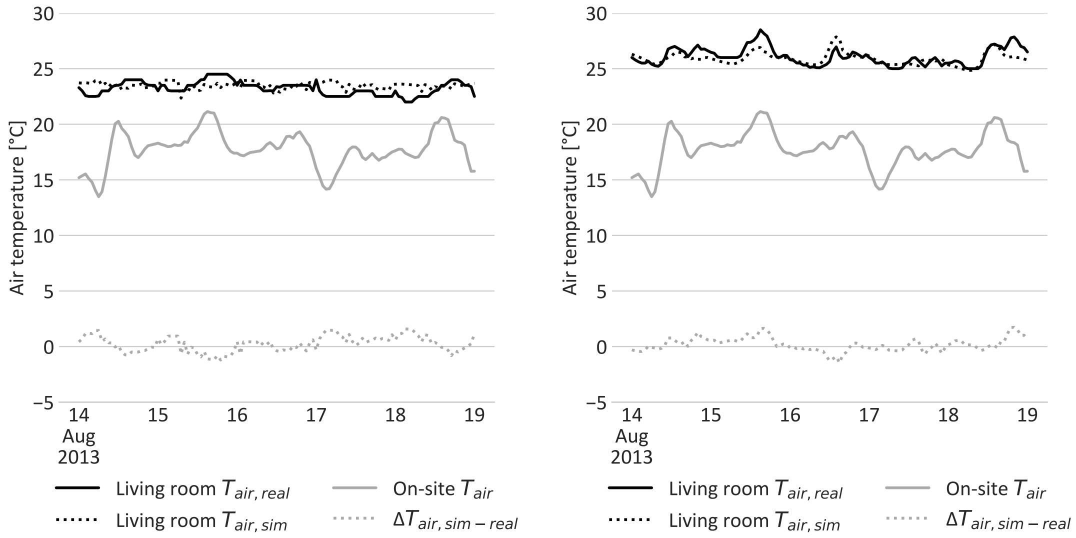
2.5.3 Validation

The models were validated from data recorded in an apartment and a detached house in Southern England (fig. 2.4; key characteristics of the monitored houses in table 2.6). Model performance was appraised through the internal temperature time series in summer (fig. 2.5) and the space heating demand in winter (fig. 2.6).

Table 2.6: Characteristics of the monitored dwellings

Building Fabric	Opaque transmittances	0.11–0.15 $\mathrm{W\,m^{-2}\,K^{-1}}$
	Windows transmittances	0.78–1.24 $\mathrm{W\,m^{-2}\,K^{-1}}$
	Thermal Mass Parameter	250 $\mathrm{kJ\,m^{-2}\,K^{-1}}$
	Window-to-floor-ratio	≈ 25 % (double sided)
	Airtightness	1.25 ach $\mathrm{h^{-1}}$@50Pa
MVHR unit	Airflow capacity	0.50 ach $\mathrm{h^{-1}}$
	Consumption	16.8 $\mathrm{kW\,m^{-2}\,a^{-1}}$ (apartment) 40.8 $\mathrm{kW\,m^{-2}\,a^{-1}}$ (detached house)
	Heat Recovery	77 %

For the validation, data was collected between 2013 and 2014 and weather conditions reconstructed from public databases (Met Office 2012). A typical summer week was selected according to weather conditions and occupancy as derived from electricity and gas data, consumption of the MVHR unit and dry bulb temperature and relative humidity in the living room (filtering missing periods and errors). The simulation model was created with the as-built documentation of the dwellings and building regulations information, adjusting iteratively parameters such as window opening temperature threshold based on monitored air temperatures. Agreement between the real and the simulated internal temperature time series was assessed using the standard procedure by ASHRAE (2014) through the Mean Bias Error (MBE) and the Coefficient of Variation of the Root Mean Squared Error (CV(RMSE)). The MBE was used as the indicator of the average difference, which resulted in deviations of −1.1 % (apartment, ≈ −0.25 K) and 0.7 % (detached, ≈ 0.19 K). Similarly, the CV(RMSE) was taken as the indicator of the hourly differences and gives 3.2 % (apartment, ≈ 0.75 K) and 2.4 % (detached, ≈ 0.63 K). These can be interpreted as a strong indication that the models are performing as expected since the ASHRAE standard considers models as validated when the MBE is within ±10 % and CV(RMSE) is within ±30 % when using hourly data (ASHRAE 2014). Since our study involves only model-to-model comparisons the differences observed during the "validation" process do not affect their ability to characterize the phenomenon at hand.



(a) Apartment

(b) Detached house

Figure 2.5: Comparison of monitored (real) and base models simulated (sim) internal air temperature (with the model performance assessed via the MBE and the CV(RMSE); see section 2.5.3 for a description of these metrics)

The winter space heating demand was used to ensure the parametric simulations are within reasonable limits and no gross errors had been made. This was done by selecting those simulations in London with relevant pairs of insulation and airtightness (fig. 2.6). Results are expressed according to the building fabric standard they represent and are in agreement with expected values (Palmer and Cooper 2013). Figure 2.6 summarizes the space heating demand performance of the parametric and base case (validation) simulations in London according to the house type. Building characteristics are mapped to equivalent Building Regulations (i.e. 1985, 1995, 2006) and standards for low energy buildings (i.e. FEES and PHIS). These can then be compared to energy consumptions in the UK and the specific frameworks of each standard. For the 1985, 1995 and 2006 Building Regulations, it must be noted that, for comparison purposes, the total heating energy consumption takes into account domestic hot water energy and the efficiency of the equipment. Considering that domestic hot water is about 30 % of the demand and a typical boiler efficiency of 85 %, values would be 1.5 times greater than those in fig. 2.6. FEES and PHIS directly specify their heating energy demand targets (39 kW h m^{-2} a^{-1} and 15 kW h m^{-2} a^{-1} respectively); this means that demands beyond these limits are due to cases in the parametric study that are not optimized to satisfy them. Altogether, the results indicate reliable performance of the parametric simulations.

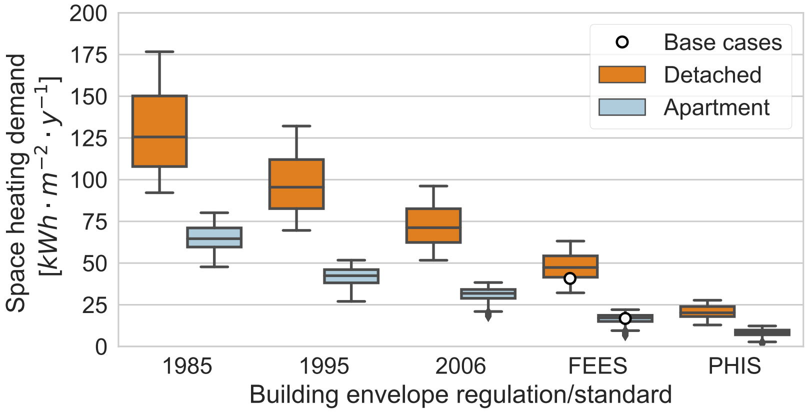


Figure 2.6: Space heating demand in London models[5] (dots: monitored cases space heating demand; 1985, 1995 and 2006 represent models comparable to buildings built to their respective UK Building Regulations; FEES represents models comparable to the expected performance of the Fabric Energy Efficiency Standard; PHIS represents models comparable to the expected performance of the Passivhaus Institute Standard)

2.6 Results and discussion

In our results, overheating is found to be highly sensitive to the building design parameters and the operation of the building (fig. 2.7). While in most locations it is possible to ensure low levels of overheating by using good design and behavioural strategies, poor design decisions or poor operation of the building leads to considerable overheating, which underscores the importance of good design in ensuring resilient performance.

2.6.1 Relative contribution of parameters to annual overheating

To understand the impact of the different input parameters on overheating and the role of the insulation, a regression approach is used based on regression trees (Hastie et al. 2009). This technique finds a model made of simple decision rules based on the study's input parameters by the recursive partitioning of the input parameter space.

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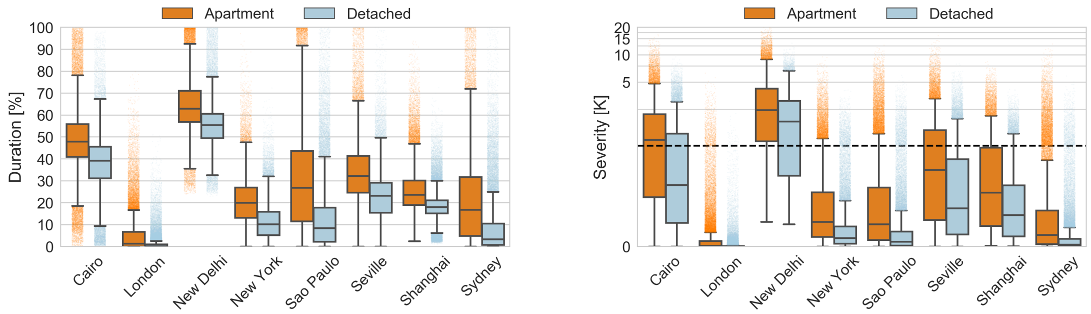
[5] Box plot convention: the box represents data between the first and third quartile, with the median drawn as a horizontal bar within this interquartile range. Whiskers represent the data outside the box but within 1.5 times the interquartile range. Data points beyond the whiskers are potential outliers and they are represented individually with dots, if any.



(a) Duration of overheating over a full year (eq. (2.3) in section 2.5.2)

(b) Severity of overheating over a full year (eq. (2.4) in section 2.5.2; values below dashed line (severity = 1) are on a linear scale and values above on a log scale)

Figure 2.7: Overview of overheating results for all cases[6]($n = 1\,152\,000$; i.e. twice the number of simulations because the overheating in both the living room and bedroom are reported; y-axis range spans the minimum and maximum values in the dataset)

The algorithm disaggregates data into groups considering one parameter at a time, and chooses the partitioning rule which best explains the difference in the overheating performance of the buildings. One of the key features of the technique for this study is its suitability for a large number of parameters and the depiction of their interactions.

In our case, a collection of trees was trained by randomly sampling 70 % of the dataset with replacement (i.e. a case can be selected in more than one tree). These trees are then integrated into an ensemble that makes predictions by averaging the individual predictions of each of its trees. This 'bagging' of trees results in a more robust model when evaluating its performance against the remaining 30 % of the dataset. The performance of the regression ensemble is appraised with the coefficient of determination R^2.

The importance of each explanatory parameter is obtained by measuring how much variance in overheating it accounts for in the modelled response for each tree in the ensemble (fig. 2.8). This information is then used to appraise the overall influence of a parameter. Thus, they can be ranked (i) considering that their maximum and minimum values (range) do not overlap with that of other parameters and (ii) through statistical tests. The variable importance distribution of most parameters follows the same distribution, but normality could not be assumed. Under these conditions, the non-parametric Kruskal-Wallis test allows the study of the medians. The χ^2 statistic adjusted for ties obtained through this test rejects the null hypothesis of the same medians for data in fig. 2.8(a) ($\chi^2_{11} = 5956.5$, p-value $\leq 2.2 \cdot 10^{-16}$), and in fig. 2.8(b) ($\chi^2_{11} = 5941.4$, p-value $\leq 2.2 \cdot 10^{-16}$). The post-hoc analysis is done through Dunn's

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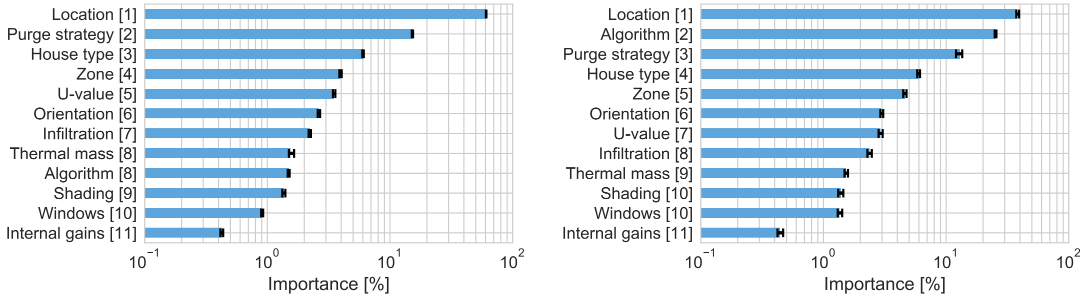
[6] Box plot convention: the box represents data between the first and third quartile, with the median drawn as a horizontal bar within this interquartile range. Whiskers represent the data outside the box but within 1.5 times the interquartile range. Data points beyond the whiskers are potential outliers and they are represented individually with dots, where applicable.

test to expose the groups where the medians are different. The null hypothesis remains the same, but now refers to each pairwise comparison. The adjustments for the false discovery rate that can arise from multiple tests are computed after Bonferroni. The cases where the pairwise comparisons suggested rejection of the null hypothesis were ranked. The cases where there was not enough evidence to reject the null hypothesis or where the distribution of the variable importance did not allow the comparison of medians were reported as ties.

Every parameter was found to have some impact on overheating (fig. 2.8). Altogether, the top four parameters explain 86 % and 82 % of the overheating variance between buildings for duration and severity, respectively. ‘U-value’, i.e. the level of insulation, explains only about 3.5 % and 2.9 % of the variance, respectively.



(a) Duration of overheating

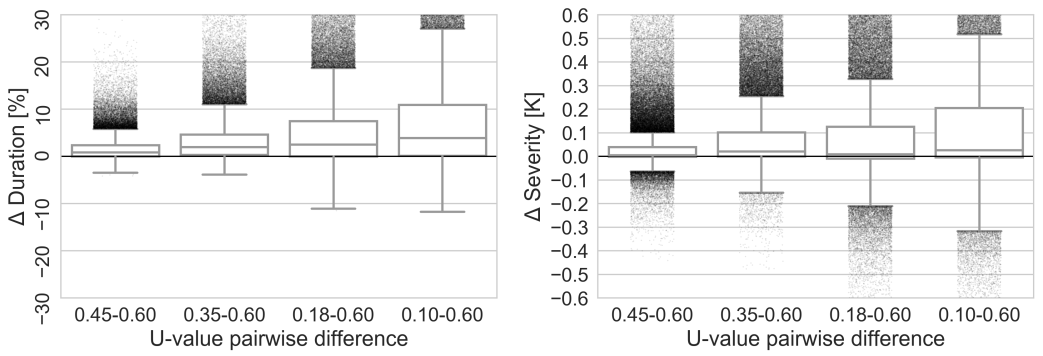
(b) Severity of overheating

Figure 2.8: Overall performance: variable importance in the ensemble model of bagged regression trees ($n_{trees} = 500$; bars indicate average value; lines indicate min-max range; total sum of parameters adds to 100 %; $R^2 \approx 99.8\,\%$ for duration and severity models, obtained for the respective validation datasets of unseen cases; purge strategy and algorithm refer to the ten window opening rubrics; house type, to apartment or detached house; zone, to the main bedroom or living space)

2.6.2 Relative contribution of different insulation levels to overheating

Due to the way the study was designed, it is possible to isolate the exact influence of insulation on overheating by taking pairwise comparisons between buildings identical in every aspect except for the level of insulation.

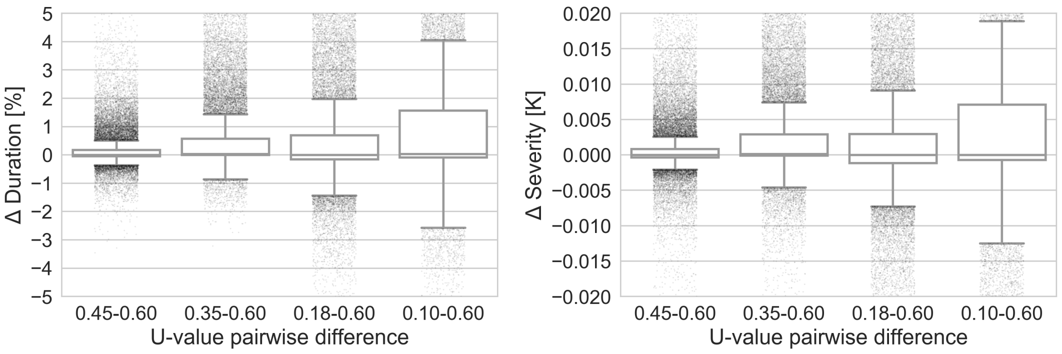
Such pairwise differences in duration of overheating show that greater insulation levels exacerbate the risk in about three-quarters of the cases under study, but reduce it in one quarter (fig. 2.9(a)). In the case of severity, increased insulation increases overheating in approximately two-thirds of cases and reduces it in about one-third (fig. 2.9(b)). However, many of the cases represent buildings that are already overheating, often severely (see fig. 2.7(a) and section 2.5, e.g. overglazed buildings with no shading).



(a) Duration of overheating

(b) Severity of overheating

Set 1: Full dataset[7]



(c) Duration of overheating

(d) Severity of overheating

Set 2: Subset[8] where absolute values of overheating duration are less than 3 %

Figure 2.9: Pairwise comparisons of overheating (insulation case $U_{0.60}$ taken as the baseline; plot conventions in footnote 6; n.b. plots focus on the interquartile range for clarity and hence y-axis scale changes)

If we select cases with overheating duration below 3 % of the occupied hours and analyse their pairwise insulation variants, the distribution between positive and negative cases is remarkably different: the groups are approximately equal (fig. 2.9(c) and fig. 2.9(d)). It is noteworthy that typical standards recommend an upper threshold limits between 1 % and 3 % (BSI 2007; CIBSE 2017b), hence our selection of 3 % can be treated as conservative. In fact, when selecting thresholds below 3.7 % increased insulation reduces overheating (fig. 2.10).

The question now becomes why increased insulation exacerbates overheating in some buildings but not in others. This is achieved by focusing on classification rather than regression. The overheating indicators (duration and severity) are continuous variables which are converted to categorical ones with two possible values: 'increase' (for positive differences in overheating as insulation levels increase) and 'other' (for zero

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[7] Set 1 details: $n = 921\,600$, i.e. 4/5 of the full dataset, with 1/5 of insulation cases (U=0.60) being taken as the baseline.

[8] Set 2 details: $n = 193\,380$, i.e. $\approx 21\,\%$ of the 'Set 1: Full dataset'

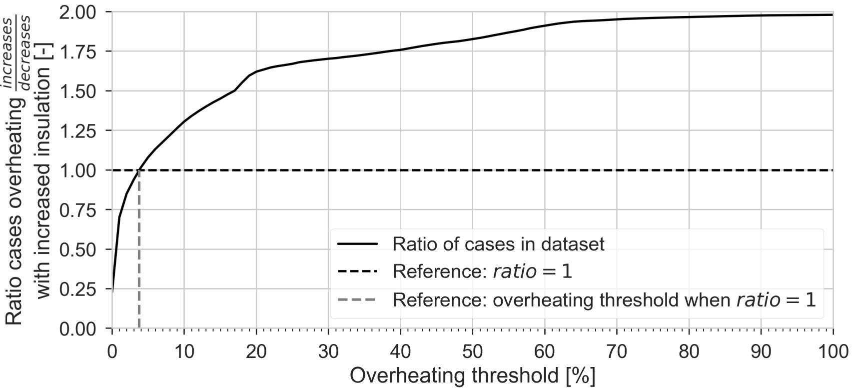
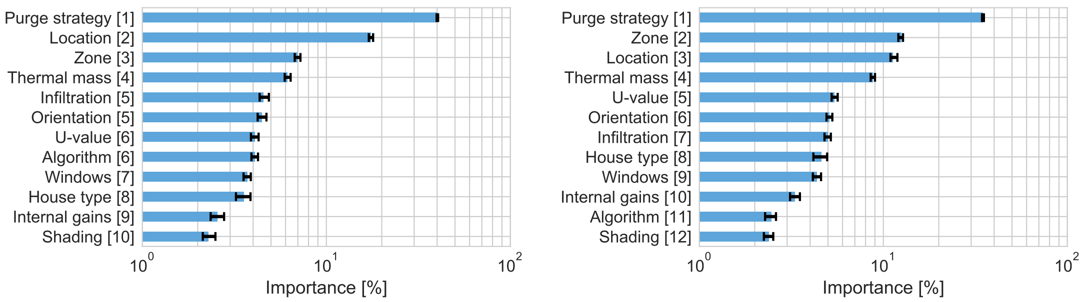


Figure 2.10: Ratio between cases where overheating increases and decreases with increased insulation for different overheating thresholds (if ratio < 1, increased insulation levels reduce overheating on average for the selected data; dashed grey segment indicates case where ratio $= 1$ leading to overheating threshold $\approx 3.7\,\%$)

or negative ones). The classification tree algorithm then finds rules to disaggregate these two groups by considering one parameter and level at a time, and chooses the parameter split with the best performance. The contribution of each parameter in each tree in the ensemble is then aggregated in the same way as before to express their overall influence (fig. 2.11).

The performance of the classification ensemble is summarized through the Kappa statistic (κ) and the F_1 measure, which rate the model from 0 (poor/random classifier) to 1 (perfect). The classification ensemble generalizes the situation highly successfully based on these values (see sub-captions in fig. 2.11). Like in the previous bagged tree models, Kruskal-Wallis test suggests the null hypothesis can be rejected (fig. 2.11(a): $\chi^2_{11} = 11\,832, p - value \leq 2.2 \cdot 10^{-16}$; fig. 2.11(b): $\chi^2_{11} = 11\,868, p - value \leq 2.2 \cdot 10^{-16}$) and Dunn's test allows for the individual ranking. This categorical analysis reveals that the four most important parameters are the same for both overheating duration and severity and, altogether, they account for 71 % and 67 % of the variable importance, respectively. Changing the level of insulation (i.e. U-value) has a comparatively small effect (4 % for duration and 5 % for severity).

The categorical results are directly visualized in fig. 2.12. This displays the cases where overheating does not increase with increased insulation (fig. 2.12(a) and fig. 2.12(c)) and the opposite one (fig. 2.12(b) and fig. 2.12(d)). The plot is arranged in four sorted stages, one for each of the four main parameters of importance noted above. Each stage shows the relative proportion of the cases within that parameter, sorted from highest (left) to lowest (right). For example, in fig. 2.12(a) which shows all cases not displaying overheating with increased insulation levels, those cases controlled by the 'Occupied T_{neu}' strategy are approximately three times as many as those cases controlled by 'Day-O T_{neu}'. This is easily seen through the relative proportions of the respective horizontal segments in the 'Purge strategy' stage on top. This is many times



(a) Duration of overheating ($\kappa = 0.92; F_1 = 0.98$) (b) Severity of overheating ($\kappa = 0.94; F_1 = 0.98$)

Figure 2.11: Variable importance in ensemble model of classification trees ($n_{trees} = 1000$; bars indicate average value; lines indicate min-max range; parameter ranking in square brackets; model performance indicators (κ, F_1) refer to the validation dataset of unseen cases by the trained model; total sum of parameters adds to 100 %)

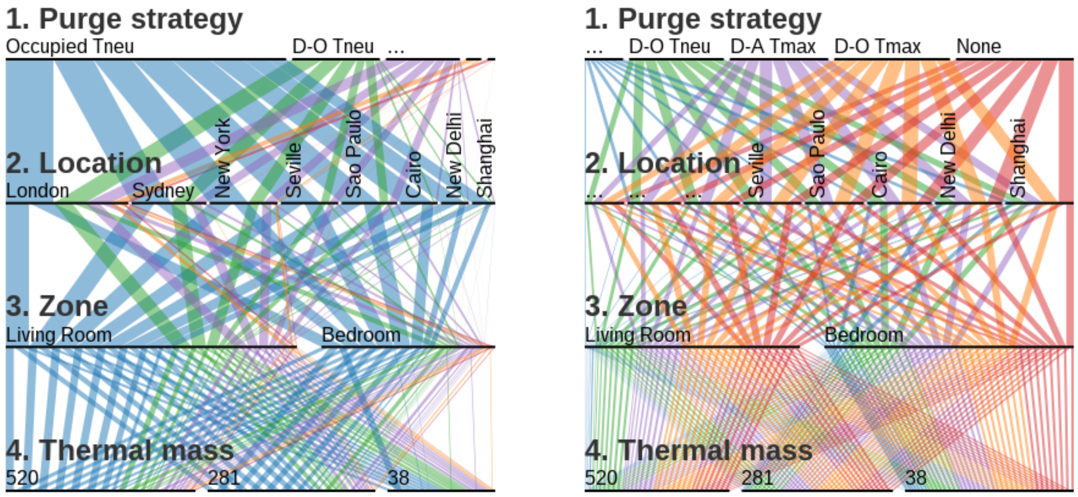
the number than when controlled by strategy 'None', where occupants do not react to increased temperatures. This representation not only exposes the internal composition of the results (as the width of each vertical ray is proportional to the number of buildings meeting the criterion), but it also captures interactions — as individual rays in the bottom stage can be traced to their origins.

When windows are not opened, higher insulation levels almost always increase overheating (except for a few cases in London) and for warmer locations such as Cairo, Shanghai and New Delhi, higher insulation levels reduce overheating duration mainly if windows can be opened during the night (fig. 2.12(a)).

This analysis also holds for severity (fig. 2.12(c)). Moreover, it also indicates that higher insulation levels are generally useful against severe overheating given that the plot now involves 34 % of the dataset (c.f. 23 % for duration).

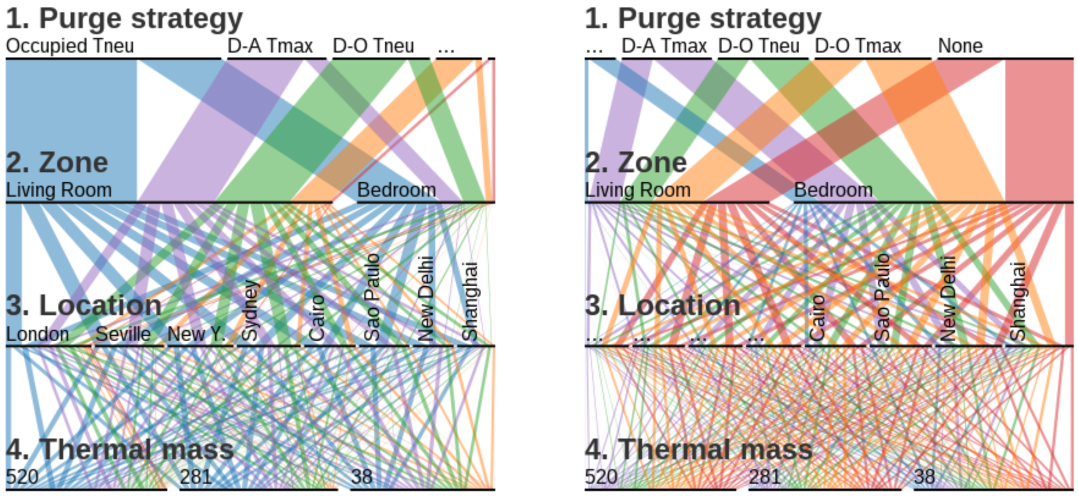
A potential reason for the conflicting results of previous studies, can be seen by visually comparing the overheating found in poorly insulated and well insulated buildings (fig. 2.13(a) and fig. 2.13(b)) as a function of the ventilation provided during occupied hours averaged over the year. This is only possible now that the relative contributions of each parameter have been exposed in the model underlying fig. 2.11. The overheating found in un-insulated ($\mathrm{U}_{0.60}$) and super-insulated ($\mathrm{U}_{0.10}$) buildings separate naturally into three distinct groups, dependant on the ventilation strategy. The median overheating hours found for each group reduces linearly as the median ventilation increases. The overall arrangement shows that whilst in general overheating is greater for highly insulated buildings when occupants do not open windows (case 'None'), this is not so if occupants open windows (case 'Occupied $\mathrm{T}_{\mathrm{neu}}$'). It is worth reiterating that the 'None' case still includes enough ventilation to ensure good air quality.

Figure 2.13 subtracts the duration of overheating obtained for otherwise identical but differently insulated buildings (uninsulated ($\mathrm{U}_{0.60}$) minus super-insulated buildings



(a) Duration of overheating in cases where higher insulation levels do not increase overheating ($n = 207\,844$; i.e. 23 % of the dataset)

(b) Duration of overheating in cases where higher insulation levels increase overheating ($n = 713\,756$; i.e. 77 % of the dataset)



(c) Severity of overheating in cases where higher insulation levels do not increase overheating ($n = 309\,208$; i.e. 34 % of the dataset)

(d) Severity of overheating in cases where higher insulation levels increase overheating ($n = 612\,392$; i.e. 66 % of the dataset)

Figure 2.12: Analysis of the four main parameters in the classification ensemble and the relative frequency of their cases where higher insulation levels do not increase overheating. Numbers (1 to 4) indicate variable importance ranking in fig. 2.11; horizontal segments indicate relative proportion of a particular case within each numbered parameter; rays show the breakdown of cases as they are conditioned in subsequent levels, top to bottom; parameters and cases as per table 2.3; the thermal mass is in units of $\mathrm{kJ\,m^{-2}\,K^{-1}}$; n.b. subfigures on the left and on the right are complimentary, with the same labels, colours and order)

($U_{0.10}$)). When the ventilation strategy is modelled in a way that accounts for the most likely response of occupants, i.e. opening the windows, improving fabric insulation does not lead to an increase in overheating. Indeed, as the median for 'Occupied T_{neu}' lies just below the axis, increased insulation is found, on average, to slightly reduce overheating. It is noteworthy that in cases where insulation appears to increase the risk of overheating, this is only true in buildings that are already overheating severely due to the ventilation mode selected.

Overall, it must be noted in the x-axes of fig. 2.13 that the average air changes in these models are rather constrained and well below expected monitored values. This indicates that, to benefit from reduced overheating levels with higher insulation, the airflow magnitude is not the critical factor. What influences one behaviour or the other is when windows are opened (temperature thresholds, time of the day).

To ascertain the influence of wind-pressure coefficients on our results, the 576 000 cases were also simulated with wind pressure coefficients for isolated buildings. Overall results were similar to those presented here although air changes, expectedly, were significantly higher[9]. This suggests that our findings are robust against the uncertainty associated with wind pressure coefficients.

2.7 Conclusions

Given the proven relationship between overheating in buildings and mortality, concerns have been voiced over whether increasing fabric standards might entail increased overheating risk. This is a serious question of great interest to those devising energy policies across the world since such improvements in insulation play a key role in climate change mitigation strategies. To resolve this question, a large parametric study was undertaken that correctly accounts for the complete range of variables, including ventilation strategy and climate. The analysis methods used allow the quantification of the relative impact of each parameter in the dataset for the first time while accounting for non-linear effects.

A regression-based and a categorical-based analysis both suggest that insulation plays a minor role in overheating even when comparing un-insulated to super insulated buildings. In the dataset, it can at best explain 5 % of the difference in overheating performance. However, the key finding is that little evidence was found for increases in insulation levels also increasing overheating, unless access to purge ventilation is either severely ('Day-O T_{max}') or unrealistically ('None') curtailed. If purge ventilation is sensibly used, better insulation levels tend to result in both lower durations of overheating and reductions in severity. Our results align with the empirical evidence from the 2003 heat-wave (Vandentorren et al. 2006) that increased insulation levels counteracted overheating in buildings.

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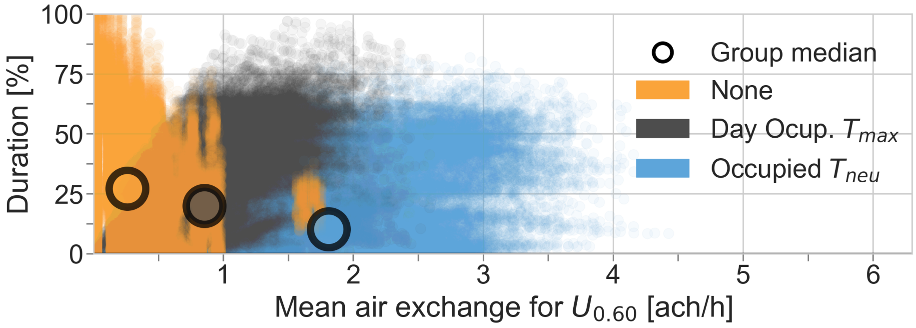
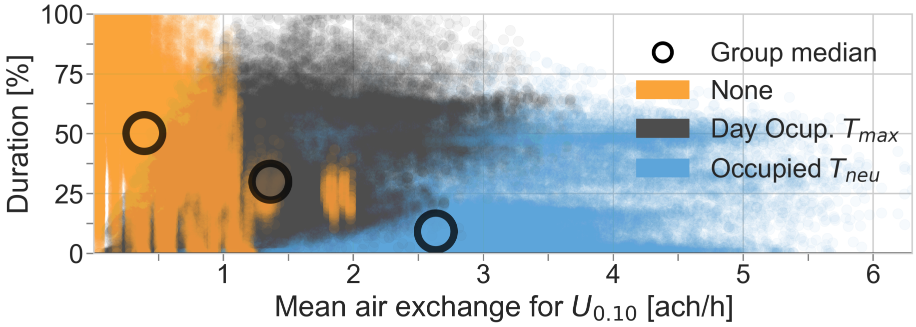
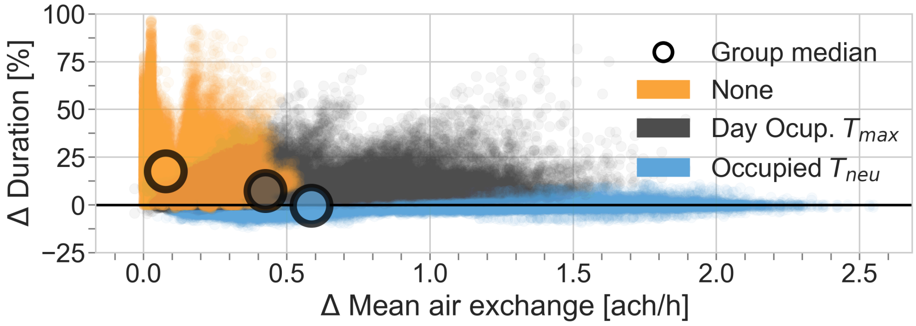
[9] These results are not presented here due to space constraints.



(a) Duration of overheating for poorly insulated buildings ($n = 138\,240$)



(b) Duration of overheating for well insulated buildings ($n = 138\,240$)



(c) Duration of overheating for $U_{0.10} - U_{0.60}$ pair-wise comparisons ($n = 138\,240$; n.b. x-axis scale change)

Figure 2.13: Overheating duration in the living room and mean air exchange during overheating for the three selected purge strategy cases

It is possible that some social groups might not deploy purge ventilation, either through lack of mobility, concerns about security, or a lack of understanding of the potential dangers of not doing so. Our results do indicate that in such cases improving the insulation can increase overheating. However, this is mainly in buildings in our dataset that are already overheating severely; hence it would be difficult to conclude that insulation is the issue, but rather the lack of window opening or an unfortunate combination of design parameters, such as large unshaded windows in a hot climate.

These results suggest that, in cases with acceptable overheating levels (below 3.7 %, mainly cases with adequate purge ventilation strategies), the use of improved insulation levels as part of a national climate change mitigation policy is not only sensible, but also help delivering better indoor thermal environments.

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2.9 Data access statement

Datasets created during this study are openly available from the data archive at `https://doi.org/10.15125/BATH-00390`.

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2.11 Appendix

Table 2.7 extends table 2.2 to review the ventilation modelling techniques used. Since purge ventilation is the most critical overheating countermeasure, this exposes potential causes for discrepancy regarding insulation performance.

Table 2.7: Comparative analysis of ventilation

Author	**Year**	**Purge ventilation model**	**Comments**
Chvatal & Corvacho	2009	Constant air change rates. Houses ventilate in the evening $0.6\,\mathrm{ach\,h^{-1}}$ (min) and $3\,\mathrm{ach\,h^{-1}}$ (max). Offices ventilate at night time $5\,\mathrm{ach\,h^{-1}}$.	NV has time-varying pressure-driven air exchanges with the outdoor environment.
Mavrogianni et al.	2012	Based on fixed temperature thresholds: living rooms at 25 °C and bedrooms at 23 °C. No night time NV.	NV model is not described besides the rules under which ventilation is activated.
Porrit et al.	2012	Constant and scheduled ventilation rates Double-sided cases $8\,\mathrm{ach\,h^{-1}}$ and single-sided $5\,\mathrm{ach\,h^{-1}}$. Openings close if $T_{out} > T_{int}$. Allow ground-floor ventilation.	NV has time-varying pressure-driven air exchanges with the outdoor environment. Nevertheless, constant values are based on standard methodology.
Beizaee et al.	2013	Field study (NA).	NV outside the scope of the study.
Lomas & Kane	2013	Field study (NA).	NV outside the scope of the study.

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Author	Year	Purge ventilation model	Comments
McLeod et al.	2013	Purge ventilation based on internal temperature thresholds. Windows can open up to 10° under overheating (restrictors).	NV model is not described besides the rules under which ventilation is activated. Airflow rates not reported. The presence of restrictors is relevant in the original study, but it cannot be extrapolated to other situations.
Mavrogianni et al.	2014	Explicit ventilation model based on building physics. Sets of ventilation patterns based on temperature thresholds.	Covers fundamental occupant behaviours. Airflow rates not reported. Full appraisal of the role of insulation is out of the scope of the original study.
Taylor et al.	2014	Naturally-driven ventilation, based on thresholds. NV model barely described.	Insufficient data for critical review of the ventilation model (out of the scope of the original study).
van Hoof et al.	2014	Windows cannot be opened in the base case. In others, windows can open 8–20 h when above 24 °C or opened at any time.	NV model is not described besides the rules under which ventilation is activated. Airflow rates not reported.
Gupta & Kapsali	2015	Field study (NA).	Windows open/close state recorded. Dwellings did not overheat according to suitable overheating metrics for naturally ventilated buildings. Airflow rates not reported.

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Author	**Year**	**Purge ventilation model**	**Comments**
Makantasi & Mavrogianni	2015	Ventilation based on different scenarios. For the elderly people, no ventilation is assumed. Other scenarios implement temperature thresholds.	Ventilation model is not described besides the rules under which ventilation is activated. Airflow rates not reported.
Sameni et al.	2015	Field study (NA).	NV outside the scope of the study.
Mulville & Stravoravdis	2016	The study includes ventilation rates as a parameter at 0, 1, 4 and 8 $\mathrm{ach\,h^{-1}}$, which are activated based on temperature thresholds.	NV has time-varying pressure-driven air exchanges with the outdoor environment. The constant values modelled span the values considered in previous studies.

Table 2.8 defines the thermal properties for each building fabric element according to its constituent layers, which vary according to the thermal mass case.

Table 2.8: Element constructions according to thermal mass case (layers defined from the internal to the external environment; see insulation thickness in table 2.9)

Element	**Case**	**Layer**	**d** [mm]	**ρ** [$\mathrm{kg\,m^{-3}}$]	**c_p** [$\mathrm{J\,kg^{-1}\,K^{-1}}$]	**λ** [$\mathrm{W\,m^{-1}\,K^{-1}}$]
Floor	38	Carpet	5	200	1300	0.6
		Timber flooring	10	500	1600	0.13
		Timber structure	200	80	1000	1
	281	Carpet	5	200	1300	0.6
		Screed	20	1200	1000	0.46
		Concrete hollow-core slab	200	900	1000	1.13
	528	Carpet	5	200	1300	0.6
		Concrete slab	200	2000	1000	1.33
		Plaster	15	1300	1000	0.57

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Element	**Case**	**Layer**	**d** [mm]	**ρ** [$\mathrm{kg\,m^{-3}}$]	**c_p** [$\mathrm{J\,kg^{-1}\,K^{-1}}$]	**λ** [$\mathrm{W\,m^{-1}\,K^{-1}}$]
Roof	38	Plasterboard	10	700	1000	0.21
		Insulation	*varies*	40	1400	0.04
		Plywood	15	1300	1600	0.57
		Tiles	25	2000	1400	1.8
	281	Plasterboard (dense) ×2	30	900	1000	0.21
		Timber structure	200	80	1000	1
		Insulation	*varies*	40	1400	0.04
		Tiles	25	2000	1400	1.8
	520	Plaster	15	1300	1000	0.57
		Concrete slab	200	2000	1000	1.33
		Insulation	*varies*	40	1400	0.04
		Tiles	25	2000	1400	1.8
External wall	38	Plasterboard	10	700	1000	0.21
		Mineral Wool	50	12	1450	0.04
		EPS	*varies*	40	1450	0.04
		Brick slips	20	1750	1000	0.56
	281	Plaster	20	1300	1000	0.57
		Brick	50	1750	1000	0.77
		EPS	*varies*	40	1450	0.04
		Brick slips	20	1750	1000	0.56
	520	Plaster	15	1300	1000	0.57
		Brick	100	1750	1000	0.77
		EPS	*varies*	40	1450	0.04
		Brick slips	20	1750	1000	0.56
Partition	all	Plasterboard	10	700	1000	0.21
		Mineral Wool	50	12	1450	0.04
		Plasterboard	10	700	1000	0.21

Table 2.9 indicates the insulation thickness required to achieve the target U-value considering the different element composition according to the thermal mass case (table 2.8).

Table 2.9: Insulation thicknesses for thermal envelope elements (U-value$_{\text{base}}$ represents the U-value of the elements without the insulation layer, as per table 2.8)

Element	**Insulation (U)**	**Thermal mass (M)**	**U-value$_{\text{base}}$** [W m^{-2} K^{-1}]	**d$_{\text{insulation}}$** [mm]	**U-value** [W m^{-2} K^{-1}]
External Wall	0.60	520	2.76	0.05	0.60
		281	0.67	0.01	0.60
		38	3.27	0.05	0.60
	0.45	520	2.76	0.07	0.45
		281	0.67	0.03	0.45
		38	3.27	0.08	0.45
	0.35	520	2.76	0.10	0.35
		281	0.67	0.06	0.35
		38	3.27	0.10	0.35
	0.18	520	2.76	0.21	0.18
		281	0.67	0.16	0.18
		38	3.27	0.21	0.18
	0.10	520	2.76	0.39	0.10
		281	0.67	0.34	0.10
		38	3.27	0.39	0.10
Roof	0.60	520	3.02	0.10	0.35
		281	4.39	0.11	0.35
		38	2.01	0.09	0.35
	0.45	520	3.02	0.15	0.25
		281	4.39	0.15	0.25
		38	2.01	0.14	0.25
	0.35	520	3.02	0.15	0.25
		281	4.39	0.15	0.25
		38	2.01	0.14	0.25
	0.18	520	3.02	0.29	0.13
		281	4.39	0.30	0.13
		38	2.01	0.29	0.13
	0.10	520	3.02	0.39	0.10
		281	4.39	0.39	0.10
		38	2.01	0.38	0.10

Table 2.10 defines how the apartment is used in each of the two profiles designed for internal gains, where ventilation rates adapt to the activities performed. Values reported correspond to the zones assessed. Ventilation values depend on the activities performed in other zones. Since the living room and the bedroom are fresh air intake zones, they can have ventilation values greater than $0\,\mathrm{L\,s^{-1}}$ even though they are not occupied.

Table 2.10: Apartment: occupancy, gains and ventilation according to "internal gains" profiles

Case	**Home**									
	Living Room + Kitchen					**Bedroom**				
Fields	**Occupancy**	**Metabolic Rate**	**Lighting**	**Other gains**	**Ventilation**	**Occupancy**	**Metabolic Rate**	**Lighting**	**Other gains**	**Ventilation**
Hour	[p]	$[\mathrm{W\,p^{-1}}]$	[W]	[W]	$[\mathrm{L\,s^{-1}}]$	[p]	$[\mathrm{W\,p^{-1}}]$	[W]	[W]	$[\mathrm{L\,s^{-1}}]$
01:00	0	0	0	49.4	8.8	2	73.1	0	3.7	8.8
02:00	0	0	0	49.4	8.8	2	73.1	0	3.7	8.8
03:00	0	0	0	49.4	8.8	2	73.1	0	3.7	8.8
04:00	0	0	0	49.4	8.8	2	73.1	0	3.7	8.8
05:00	0	0	0	49.4	8.8	2	73.1	0	3.7	8.8
06:00	0	0	0	49.4	8.8	2	73.1	0	3.7	8.8
07:00	2	114.8	129.3	49.4	8.8	0	0	61.4	3.7	8.8
08:00	2	114.8	0	49.4	8.8	0	0	0	3.7	8.8
09:00	2	114.8	0	109.4	8.8	0	0	0	3.7	8.8
10:00	2	114.8	0	109.4	8.8	0	0	0	3.7	8.8
11:00	2	114.8	0	709.4	16.7	0	0	0	3.7	8.8
12:00	2	114.8	0	109.4	8.8	0	0	0	3.7	8.8
13:00	2	114.8	0	109.4	8.8	0	0	0	3.7	8.8
14:00	2	114.8	0	109.4	8.8	0	0	0	3.7	8.8
15:00	2	114.8	0	109.4	8.8	0	0	0	3.7	8.8
16:00	2	114.8	0	109.4	8.8	0	0	0	3.7	8.8
17:00	2	114.8	0	109.4	8.8	0	0	0	3.7	8.8
18:00	2	114.8	0	109.4	8.8	0	0	0	3.7	8.8
19:00	2	114.8	129.3	509.4	16.7	0	0	61.4	3.7	8.8
20:00	2	114.8	129.3	109.4	8.8	0	0	61.4	3.7	8.8
21:00	2	114.8	129.3	174.9	8.8	0	0	61.4	3.7	8.8
22:00	2	114.8	129.3	174.9	8.8	0	0	61.4	3.7	8.8
23:00	0	0	0	49.4	8.8	2	73.1	0	3.7	8.8
00:00	0	0	0	49.4	8.8	2	73.1	0	3.7	8.8

(continued from previous page)

Case	**Away**									
	Living Room + Kitchen					**Bedroom**				
Fields	**Occupancy**	**Metabolic Rate**	**Lighting**	**Other gains**	**Ventilation**	**Occupancy**	**Metabolic Rate**	**Lighting**	**Other gains**	**Ventilation**
Hour	[p]	[W p^{-1}]	[W]	[W]	[L s^{-1}]	[p]	[W p^{-1}]	[W]	[W]	[L s^{-1}]
01:00	0	0	0	49.4	8.8	2	73.1	0	3.7	8.8
02:00	0	0	0	49.4	8.8	2	73.1	0	3.7	8.8
03:00	0	0	0	49.4	8.8	2	73.1	0	3.7	8.8
04:00	0	0	0	49.4	8.8	2	73.1	0	3.7	8.8
05:00	0	0	0	49.4	8.8	2	73.1	0	3.7	8.8
06:00	0	0	0	49.4	8.8	2	73.1	0	3.7	8.8
07:00	2	114.8	129.3	49.4	8.8	0	0	61.4	3.7	8.8
08:00	2	114.8	0	49.4	8.8	0	0	0	3.7	8.8
09:00	0	0	0	49.4	0	0	0	0	3.7	0
10:00	0	0	0	49.4	0	0	0	0	3.7	0
11:00	0	0	0	49.4	0	0	0	0	3.7	0
12:00	0	0	0	49.4	0	0	0	0	3.7	0
13:00	0	0	0	49.4	0	0	0	0	3.7	0
14:00	0	0	0	49.4	0	0	0	0	3.7	0
15:00	0	0	0	49.4	0	0	0	0	3.7	0
16:00	0	0	0	49.4	0	0	0	0	3.7	0
17:00	2	114.8	0	151.4	8.8	0	0	0	3.7	8.8
18:00	2	114.8	0	149.4	8.8	0	0	0	3.7	8.8
19:00	2	114.8	129.3	749.4	16.7	0	0	61.4	3.7	8.8
20:00	2	114.8	129.3	199.4	8.8	0	0	61.4	3.7	8.8
21:00	2	114.8	129.3	199.4	8.8	0	0	61.4	3.7	8.8
22:00	2	114.8	129.3	199.4	8.8	0	0	61.4	3.7	8.8
23:00	0	0	0	49.4	8.8	2	73.1	0	3.7	8.8
00:00	0	0	0	49.4	8.8	2	73.1	0	3.7	8.8

Table 2.11 defines how the detached house is used in each of the two profiles designed for internal gains, where ventilation rates adapt to the activities performed. Values reported correspond to the zones assessed. Ventilation values depend on the activities performed in other zones. Since the living room and the bedroom are fresh air intake zones, they can have ventilation values greater than $0\,\mathrm{L\,s^{-1}}$ even though they are not occupied.

Table 2.11: Detached dwelling: occupancy, gains and ventilation according to "internal gains" profiles

Case	**Home**									
	Living Room + Kitchen					**Bedroom**				
Fields	**Occupancy**	**Metabolic Rate**	**Lighting**	**Other gains**	**Ventilation**	**Occupancy**	**Metabolic Rate**	**Lighting**	**Other gains**	**Ventilation**
Hour	[p]	$[\mathrm{W\,p^{-1}}]$	[W]	[W]	$[\mathrm{L\,s^{-1}}]$	[p]	$[\mathrm{W\,p^{-1}}]$	[W]	[W]	$[\mathrm{L\,s^{-1}}]$
01:00	0	0	0	5.7	13.2	2	73.1	0	3	8
02:00	0	0	0	5.7	13.2	2	73.1	0	3	8
03:00	0	0	0	5.7	13.2	2	73.1	0	3	8
04:00	0	0	0	5.7	13.2	2	73.1	0	3	8
05:00	0	0	0	5.7	13.2	2	73.1	0	3	8
06:00	0	0	0	5.7	13.2	2	73.1	0	3	8
07:00	0	0	117.2	5.7	13.2	1	94	61.1	3	5.3
08:00	0	0	0	5.7	13.2	0	0	0	3	5.3
09:00	2	114.8	0	5.7	13.2	0	0	0	3	5.3
10:00	2	114.8	0	5.7	13.2	0	0	0	3	5.3
11:00	1	114.8	0	5.7	60	0	0	0	3	5.3
12:00	3	114.8	0	5.7	13.2	0	0	0	3	5.3
13:00	2	114.8	0	105.7	13.2	0	0	0	3	5.3
14:00	2	114.8	0	105.7	13.2	0	0	0	3	5.3
15:00	2	114.8	0	105.7	13.2	0	0	0	3	5.3
16:00	2	114.8	0	105.7	13.2	0	0	0	3	5.3
17:00	2	114.8	0	105.7	13.2	0	0	0	3	5.3
18:00	2	114.8	0	105.7	60	0	0	0	3	5.3
19:00	2	114.8	117.2	105.7	13.2	0	0	61.1	3	5.3
20:00	2	114.8	117.2	105.7	13.2	0	0	61.1	3	5.3
21:00	3	114.8	117.2	105.7	13.2	0	0	61.1	3	5.3
22:00	3	114.8	117.2	92.7	13.2	0	0	61.1	3	5.3
23:00	0	0	0	5.7	13.2	2	73.1	0	3	8
00:00	0	0	0	5.7	13.2	2	73.1	0	3	8

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Case	**Away**									
	Living Room + Kitchen					**Bedroom**				
Fields	**Occupancy**	**Metabolic Rate**	**Lighting**	**Other gains**	**Ventilation**	**Occupancy**	**Metabolic Rate**	**Lighting**	**Other gains**	**Ventilation**
Hour	[p]	$[\mathrm{W\,p^{-1}}]$	[W]	[W]	$[\mathrm{L\,s^{-1}}]$	[p]	$[\mathrm{W\,p^{-1}}]$	[W]	[W]	$[\mathrm{L\,s^{-1}}]$
01:00	0	0	0	9.5	13.2	2	73.1	0	5	8
02:00	0	0	0	9.5	13.2	2	73.1	0	5	8
03:00	0	0	0	9.5	13.2	2	73.1	0	5	8
04:00	0	0	0	9.5	13.2	2	73.1	0	5	8
05:00	0	0	0	9.5	13.2	2	73.1	0	5	8
06:00	0	0	0	9.5	13.2	2	73.1	0	5	8
07:00	1	114.8	142.8	9.5	13.2	1	94	74.4	5	5.3
08:00	0	0	0	9.5	20	0	0	0	5	5.3
09:00	0	0	0	9.5	13.2	0	0	0	5	5.3
10:00	0	0	0	9.5	13.2	0	0	0	5	5.3
11:00	0	0	0	9.5	13.2	0	0	0	5	5.3
12:00	0	0	0	9.5	13.2	0	0	0	5	5.3
13:00	0	0	0	9.5	13.2	0	0	0	5	5.3
14:00	0	0	0	9.5	13.2	0	0	0	5	5.3
15:00	0	0	0	9.5	13.2	0	0	0	5	5.3
16:00	0	0	0	9.5	13.2	0	0	0	5	5.3
17:00	2	114.8	0	9.5	13.2	0	0	0	5	5.3
18:00	2	114.8	0	9.5	60	0	0	0	5	5.3
19:00	2	114.8	142.8	9.5	60	0	0	74.4	5	5.3
20:00	2	114.8	142.8	9.5	13.2	0	0	74.4	5	5.3
21:00	5	114.8	142.8	150.9	20	0	0	74.4	5	5.3
22:00	5	114.8	142.8	150.9	20	0	0	74.4	5	5.3
23:00	0	0	0	9.5	13.2	2	73.1	0	5	8
00:00	0	0	0	9.5	13.2	2	73.1	0	5	8

2.12 Addendum

This section was *not* part of the paper, but it has been included to expand and substantiate aspects that could not be directly addressed in the publication due length, complexity and relevance to core objectives.

2.12.1 Bagged trees models

Like all classification and regression techniques, bagged trees models are constructed by searching for a potential association between a set of candidate explanatory variables and the response variable or variables. In the study, the explanatory variables are the design parameters (e.g. house type, insulation level, thermal mass) and the response variable the chosen metric for overheating (i.e. duration and severity, modelled independently). In classical text books, these techniques are typically introduced with a regression example between two numerical variables, for example, doses of a drug and number of cases displaying a condition. However, in the case presented in the paper, the explanatory variables are 'names' which are referred to as factors, nominal or categorical variables in the literature. These 'names' must be encoded numerically to make the problem amenable to these types of modelling exercises (Faraway 2015; Hastie et al. 2009).

A way to encode categorical variables is through 'dummy coding' (Faraway 2015; Hastie et al. 2009). For instance, the explanatory variable 'house type' has two levels, 'apartment' and 'detached house' (table 2.12). This could be translated as a numerical variable that models the question 'is it an apartment?', where a 0 signifies 'no' and 1 'yes'. This is the equivalent to asking the inverse question 'is this case a detached house?' and inverting the numerical code. Such numerical encoding will be directly used to construct the model, where $n-1$ 'dummy variables' are needed for each n-level parameter. Taking one of the levels as a reference in a parameter, only $n-1$ dummy columns are needed because the reference level could be expressed as a function of every other dummy column and thus avoid redundant information. Which parameter-level is taken as a reference in the encoding affects coefficients of the model for that parameter. The reason is that it establishes the reference point from which to measure the coefficients of every other parameter-level, but it does not affect the properties of the overall model. In the previous example, if the 'house type' variable is encoded taking 'detached' as a reference, it means that the dummy column evaluates if the case is an 'apartment'. The coefficient for this parameter will be indicative of how the response changes moving from a 'detached' case (the reference) to an 'apartment'. Conversely, if 'apartment' was taken as a reference, the coefficient will be indicative of how the response changes from moving from an 'apartment' to a 'detached' case.

A number of encoding schemes and scales exist for dummy variables, which only affect the interpretability of individual coefficients (Faraway 2015). In the study presented in

Table 2.12: Example of dummy coding of a 2-level factor

Case	House type	Is it an apartment?
0	Apartment	1
1	Detached	0
2	Detached	0
...	...	...
n	Apartment	1

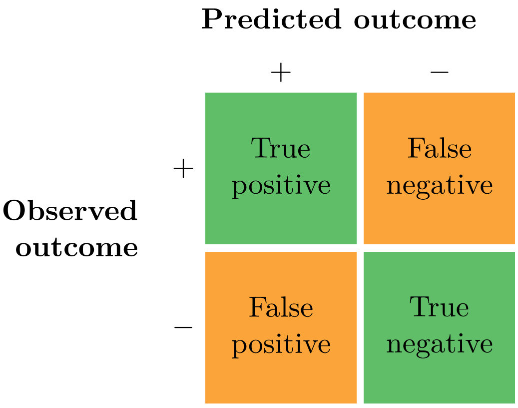
this chapter, the overall effect of a parameter is discussed, not the individual values, and thus the choice of encoding system and reference level do not affect any of the properties discussed. In terms of the variable importance of every explanatory parameter of the tree, it is calculated through the Ginni criterion (Breiman et al. 1998; Pedregosa et al. 2011).

As presented in the study, the relative merits of the bagged tree classification models are evaluated through the Kappa (κ) and F_1 measures, whereas the regression ones are evaluated through the well-known R^2. For the completeness of the discussion, the following focuses on these lesser known classification metrics. From a classification perspective, a 2-level factor can be modelled as a binary response, where 1 signifies that the level of interest is present and 0 if it is not. In the case presented, the interest was on whether overheating increased or not with increased insulation levels, and the number 1 would be associated to one of these possible outcomes and 0 to the other. Which number is associated to what outcome can matter to the model depending on the criteria used to train it, as discussed next.

The relative merits of a binary classifier can be easily represented through the confusion matrix, a matrix that compares what the true categories are and how a classifier identifies them (fig. 2.14). Choosing one of the 2-levels as the reference level, known as the ‘positive’ category (hence the other level is known as the ‘negative’ category), there are four possible outcomes:

1. The model correctly classifies a positive condition (true positive, TP).
2. The model misclassifies a positive condition (false negative, FN).
3. The model correctly classifies a negative condition (true negative, TN).
4. The model misclassifies a negative condition (false positive, FP).

A perfect classifier would have all its predictions in the true positive / true negative diagonal, whereas a model that systematically fails to generate any correct prediction would have everything in the false positive / false negative one. For cases in-between, it is useful to evaluate how well the classifier does, a task for which there are many metrics. Different metrics evaluate the performance of a classifier from different perspectives. In the case presented in the paper, the interest lies in distinguishing both the positive



		Predicted outcome	
		+	−
Observed outcome	+	True positive	False negative
	−	False positive	True negative

Figure 2.14: Confusion matrix that displays the performance of a prediction model for a binary outcome (+ and −) with respect to observations

and negative conditions, and it is desirable to penalise for any misclassification of these two outcomes. However, the two outcomes are not equally represented in the dataset: overheating does not increase with increased insulation for 23 % or 34 % of the cases (duration and severity, respectively). This is called an unbalanced dataset. Taking increases of overheating as the condition of interest, if the classifier assumed that overheating increases with increased insulation no matter the input conditions, it would be correct between 66 % (100 % − 34 %) and 77 % (100 % − 23 %) of the cases. Conversely, if the opposite outcome was the condition of interest, such a classifier would not identify correctly any of the cases (100 % misses). Choosing the less frequent outcome as the reference case (positive) leads to a fairer but disadvantageous measure of the merits of the classifier in these circumstances.

Since the interest of the study is to correctly identify positive and negative outcomes in an unbalanced dataset, the less frequent outcome is chosen as the reference level, and the metrics chosen must penalise misclassifications. Here, the κ and F_1 measures are particularly apt to evaluate the performance. The κ metric is defined as

$$\kappa = \frac{p_0 - p_e}{1 - p_e}. \tag{2.5}$$

where p_0 is the relative observed agreement between the two raters and p_e is their expected chance agreement. This latter term penalises random classifications because it is adjusted by the prevalence. The F_1 indicator is defined as

$$F_\beta = (1 + \beta^2)\frac{\text{precision} \cdot \text{recall}}{\beta^2 \cdot \text{precision} + \text{recall}} \tag{2.6}$$

with

$$\text{precision} = \frac{\text{true positives}}{\text{true positives} + \text{false positives}} \tag{2.7}$$

and

$$\text{recall} = \frac{\text{true positives}}{\text{true positives} + \text{false negatives}} \tag{2.8}$$

where true positives, false positives and false negatives are defined in the confusion matrix (fig. 2.14) and β is a parameter that allows adjusting the relative importance given to false positive and false negatives cases. In the paper, $\beta = 1$ is chosen to place equal importance to both misclassifications and impose stringent conditions to the classification models. Therefore, as previously reported, having models with scores for κ and F_1 above 0.90 in the unseen dataset is indicative of strong predictive performance.

2.12.2 Occupant behaviour

The study focused on a parametric analysis of building features to understand the role of increased insulation levels through modelling, as it is argued that this is something that could not be observed empirically for a wide range of parameters and cases. This aims to establish the overheating potential according to the design features in the presence of variability due to climate (location), building type, thermal comfort models and *assumed* occupant behaviour. This latter aspect was addressed through two fundamental occupancy profiles and associated internal heat gains to bound the performance with a low and high estimate.

With respect to occupant behaviour for window opening, a rule-based algorithm was established congruently with the thermal comfort through which overheating was then evaluated against. The rationale is that, if it is assumed that the lower percentage of dissatisfied people happens at thermal neutrality, people would take action to ensure they remain in such comfortable conditions. If they did not, this would be overheating attributable to occupant behaviour rather than overheating attributable to, for example, increased levels of insulation. Notice that this is an assumption based on first-principles of the problem at hand once the overheating metrics are selected.

Such an approach contrasts with the developments of occupant behaviour algorithms that embrace the stochastic nature of window opening events, as observed in empirical studies. These model observations that people might not necessarily interact with windows in the most thermally-advantageous way possible, since interaction with windows responds to a more complex set of stimuli and varies between occupants. Studies addressing the topic have been interested in developing models that capture the window opening and closing events, to facilitate their integration into building performance simulation software to benefit from increased rigour in the simulation when it comes to representation of occupant behaviour (Haldi and Robinson 2009; Schweiker et al. 2012; Andersen et al. 2013; Fabi et al. 2015; Balvedi et al. 2018; Chapman et al. 2018).

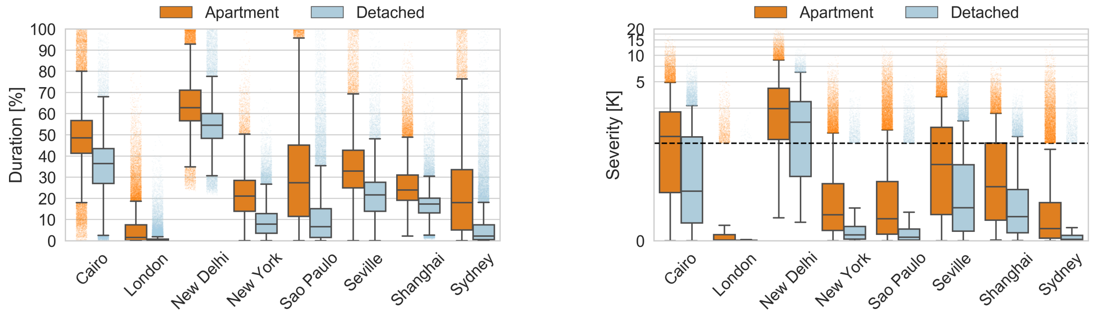
These models have been developed and evaluated through goodness-of-fit metrics with respect to observations, and model performances can vary significantly depending on aspect of interest (Haldi and Robinson 2009; Markovic et al. 2018). These metrics rate how well the interaction is represented when compared to observations in the dataset and, in some cases, they have been found to apt to forecast behaviour in completely new situations, albeit under the same climatic conditions (Schweiker et al. 2012). However, a systematic comparison in terms of ventilation rates and heat-losses, specially compared to rule-based models, could not be found in the reviewed literature. In the summary paper of the IEA EBC Annex 66 on occupant behaviour in buildings, authors reflect that stochastic models of occupant behaviour were not found to be necessarily superior to rule-based model ones (Yan et al. 2017). In a recent study, Schweiker et al. (2019) looked at the outputs of selected window opening behaviour models in ASHRAE building simulation reference buildings (ANSI/ASHRAE 2017a) under hot and cold climates, and found moderate discrepancies in the output metrics selected, namely total duration of open windows in a year, number of interactions and 24-hour typical pattern during the cold and hot season. Results showed that modelled occupants would frequently have windows open to some degree at least for the central hours of the day during typical cold season day in the cold climate (12–18 h), if not always (every other case). The authors of the study caution against generalisations, since the scenarios evaluated and sample size are limited, but exemplifies some of the salient practical implications of occupant behaviour models.

In general, the heat loss due to purge ventilation is not determined from the occupant behaviour alone. Although behaviour is a central parameter, the actual heat transfer will also depend on wind pressure coefficients, discharge coefficients, local characteristics of wind (flow pattern and speed due to influence of immediate urban environment), among others, as reviewed in the paper. Given that the sample size was already large, the chosen overheating metrics, and being unclear the advantages of stochastic occupant behaviour models for the scope of the paper, it was decided to use a rule-based window opening behaviour model, as described previously.

The results of the paper (fig. 2.13) show that the overall air change involved is rather moderate, and they point towards how the building is operated rather than the amount of ventilation as being important to benefit from increased insulation levels. In this regard, rigorous occupant behaviour models could be arguably increasingly important to discern whether this performance could be observed in practice, and it is highly recommended that future research considers this aspect to ascertain the prevalence of overheating in the built environment.

2.12.3 Influence of wind pressure coefficients

The following substantiate the assertion that results were similar for the case with wind pressure coefficients for isolated buildings (footnote 9). These versions have been tagged as ‘Isolated version’ and axes scales have been adjusted to capture the same type of information as the figures presented in the paper (figs. 2.15 to 2.18).



(a) Duration of overheating over a full year (eq. (2.3) in section 2.5.2)

(b) Severity of overheating over a full year (eq. (2.4) in section 2.5.2; values below dashed line (severity = 1) are on a linear scale and values above on a log scale)

Figure 2.15: Isolated version – Overview of overheating results for all cases[10]($n = 1\,152\,000$; i.e. twice the number of simulations because the overheating in both the living room and bedroom are reported; y-axis range spans the minimum and maximum values in the dataset)

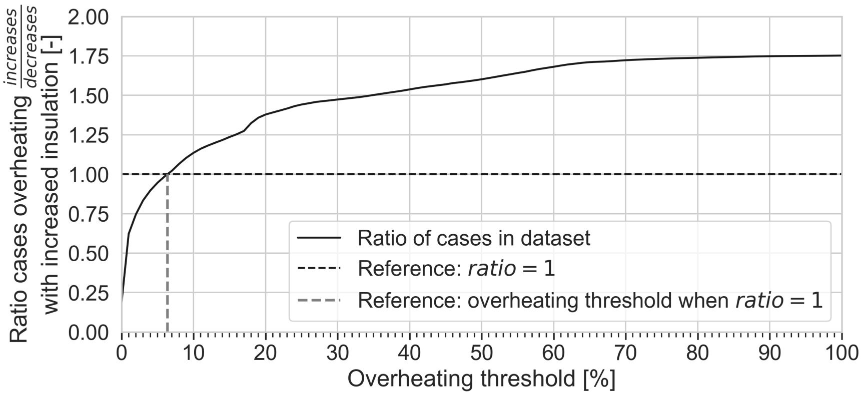
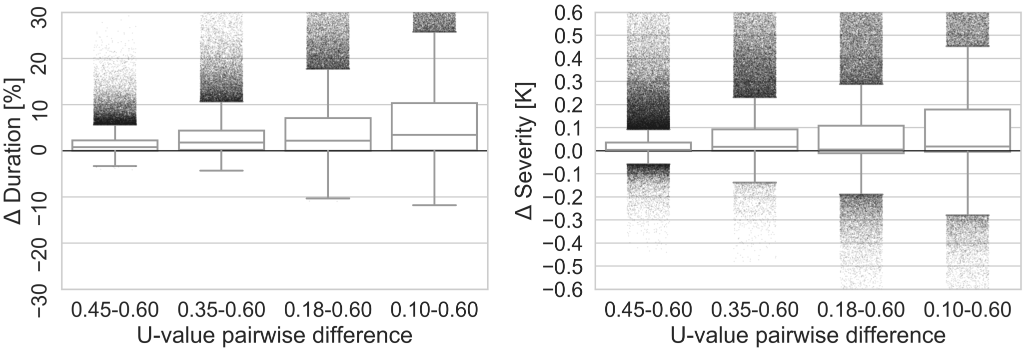
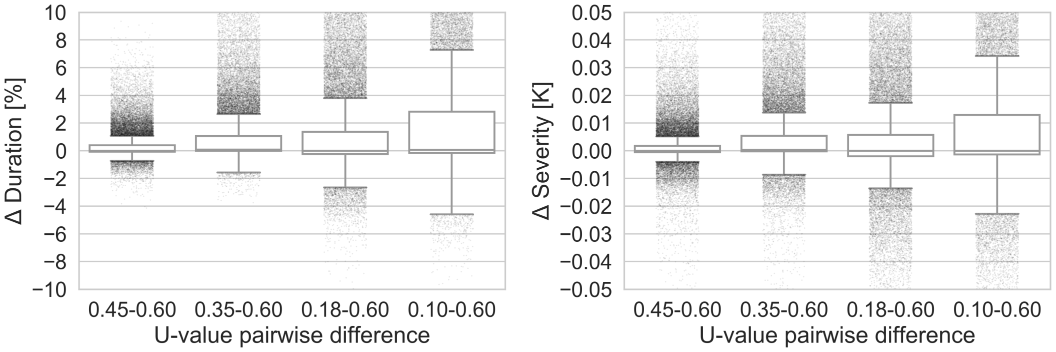


Figure 2.16: Isolated version – Ratio between cases where overheating increases and decreases with increased insulation for different overheating thresholds (if ratio < 1, increased insulation levels reduce overheating on average for the selected data; dashed grey segment indicates case where ratio = 1 leading to overheating threshold ≈ 6.4 %)



(a) Duration of overheating (b) Severity of overheating

Set 1: Full dataset[11]



(c) Duration of overheating (d) Severity of overheating

Set 2: Subset[12] where absolute values of overheating duration are less than 6 %

Figure 2.17: Isolated version – Pairwise comparisons of overheating (insulation case $U_{0.60}$ taken as the baseline; plot conventions in footnote 6; n.b. plots focus on the interquartile range for clarity and hence y-axis scale changes)

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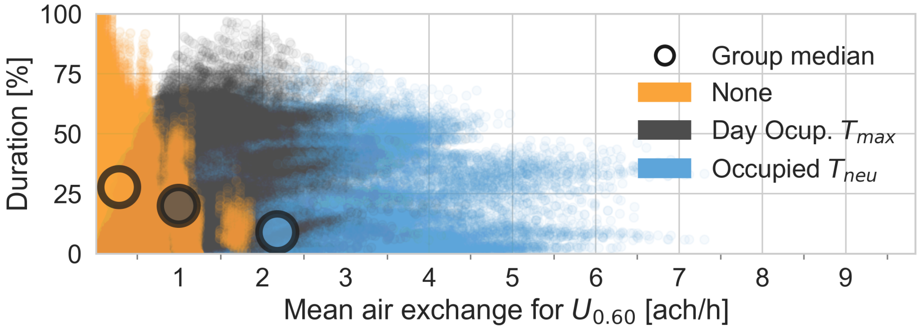
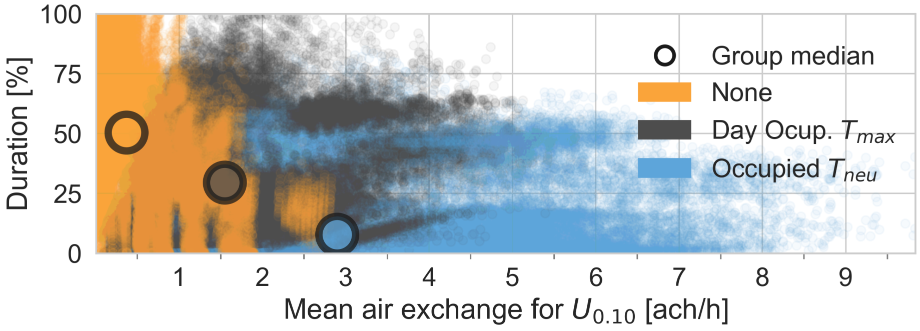
[11] Set 1 details: $n = 921\,600$, i.e. 4⁄5 of the full dataset, with 1⁄5 of insulation cases (U=0.60) being taken as the baseline.

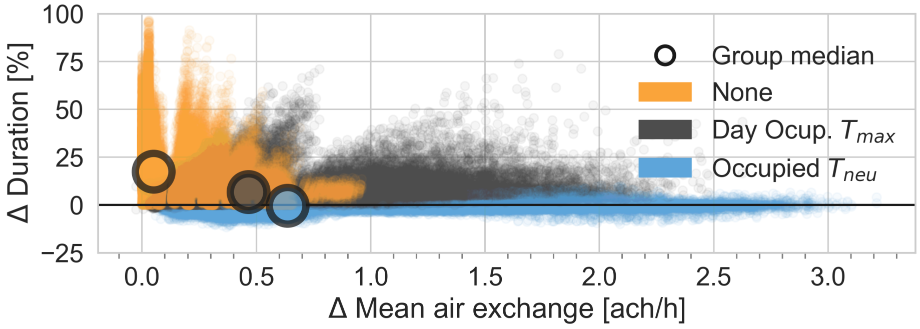
[12] Set 2 details: $n = 268\,080$, i.e. $\approx 29\,\%$ of the 'Set 1: Full dataset'



(a) Duration of overheating for poorly insulated buildings ($n = 138\,240$)



(b) Duration of overheating for well insulated buildings ($n = 138\,240$)



(c) Duration of overheating for $U_{0.10} - U_{0.60}$ pair-wise comparisons ($n = 138\,240$; n.b. x-axis scale change)

Figure 2.18: Isolated version – Overheating duration in the living room and mean air exchange during overheating for the three selected purge strategy cases

2.13 Postscript

This paper reported a novel characterization of passive building features for overheating with a special focus on the role of insulation. This is underpinned by parametric building simulations, fundamental overheating metrics, and new analyses methods. This allows for an understanding of the performance of these measures at a global scale, covering several climates and two extreme dwelling types through the ranking of all parameters involved. The method also allows accounting for contradictory evidence in previous studies and aimed to provide consensus in the characterization of the role of insulation, which is found to be a function of natural ventilation.

The findings of the study can be grouped into two categories with regard to Research Question 1, the analysis framework and the performance of passive strategies. Developments for the first included building simulation, statistical, data mining and visualization methods that allowed breaking down the results and accounting for the building physics behind them.

1. The building simulation required carefully constructed models which made explicit how modelling choices affect the thermal performance of free-running environments. Equally important is the possibility to create pair-wise comparisons to allow identifying underlying causes for changes in performance.

2. The statistical and data mining methods allowed a full characterization of the phenomena, exhibiting ways in which overheating mitigated and exacerbated overheating. One example is the analysis motivated by fig. 2.9. Previous studies focused implicitly on the average or the median performance of the parameters, metrics which are sensitive to the prevalence of parameter and cases in the study. As observed, that narrows down what here is shown to have a two-fold behaviour sensitive to interactions with other parameters. The combination of regression and classification techniques allowed focusing on areas of interest in the dataset while accounting for data imbalances that arise naturally in overheating (overheating metrics are non-negative quantities and successful strategies aim to deliver no overheating at all, inflating counts at 0).

3. Building on the previous two aspects, visualization techniques can be specialised to understand cases of interest in the dataset. Interpretability is enhanced given the pairwise comparisons created through building simulation.

Overall, this method facilitates not only quantification but understanding of the role of passive strategies in free-running buildings. To the best of our knowledge, this is the first comprehensive assessment of the role of insulation in overheating, aiming for clarity and consensus of its performance. Crucially, our results show that purge ventilation does not need to be maximised to benefit from increased insulation levels, which has important implications for building regulations and energy-efficiency policies.

Further to the aim for an overall methodology to study overheating at design stage, the following aspects are found to be particularly important:

Overheating: Appraising overheating via the fundamental metrics, duration and severity, is useful to overcome the potential bias that standard overheating criteria can introduce, and they are reasonable for studies relying on pairwise comparisons. However, if the goal is to understand how buildings modify the risk of overheating for its occupants, metrics should be standardized according to the potential impact on occupants. For example, the impact of a temperature increment of 1 K is different if the baseline temperature is 25 °C or 35 °C.

Parametric analysis: The parametric analysis proves successful in identifying qualitative changes in behaviour. This allows exploring 'intrinsic' performance of strategies and is independent of their prevalence in the study. The real prevalence of cases is unknown, complex and worthy of dedicated studies to make them apt for simulation studies. Recent development in this sense are the advances on the characterization of the UK building stock (Sousa et al. 2018) or occupant behaviour by IEA-EBC Annex 66 (Yan et al. 2017). These are aspects that need to be resolved before attempting to make predictions of the impact of design strategies in overheating at epidemiological level.

Ventilation models: Natural ventilation is an important parameter in determining indoor temperature in free-running buildings and, in this study, it determines the role of insulation in overheating. However, modelling natural ventilation for studies interested in the long-term performance of buildings is challenging for the reasons covered in the study. It requires

1. a relevant weather file that reflects air speeds at the location of interest;
2. consideration of the wind patterns around the building, not necessarily accounted for by customized wind pressure coefficients alone;
3. hydraulic properties of openings (discharge coefficients according to opening type and relative to the opening angle, among others);
4. suitable airflow models for the room;
5. different models that account for the airflow nature in single sided or cross ventilated spaces, since the airflow characteristics and rates vary significantly from one case to the other;
6. occupant behaviour.

The results of this paper are shown to be not sensitive to the first five assumptions, but statements about the forecasted performance of a model in absolute terms will be indeed. Regarding occupant behaviour, the study considered a congruent choice with how overheating was conceived in the study (comfort-based, conventional metrics), assuming perfect behaviour, to understand the intrinsic performance of different passive strategies. Considering overall results and the influence purge ventilation has on the role of increased insulation levels, further studies are recommended to understand what the empirical prevalence is for beneficial increased insulation levels across the built stock.

These aspects motivated the studies presented in the next chapters. Chapter 3 considers alternative characterizations of overheating, for which it turns to physiological human thermal models to normalise the overheating stress in the body. Chapter 4 addresses the fact that overheating is more sensitive to absolute values than energy studies are, needing to evaluate the role building simulation has in overheating prediction at design stage.

Chapter 3

Refugee housing through cyclic design

3.1 Preamble

As shown in the context of chapter 2, there are a limited number of guidelines to establish what constitutes unacceptable overheating in buildings, all of which are based on thermal comfort and expert judgement. These guidelines understand overheating as the absence of comfort, but this decision entails several assumptions and limitations.

Duration of discomfort This is the sum of all the periods in which excessive discomfort due to hot conditions take place. Taking the 1 % limit as an example, this represents up to 88 h in a year, the equivalent of four full days with a temperature of 1 K over the threshold. For example, there are no restrictions to the distribution of the duration, where it could be hypothesised that continuous durations are more disruptive for occupants than isolated deviations. Additionally, CIBSE (2017) refers to the use of Design Summer Years (DSYs) and related updates (Herrera et al. 2017), which do not necessarily aim to provide a pre-established duration of indoor overheating.

Weighted hours This metric scales linearly with both increasing duration and temperature difference. This does not follow the functional sigmoid form of the PPD — neither that of Fanger's PMV-PPD model, nor that of the European adaptive comfort model (CIBSE 2013) —, and does not reflect the fact that increasing temperature differences do not necessarily cause linear increases of heat strain. Under this metric, a deviation of 10 K during an hour and a difference of 1 K over ten hours yield the same 10 K h, even though the first entails a far greater risk. Even if the sigmoid functional form of the PPD was accounted for, it loses resolution for the severest deviations.

Severity of discomfort This is included only in CIBSE's TM-52 (2013) and regrettably disregarded in CIBSE's TM-59 (2017) as it is the only criteria that addresses severity, although indirectly and as a pass-or-fail criterion.

The combination of these metrics seems to provide a reasonable framework to study small deviations from comfort. However, there is no empirical evidence that correlates these metrics with actual occupant dissatisfaction (see appendix A). The study by Robinson and Haldi (2008) is the only one found in the literature that conducts a longitudinal survey (60 occupants) that explicitly sought to study long-term overheating discomfort as an accumulation. In their study, occupants could report overheating only once in the monitoring period, when they consider having clearly overheated. The breakdown of self-reported reasons of the 22 occupants to have overheated were: the temperature during a period (58 %), the temperature during the day (27 %) and the temperature at the moment (18 %). The authors could provide an overheating risk model based on an electrical capacitor analogy that required tuning with empirical evidence two parameters, the charging and discharging coefficients. In the case presented, only the charging parameter could be tuned, meaning that it is possible to predict when overheating is likely to start taking place, not when comfort might have been resotred. Given that the study was based on 60 office occupants in Switzerland, and that parameters need to be tuned based on empirical data, the work presented in the thesis did not consider this model because it could not be assessed whether these would be applicable to occupants in other climates and what the numerical values of the coefficients should be.

Despite challenges and limitations with comfort frameworks, in situations in which substantial discomfort takes place, they are not suitable to quantify the severity of the deviation. In these cases, physiological models and their related indices are arguably more suited to capture such a severity, which could be translated into more meaningful metrics to inform design decisions. Based on the rationale presented in chapter 1, there is consensus in physiology to consider sweat budgets and changes to deep body temperature as proxies for moderate discomfort, heat strain and health risks. Therefore, this chapter explores the application of comfort and physiological models to quantify heat strain rather than discomfort (Research Question 2).

This work considers well-known models and indices that are suitable for integration at design stage together with building simulation. Comprehensive overviews of these models are provided in canonical publications in the literature (Fountain and Huizenga 1995; Parsons 2015; Auliciems and Szokolay 2007; Havenith and Fiala 2016), and only the main considerations are presented here. Rational thermal models have been favoured over empirical ones because they provide a transparent account of the physics involved in thermoregulation, where all relevant environmental parameters affect the response. From these, the Pierce 2-node (Gagge et al. 1986; Haslam 1989; Neale 1999) and Predicted Heat Strain (PHS) (Malchaire et al. 2001; BSI 2004) models have been selected because (1) they entail the lowest computational cost, (2) they have a complexity congruent with the resolution of a building model for annual studies, (3) they are the best-in-class instances in their areas for warm environments and (4) they have been extensively validated in these conditions. A defining condition of these models is that, given the underlying evidence, they represent a standard occupant based on healthy, fit adult individuals. The key difference between the Pierce 2 node model and the PHS is that the first is a steady-state model whereas the second is a dynamic model developed to assess workloads lasting several hours.

Besides models, it has been of great interest the design of indices that integrate the effect of all the variables affecting thermal balance — at least six, four environmental and two personal — into a normalised result. This normalisation from a multivariate to a univariate description can be carried out according to multiple criteria, but it generally expresses either a reference condition that would cause the same energy transfer (stress) or response in the body (strain). This has led to a prolific area of research, with more than 160 proposed indices[1]. In this chapter, the concept of strain is favoured to highlight the impact on the occupant in a meaningful scale.

The PHS leverages this concept through two indicators, cumulative sweat and deep body temperature increment during the workload. The workload is considered safe until one of the indicators surpasses its limit, i.e. 5 % body weight loss for sweat and 38 °C for deep body temperature (BSI 2004). In the case of the Pierce 2-node model, a number of indices can be computed based on it. Here, the index DISC by Gagge et al. (1986) demonstrates the approach. DISC signifies discomfort due to heat strain on the thermoregulatory system due to sweating in hot conditions. It establishes the strain on a 5-point dimensionless scale (table 3.1) based on the sweating ratio as compared to neutral conditions,

$$\mathrm{DISC} = 5\frac{E_{\mathrm{rsw}} - E_{\mathrm{comf}}}{E_{\mathrm{max}} - E_{\mathrm{comf}} - E_{\mathrm{diff}}} \tag{3.1}$$

where E expresses evaporative heat loss (e.g. $\mathrm{W\,m^{-2}}$): E_{rsw} that of regulatory sweating, E_{comf} that experienced under comfortable conditions, E_{max} the maximum attainable through the skin, and E_{diff} that of diffusion of moisture through the skin. Notice that, in practice, the scale is continuous since it is based on actual heat losses.

The context for this study is the Syrian refugee camp of Azraq in Jordan (figs. 3.1 and 3.2) introduced in chapter 1. Attending to the peculiarities of camp provision compared to other kinds of buildings, we propose here a cyclic design process of shelters based on such overheating metrics (Research Question 2). Preliminary work on physiological models was presented in PLEA 2017 (appendix B). In that publication, the ASHRAE adaptive thermal comfort model was used to get the baseline of overheating, which was then compared to the Pierce 2-node and the PHS models. The results of the

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[1] See de Freitas and Grigorieva (2017) for one of the latest catalogues and classification attempts and Havenith and Fiala (2016) for a dedicated review of those for heat stress.

Table 3.1: DISC scale according to Gagge et al. (1986, p. 713)

Value	Meaning
0	Comfortable and pleasant
1	Slightly uncomfortable but acceptable
2	Uncomfortable and unpleasant
3	Very uncomfortable
4	Limited tolerance
5	Intolerable

simulation study showed severe overheating that surpassed recommended thresholds of the PHS model, namely excessive sweat and deviations from acceptable core body temperature. While the first principles presented do not discourage the use of the PHS model (being crucial the fact that it is a dynamic model capable of accounting for heat accumulation), the lack of validation data to confirm such estimates, like records of health assistance in the camp, precluded its inclusion in the following publication.

This chapter is based on the paper “Refugee Housing through Cyclic Design” published as an invited paper in the journal Architectural Science Review in 2018 (Special Issue). This study was conducted as part of the HHftD project [grant number EP/P029175/1] to understand the ways in which overheating could be normalized according to severity and how that could inform the design process of shelters. The candidate has predominantly contributed to the publication in collaboration with other researchers from the HHftD project. The collaboration focused on the formulation of the cyclic design process and the global understanding of the shelter provision process. Section 3.5.2 reports on field work carried out by Dr Albadra. Details about the authorship of this paper are provided in table 3.2.

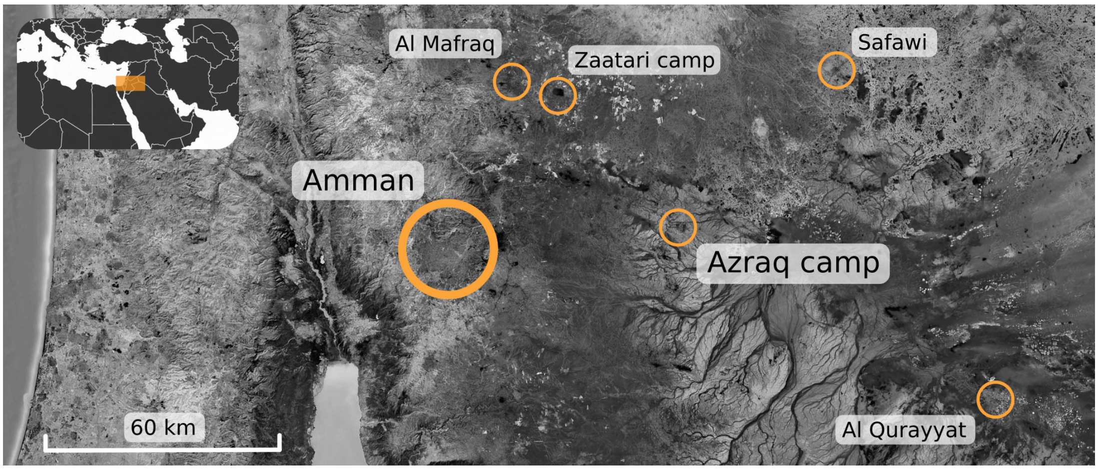

Figure 3.1: Azraq context (see image credits in fig. 3.2)

Figure 3.2: Azraq aerial view (image credits embedded)

3.2 Declaration of authorship

Table 3.2: Declaration of authorship

This declaration concerns the article entitled:
Refugee Housing through Cyclic Design

Publication status:
Published

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D. Fosas, D. Albadra, S. Natarajan, and D. A. Coley (2018b). “Refugee Housing through Cyclic Design”. *Architectural Science Review* 61 (5), pp. 327–337. DOI: `https://doi.org/10.1080/00038628.2018.1502155`.

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Candidate’s contribution to the paper:
The author of this thesis has predominantly contributed to the publication (84 %). The contributions of each author are as follows:

- Formulation of ideas: D. Fosas (80 %), D. A. Coley and S. Natarajan (20 %).
- Background: D. Fosas (50 %) and D. Albadra (50 %).
- Design of methodology: D. Fosas (100 %).
- Experimental work: D. Fosas (100 %).
- Analysis: D. Fosas (100 %).
- Preparation of manuscript: D. Fosas (80 %), D. A. Coley (15 %) and D. Aldabra (5 %).
- Editing drafts of manuscript: D. Fosas (80 %), D. A. Coley and S. Natarajan (20 %).

Statement from Candidate:
This paper reports on original research I conducted during the period of my Higher Degree by Research candidature.

Signed **Date** 20 December 2019

3.3 Abstract

There are more than six million refugees living in camps globally, primarily in places with severe climates. While camps are planned to be temporary, they can often be in use for decades. This “planned temporariness” despite their potential longevity, together with the pressures of rapidly emerging situations, means that the construction and monitoring of demonstrators is not a primary concern for their developers. This lack of iterative design improvement results in shelters with thermal environments far from ideal and a risk of increased morbidity. Here we propose a cyclical process for improving such shelters involving the thermal monitoring of pre-existing shelters to construct validated baseline simulation models of similar shelters in other areas of emerging crisis. These models can then be evolved and improved within a modelled optimisation cycle before mass-construction and field testing. Here we demonstrate the method for the case of Azraq camp in Jordan. Starting from an analysis of field survey data which exposes a high incidence of heat-stress experienced in the shelters, a series of architectural strategies are applied to the design, resulting in significant reductions in overheating. This work suggests that the proposed cyclical approach can lead to significant improvement in conditions currently experienced in refugee camp shelters.

3.4 Introduction

Current figures of forcibly displaced populations in the world are among the highest on record, of which 37 % (25.4 million) are refugees (UNHCR 2018a). As part of the response to the crisis behind these figures, refugees are often hosted in camps and the humanitarian agencies behind them face the challenging task of providing a housing solution to an unexpected crisis of unknown duration. However, due to a number of factors that arise in the decision-making process of the design of these camps, solutions tend to be temporary in nature. Given that many of these camps often exceed their expected lifetime and that humanitarian agencies are already under extreme pressure in rapidly emerging situations, little attention tends to be paid to the thermal adequacy of indoor environments in these shelters. Focusing on this aspect of shelter provision for refugees, we give an overview of how refugee housing is currently addressed, highlighting gaps and opportunities that exist for the application of sound passive design principles via a cyclical design process to mitigate thermal conditions at the extremes.

3.4.1 Background

Refugees and forcibly displaced people fall under the mandate of the UNHCR, the UN refugee agency. UNHCR is the main provider of assistance to host countries at the request of their governments or the UN Secretary General. In addition, the UNHCR has several operational partners such as NGOs who act along with the UNHCR at the local level in so-called ‘clusters’. In terms of shelter provision in refugee camps, the UNHCR is the cluster leader (UNHCR 2007). More often than not, the UNHCR and its operational partners have very limited time to propose shelter solutions suitable for the situation at hand. Therefore, it is often the case that the refugees are initially housed in tents before other options are proposed. As such, provision of those shelters usually occurs in following stages: emergency, temporary or transitional and permanent (Félix et al. 2013). In general, host governments are resistant to permanency and tend to encourage shelter solutions that are temporary in nature, dismantlable and made of lightweight materials. This means that refugees can end up living in temporary shelters for several years, sometimes even decades.

Understandably, the shelter design focus is generally on transportability and deployability of shelters, but despite the numerous attempts to design new shelter solutions, their thermal performance is still largely overlooked (Albadra et al. 2018). Moreover, other aspects related to indoor environmental quality such as visual and acoustic performance, as well as social and cultural factors, are often neglected despite their acknowledged importance. Even available standards and guidelines for temporary shelter design are generic when it comes to climatic and cultural considerations and those that do, focus mostly on ‘winterisation’ (UNHCR 2007; The Sphere project 2011; Corsellis 2012). This results in an underdeveloped area of research considering the number of people involved and the potential risks associated.

3.4.2 Cyclic design

We argue that within the procurement process for such shelters, the inclusion of a holistic appraisal system evaluating the relative merits of a range of low-cost passive techniques could be transformative, particularly in hot climates where, to-date, they have received relatively little attention. Since current shelter provision procedures involve complex decision-making often involving different agencies, we hypothesize that many key lessons that could aid in the development of shelters with improved thermal performance are being overlooked. To mitigate this, we propose a ‘cyclic design’ process in which

(a) refugee camps are surveyed to understand the possible shortcomings of the shelters in place;

(b) optimization simulations are undertaken to mitigate against the revealed flaws and to explore best fit solutions to maximally improve the thermal performance of the shelters acceptable costs to the agencies involved;

(c) demonstrator shelters are erected in the camps and monitored to validate the model findings and

(d) the process begins again at the next camp (or next iteration of shelters at the same camp) using the knowledge gained.

The advantage of such an approach is that it can be undertaken within the current ‘planned temporariness’ paradigm of camp design while building on a progressively developing local expertise across several verticals such as supply network, materials, and construction techniques.

3.4.3 Objectives

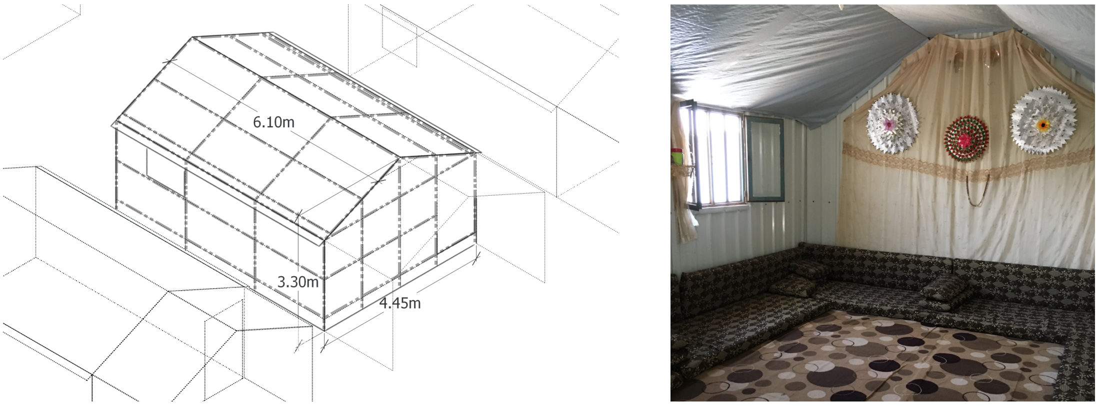
Our main objective is to use the large refugee camp of Azraq in Jordan as a case study of how a cyclical design process can be applied to improve shelter design, particularly with respect to overheating and heat stress. Jordan is chosen as an ideal case study as it provides all the key features of the current challenges facing refugee shelter design globally:

- the influx of a large number of refugees over a very short period (2014 onwards) in contrast to other camps (e.g. those on the West Bank) where the process of camp building has occurred over several decades;
- its extreme climate with both hot (day) and cold (night) extremes, though our focus is primarily on the former; and
- the delicate socio-political conditions that limit designers from developing solutions that either are, or appear to be, permanent in nature.

The paper describes the housing context of the study camp and explores the challenges faced by camp residents and authorities. Then, the annual overheating evaluation methods used to measure the performance of shelters and the predicted impacts on occupants are described. The following two sections then present the results of applying the method for the case study, one for the original shelters and another incorporating the potential design improvements informed by the field work. Finally, the findings and the limitations of the study are discussed and its implications for future research are summarised.

3.5 Housing context: desert refugee camp

The case study is located in the Azraq refugee camp in Jordan at an elevation of around 700 m above sea level, established as part of the regional response to the Syrian crisis that began in 2011. Located at 31.90°N 36.58°W, the camp is exposed to a hot desert climate (Kottek et al. 2006). As of June 2018, there were 40 092 persons of concern here, with 59 % of the population under 18 years old, 2 % above 59 years old and an equal gender split (UNHCR 2018b). Nearly 9000 transitional shelters house the population at the moment, all of which are based on the same design (fig. 3.3).



(a) Overview (interlocking steel structure superimposed)

(b) Example of shelter interior

Figure 3.3: Transitional shelter at Azraq refugee camp

Azraq camp was pre-planned, on a site that had been developed in the 1990s to accommodate Iraqi refugees. As the war in Syria intensified and Zaatari camp in Jordan reached its full capacity, over 13 000 transitional shelters were planned in Azraq in preparation for a new influx of refugees in 2014 (IFRC et al. 2014). The shelter was designed by UNHCR and structural safety, protection from the elements, speed of construction and use of local materials were all factors considered in the selection process (IFRC et al. 2014). At a later stage, kitchen extensions were built and the whole of Azraq camp was connected to an electricity grid by the end of 2017, among other improvements (UNHCR 2018b).

The following sections introduce the climate at this location and the field study conducted. The first helps to understand challenges and opportunities for passive architecture and the second characterizes the housing conditions.

3.5.1 Climate overview

To ease the interpretation of results in this study, the climate at Azraq is considered through the weather file used in the simulation method presented in section 3.6.1. Temperatures are within comfortable ranges for 37 % of the time and the average temperature is 20 °C, with minimums below 0 °C and peak temperatures surpassing 43 °C (fig. 3.9(a)). The difference between the maximum and minimum temperature over a day is, on average, 12 °C and days are typically sunny, with clear skies at night, consistent with the expectations for a hot desert climate.

3.5.2 Field studies: lessons learned

Field studies were carried out in summer 2016 and winter 2017 to examine the thermal performance of the shelters, evaluate residents' thermal satisfaction and understand camp development dynamics (for an explanation of materials and methods of the field studies referenced in this section see Albadra et al. (2017)).

Spot surface temperature measurements, air temperature and relative humidity were taken in 38 shelters between 09:00 and 15:00, from 31st August to 23rd September 2016. A weather station located on a tripod 2.5 m high on the roof of UNHCR office caravan at the nearby Zaatari camp provided concurrent external weather data. The monitoring was limited to these periods and methods due to political and other sensitivities. Thus, whole-, or multi-year monitoring of occupied shelters was not possible.

Camp residents ($n = 84$) were interviewed and confirmed that overheating inside the shelters was a problem. The analysis of the thermal survey completed by randomly selected families indicated a comfortable temperature band between 17.2 °C and 28.4 °C (i.e. thermal sensation votes between ±1, 80 % acceptability). The social survey focused on factors such as perceived security, privacy or adaptation opportunities. The main cooling strategy at shelter level was found to be natural ventilation and reported coping mechanisms against heat were mainly to pour water onto themselves with their clothes on and to spray water on the floor (Albadra et al. 2017). However, more recent improvements in electricity supply has allowed the use of fans (UNHCR 2018b). Lastly, shelter units were documented ‘as built’ to track any discrepancies between the original specification and their actual conditions as discussed in section 3.6.1 and section 3.7.1 below.

Based on these findings, UNHCR Jordan welcomed further collaborations to understand and quantify annual overheating in these shelters and, if need be, to suggest design upgrades. Should overheating mitigation measures be needed, their scope should be restricted to the shelters themselves because, due to security concerns — among other considerations — the structure of the camp cannot be modified. In addition, they were requested not to have a significant impact on the original structure and to keep fundamentally the same external appearance.

3.6 Overheating evaluation methods

Owing to the impossibility of determining annual overheating empirically for a wide range of potential solutions, simulation was used to find the likely thermal conditions in the shelters, and estimate the likely occupant perception over the year. Here, these are addressed with two types of heat and mass transfer simulations, the simulation of the shelter on one side via building physics, and the simulation of occupants via human thermal models on the other. The former depicts the indoor thermal environment given descriptions of the weather, shelter structure and occupant behaviour. The second uses a model to evaluate that computed indoor thermal environment and information about the occupants to estimate how they perceive or react to such conditions. These simulations, although tightly coupled, are consider here different and, to a certain extent, independent. Thus, they are introduced separately in the following.

3.6.1 Shelter thermal model

A shelter model was created based on the original design specifications (UNHCR 2016) in E+ v8.9 (NREL 2018; Crawley et al. 2001). The approach is the creation of a 'reasonable model template' that is later informed by the field study findings and validated against collected data, and eventually upgraded with potential overheating countermeasures.

The simulation relies on the weather description provided by a 'typical year' selection algorithm (Herrera et al. 2017) for the nearest available location under the same climate (Safawi, 60 km North-West from Azraq (Meteonorm 2018)), meaning that months in historical data are selected to create a composite year that aims to represent the average weather conditions (approximating the Test Reference Year method (NCDC 1976)). A difficulty found in the context of refugee housing is the scarcity of readily and publicly available weather files. Refugee camps can be located at considerable distances from weather stations with complete and long-term records. It must be noted that the weather file previously mentioned combines observed weather data and modelled weather data — mainly solar radiation and cloud cover — to create complete hourly records (Meteonorm 2017).

The shelter is surrounded by other units, following the regular grid of the camp. Surrounding shelters provide basic shading and solar radiation reflections are accounted for. They also limit the windspeed for natural ventilation, roughly approximated as the wind profile of an urban environment as a worst-case scenario (ASHRAE 2017).

The shelter is considered in its original form but with the shading upgrade on the front façade (i.e. that with the door, fig. 3.3). Viewed from the outside, the walls are made of Inverted Box Rib (IBR) panels, 15 mm foam insulation covered with aluminium foil, 60 mm cavity created by interlocking steel structure, and an internal IBR panel. The roof follows a similar arrangement except for the internal IBR panel, substituted by tarp-like materials. The floor is a 10 cm concrete ground slab, modelled through the F value method (Baylon and Kennedy 2007; ANSI/ASHRAE 2009).

Internal gains are mainly limited to occupancy, typically up to 6 persons per unit, two adults and four children, and small electrical appliances. These have been simplified to 6 adults always present in the shelter as electricity supply in the camps has only happened at a later stage and still does not cover all the residents in every camp village (UNHCR 2018b).

Ventilation is provided through two pairs of 6-inch ventilation pipes, one at the top of each gable wall. The shelter can also ventilate through the front door and the 1 m^2 window in one of the side walls. Although the field survey raised issues with sand ingress through the ventilation pipes, and privacy issues with the location of the door and the window, here they are considered openable because the interest lies on the provision of natural ventilation opportunities and because residents do open windows nonetheless. These elements are modelled, together with infiltration, as a single-zone airflow network (Gu 2007). Due to limitations in the monitoring campaign, optimistic guesses were used to provide input data based on the literature: discharge coefficient of 0.7, airflow exponent of 0.65 and wind pressure coefficients by Swami and Chandra (ASHRAE 2017; CIBSE 2017; Swami and Chandra 1987; Orme et al. 1998). In addition, perfect window opening behaviour is assumed whenever is thermally advantageous and above 21 °C. Lastly, a minimum ventilation at $8\,\mathrm{L\,s^{-1}\,p^{-1}}$ is always provided to ensure CO_2 levels are always kept below 1000 ppm. Although it is unlikely that this constant ventilation is achieved in practice, it constitutes a worst-case scenario for the severest overheating in this climate. As temperatures rise over 40 °C, it might be best to reduce ventilation from an overheating point of view. Thus, this assumption hinders the performance of overheating mitigation measures.

3.6.2 Human thermal models

To quantify the impact of indoor overheating two models are used, one to assess comfort and one to assess heat strain. The first is the ASHRAE's adaptive comfort model (ANSI/ASHRAE 2017; de Dear et al. 1997). The model provides a temperature band T_{acm} that describes the temperature that most occupants would find comfortable in free running buildings (80 % acceptability)

$$T_{acm} = 0.31 \cdot T_{pma} + 18.8 \pm 3.5 \tag{3.2}$$

where T_{pma} is the prevailing mean outdoor air temperature. Here, T_{pma} is taken as the exponentially weighted running mean of the daily mean outdoor air temperature to give more importance to recent thermal experiences (with $\alpha = 0.8$). In light of the social survey, it might seem that adaptation assumptions are not entirely satisfied as, for instance, female residents reported limited ability to adapt their clothing. Yet, it was also found that the thermal survey fitted well within this adaptive comfort model (Albadra et al. 2017). The second approach is the Pierce 2-node model, a simplified representation of the heat transferences in the body (passive system) subject to the thermoregulatory control (active system) that adjusts physiological responses to the surrounding environment (Gagge, Fobelets, and Berglund 1986; Fountain and Huizenga 1997). This exposes the 'strain' the body is under to keep the heat balance with the environment, and it considers the influence of air and radiant temperatures, relative humidity, air velocity, activity level, work efficiency and clothing on a standardized individual. The first four variables are provided by the shelter simulation, with internal air speed estimated through the time-varying natural ventilation air flow divided by the cross-section of the shelter unit. Activity level has been considered between 0.9 met and 1.1 met (night-time and daytime, respectively, no work being carried out) and clothing was taken as that of female residents, 0.93 ± 0.05 clo.

Among the many possible indicators and indices that can be derived from the Pierce 2-node model, the Discomfort index (DISC) is used to report heat strain. As noted by

Gagge et al. (1986) and Fountain and Huizenga (1997), this index measures the effort made by the body to restore comfort and, in the context of overheating, it measures the relative strain caused by the thermoregulatory sweating on a 5-point scale, with 0 describing comfortable conditions and 5 intolerable.

3.6.3 Evaluation method

The thermal indoor environment was evaluated with the following variables:

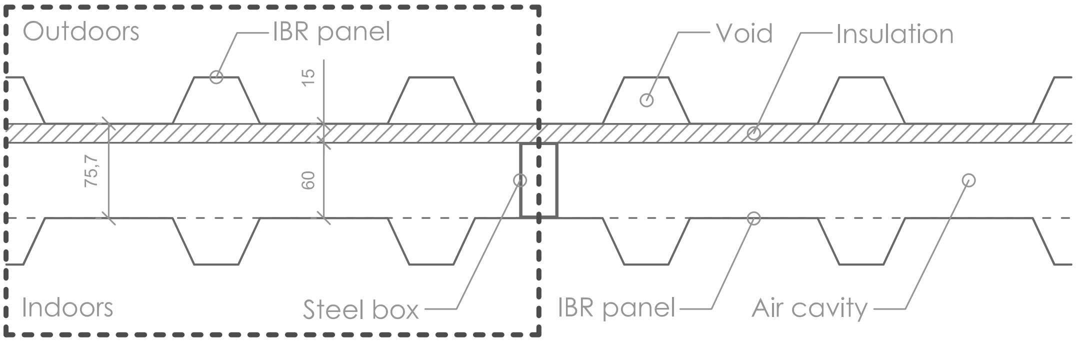
1. Mean indoor air temperature. Relative humidity is not included in this dry desert environment.
2. Mean surface temperature of walls. Interviewed residents reported that internal surfaces were often too hot to touch, being one of the reasons why many upgraded their shelters with additional internal insulation. The indicator here is the weighted average of wall surface temperatures because these are elements within residents' reach.
3. Temperature difference between indoor operative temperatures and adaptive comfort model upper limit (ΔT). It is widely recognized that the acceptability of the indoor thermal environment is influenced, among others, by the duration and the severity of uncomfortable conditions outdoors (ANSI/ASHRAE 2017; BSI 2007). Although there is much debate in the literature on how to define overheating, standard guidelines define overheating as conditions where temperatures surpass the adaptive comfort upper limit by more than 1 K for more than 1 % of the occupied time or $\Delta T \geq 4\,\mathrm{K}$ (CIBSE 2013; CIBSE 2017).
4. DISC votes in the Pierce 2-node model. Inspired in the previous limits of discomfort, it is assumed that votes of +3 or above in the DISC scale for more than 1 % of the annual occupied time imposes excessive heat strain on the thermoregulatory system.

3.7 Current shelters: extrapolated thermal performance

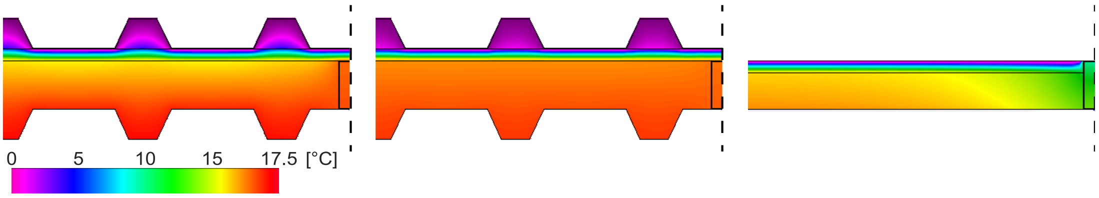
3.7.1 Base models and validation

Despite these shelters being all based on the same design and having relatively few number of design features, no two shelters are identical. Between-shelter variability and uncertainties were broadly constrained to ventilation, orientation and thermal resistance of constructions. Occupancy was deemed to not vary as overheating typically occurs during peak daytime, at which time the shelters are usually fully occupied.

Focusing on the latter as an example, inspections revealed that insulation was often squashed, loose, by-passed or covered in dust. This is assumed to differ from the likely design intent (fig. 3.4(a)). The influence on thermal conditions is illustrated in thermal bridge analyses (fig. 3.4(b)). Just the overall 2D thermal resistances range 0.63–0.5 times what simple calculations show under different assumptions of surface emissivity, air cavity thermal resistance and position of insulation.



(a) Wall description (dimensions in mm; dashed rectangle indicates fig. 3.4(b) view extent)



(b) 2D Thermal bridge analyses of three scenarios: 'best-case scenario' (left), 'best-case implementation' (centre) and 'assessed scenario' (right) (boundary conditions $T_{out} = 0\,°\mathrm{C}$, $T_{int} = 20\,°\mathrm{C}$; see description in fig. 3.4(a); simulation software Therm (Huizenga et al. 2017))

Figure 3.4: Horizontal section through a typical wall support (see interlocking steel box structure arrangement in fig. 3.3)

To capture the expected variability, 32 model variants attempt to bound the performance of current shelters (low and high estimates of insulation thickness, air cavity resistance and emissivity of surfaces, ventilation effectiveness and infiltration, table 3.3). The air temperature spot measurements of different shelters were combined into a single time series and split into two groups, one to calibrate the model and another one to validate it. The goodness of fit was evaluated in the validation group for every model (fig. 3.5). Considering the between-shelter variability, the uncertainties and limitations involved, as well as the coverage of monitored ranges, these results were regarded as sufficiently accurate for the purposes of this study.

3.7.2 Performance

The results are presented in fig. 3.6 for extrapolated annual overheating in current shelters, under typical weather conditions in Safawi. Although shelters do have heating, metrics are reported for free-running variants to expose their baseline performance. Indoor air temperatures span a wide range, with minimums at 5 °C in the winter and

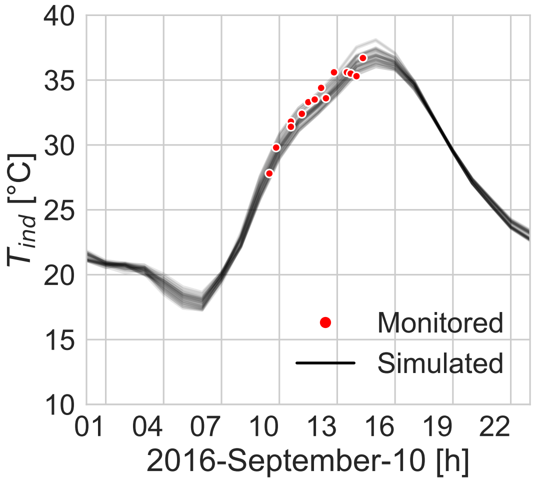


Figure 3.5: Current shelters: monitored indoor conditions ($n = 14$) and simulated models ($n = 32$) over 24 h (average mean normalized error 4.4 %, average root mean squared error 1.49 K)

maximums under 45 °C in the summer across all variants (fig. 3.6(a)). Unsurprisingly, given the lightweight construction and little thermal insulation, the overview of indoor air temperatures follows closely the external ones, except for moderately warmer conditions in the cold season due to occupancy gains. Contrarily to extreme values, results obtained for the median and quantiles 0.25 and 0.75 show that, for nearly 50 % of the time, indoor air temperature is within the comfort zone of 17.2 °C and 28.4 °C established by Albadra et al. (2017).

The acceptability of the indoor environment is also determined by the surface temperature of its enclosing elements. Ignoring for the moment the temperature of the radiant environment as a whole, which is accounted for in the human thermal models, results for the average wall surface temperature follow the patterns for air temperature (fig. 3.6(b)). The only noteworthy difference is that extreme values show greater variability across model variants due to the different thermal resistances of the walls. Numerically, the median of the maximums is 43.85 °C, in the 42 °C to 44.5 °C range where onset of contact pain is generally considered to take place (Ungar and Stroud 2010), which aligns with residents' testimonies. Note that the onset of contact pain is a function of the time of contact and thermal properties of the materials. The model by Ungar and Stroud (2010) approaches a threshold of 44 °C for contacts with aluminium objects (which is used in the shelter's IBR panel) for longer than 30 s.

Results for the adaptive thermal comfort, based on the operative temperature index (calculated as per ISO 7726 (BSI 2002)), display large deviations from comfort (fig. 3.6(c)). Note that fig. 3.6(c) shows the various subgroups discretized in 'bins' to separate the results. Here, bins represent normalized value counts of a variable. For example, the bin $[4, \infty)$ for ΔT reads 8 %, which means that the upper limit of adaptive thermal comfort is surpassed by 4 K or more 8 % of the time. Since shelters are considered here constantly occupied and evaluated over a non-leap year, this reads as $\frac{8}{100}8760\,\mathrm{h\,a^{-1}} = 700.8\,\mathrm{h\,a^{-1}}$.

The cumulative annual overheating ranges between 16 % and 21 %, greatly surpassing every recommended threshold. More worryingly, the breakdown reveals that the vast majority of this overheating happens in the severest bin considered, $[4, \infty)$. Values in this bin exhibit a wider variability than their counterparts in the other indicators, suggesting a certain sensitivity to model assumptions.

The heat strain indicator further depicts an unacceptable indoor environment from the physiological perspective, with an annual cumulative average between 29 % and 32 % (fig. 3.6(d)). Unlike in the adaptive comfort evaluation, results follow a diminishing progression at greater strains. Yet, minimum values in the $[3, \infty)$ bin are still above the selected illustrative limit.

3.8 Design improvements: the role of passive architecture

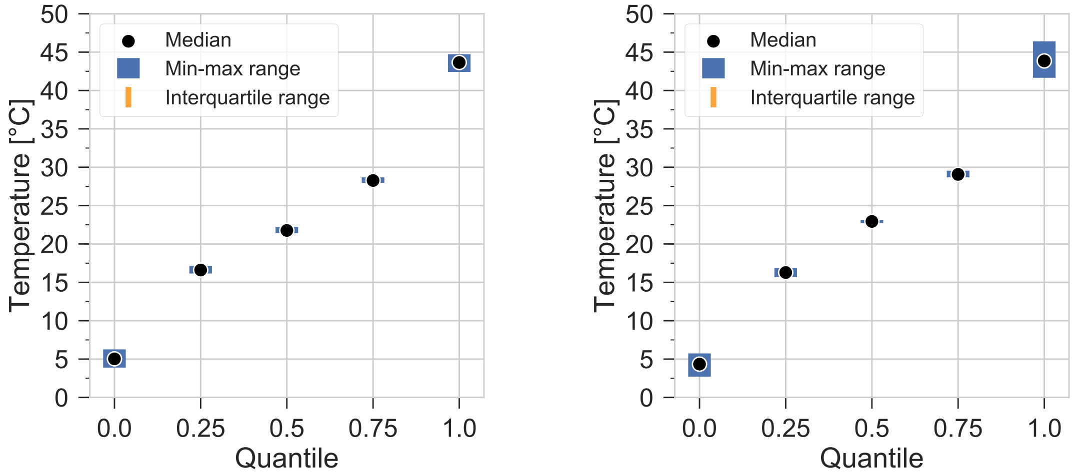
3.8.1 Design brief

A parametric approach was adopted to assess every combination of the selected passive design strategies since the physical processes they control are tightly related (table 3.3). Equally important, this exposes estimates of performance robustness, as some measures might yield significant benefits if and only if others are present.

3.8.2 Performance

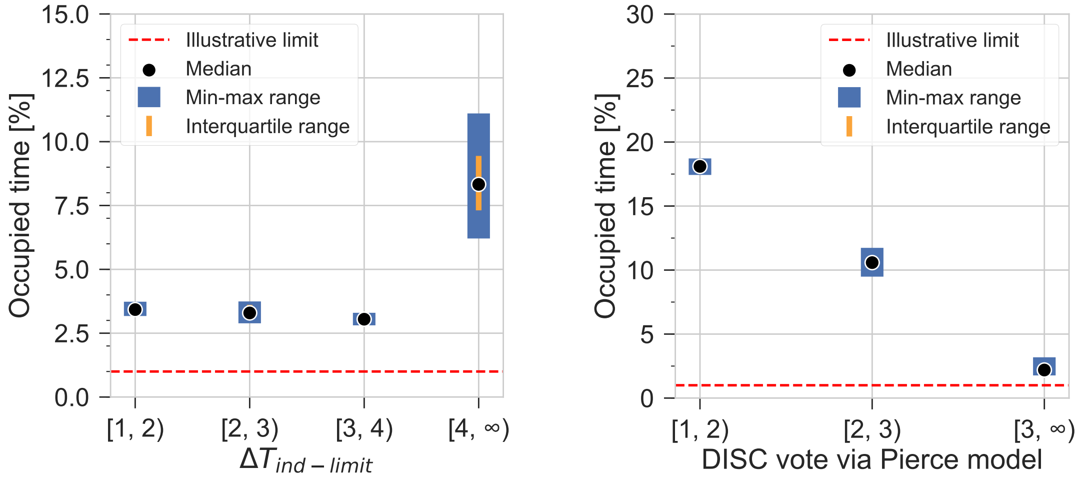
Figure 3.7 shows the results for the 7200 free-running combinations of every parameter case. Compared to the current shelters baseline in fig. 3.6(a), the main change in indoor air temperatures is a greater minimum-maximum range in every quantile, especially for the extreme ones (fig. 3.7(a)). Although coldest and hottest temperatures are the same — model variants do include those of section 3.7 — passive strategies can deliver minimum temperatures above 10 °C and maximum ones under 36 °C in the best-case scenarios. Still, the interquartile range of minimums and maximums temperature is just of a few degrees, indicating that this moderation in extreme temperatures is consistent for 50 % of all these models. Wall surface average temperatures follow similar trends, with even greater moderation of extreme temperatures (fig. 3.7(b)).

The cumulative annual overheating according to the adaptive comfort model ranges from nearly 0 % to 23 % (fig. 3.7(c)). The key benefit of these passive strategies alternatives is clearly shown for the severest overheating: the median values for the bin $[4, \infty)$ are reduced from 8 % in current shelters to nearly 0 %. It must also be noted that maximum values here increased from 11 % to more than 13 %, indicating that a small proportion of strategies are counter-productive. Results in remaining bins depict



(a) Indoor air temperatures

(b) Indoor wall surface average temperatures



(c) Annual overheating according to adaptive comfort model (n.b. Y axis scale)

(d) Annual heat strain according to the Pierce 2-node DISC indicator (n.b. Y axis scale)

Figure 3.6: Current shelters: extrapolated conditions in free-running shelter variants ($n = 32$ in each quantile or bin)

further decreases in median overheating, with interquartile ranges featuring a wide range given the migration of the severest overheating to these categories.

Lastly, results for the heat strain indicator follow analogous improvements to those obtained in the adaptive comfort model. The median for the bin $[3, \infty)$ is below the illustrative 1 % limit, with its interquartile range just surpassing this threshold. Here too, a small number of combinations can exacerbate overheating, with a maximum increase of +5 % for the severest category assessed. Despite these benefits, female residents are still considered to vote DISC ≥ 1 for more than 24 % of the time.

Having proved the extent to which shelter variants can mitigate overheating, the question now becomes how parameters and cases in table 3.3 contribute to the results.

Table 3.3: Parametric design (starred cases correspond to bound estimates for current shelters in section 3.7.1)

Parameter	**Description**
Orientation	Cases: {North*, West, South*, East} Notes: Orientation with respect to the façade with the window.
Insulation	Cases: {0.75*, 1.5*, 3, 6, 12} cm Notes: Insulation thickness for both walls and roof.
Construction	Cases: {original ideal*, original assessed*, sand in the 6 cm cavity, 36 cm sandbags, 12 cm bricks} Notes: Constructions for the walls.
Shading	Cases: {current shading*, full shading of the whole shelter} Notes: Windspeed around shelter is the same in both cases.
Ventilation	Cases: {daytime, night time, day and night*} Notes: This refers to availability of the window and the door.
Infiltration	Cases: {1.5*, 2.3*} ach h^{-1}
Opening size	Cases: {1*, 1/2*, 1/4, 1/8, 1/16, 1/32} Notes: Cases are multipliers over 'as-designed' openable areas.
Heating	Cases: {available*, not available} Notes: Allows appraisal of free-running conditions and heating demand.
Total	**14 400**

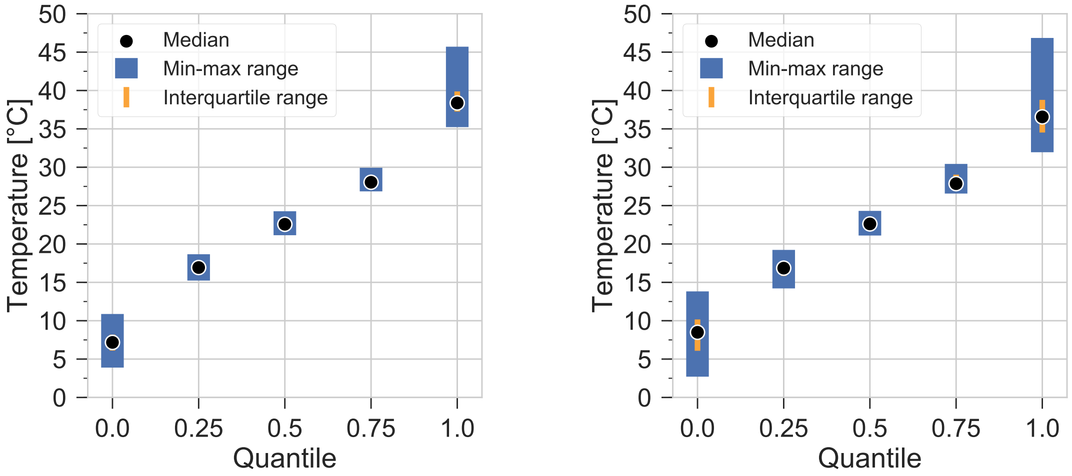
This is approached showing how overheating changes keeping constant one parameter-case at a time (i.e. the 'main effects', provided for overheating under the adaptive comfort model, fig. 3.8).

Three parameters stand out:

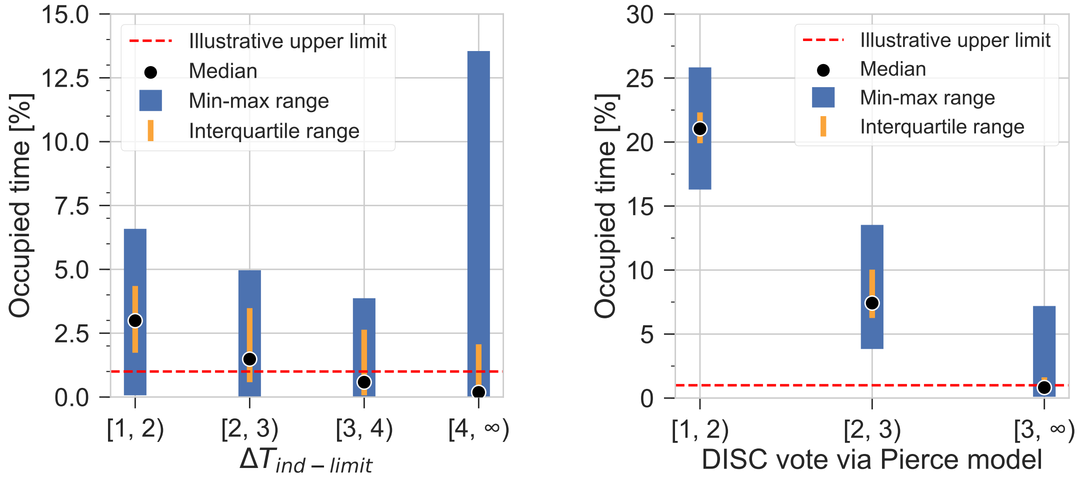
Shading Blocking completely solar radiation is the single most powerful measure, capable of mitigating maximum overheating levels to under 8 %. Although this is a theoretical scenario, this illustrates great potential for measures such as exterior ventilated air cavities.

Insulation Increasing insulation thickness proves to be second best in moderating maximum overheating levels.

Thermal mass As noted in the climate overview, comfortable temperatures can often be met at some point over the day all year round. Thermal mass can take advantage of this by dampening extreme temperatures and delaying their influence in the internal environment. However, this measure alone cannot guarantee meaningful changes in performance, as all thermal mass cases score maximum values above 20 %. Still, only medium to heavyweight solutions can reduce annual overheating to under 1 %.



(a) Indoor air temperatures (b) Indoor wall surface average temperatures



(c) Annual overheating according to adaptive comfort model (n.b. Y axis scale) (d) Annual heat strain according to the Pierce 2-node DISC indicator (n.b. Y axis scale)

Figure 3.7: Design improvements: extrapolated conditions in free-running shelter variants ($n = 7200$ in each quantile or bin)

Overheating performance of the other parameters is highly conditional on the context set up by the three main variables, as hinted by their value distributions. For example, there is real value in providing large ventilation openings or opening windows during cooler parts of the day, night and year, even in lightweight, poorly insulated shelters of this size. Further work is needed on this subject.

The heating demand of the shelters could not be investigated in the field work (i.e. constant heating to a set point, regardless of the fuel available). Hence, it is estimated with shelter simulation variants. Although absolute values are reported, the interest is in the relative change of performance from the heating demand obtained for current shelters (those cases reported in section 3.8 but with heating available). The median heating demand of these reference shelters is 89.20 $\mathrm{kW\,h\,m^{-2}}$, with a standard

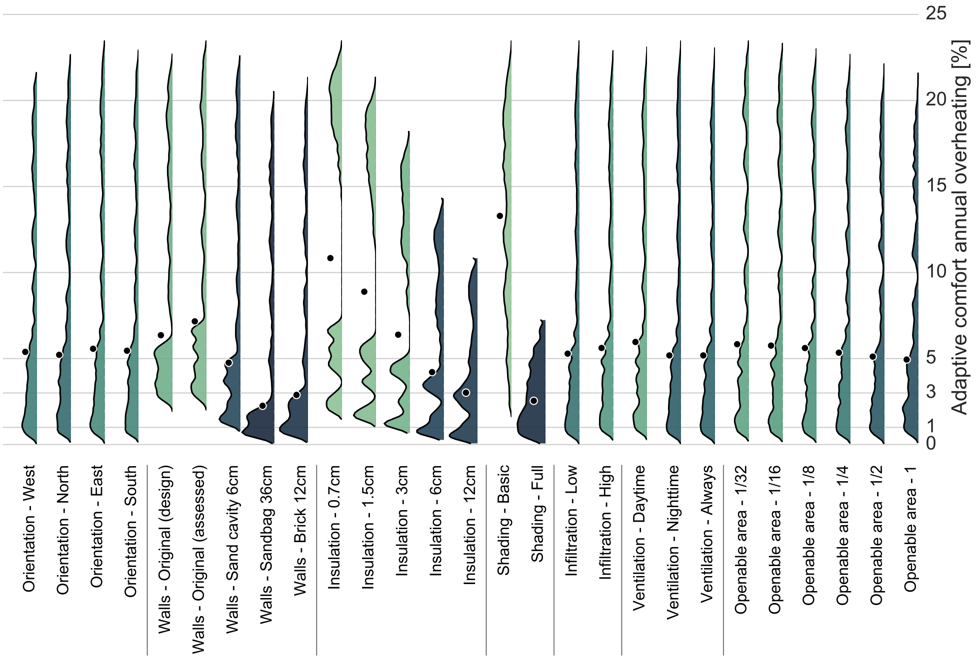


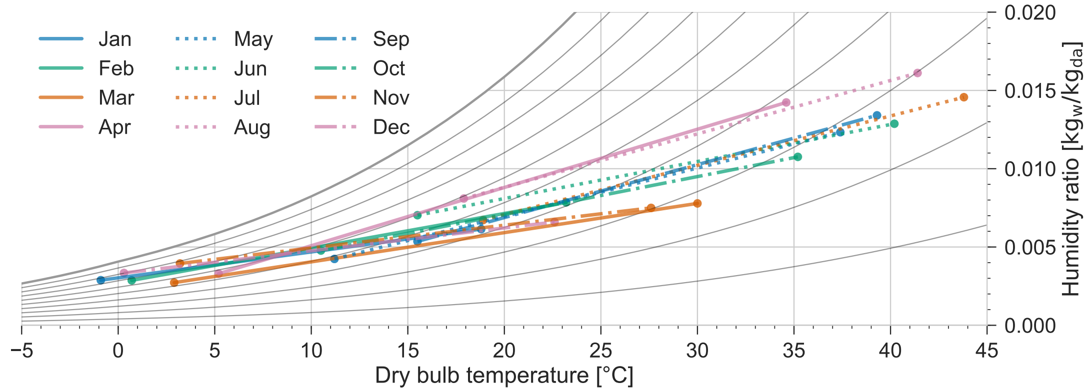
Figure 3.8: Distribution of annual overheating according to the adaptive comfort model in shelter proposals grouped by parameters and cases ($n_{\text{unique}} = 7200$; dot and density shade colour indicate the median)

deviation of 13.82 kW h m^{-2}. In contrast, median heating demand across all 7200 cases is 50.89 kW h m^{-2}, with a standard deviation of 21.14 kW h m^{-2}. Not only do these passive strategies mitigate overheating but they also reduce the heating demand. This could potentially improve indoor environment acceptability in winter, saving operational costs of the camp.

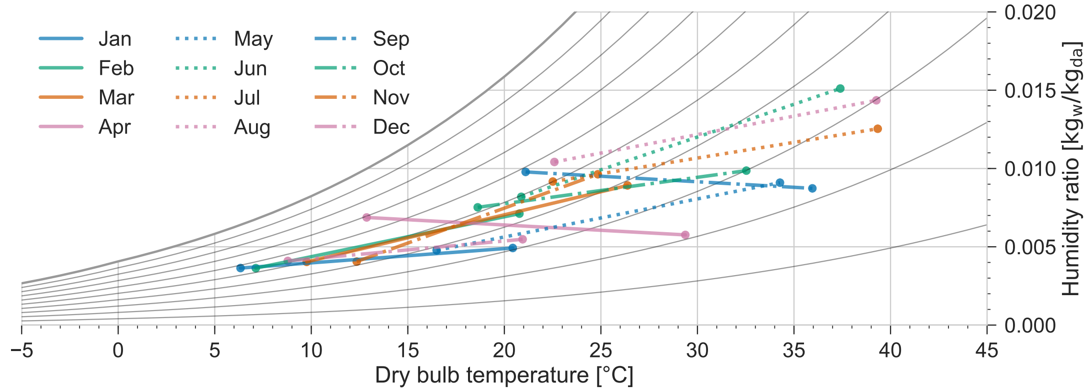
3.9 Discussion

Figure 3.9 shows a summary overview of the extent to which passive architecture, through a cyclical process of design improvements, can enhance thermal living conditions in the shelter. The climate and environmental conditions at the study camp are severe, resulting in large deviations from generally accepted comfort norms throughout the year (fig. 3.9(a)). These conditions in turn are transmitted to the indoor space in the current shelters since they fail to moderate heat transfer (fig. 3.9(b)). In contrast to this, we demonstrate that carefully designed shelters can take advantage of the external environment to actively promote an internal environment that is significantly closer to comfort (fig. 3.9(c)), with even the limited number of strategies considered here.

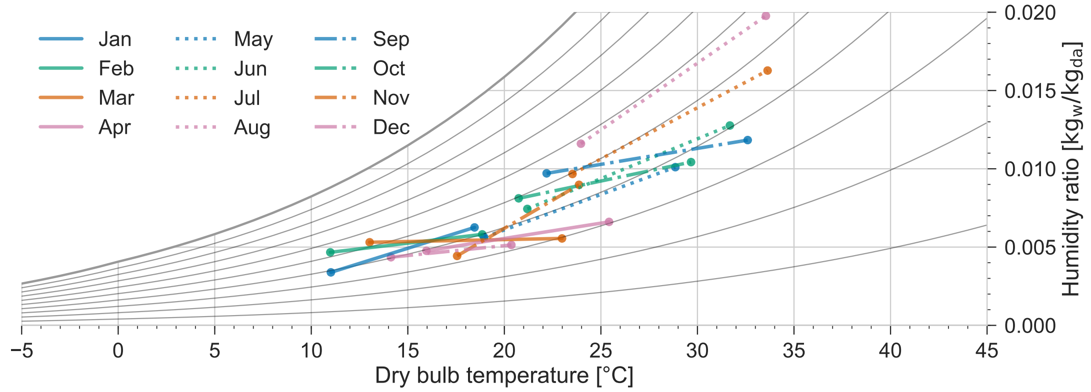
The measures shown in table 3.3 could be materialised in several ways and create a compelling case for the approach. However, there is still the need to consider other elements of camp life. For example, efforts to provide cross ventilation with an increased



(a) Climate description based on typical year weather file (see section 3.5.1; range selection based on monthly minimum and maximum temperatures)



(b) Overview of free-running version of original shelters (see section 3.7; ranges based on the 5th and 95th percentile of indoor air temperatures)



(c) Free-running shelter proposals with lowest annual overheating duration (see section 3.8; ranges based on the 5th and 95th percentiles of indoor air temperatures)

Figure 3.9: Psychrometric chart summaries ($p_{atm} = 93\,978\,\text{Pa}$, i.e. mean atmospheric pressure at location; ranges based on two sample points per month)

number of windows would be a poor choice if privacy and security concerns of the residents are not addressed.

3.9.1 Limitations and challenges in overheating simulation

This work highlights the potential benefits of cyclic design in shelter provision. Like all modelling work, there are limitations to the accuracy of the results, arising from the limitations of the simulation model used, for example here in the airflows and heat exchanges within the envelope cavities and also by the impossibility of predicting how interventions will be used by occupants. The model does not deal well with issues of natural ventilation or energy storage in the system and further work needs to be done to optimise the potential for comfort cooling and heating in the structures using these strategies.

Finally, despite the fact that the limits of discomfort and heat stress are widely used, we can only treat them as educated guesses of the actual limits of discomfort and heat stress since these are typically based on healthy adults in very different climates, many developed purely for male adults in the military or mining industries. Hence, how they relate to children, women and the elderly in these shelters is unknown.

3.10 Conclusions

The provision of adequate shelter for refugees is becoming a globally pressing issue. Understandably, thermal conditions are not initially a primary concern when housing large number of individuals as a response to a humanitarian crisis. However, as the lifetime of camps is extended, the quality of indoor environments is expected to become of greater interest to ensure the well-being of residents.

Since the thermal performance of structures is deeply affected by their design, it is tempting to assume that shelters need to be rethought from the ground up. However, considering the established dynamics behind refugee housing provision, this approach is likely to ignore the lessons learned in broader aspects of shelter design. Instead, taking advantage of the ‘planned temporariness’ of shelters, we have explored the potential for a ‘cyclic design approach’, a way of building up on top of current solutions to improve shortcomings in their performance while retaining their proven advantages.

This cyclic design approach was demonstrated in the Azraq refugee camp in Jordan. Validated simulations models and on-site measurements showed that the current transitional shelters of this camp overheat causing both discomfort and at times heat stress. Based on these findings simulated modifications to the shelters incorporating a range of simple passive design improvements resulted in significant performance improvements, even completely removing the severest overheating incidences in some cases.

The lack of a regulatory framework regarding the thermal performance of refugee shelters results in a general acceptance of the existence of low levels of comfort and high levels of thermal stress inside such temporary camps. That shelters are a temporary housing solution, need not mean the global community should acquiesce to this. Furthermore, it is clear from the field surveys that shelter designs need to be sensitive to the background and cultures of camp residents if the shelters are to be a humane and sustainable solution during their lifetime.

3.11 Acknowledgements

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3.12 Disclosure statement

No potential conflict of interest was reported by the authors.

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3.14 Data access statement

Dataset in this study is openly available at `https://doi.org/10.15125/BATH-00424`.

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3.16 Postscript

In this chapter, we propose a new method for cyclic design of refugee shelters, whose design process lacks a procedure to evaluate designed and delivered thermal performance. It included the assessment of heat strain based on the Pierce 2-node physiological model as well as appraisals based on the classical thermal comfort theory that underpins standard overheating criteria. The comparisons of air and surface temperatures, deviations from adaptive comfort, and the DISC index, indicated that the latter scales consistently with increased severity of indoor conditions, as depicted by the differences in duration in the extreme bins of these metrics.

A first principles analysis further supports the case for overheating assessment schemes based on physiological indicators using rational models. These models transparently account for heat and mass transfers, and their effect in thermoregulation system, an approach which aligns with the motivation behind high-fidelity building simulation for design. This approach represents an improvement over current methods in overheating, but they do not provide a complete answer with regard to the motivating factors to study overheating in buildings. There remain challenges in physiological models to represent vulnerable sectors of the population, and relationships with increased morbidity and mortality are yet to be clearly established (Havenith and Fiala 2016). Further to these, this work did not find a suitable model to appraise conditions over periods of time exceeding several hours. Approaches to study heat waves could include normalising conditions under long-term deviations of core temperatures given that a sweat budget approach could be more sensitive to assumptions of sweat capacity, rehydration rates and strain on the heart. Such approaches have long been established and they are still under research (Deng et al. 2018), but their accuracy and correlations with epidemiological impacts remain open questions.

Focusing on the context of transitional shelter design, hosting forcibly displaced populations presents a particularly complex topic given the sensibilities of the different agents involved (host government, aid agencies and those displaced) and the limited resources available. Even though passive strategies improve considerably indoor thermal conditions, their suitability and implementation need to be further judged together with the views of residents and camp managers. Complementary work addressing this aspect is reported in appendix D.

The building simulation framework developed in these last two chapters establishes a way to study overheating at design stage. Taking into consideration the large number of input parameters defining a model, augmented by those of the design variants, the question then becomes to what extent they can predict delivered indoor conditions. This is examined in the next chapter.

Chapter 4

The importance of thermal modelling and prototyping in shelter design

4.1 Preamble

The work conducted in chapters 2 and 3 point to the fact that there is a qualitative distinction in the use of modelling between overheating studies in free-running buildings and studies on energy performance. The definition of overheating is based on a notional maximum temperature threshold above which overheating is considered to take place, which is entirely dependent on the ability of a model to capture real absolute temperatures. On the other hand, energy is proportional to a weighted area that relates temperature differences and time. Given a sufficiently long period of time, like in the case of annual building simulation, energy demand is, comparatively, less sensitive to errors in estimates. In overheating, a temperature bias in a model of 2 K can significantly change the results of an assessment.

This chapter examines the extent to which tools that have been historically developed to study energy are apt to study free-running buildings (Research Question 3). The next paper addresses the core assumption that indoor temperatures can be predicted at design stage to the level implied by overheating criteria. This work adds to the efforts for whole-model empirical validation by IEA EBC Annex 58 (Strachan et al. 2016), although here the focus is on the actual appraisal of performance in terms of accuracy and precision. The paper compares forecasts of indoor air temperatures obtained through high-fidelity building simulation to those obtained empirically by building and monitoring prototypes. Then, a series of evaluations with uncalibrated and calibrated variants are used to judge the benefits of prototyping solutions, either as an alternative or to inform model predictions.

The work conducted in the context of Azraq and the HHftD project (Fosas et al. 2017; Fosas et al. 2018a; Fosas et al. 2018b), proposed passive design solutions and design frameworks to inform the shelter provision process. As a result, UNHCR Jordan welcomed running an experiment in Azraq camp to evaluate the benefits of upgrading these shelters, following the cyclic design approach previously introduced. Importantly, this experiment allows gathering of empirical evidence to address the goals previously mentioned, and the testing of the suitability of high-fidelity building thermal performance simulation in this context. Methodologically, the work is supported by appendix C, which integrates reanalysis datasets and satellite observations to define weather files for locations at considerable distance from the nearest public weather station with suitable records.

The experiment was implemented in August 2018 and it was since maintained and improved in subsequent visits, which are expected to continue until the foreseeable end of the experiment in spring 2020. The decision to work iteratively on the experiment responds to how access to the camp works. Permits to enter the camp are for a limited period of time and they need to be arranged in advance with the local government through project collaborators in the country. Permits might not be granted, either at all or in a timely manner that allows for long-term planning, due to, for instance, current demand or ongoing events at the camp. Materials and equipment must be declared in the permit request and cleared by security forces at the entrance of the camp. Access to the camp is generally allowed from 09:00 until 16:00, Sunday to Thursday, which in practice translates roughly as 25 working hours at the compound per week. Considering the limited planning around camp permits, transportation costs and potential embargo of shipped equipment, the limited planning around camp permits, and potential setbacks in the work itself (e.g. delays in completing work, adverse conditions for experimental testing, the need for new tools or materials), it was decided to work incrementally on the experiment, building on the lessons learned from the previous visits and the durability of implemented solutions.

The first monitoring campaign allowed capturing the overall thermal performance of the shelters during the hot season and corresponds to the period between the first two visits to the experimental compound, from 17th of August until 7th of October 2018. In the first visit, the experiment was built, and the main sensors deployed. Sensors monitored internal air temperature at three heights in the centre of every shelter, selected spots in internal and external surfaces, and custom-made black globe temperature sensors were built inside every shelter. Since there is a need in the following to study to replicate observed thermal performance, the weather file for the simulations replicate on-site conditions. Therefore, this weather file is not that used in chapter 3. A local weather station could not be deployed for the first monitoring campaign, but shielded and ventilated sensors did monitor air temperature and relative humidity on-site, as detailed on the paper. This was further supported with satellite-derived solar radiation data following the method presented in appendix C. The experiment ran offline because these shelters had no access to power at this time. In the second visit, data was collected and filtered according to observed damages and reported events by the on-site security team (e.g. surface temperature sensors out of place in some shelters). Data was then judged to be complete enough to carry out rigorously the study presented in this chapter. Further visits and activities around this experiment is discussed in section 4.13 for completeness.

This chapter is based on the paper “The Importance of Thermal Modelling and Prototyping in Shelter Design” published in the journal Building Research & Information in 2020. This study was conducted as part of the HHftD project [grant number EP/P029175/1] to compare thermal modelling and prototyping and understand their potential role in the design of transitional shelters. The candidate has predominantly contributed to the publication in collaboration with other researchers from the HHftD project. In particular, there was a close collaboration with the project’s Work Package for Physical solutions (J. Orr, F. Moran). The experiment was designed by the candidate together with F. Moran and under his leadership. The implementation of the experiment was led by F. Moran (design and construction) and D. Fosas (design and monitoring), assisted by N. Paszkiewicz (HHftD), O. Hassan (PSUT), thanks to the support of UNHCR and NRC (see details in section 4.9). Details about the authorship of this paper are provided in table 4.1.

4.2 Declaration of authorship

Table 4.1: Declaration of authorship

This declaration concerns the article entitled:
The Importance of Thermal Modelling and Prototyping in Shelter Design

Publication status:
Accepted

Publication details:
D. Fosas, F. Moran, S. Natarajan, J. Orr, and D. A. Coley (2020). "The Importance of Thermal Modelling and Prototyping in Shelter Design". *Building Research & Information*. DOI: `10.1080/09613218.2019.1691489`.

Copyright status:
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Candidate's contribution to the paper:
The author of this thesis has predominantly contributed to the publication (83 %). The contributions of each author are as follows:

- Formulation of ideas: D. Fosas (70 %), F. Moran, S. Natarajan and D. A. Coley (30 %).
- Background: D. Fosas (100 %).
- Design of methodology: D. Fosas (90 %) and D. A. Coley (10 %).
- Experiment – Field work: F. Moran (50 %) and D. Fosas (50 %).
- Experiment – Simulations: D. Fosas (100 %).
- Analysis: D. Fosas (100 %).
- Preparation of manuscript: D. Fosas (85 %) and F. Moran (15 %).
- Editing drafts of manuscript: D. Fosas (70 %), F. Moran, S. Natarajan, J. Orr and D. A. Coley (30 %).

Statement from Candidate:
This paper reports on original research I conducted during the period of my Higher Degree by Research candidature.

Signed **Date** 20 December 2019

4.3 Abstract

More than 9 million people live in shelters globally, often in extremely hot climates. The thermal performance of shelters is often overlooked in the design process, despite being a consideration second only to safety in surveys of camp dwellers. Indeed, indoor temperatures exceeding 40 °C have been recorded in previous studies. To aid in improving conditions, the roles building simulation and prototyping could play in forecasting shelter thermal performance as part of a new shelter design process are examined. The thermal performance of prototypes, built in the refugee camp of Azraq, was monitored during the hot season to evaluate four design approaches: (1) "blind" (uncalibrated) models, (2) calibrated models, (3) on-site design-variants and (4) off-site prototypes. These included the original shelter and six design alternatives implementing different overheating countermeasures. The results demonstrate that blind models are sensitive to the judgement of uncertainties but were still qualitatively useful. Model calibration vastly improves the agreement and significantly enhances forecasts of performance for the design alternatives, which remained similar across examined climates. It is therefore concluded that simulation and prototyping, either on-site or off-site, should be adopted within the shelter design process before mass deployment, to create better living conditions for their dwellers.

4.4 Introduction

The UNHCR is currently interested in the protection of more than 71 million people worldwide, a figure that includes nearly 20 million refugees and 39 million internally displaced (UNHCR 2019b; UNHCR 2017a). As natural disasters and conflicts force large migrations, those affected need urgent accommodation for an unknown period of time. The response to these crises varies according to the context but just within the population of concern to the UNHCR, there are 9.5 million living in shelters at the moment[1].

Shelters in managed and UNHCR-assisted camps are conceived as temporary solutions to rapid displacement and are established through the collaboration between the local government and aid agencies. Although there is no clear definition of temporary, the assumption is: approximately 1 year for emergency, 4 years for transitional shelters, and 10 years or more for durable and permanent shelter solutions (Félix et al. 2013; UNHCR 2016). Transitional shelters are a mid-term affordable measure that are not as vulnerable as the tents deployed during the emergency stage, nor signify the permanence of the other solutions; the latter being a key consideration for the governments of the hosting countries.

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[1] Authors' estimate from the 8.7 million living in shelters by the end of 2016 (UNHCR 2017b) and the 0.8 million that arrived since to Bangladeshi camps as of May 2019 (UNHCR 2019a).

This work focuses on transitional shelters because past experiences demonstrate they remain in use for many years, becoming a semi-permanent solution (Albadra et al. 2018). Due to logistical, economic and political considerations, institutional agents favour shelters that are lightweight, dismountable and low-cost, paying less attention to their thermal performance (Albadra et al. 2018). For example, the Syrian refugee camp of Azraq in Jordan had to be built at a rate of 100 transitional shelters a day for more than 4 months to house the increasing number of refugees in the country (UNHCR pers. comm.). Each of these lightweight shelters had an estimated cost of $2300 in Jordan in 2013 and could be built under 16 hours by a team of 4 people (UNHCR 2016). Similarly, 723 000 refugees from Myanmar arrived in Bangladesh over a 4-month period in 2017, all requiring shelter at an average of 6000 people per day (UNHCR 2019a).

Concerns have been voiced regarding the indoor thermal environments these shelters deliver and the potential effects on comfort, health and well-being for their occupants (Albadra et al. 2017; Cornaro et al. 2015; Fosas et al. 2018a). The initial shelters provided by humanitarian agencies, whilst offering protection from the elements, may not be effective enough against the climate at the location in question, which is often aggressive (fig. 4.1). The potential indoor heat stress can be estimated with Steadman's Apparent Temperature for indoor environments, which combines the effect of air temperature and relative humidity in a shaded environment protected from wind (Steadman 1979a; Steadman 1979b; Steadman 1984). The metric is in degree Celsius and scales linearly with thermal stress. An Apparent Temperature of 25 °C represents comfortable conditions and 36 °C represents severe heat stress. Empirical studies have supported this hypothesis for shelters in camps such as Azraq in Jordan (Albadra et al. 2017), Hitsats in Ethiopia (Paszkiewicz and Fosas 2019) and Kutupalong in Bangladesh through preliminary field work conducted by the authors, with air temperatures greater than 40 °C being measured inside shelters at these locations.

This begs the question, how might such situations be avoided? In each setting the design space will be restricted by the material palette, the attitudes of the local government, money, and time. For those designing off-the-shelf solutions for mass dispatch from warehouses, the time constraint is less; as it will also be in camps where the displaced are initially housed in emergency tents. This suggests that in such situations, a modest period of design work could be entertained, and one element of this could look at the thermal conditions inside the shelter and offer improvements. For example, increased ventilation pathways, or the suggestion to use insulation.

One avenue to make informed design decisions about the thermal performance of transitional shelters is building simulation, an aspect known to be overlooked in the current shelter design process (The Sphere project 2011; Corsellis 2012). Among the options available, physics-based building simulations (also termed white-box models) would seem apt since their implementation of heat and mass transfers laws is particularly suited to evaluating new designs (Clarke 2001; Clarke and Hensen 2015). However, a key barrier for their adoption is that it is unknown if accurate predictions can be

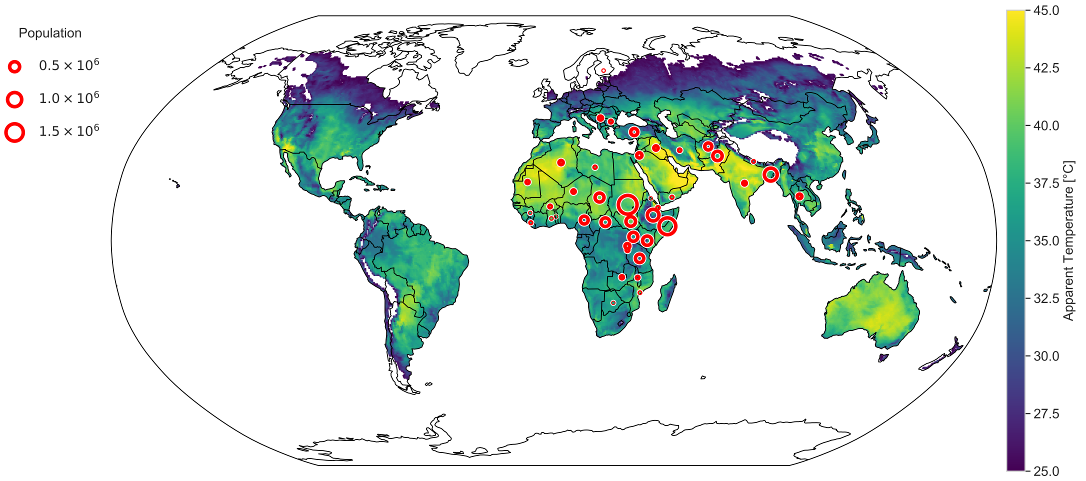


Figure 4.1: UNHCR people of concern living in shelters and heat stress in 2017 (total population 9.5 million, aggregated to hosting country (UNHCR 2019a; 2019b); Apparent Temperature for indoor environments as per Steadman (1979a; 1979b; 1984); map constructed using environmental parameters from NASA (Gelaro et al. 2017) for 99th percentile of maximum annual temperatures; Apparent Temperature reported for values above 25 °C and clipped to 45 °C)

made in this context. Apart from the well-known challenges for white-box building simulation in predicting thermal performance in conventional buildings (de Wilde 2014; Mantesi et al. 2018; de Wit and Augenbroe 2002), the fact that transitional shelters are hastily built to unknown qualities and their reliance on passive strategies like natural ventilation, add further complexity (Cornaro et al. 2015; Fosas et al. 2018a). Many of the parameters such as the air tightness or true U-value of cavity walls, which are critical to successful simulation, are likely to be unknown and hence potentially undermine any possible benefit gained from simulation. Yet, transitional shelters are mass-produced and comparatively simpler than conventional buildings, where simulation is routinely used (Deru et al. 2011; Hamilton et al. 2017; Kavgic et al. 2010; Swan and Ugursal 2009; Taylor et al. 2016). This suggests the potential for a highly favourable cost to benefit ratio: the additional work needed to undertake simulation is likely to be small against the scale of positive impact on dwellers resulting from a thermally improved shelter design.

Another possibility is to prototype shelters on-site, where an initial design is constructed, monitored, then possibly adjusted. However, prototypes are likely to be created in a climate remote from their intended destination, a common situation in the case of off-the-shelf solutions. Simulation could then play a role in allowing the shelter to be moved in the software to any location in the world, with the initial monitoring being used to calibrate the model. This is termed here “off-site prototyping”.

Despite the importance of the thermal performance of shelters, there is a limited number of studies in the literature. Overall approaches to site selection and analyses are offered by Corsellis (2001) and Potangaroa and Hynds (2008), but given the mass-production of shelters, the focus of this study is on the shelters themselves. Studies have mostly focused on the thermal performance of emergency tents in cold climates, according to the recent displacement experiences at the time (Manfield et al. 2004; Pöschl 2016). For example, Crawford et al. (2005) analysed two tent prototypes developed at Cambridge under laboratory conditions inside a freezer to characterize their thermal behaviour. This forms the basis of a calibrated model that is then simulated in selected locations in the world. Cornaro et al. (2015) performed a similar exercise for another emergency tent powered by solar energy in Italy (temperate climate). Using the calibrated model to assess design improvements for cold and hot conditions based on increased insulation and an ideal load heater and cooler, they showed that the passive performance of the tent could be little improved for hot season conditions. Obyn et al. (2015) studied the thermal performance of the standard family tent deployed by aid-agencies, questioning the extent to which building simulation could reproduce performance of this lightweight semi-translucent structure. Yu et al. (2016) studied the night-time performance of bamboo shelters and proposed construction variants based on their thermal performance in scale models during the cold season. On the other side of the spectrum, it has also been of interest the energy performance of durable shelter solutions like those in Haití (Borge-Diez et al. 2013b; Borge-Diez et al. 2013a). However, such solutions fall beyond the scope of this study given they are closer to regular housing solutions than temporal ones.

Overall, even fewer studies deal with the simulation of temporal shelters, all of which focus on emergency tents (Crawford et al. 2005; Cornaro et al. 2015; Obyn et al. 2015). Of these studies, only Obyn et al. (2015) focus explicitly on the agreement between simulation and experimental results, assuming full knowledge of design specification and construction. Here, the 95 % confidence intervals of indoor temperatures are reported to be within 2 °C for their control case in Brussels. Replicas in Burkina Faso and Luxembourg increase to 4.5 °C and 5.6 °C, respectively. Like the other studies, they make active use of all the monitored data to manually arrive at a single model that is considered to best represent observations, being uncertain who well the model performs for unseen data not used as part of the calibration process, let alone design variants. In this case, calibration involved wind pressure coefficients (generated through simulation) and soil thickness (assuming a constant ground temperature). The methodological recommendations for modelling are of unknown validity considering the challenges in replicating the thermal behaviour of interconnected air cavities with respect to, for instance, simpler single-zone models with the same accuracy. This could be a contributing factor to the limited extent to which the model responds to night-time overcooling, as judged by the authors.

Aid agencies already work under pressure and with scarce resources to meet the needs of the displaced. An evidence-based account of the merits of building simulation needs to be established before they can rely on its predictions to deliver safer thermal indoor environments, especially in transitional shelters given their lifespan. The envisaged use of simulation in this context is to forecast the performance of models based exclusively on expert-judgement or assisted by the monitored performance of a design prototype during the emergency stage of a crisis. This study therefore evaluates if forecasting indoor thermal conditions in transitional shelters is a tractable problem through building simulation and how it compares to experimental observations of shelter prototypes. Therefore, the objectives are to evaluate:

1. Whether simulated models based on the design specification and expert judgement (termed here blind models) alone can predict the as-built thermal performance of transitional shelters;
2. The extent to which models calibrated against the observed performance of a built prototype improve predictions of simulated thermal performance;
3. How well predictions of thermal performance of design variants based on the simulation of blind and calibrated models relate to observed thermal performance;
4. Whether shelter solutions can be prototyped in a different climatic context to that in which it is intended to be used at, and the role building simulation can play in this scenario.

The paper is organied as follows. First, the materials and methods are introduced, which presents (1) the as-built shelter prototypes considered, (2) the experimental conditions and data collection, (3) the different simulation models that attempt to replicate observed performance, and (4) the analysis techniques used. Next, results are presented according to each of the objectives of the study namely blind models, calibrated models, design alternatives and off-site prototyping. Lastly, the discussion of the results and the overall conclusions are presented.

4.5 Materials and methods

To evaluate the potential benefits of prototyping and simulation models at the design stage of a shelter solution, the real performance of prototypes against their modelled counterparts is compared, judging at every stage if the simulation-based approach adequately represents the real performance of the prototype table 4.2. Mapping to the objectives, the outline of the devised method is as follows:

1. Scope: A relevant case is selected. This comprises a pre-established transitional shelter (control) and the location where it is intended to be deployed.
2. Stage 1 – Control shelter prototype versus blind models:

   a) The shelter prototype is built and monitored to capture its thermal performance.
   b) Blind models of the shelter are created based on the design documentation and simulated under the same experimental weather conditions.
   c) The simulated thermal performance of the blind models is compared to that of the control prototype.

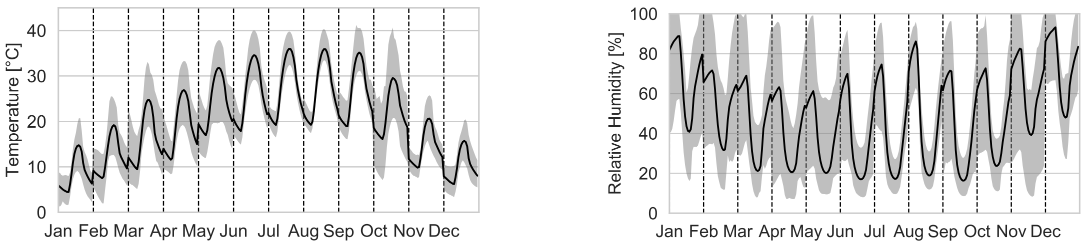
3. Stage 2 – Control shelter prototype versus calibrated models:
   a) The blind models from Stage 1 are trained with the first 70 % of the monitored data that characterizes thermal performance of the shelter prototype to produce a calibrated model.
   b) The calibration is then validated with the last 30 % of the data.
   c) The simulated thermal performance of the calibrated model is compared to that of the control prototype.
4. Stage 3 – Design alternative prototypes versus simulations based on the control model:
   a) Several design alternatives for the control shelter are established.
   b) Prototypes of these design alternatives are built and monitored to capture their thermal performance.
   c) Two types of models are built for each design alternative, one based on the blind models for the control shelter (Stage 1) and another based on the calibrated one (Stage 2). The only modifications to these models are the changes introduced by the design alternatives, preserving every other aspect.
   d) The thermal performance of each type of model is compared to that of the prototype.
5. Stage 4 – Ranking of models for design alternatives in different climates:
   a) Use the models obtained in Stage 3 and simulate them under the climate they were devised for and a different climate in which they are assumed to be prototyped at.
   b) Rank the performance of every model in each climate against a chosen baseline.
   c) Compare the consistency of the rankings obtained across climates.

Since the population of concern is concentrated in countries with severe hot conditions (fig. 4.1), the focus is on overheating during the hot season in the Middle East for the case study, where the Syrian refugee camp of Azraq is selected (Jordan, 31.90°N,

Table 4.2: Study overview (n.b. models are here referred to physics-based models, also termed white-box models)

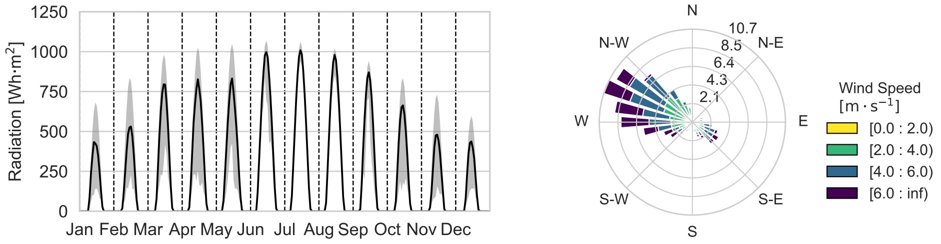
Can physics-based models be used to inform the thermal design of transitional shelters?

Objective	**Approach**	**Method**
1) Evaluate whether simulated models based on design specification and expert judgement (termed here blind models) alone can predict the as-built thermal performance of transitional shelters.	Build and monitor a shelter prototype on-site. Then replicate in a white-box model using only information that would be available to a third-party. Compare differences in performance.	Monitor indoor air temperature at the centre of the room. Replicate in simulation model considering educated guesses for unknown parameters, accounted for by single and range estimates. Compare differences in binned air temperature histogram and goodness-of-fit metrics.
2) Appraise the extent to which models calibrated against the observed performance of a built prototype improve predictions of simulated thermal performance.	Build and monitor a shelter prototype on-site. Then replicate in a white-box model using design specifications. Use calibration and validation as part of the model development by using the monitored data. Compare differences in performance.	Monitor indoor air temperature at the centre of the room. Replicate in simulation model, developed through formal calibration and validation procedure. Establish model with the best estimates for unknown parameters. Compare differences in binned air temperature histogram and goodness-of-fit metrics.
3) Compare how well predictions of thermal performance of design variants based on the simulation of blind and calibrated models relate to observed thermal performance.	Build and monitor shelter design variants on-site. Then replicate in white-box models based on blind and calibrated simulations. Compare differences in performance.	Select and build shelter design variants leveraging passive strategies. Monitor indoor air temperature at the centre of the room. Replicate in simulation model based on those developed for objectives 1 and 2. Compare differences in binned air temperature histogram and goodness-of-fit metrics.
4) Judge whether shelter solutions can be prototyped in a different climatic context to that in which it is intended to be used at, and the role building simulation can play in this scenario.	Rank the thermal performance of shelters and their design variants in the climate where their use is intended and another climate in which they might have been prototyped. Assess the consistency of the ranking in the two locations.	Select calibration-based model developed for objective 3 and rank their performance according to normalised goodness-of-fit metrics. Compare their correlation to the ranking obtained for those models in a different climatic zone.



(a) Dry-bulb temperature

(b) Relative humidity



(c) Global horizontal radiation

(d) Wind rose (orientation referenced to wind origin)

Figure 4.2: Weather at Azraq (year 2018; black: hourly average for month; grey: hourly max/min range for month; hot arid climate (BWh) according to the Köppen–Geiger climate classification (2006); data source: see section on data collection)

36.58°E, fig. 4.2). Established 2014, it is the largest refugee camp of the country, hosting 40 615 people in 8952 shelters as of December 2018 (Yacout et al. 2018). It has been regarded by camp authorities as one of the world's best camps in terms of planning, structure and overall management, considering that it was pre-planned and mindful of the shortcomings perceived by care-givers in the older neighbouring camp of Zaatari (Dalal et al. 2018).

The next subsection presents all the shelter variants considered in this study. This includes the original shelter designed by UNHCR Jordan and selected design alternatives. This is followed by the description of experimental conditions and the data collection plan and the corresponding definition of thermal simulation models. Lastly, the analysis used to compare the real performance to the simulated ones and the criteria to evaluate what constitutes an acceptable agreement between them is described. It also presents the analysis method to judge if the performance of a shelter prototyped in a different climate can be extrapolated to that of the one where it is intended to be used at.

4.5.1 Shelters

The control shelter and six design alternatives were selected for this study (fig. 4.4). These were built in a secure compound in Azraq camp (fig. 4.3). This compound houses 12 shelters that were built at the same time and by the same team of builders as the rest of the camp and are consequently considered representative.

The seven shelters under consideration are here referred to as prototypes because they would be so at the design stage of shelter solutions. Their goal within the proposed design framework would be to have a proof-of-concept of their thermal performance. Six of these were retrofitted with different strategies aimed at delivering thermally safe indoor environments based on the work by Fosas et al. (2018a). That study considered a number of passive design strategies based on their suitability to reduce overheating for the climate at hand and reported shortcomings in the current shelter solution by their occupants. The overheating countermeasures considered did not hinder the thermal performance of the shelter during the cold season. Drawing on the major influences on performance identified, strategies examined here are increased insulation, thermal mass, ventilation, shading and their combinations. These design alternatives do not necessarily represent the views of what UNHCR Jordan nor the authors would consider apt for final use. Like in the previous study, the main requirement by camp authorities was that external appearance of shelters and underlying structure remained the same. In addition, options that could inform the retrofit strategy for shelters already deployed were prioritized. One shelter was maintained in its original form as a control to establish the baseline of thermal performance.

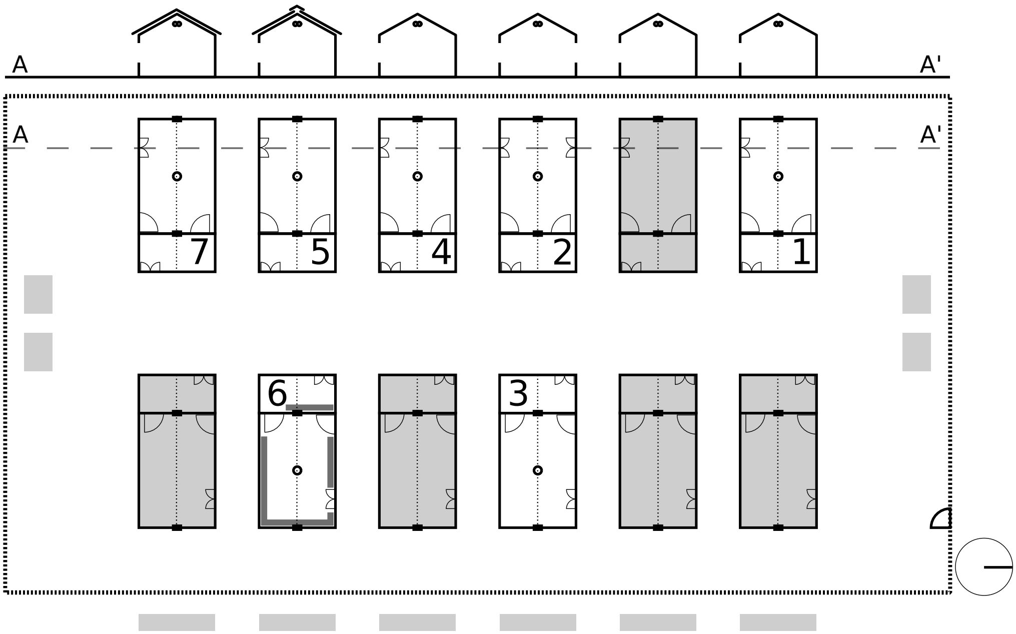


Figure 4.3: Compound shelter layout (refugee camp of Azraq in Jordan, internal address V02/B11/P13; see shelter overview in fig. 4.4; circle indicates internal sensor location; greyed fill indicates shading from surrounding objects, including other shelters not used in this study)

(a) Control (ID 1; Original T-Shelter at Azraq by UNHCR; outdoors view)

(b) Control (ID 1; Original T-Shelter at Azraq by UNHCR; indoors view)

(c) Increased ventilation (ID 2; 4 high and low-level vents each and additional window)

(d) Thermal mass by cavity fill (ID 3; 60 mm sand and gravel mix in wall cavity)

(e) Increased insulation (ID 4; doubled insulation and removal of thermal bridges)

(f) Roof shade (ID 5; 150 mm above existing roof and increased overhang)

(g) Thermal mass with internal sandbags (ID 6; Internal wall layer of 250 mm)

(h) XPS insulation and roof shade (ID 7; 40 mm insulation and roof shade with increased overhang)

Figure 4.4: Shelter prototypes in the experimental compound (refugee camp of Azraq in Jordan in August 2018, internal address V02/B11/P13; see location in fig. 4.4)

Control

This is the Azraq T-Shelter as implemented by UNHCR after a public design competition in 2013 (figs. 4.4(a) and 4.4(b)). The shelter comprises a 60 mm × 30 mm steel frame structure anchored to the ground with shallow ground plates. The frame is covered with sheets of 15 mm foil faced expanded foam insulation and clad externally with a 0.35 mm IBR steel panel. The walls are also clad internally with the same IBR panels. A tarpaulin is fixed to the underside of the roof to provide a ceiling. The internal floor is an uninsulated concrete slab at least 50 mm thick poured once the cladding is completed. To the side of the shelter is an uninsulated kitchen extension. The design documentation was updated to reflect the final as-built state; all dimensions and effective opening sizes were verified. Taken as the control for the experiment, no changes from the design approved by UNHCR were made to this shelter.

Increased ventilation

Albadra et al. (2018; 2017) reported the occupied shelters in the camp (which are identical to the control) developed higher indoor temperatures than that of the external air during the hot season, and occupants cutting additional openings in their shelters to improve ventilation. Therefore, this variant focuses on increased ventilation. A new window facing the original one was included to allow cross-ventilation (the original design has the main window and door on the same wall). The original vents in the gable ends were sealed and replaced by 100 mm ⌀ rotating roof cowls and 4 new 100 mm ⌀ low-level vents were installed to promote stack ventilation (fig. 4.4(c)).

Thermal mass by cavity fill

The thermal performance of the original thermally lightweight design is bounded by the current outdoor conditions, heating up and cooling down quickly. Given the large daily temperature swing characteristic of this climate (fig. 4.2(a)), this measure focuses on increasing the thermal mass.

This was achieved by filling the wall cavity (60 mm main walls, 30 mm gable ends, fig. 4.4(d)). There is a horizontal steel member that runs around the shelter. It was necessary to cut a horizontal slot 75 mm below this horizontal member in the internal cladding to allow the sand/gravel mix to be inserted. Cutting the slot necessitated the introduction of a horizontal timber batten (100 mm × 25 mm) to maintain the integrity of the cladding sheets and to prevent bulging. The timber batten was secured using 10 mm thru-bolts at 600 mm c/c. The sand/gravel mix was placed in a labour-intensive process using a small metal chute fabricated form a cladding off cut. Once filled to the top of the sheet, 3 layers of 15 mm insulation were inserted between the top of the thermal mass infill and the underside of the metal transom. The process was then repeated to just below the eaves' structural member. No thermal mass was added to the gable end above eaves level. Although this prototyped solution does not include sand-proof seals, minimal sand loss was reported at the end of the experiment.

Increased insulation and removal of thermal bridges

The envelope of this shelter was retrofitted with an additional layer of the same 15 mm insulation (fig. 4.4(e)). This necessitated removing and re-fixing the wall cladding sheets. The insulation was fixed to the structure using PVC spacers cut from off cuts of 20 mm ⌀ water pipe to prevent compressing the insulation where it meets the metal frame (not employed in the original T-Shelter design but since adopted as the preferred construction method). The butt joints were staggered and taped. Holes in the IBR panels were sealed with duct tape and gaps were filled with insulation foam.

Roof shade

This variant uses a roof shade to minimise solar-related heat gains through the roof (fig. 4.4(f)). In addition, the roof shade overhung the existing walls by an additional 400 mm to provide shading to the south-facing window and to reduce solar gains through the walls. The roof shade was formed with 150 mm metal angle (30 mm × 30 mm) frames at 1000 mm c/c, an air path from eaves to ridge, with air exiting via a raised ridge cap (fig. 4.4(f)).

Thermal mass with internal sandbags

Following the rationale presented for the cavity fill case, this one has an inner wall cladding of sandbags to benefit from even greater thermal mass (Fosas et al. 2018a) (fig. 4.4(g)). The sandbags measured 600 mm long × 250 mm wide × 150 mm high. In order to save time these were filled off-site and delivered ready for use. The sandbags were bought in long strips, cut down to length and a ribbon was sewn on for tying up the bag. At 600 mm long, each sandbag weighs 45 kg. The sandbags were compacted using a heavy club hammer, angle straps were fitted to the shelter steel frame and a barbed wire was laid around the perimeter every fifth row. The height of the sandbags was taken to eaves height and up to 1.25 m on the external side of the kitchen wall.

XPS insulation and roof shade

This prototype provides higher insulation levels by replacing the original insulation with 40 mm extruded polystyrene (XPS, fig. 4.4(h)). The installation process necessitated removal of the outer cladding and the existing insulation sheet. The new interlocking insulation was then fitted, and the wall and roof cladding fixed over. To avoid exacerbating indoor overheating a roof shade was fitted as in the roof shade case but with a 300 mm gap and no ridge ventilation.

4.5.2 Experimental conditions and data collection

Monitoring started after the completion of the construction work, from the 17th of August until the 7th of October 2018, and access to the fenced compound was controlled by security guards. During the first month every shelter remained closed except for the window of the kitchen extension, which was propped open as well as the four vents of the main space. This allowed a baseline to be obtained for the performance of the shelters. From the 17th of September onwards, a designated person visited the experiment twice a day to operate each shelter. Windows were opened from 09:00 until 21:00 in every shelter except those aimed at increasing thermal mass. For the latter, windows were opened from 21:00 until 09:00 to benefit from the colder night-time temperatures. Doors remained closed outside inspection times.

Indoor conditions were recorded at the centre of each shelter with a temperature and relative humidity logger at 1 h intervals (iButton DS1923, temperature accuracy ±0.5 °C, relative humidity ±5 %, response times under 130 s, calibrated by manufacturer in climate chamber). State sensors recorded if the main door and main window were open or closed accordingly to the pre-established ventilation plan. The sensors employed were HOBO UX90-001, which have a pair of magnets to record the times at which the state of the element changes. It must be noted that doors and windows of these shelters are custom-made at the camp from steel angle profiles and have gaps up to 20 mm whilst shut. This made sensor readings unreliable at times.

In the absence of a local weather station, the conditions were reconstructed combining three sources of information:

1. On-site sensors: two independent shielded temperature and relative humidity loggers at 1 h intervals (Tinytag TGP-4500, temperature accuracy under ±0.5 °C, relative humidity ±3 %, response time up to 25 min, IP68, calibrated by manufacturer in climate chamber).

2. NOAA weather stations (USDoC 2019): three weather stations 60 km away triangulate this location (USAF numbers 402 600, 402 700, 403 600). Although complete hourly weather records were not available, those for dry-bulb temperature were.

3. MERRA-2 (Gelaro et al. 2017) and CAMS (Schroedter-Homscheidt et al. 2017): MERRA-2 is a reanalysis dataset that contains all the main variables used to reconstruct full weather observations for building simulation except for infrared radiation, cloud cover and the direct/diffuse solar radiation split. This can be combined with the satellite observations from CAMS that provide full solar radiation records and cloud cover during daytime (Fosas et al. 2018b).

Given the successful results obtained for weather files based on MERRA-2 and CAMS datasets for this location[2], a weather file was produced based on them. Cross-comparisons with on-site and NOAA data show that up until the 30th of September the agreement for dry-bulb temperature is about ±1 °C between the three sources, but MERRA-2 data presents inconsistencies compared to the other two sources from the 30th of September until the 7th of October. Data was taken from the on-site sensors for dry-bulb temperature and relative humidity for this period, recalculating the dew-point for physical consistency of observations.

4.5.3 Thermal simulation models

This study relies on careful management of simulation models to maintain synchronized shared model parameters across shelter variants while controlling those that make each one unique. A custom workflow is implemented to programmatically define models and to simulate, collect and analyse results. Every simulation is based on a template that is later parameterized according to the tasks at hand. The following details the overall modelling approach and consecutive sections describe the input parameters for each model.

The interest of the study is in the as-built thermal performance of the prototypes at design stage. The information regarding geometry, final operation and real weather is considered known for the model. The premise is that both the models and the built prototypes respect the main features of the design intent (e.g. four ventilation vents are in place and opened) but not aspects that are unknown at design stage (e.g. infiltration levels or real weather conditions during the monitoring period). This way, potential performance gaps will be more likely due to the definition of the model and suitability of the simulation approach than to the well-known ones due to weather variability and user behaviour. Therefore, the information for the model template comes primarily from design specifications (UNHCR 2016) and internal communications with UNHCR Jordan (interview with camp authorities about the construction sequence, the materials used and updates to the design information).

The simulation models are created for EnergyPlus v9.0.1 (NREL 2018) and simulated at 10-minute time-steps. The shelter is defined in a single zone that describes the main space. The kitchen unit is considered as self-shading because it is enclosed by a single layer of uninsulated IBR panels with windows propped open for the experiment. The heat balance algorithm chosen is the Conduction Transfer Function and the surface convection model is adapted according to the most suitable one relevant to the conditions developed at each timestep. Heat transfer with the ground is particularly important in these shelters and they are accounted for through the Kiva, a calculation tool that

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[2] The reasons for the good agreement are that Azraq is in the middle of a geographically homogeneous area that is flat, far from large bodies of water and with a high frequency of clear sky days (Fosas et al. 2018b).

couples the ground and shelter domains using an accurate 2D approximation of the 3D heat transfers (Kruis and Krarti 2017). The influence of surrounding shelter units in this regard is accounted for by setting the far-field width to 1.2 m, half the minimum distance between consecutive shelters. The only thermal mass available to the control shelter is that of the concrete slab.

Natural ventilation is modelled with an airflow network that accounts for stack and wind-driven air exchanges. The casement window is modelled using the real openable area, accounting for frames and anti-burglar bars. This reduced the 0.90 m^2 opening in the wall to a free area 0.52 m^2 (implemented as a change in window width). The two 152 mm diameter vents at each gable-end walls are modelled as the hydraulic equivalent rectangle of 139 mm × 278 mm according to Huebscher (Huebscher 1948). The influence of surrounding shelter units on wind-driven ventilation is accounted for through wind pressure coefficients defined for each element as described next. Infiltration is included in the airflow network as cracks in the building envelope. Given that air permeability of individual elements is unknown, a notional infiltration level is defined for the entire shelter and split between envelope components according to their relative area.

Control shelter: uncertainties, and blind and calibrated models

The data available at design stage includes unknowns that require further considerations. These are either missing information from the specification, boundary conditions of the model or aspects judged to be particularly sensitive to the construction process. The parameters are also selected according to the heat transfer mechanism and the perceived potential impact on the model.

Thermal properties of elements: The thermal resistance of the 60 mm air cavity of the walls (30 mm in the gable-ends) mainly depends on the effective emittance and the convection that develops between the insulation and the IBR panel. Potential values for the resistance are between 0.15 $\mathrm{m^2\,K\,W^{-1}}$ and 0.39 $\mathrm{m^2\,K\,W^{-1}}$ for cases of these dimensions with low and high effective emittance, respectively (ASHRAE 2017). The conductivity of the foam insulation is not specified, and it is estimated to vary between 0.04 $\mathrm{W\,m^{-1}\,K^{-1}}$ and 0.5 $\mathrm{W\,m^{-1}\,K^{-1}}$. As the insulation layer is simply laid over the metal frame before cladding thermal breaks are likely to occur at structural elements and the foam might be severely compressed where the cladding is bolted to the frame. In addition to changes in conductivity, the average insulation thickness is considered to vary from 5 mm to 15 mm.

Ground thermal properties: The ground temperature underneath the concrete slab affects the internal temperature of the space. Considering that boundary conditions are well-defined through the weather file and that the indoor thermal simulation is coupled to that of the ground, the unknown variable is the effective thermal diffusivity of the ground. This is split between the conductivity and specific heat capacity of the soil for an assumed density of 1300 kg m^{-3}. Parameter ranges are described in table 4.3, based on soil properties ranging from loose sand to sandstones (CIBSE 2017b; Van Wijk and De Vries 1963).

Ventilation and infiltration: Wind pressure coefficients moderate the effective windspeed for natural ventilation according to the characteristics of the building, its surroundings and the relative angle between every surface and wind direction. Two suitable databases for the characteristics of the shelter and the pattern of surrounding units were identified, that of Swami and Chandra (1987) and that of Liddament (1996). Similarly, discharge coefficients approximate the relationship between the real and the theoretical mass flow rate through openings. Here, it is assumed to vary between the typical value of 0.60 up to 0.90 (ASHRAE 2017). The infiltration level is particularly difficult to define at design stage because no limit is enforced during construction. Likely bounds are established roughly between 0.5 ach h^{-1} and 2.5 ach h^{-1} according to the two calculation methods, component and whole-building, described by Orme et al. (1998). However, these describe annual averages. The overall leakage flow that causes these air changes for this case was found iteratively through simulations with window and vents shut. The total leakage mass flows were 0.05 kg s^{-1} and 0.40 kg s^{-1}, respectively (reference air conditions: 20 °C, 101 325 Pa, 0.014 761 humidity ratio).

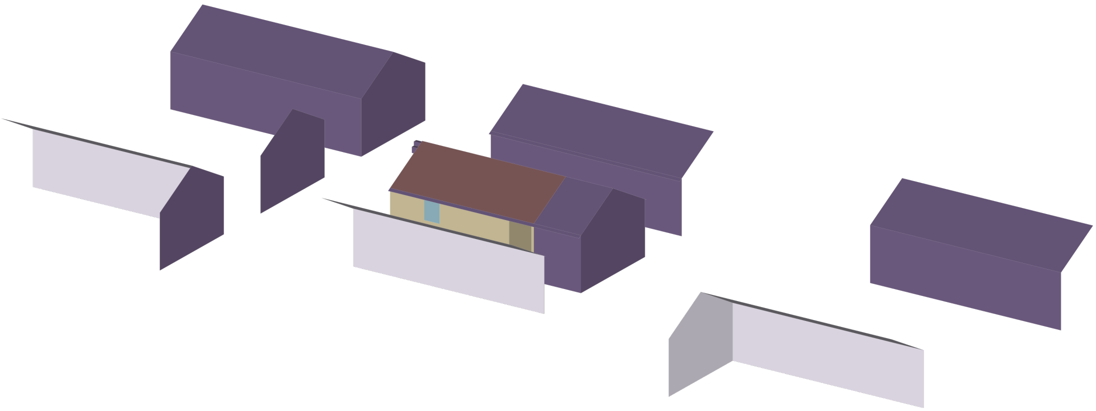


Figure 4.5: Simulation model template overview (bounding box for thermal zone: 6.1 m × 4.1 m × 3.3 m; 28° double-pitched roof; North and active shading surfaces vary according to the case as per fig. 4.3; optional roof shades not displayed)

Table 4.3: Uncertain parameters for the control shelter ($\mathcal{U}$ denotes the random uniform distribution: () continuous and {} discrete)

Parameter	**Units**	**Blind models**		**Pool for calibrated model**
		Deterministic	**Bounded**	($X \sim$)
Resistance cavity	$\mathrm{m^2\,K\,W^{-1}}$	0.15	$\{0.15, 0.39\}$	$\mathcal{U}(0.15, 0.39)$
Insulation conductivity	$\mathrm{W\,m^{-1}\,K^{-1}}$	0.04	$\{0.04, 0.5\}$	$\mathcal{U}(0.04, 0.5)$
Insulation thickness	m	0.015	$\{0.005, 0.015\}$	$\mathcal{U}(0.005, 0.015)$
Soil conductivity	$\mathrm{W\,m^{-1}\,K^{-1}}$	0.4	$\{0.4, 2.3\}$	$\mathcal{U}(0.4, 2.3)$
Soil specific heat capacity	$\mathrm{J\,kg^{-1}\,K^{-1}}$	1500	$\{400, 1500\}$	$\mathcal{U}(400, 1500)$
Total air leakage[a]	$\mathrm{kg\,s^{-1}}$	0.05	$\{0.05, 0.4\}$	$\mathcal{U}(0.05, 0.4)$
Wind pressure coefficients[b]	—	Swami	$\{\mathrm{Swami}, \mathrm{Liddament}\}$	$\mathcal{U}\{\mathrm{Swami}, \mathrm{Liddament}\}$
Discharge coefficient	—	0.6	$\{0.6, 0.9\}$	$\mathcal{U}(0.6, 0.9)$

[a] Reference air conditions: 20 °C, 101 325 Pa, 0.014 761 humidity ratio.

[b] Implemented as a choice between the two databases for the geometries and angles under consideration.

The blind models for Stage 1 are presented in two variants: *deterministic* and *bounded*. In the deterministic variant, it is assumed that the modeller made an informed decision about the values of the uncertain parameters to create a single model. The bounded version, on the other hand, assumes the modeller would perform a naïve parametric analysis with the high and low estimates for each parameter, resulting in 256 different models (2^8).

The calibrated model for Stage 2 represents a different approach to the problem. Here, it is assumed that a prototype of the shelter has been built and monitored. A formal calibration process can take place so that the thermal modeller can learn from the reality behind the model to maximise the agreement between predictions and observations. The process is as follows:

1. Predicted variable: Dry-bulb temperature. This is the main driver for thermal comfort and overheating studies, especially in this dry location. For control purposes the calibration also considers relative humidity.

2. Datasets: The observations are split into two datasets. The first 70 % of datapoints, from 17th August until 21st September, constitutes the calibration dataset to find the best estimates for the uncertain parameters. The remaining 30 % constitute the validation dataset and are used to appraise the goodness of fit of the model using data unseen by the calibration algorithm.

3. Initial samples: The variability of the parameters is assumed to be captured by a random uniform distribution within the bounds or choices identified for the blind models (table 4.3). A Latin Hypercube (LH) is created to sample values efficiently. In particular, a maximum projection design to build the LH is used because it guarantees adequate space-filling properties across all its subspaces (Joseph et al. 2015; Ba and Joseph 2018). This is desirable since it is unknown beforehand if every parameter is influential in the calibration. A pool with a number of samples 10 times the number of parameters involved is built using this method to feed the calibration algorithm.

4. Calibration: The model is calibrated through Calibro, a program by Monari and Strachan (2017). Their algorithm is agnostic to the building simulation engine and performs principal component analysis, sensitivity analysis and builds a black-box model that allows finding which parameters from those in Table 4.3 are influential and what their best estimates are.

5. Calibrated model: The calibrated model is created with the best estimates of influential parameters identified in the previous step.

6. Validation: The validation dataset is used to judge whether the prediction performance of the calibrated model outperforms those of the blind models.

Design alternatives

The six design alternatives share the same template and modelling techniques as those of the control shelter except for the reported changes (table 4.4) and geometric and shading conditions (fig. 4.5) according to their location in the compound (fig. 4.3). Two types of models are built per design alternative, one based on the blind models (Stage 1) and another based on the best parameter estimates of the calibration (Stage 2).

Table 4.4: Model differences between design alternatives and control shelter

Model	**Differences**
Increased ventilation	A new window opposite the current one is added to the model with the same characteristics. Four new vents with the same hydraulic characteristics are added at low level. Given the limitations of the airflow network to model rotating roof cowls these are modelled like the original vents in the control shelter since the main expected driver for background ventilation is infiltration and the stack effect.
Thermal mass by cavity fill	The 60 mm cavity in the walls (30 mm in the gable ends) is filled up to eaves level with dry sand (conductivity $0.6\,\mathrm{W\,m^{-1}\,K^{-1}}$). The window opens from 21:00 until 09:00 from the 17th of September onwards.
Increased insulation	Insulation thickness is doubled and includes the doors.
Roof shade	A simple roof shade is implemented by adding external shading surfaces. No other adjustments are made to the airflow in the baffle zone nor to its heat balance model.
Thermal mass by internal sandbags	An internal layer of 250 mm sandbags with the same characteristics as the cavity fill is added up to eaves level of every wall. The kitchen wall has sandbags on the external side and up to 1.25 m. The new roof cowls are implemented like in the ‘increased ventilation’ case. The window opens from 21:00 until 09:00 from the 17th of September onwards.
XPS insulation and roof shade	The structure is covered with 40 mm XPS insulation panels (conductivity $0.035\,\mathrm{W\,m^{-1}\,K^{-1}}$) instead of the original foam insulation. A roof shade is implemented in the same way as the previous case.

Prototyping in a country with a different climate

Similar to the research compound established in Azraq, the authors have a facility in South West England (UK, warm temperate, fully humid, warm summer climate (Cfb) according to the Köppen–Geiger climate classification (Kottek et al. 2006)). Lacking a prototype of the Azraq transitional shelter in the UK, the inter-agreement between the performance of simulation models presented above in these two climates is measured.

This option is only reliable if the results obtained for the simulation models indicate good agreement against monitored data. The temperate climate of the UK is considered as an example of a very different type of weather to the hot arid one of Azraq in Jordan. If the overall inter-agreement between rankings is indeed maintained in this situation, it could be speculated that it could be also the case for those climates that fall within these two.

4.5.4 Analysis

Unless there is an exact match between the simulated thermal performance of the prototype and the experimental data, a judgement needs to be made on the adequacy of the results. Yet, there is no agreement as to what constitutes a good-enough simulation model. Three approaches are here considered: qualitative, quantitative and a domain-specific evaluation. As the focus is on the improvement of indoor thermal conditions, only dry-bulb temperature is reported as the main proxy to evaluate thermal indoor environments in this hot dry climate.

The qualitative approach is the visual agreement between experimental observations and simulation in the time series. For example, simulations need to replicate not only the magnitude of the variable (e.g. amplitude and average) but also its hourly trends (e.g. frequency and phase).

The quantitative approach is based on the criteria defined by ASHRAE (2014). In the context of energy, the guideline considers whether a model is calibrated by appraising numerically the goodness of fit between simulated and monitored data. Here, these criteria are applied to dry-bulb air temperature. They are based on a pair of indicators for the variable at hand, one for the overall mean error and another for the goodness of fit at timestep level. These are the Mean Bias Error (MBE) (eq. (4.1)) and the Coefficient of Variation of the Root Mean Squared Error (CV(RMSE)) (eq. (4.2)), respectively,

$$\text{MBE} = \frac{\sum\limits_{i=1}^{N} T_{obs,i} - T_{sim,i}}{\sum\limits_{i=1}^{N} T_{obs,i}} \tag{4.1}$$

$$\text{CV(RMSE)} = \frac{\sqrt{\frac{1}{N}\sum\limits_{i=1}^{N}(T_{obs,i} - T_{sim,i})^2}}{\overline{T_{obs}}} \tag{4.2}$$

where $T_{obs,i}$ denotes the observed temperature at hour i, $T_{sim,i}$ the simulated one, N the total number of timesteps and $\overline{T_{obs}}$ the mean observed temperature. Notice that both indicators are scalar quantities that take observations as the reference, with 0 indicating perfect agreement. ASHRAE criteria considers a model is calibrated if the

MBE is within ±10 % and the CV(RMSE) is within ±30 %. For this experiment, the CV(RMSE) can only be positive since observed averages are positive.

The domain-specific approach is derived from the rationale behind thermal discomfort studies to appraise the frequency and the severity of the deviation from comfortable temperatures. Here, the focus is on air temperature differences binned at 1 K as the fundamental metric upon which proposed overheating criteria rest on (CIBSE 2017b; CIBSE 2013; CIBSE 2017a).

Lastly, there is a need to evaluate if prototyping shelters in a different climate to that where they are going to be used at provide reliable insights of performance. Since the thermal performance is determined by the climate, the rankings of the MBE and CV(RMSE) are compared because these metrics normalize the response against a selected baseline. The rankings obtained for each metric and climate can then be analysed using non-parametric rank correlation analyses after Kendall (Kendall 1938; Knight 1966) and Spearman (Spearman 1904; Kokoska and Zwillinger 2000). These statistics characterize correlation with a coefficient r where $r \in [-1, +1]$. A value of 0 indicates no correlation, +1 positive correlation and −1 negative correlation. The null hypothesis of these tests is that there is no difference between the two rankings ($r = 0$).

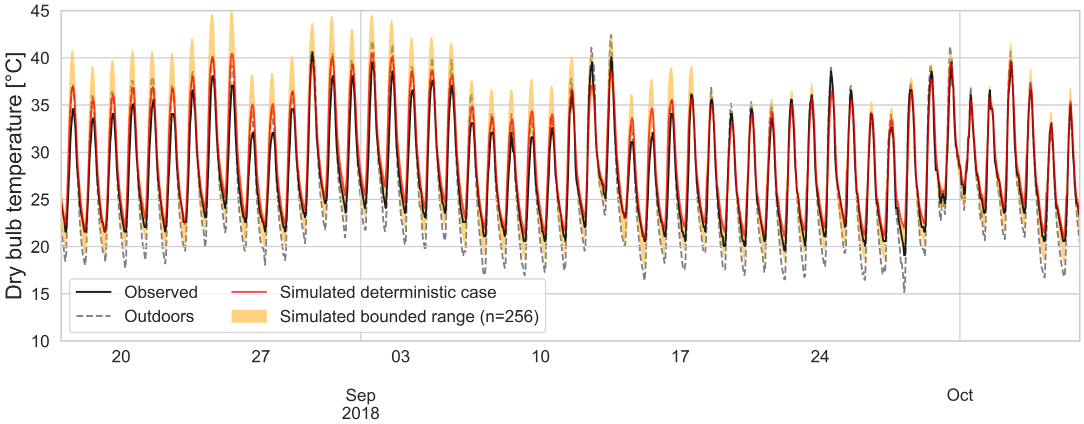
These analyses are carried out in Python (PSF 2019), its scientific ecosystem (Perez and Granger 2007; Kluyver et al. 2016; van der Walt et al. 2011; McKinney 2010; Hunter 2007; Kibirige 2019; Waskom 2018; Roubeyrie and Celles 2018; VanderPlas et al. 2018; Pedregosa et al. 2011; Jones et al. 2001) and R (R Core Team 2019).

4.6 Results

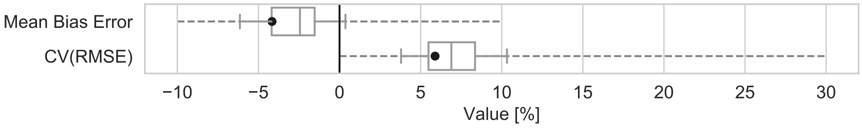
4.6.1 Blind model

The focus is first on the extent to which blind models replicate the performance of the monitored shelter prototype (fig. 4.6). Overall, blind models can replicate the trends of the monitored data in terms of averages, frequency and phase, following closely values recorded outdoors (fig. 4.6(a)). The amplitude depicted by the daily maximum and minimum temperatures show deviations between +5 K and −3 K with regard to the monitored ranges, respectively. These deviations reach their maximum values in the period where openings other than vents remained closed, between the beginning of the experiment (17th of August) and day when the natural ventilation control strategy changed (17th of September). Afterwards, in the period when the window was opened from 09:00 to 21:00, disagreement in simulated maximum and minimum daily temperatures remained under ±3 K. The amplitude of the sample case (deterministic simulation) is below the average of all blind models, which results in a better agreement to experimental temperatures.

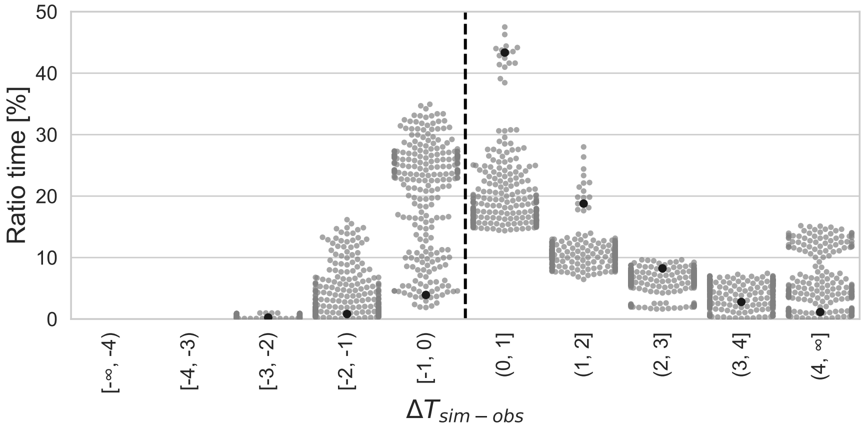
The numerical evaluation of the goodness of fit indicates that every blind model satisfies the criteria of the ASHRAE guideline (fig. 4.6(b)). The overall mean agreement



(a) Simulation results versus monitored data



(b) Goodness of fit according to ASHRAE Guideline 14 (2014) (whiskers span the minimum and maximum value; dot represents the *deterministic* case; dashed lines represent acceptability range)



(c) Histogram of $\Delta T_{\mathrm{sim-obs}}$ (grey represents all cases in the training pool; black represents the *deterministic* case; dashed line indicates 0; $\Delta T_{\mathrm{sim-obs}} \in [-2.93, +8.93]$)

Figure 4.6: Results Stage 1: Blind models

reported by the MBE is in the ±6 % interval, within the pre-established limits of ±10 % and with some instances having no bias at all. Values of CV(RMSE) are also under the 30 % limit, with minimum values under 4 %. The deterministic case shows a higher bias than most models while it outperforms them when considering hourly deviations from experimental data.

The histogram quantifies how often the mismatch between every blind simulation to the monitored data falls in the predefined bins, neglecting agreements within the ±0.5 K sensor accuracy (fig. 4.6(c)). The overall asymmetry between positive and negative intervals indicates blind simulations tend to be warmer than the monitored data, consistent with the average negative results for MBE. The best-case scenario is outside observed ranges 57 % of the time and the worst 88 %, with most differences taking place in the bins between ±1 K. If mismatches in that interval are neglected, numbers fall to 13 % and 43 %, respectively. Differences can be greater than +4 K up to 15 % of the time.

4.6.2 Calibrated model

The LHS-based simulations capture the variability in internal temperatures to a resolution better than 1 K using only 30 % of the number of simulations of the parametric approach (fig. 4.7(a)). The calibration process selected six parameters out of the eight as relevant to improve the goodness of fit to the observations, with total air leakage as the most influential parameter (table 4.5). The calibrated simulation outperforms the random ones by the LHS in both the training and validation periods (from the 22nd of September onwards, 30 % of the data), showing a performance that is not necessarily bounded by the ranges obtained by the Latin Hypercube Sampling (LHS). The numerical evaluation shows a similar quantification to the one obtained previously, albeit with a 2 % narrower range (fig. 4.7(b)). Here, the calibration process optimizes both the MBE and the CV(RMSE) which score values under 1 % and 4 % for both indicators[3], respectively. This means that the calibrated case is, on average, within 0.4 K of the observed data. The overall effect of the calibration is to centre the distribution of temperature differences around 0 K while decreasing deviations greater than 3 K at the same time (fig. 4.7(c)).

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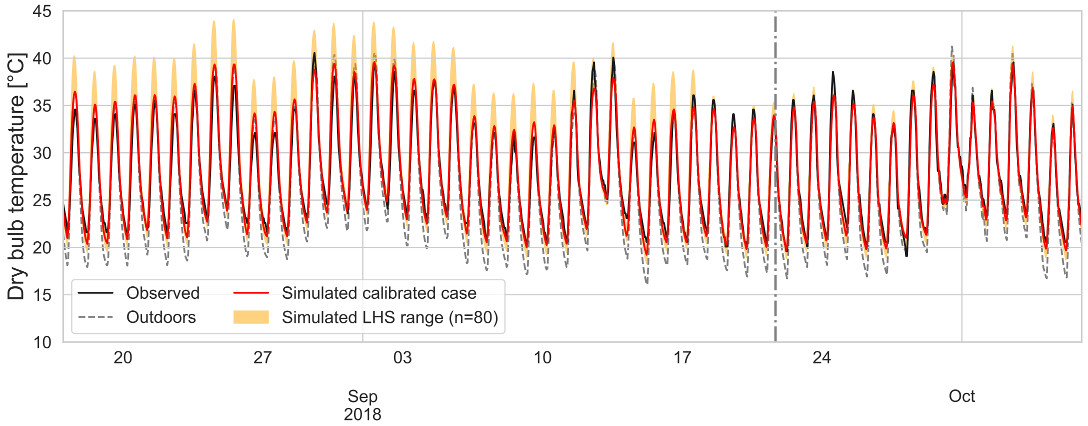
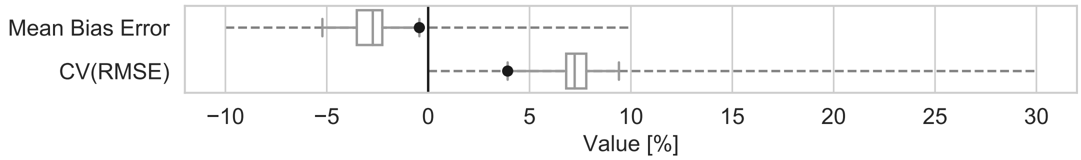
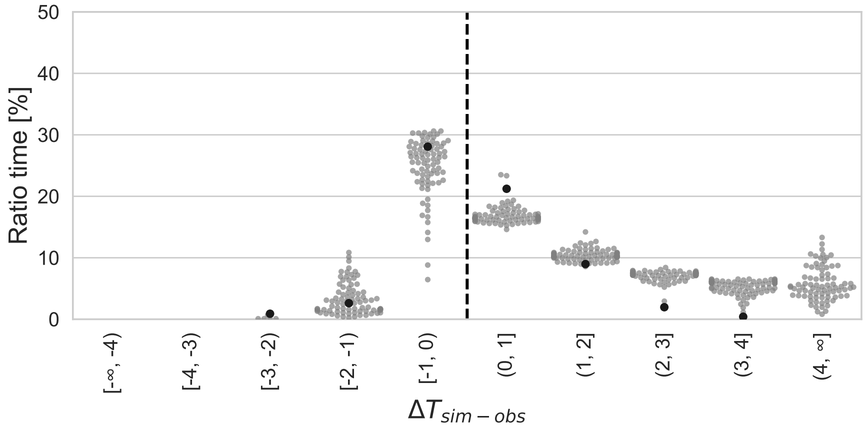
[3] These values are representative of the performance of the calibrated simulation for both the validation and the complete period of the experiment. The shelter remained completely closed except for the vents until the 17th of September, causing a wider variability in the performance of the simulations. This causes metrics for the validation period to outperform those of the training — and hence those of the complete period as well. Here, it was opted to report the maximum absolute values.



(a) Simulation results versus monitored data (vertical line separates training data for the calibration on the left to the one for validation on the right)



(b) Goodness of fit according to ASHRAE Guideline 14 (2014) (whiskers span the minimum and maximum values; dots represent the *calibrated* case; dashed lines represent acceptability range)



(c) Histogram of $\Delta T_{\mathrm{sim-obs}}$ (grey represents all cases in the training pool; black represents the *calibrated* case; dashed line indicates 0; $\Delta T_{\mathrm{sim-obs}} \in [-2.59, +8.13]$)

Figure 4.7: Results Stage 2: Calibrated models

Table 4.5: Results Stage 2: Summary of calibrated parameters ($\mathcal{U}$ denotes the random uniform distribution: () continuous and {} discrete; — indicates a non-influential parameter in the calibration)

Parameter	**Units**	**Estimated uncertainty**	**Sensitivity ranking**	**Parameter estimates**
Total air leakage[a]	$\mathrm{kg\,s^{-1}}$	$\mathcal{U}(0.05, 0.4)$	1	0.3666
Insulation conductivity	$\mathrm{W\,m^{-1}\,K^{-1}}$	$\mathcal{U}(0.04, 0.5)$	2	0.0432
Soil conductivity	$\mathrm{W\,m^{-1}\,K^{-1}}$	$\mathcal{U}(0.4, 2.3)$	3	2.1512
Resistance cavity	$\mathrm{m^2\,K\,W^{-1}}$	$\mathcal{U}(0.15, 0.39)$	4	0.3628
Insulation thickness	m	$\mathcal{U}(0.005, 0.015)$	4	—
Wind pressure coefficients[b]	—	$\mathcal{U}\{\mathrm{Swami}, \mathrm{Liddament}\}$	4	—
Soil specific heat capacity	$\mathrm{J\,kg^{-1}\,K^{-1}}$	$\mathcal{U}(400, 1500)$	5	1480.52
Discharge coefficient	—	$\mathcal{U}(0.6, 0.9)$	6	0.6303

[a] Reference air conditions: 20 °C, 101 325 Pa, 0.014 761 humidity ratio.

[b] Implemented as a choice between the two databases for the geometries and angles under consideration.

4.6.3 Design alternatives

The overview of the average temperatures developed in shelter alternatives show their effectiveness in mitigating overheating (fig. 4.8). In general, simulations capture the observed results in every case except those with increased thermal mass. In the latter, experimental results show lower temperatures than in any of the simulations, and markedly so in the case of the sandbags variant. Considering that the measurement error for air temperature is ±0.5 K, the cases that significantly reduce peak temperatures are: increased thermal mass with sandbags (3.98 K), increased thermal mass by cavity fill (2.27 K), roof shade (1.34 K), increased insulation (1.23 K) and XPS insulation with roof shade (0.95 K).

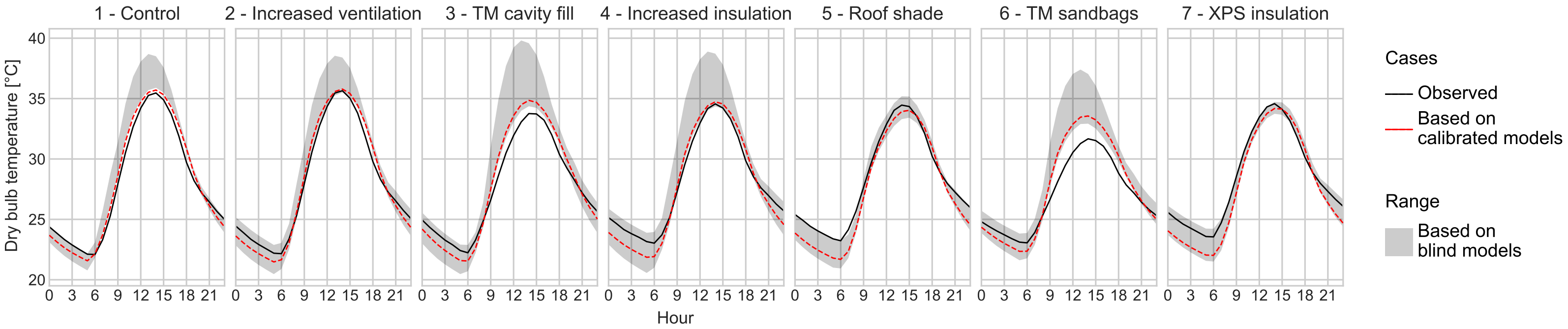
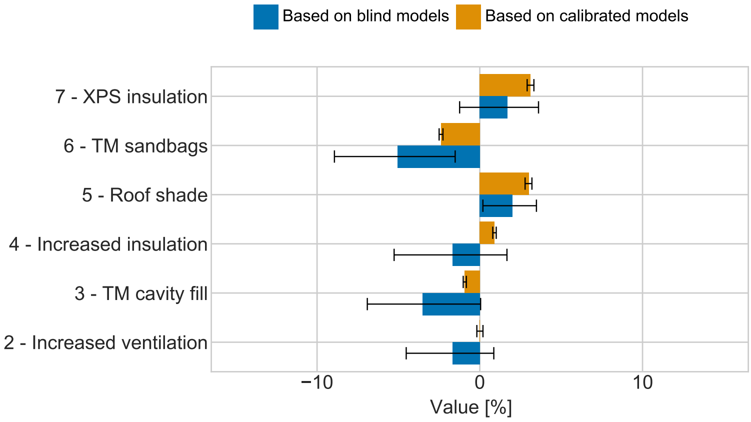
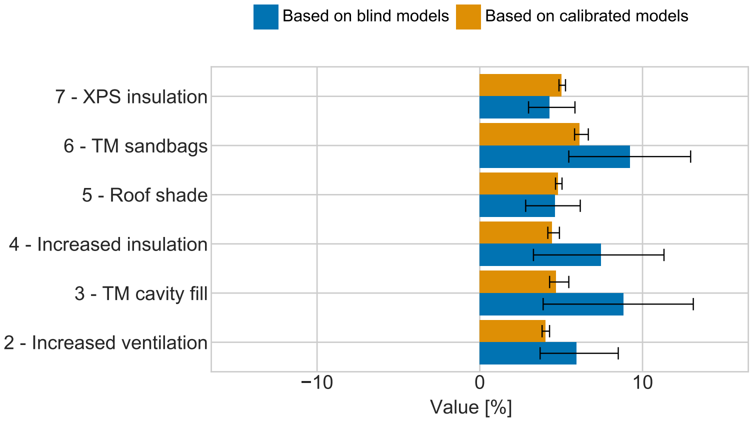


Figure 4.8: Results Stage 3: Design alternatives – Overview of temperatures (hourly averages)

The results for the goodness of fit are grouped into two according to their base model (fig. 4.9). The first group displays the performance of simulations based on the blind models for the control case, whereas the second is based on the best parameter estimates obtained through the calibration process of that same case. Every case displays an improved range for goodness of fit metrics when simulations are based on calibrated models. The average MBE across all the blind simulations for each prototype decrease from 2.7 % to 1.7 %, and CV(RMSE) are reduced from 6.7 % to 4.8 %.



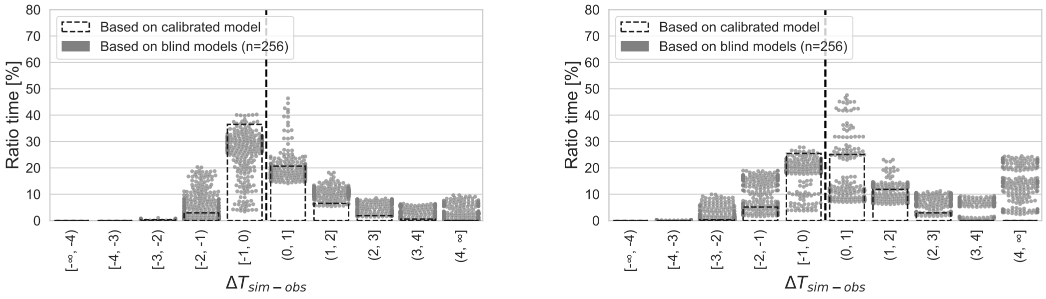
(a) Mean Bias Error
(acceptability criteria within ±10 %)



(b) CV(RMSE)
(acceptability criteria within ±30 %)

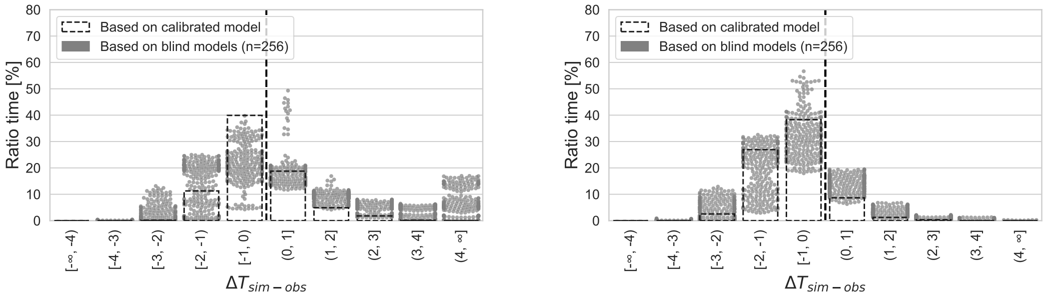
Figure 4.9: Results Stage 3: Design alternatives – Goodness of fit (acceptability criteria by ASHRAE Guideline 14 (2014))

The general improvements in the goodness of fit are further quantified in the classification of temperature differences (fig. 4.10). The effect of the calibration in all circumstances is to centre the distribution of values next to 0 K differences and penalize large deviations.



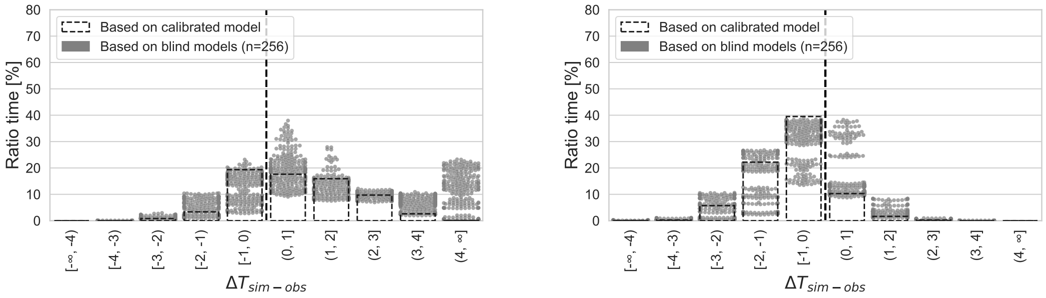
(a) Increased ventilation
$\Delta T_{\mathrm{sim-obs}} \in [-2.75, +8.31]$

(b) Thermal mass by cavity fill
$\Delta T_{\mathrm{sim-obs}} \in [-3.14, +9.72]$



(c) Increased insulation
$\Delta T_{\mathrm{sim-obs}} \in [-3.55, +10.42]$

(d) Roof shade
$\Delta T_{\mathrm{sim-obs}} \in [-3.72, +4.13]$



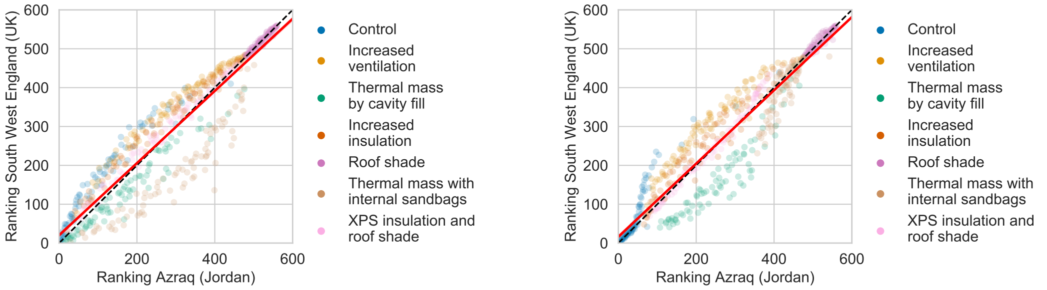
(e) Thermal mass with internal sandbags
$\Delta T_{\mathrm{sim-obs}} \in [-3.07, +9.30]$

(f) XPS insulation and roof shade
$\Delta T_{\mathrm{sim-obs}} \in [-4.69, +3.09]$

Figure 4.10: Results Stage 3: Design alternatives – Histograms $\Delta T_{sim-obs}$

4.6.4 Prototyping shelters in countries with different climates

There is a positive rank correlation of goodness of fit metrics between models simulated in the intended climate of use (Azraq, Jordan) and the hypothesised location for off-site prototyping (South West England, UK; fig. 4.11). There is a strong correlation for MBE under Kendall's rank correlation coefficient ($r = 0.79$, p-value $\ll 10^{-5}$) and Spearman's ($r_s = 0.93$, p-value $\ll 10^{-5}$), similarly to those for the CV(RMSE) ($r = 0.81$, p-value $\ll 10^{-5}$; $r_s = 0.94$, p-value $\ll 10^{-5}$). Therefore, these results suggest rejecting the null hypothesis of no correlation in every case and rank correlation metric.



(a) Mean Bias Error (b) CV(RMSE)

Figure 4.11: Results Stage 4: Ranking of goodness-of-fit metrics of models in different locations by shelter prototype (sample size: 560 cases; dashed line: reference for perfect agreement, continuous line: fitted agreement)

4.7 Discussion

Results show that building thermal simulation can predict indoor temperatures in the shelters if modelling uncertainties are accounted for. This is illustrated by the difference between the deterministic and bounded (i.e. including uncertainties) approaches when modelling the control shelter. However, the merits of the simulation cannot be determined from the performance obtained when using purge ventilation because, in such circumstances, the indoor temperatures of these single-zone light-weight shelters rapidly approach that of the external environment (fig. 4.6(a)). This would only test the ability of the weather file to replicate experimental conditions, which is what is observed in the period between the 17th of September until the 7th of October for the control case. On the contrary, the advantages of modelling are illustrated in the previous period, when shelters remained closed. Educated guesses on which parameters should be considered unknown and the likely bounds of their values prove key in capturing the real behaviour of the shelter (fig. 4.7(a)). This is because, although eight parameters represent but a small fraction of those defined in a high-fidelity building simulation model, the responses obtained are bounded to a 5 K band. The quantification of the goodness of fit through the MBE and the CV(RMSE) indicators suggest an overall good agreement, which corroborates that simulations capture the dynamics of the physics involved.

Whether such agreements are meaningful for studies on overheating needs further discussion. In fact, the goodness of fit evaluation contrasts with the differences between modelled and monitored indoor temperatures depicted in the histogram. As a reference, note that the failure standard in current overheating criteria starts at excursions of just 1 K over acceptable temperatures for either 1 % annual occupied hours or 3 % of hours during the hot season; or a 4 K excursion at any time (CIBSE 2017b; CIBSE 2013; CIBSE 2017a). Indoor temperatures in the blind models exceed observed temperatures by more than 1 K between 30 % and 80 % and 4 K differences between 0 % and 15 % during the 50 d experiment, rendering overheating predictions useless for compliance purposes. The only application of these simulations for overheating studies is *a posteriori*, once it is known that no overheating will take place in reality if none is shown in the simulation. Desirable scores in goodness of fit metrics are a necessary but not sufficient condition.

As a result, model calibration is key to faithfully portraying the thermal performance of a shelter. The process rigorously characterizes the sensitivity of the model to input parameters and, while the MBE and the CV(RMSE) metrics show a modest improvement in prediction performance, the histogram captures clear qualitative improvements over the blind models. Absolute temperature differences greater than 3 K are eradicated and remaining differences greater than 1 K are reduced from 80 % to approximately 15 %. Yet, these improvements might be still insufficient to reliably assess compliance with overheating criteria.

The best parameter estimates further support the case for prototyping and calibrating simulations (table 4.5). The reason for this is exemplified in the sensitivity analysis which suggests that total air leakage is the most important parameter, as it is one that can only be known *after* building a shelter. Indeed, the fitted value is close to the pre-established upper bound, whereas conventional wisdom might have suggested the middle of the interval. Next in rank is the conductivity of the shelter envelope, namely insulation, air cavity and soil. The results for wind pressure and discharge coefficients highlight the importance of considering obstructions in natural ventilation, even in this low-rise scenario, because the optimal discharge coefficient is still close to the lower bound of 0.60.

The role of all these values are of limited practical importance for this case study when appraising overheating in free-running conditions because this only demonstrates that unoccupied shelters properly operated will not exacerbate indoor temperatures in the hot season. Yet, they still give useful parameter estimates to predict thermal conditions in the cold season, an equally important time of the year in this climate. For example, infiltration levels, insulation and soil conductivities are key parameters for the heat loss of the shelter, and directly proportional to the heating energy demand in the cold season.

A more critical finding is the identification of the key problem in the as-built performance of the control prototype: the need to consider designs that actively mitigate overheating. This directly addresses what problem needs solving. The fact that this is a conclusion attainable even through the relatively coarse process of blind simulations attests to both the scale of the problem and the utility of modelling. The extent to which proposals are of practical value is yet to be determined through an experiment that accounts for internal heat gains, an aspect that could not be included given the lack of power supply at the time the study was conducted. Given the dynamics of free running buildings, it could be hypothesised that monitoring these single-zone buildings is only required for a short period of time if the different heat transfer mechanisms are adequately stressed to facilitate the measurement of the building properties involved. For example, envelope characteristics are best established with openings shut so that conduction and radiation drive the heat exchange, which facilitates measuring airtightness as well. Opening the envelope facilitates measurements of natural ventilation or thermal inertia could be characterized by intermittent internal heat gains.

Overall, simulation models for design alternatives do benefit from the calibration of the control. The histogram shows that every case benefitted from calibrated estimates in the same way as the control shelter. Only the cases with increased thermal mass do not completely capture the variability in the response. Here, the minimum peak temperature in the simulation is still above that observed by up to 1.25 K. This is attributable to the assumed thermal conductivity of the sand, which is known to vary ten-fold according to water content and voids ratio (Haigh 2012). Further consideration of uncertainties in new parameters of design alternatives would have captured the observed range completely[4]. Nevertheless, the effectiveness of thermal mass in reducing peak temperatures is clearly quantified. These findings are noteworthy considering that (1) calibrated estimates are fitted for a single shelter prototype; (2) no assumptions were made on the distribution of these parameters when applied to different cases; (3) the process was seamlessly applied to design alternatives whose strategies are closer to those of the control shelter (increased ventilation, increased insulation, roof shade) and those that modify them substantially (increased thermal mass, XPS insulation). No diminishing advantages of calibrating the base model are observed in this study.

Lastly, results also support the possibility of prototyping shelter solution off-site in other countries, even if these have different climates. The correlation coefficients indicate that changes in performance in one climate can be extrapolated to the other, which justifies the possibility of developing shelter prototypes remotely to the crisis. This could be particularly useful to aid agencies with established headquarters in locations far from the areas in need, for example, UNHCR in Geneva. However, it must be noted that the rank correlation, although statistically significant, is not perfect. This is to be expected as different design alternatives exercise different heat and mass transfer mechanisms, all of which are tightly coupled to the climate in these shelters. For example, the categories furthest from the perfect agreement in fig. 4.11 are those dealing with increased ventilation and thermal mass. Since the operation of the shelters in both climates is identical in the simulation, this can be attributed to changes in the temporal signature of external air temperatures and wind speeds. Considering that the warm temperature climate of the UK is very different to the hot arid one of Azraq, it is expected that cases in-between display similar, if not better, correlation coefficients.

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[4] It must also be noted that, in this experiment, design alternatives are implemented retrofitting existing shelters. Although some strategies would have delivered increased airtightness (increased insulation, increased thermal mass by cavity fill), having to disassemble the envelope and re-drill the IBR panels to the structure likely had the opposite effect.

4.8 Conclusions

The thermal performance of shelters is an aspect largely overlooked in their design process, yet emerging evidence indicates that only security and safety are more important to surveyed shelter dwellers (Albadra et al. 2017). This paper investigated if the thermal performance of transitional shelters can be studied and improved through high-fidelity building simulation or if building and monitoring shelter prototypes, either on-site or off-site, is to be preferred. Seven shelters were built in the Azraq refugee camp (Jordan) and their indoor thermal conditions monitored during 50 d in the hot season to compare them to predictions by building simulations. These shelters represent the original design implemented (treated as a prototype) in the 8952 shelters in the camp and six employing passive overheating countermeasures.

The results indicate that:

1. Blind thermal models — those based on design specifications and educated estimates — can only be used to characterize the sensitivity to model parameters and to identify performance limits of design strategies against overheating.

2. Calibrated models could not still be used to reliably predict compliance with recommended overheating criteria either because of the strict limits to overheating duration, but the improvements in indoor air temperature predictions allow a sufficient characterization of the thermal performance.

3. The advantages of calibrating the model are still maintained when comparing the predictions of different design alternatives based on both blind and calibrated models to experimental results.

4. Shelters could be prototyped off-site, even in countries with different climates, since overall relative changes in performance remained constant.

It is therefore concluded that building simulation should be adopted as part of the design process of transitional shelters to give insights of future performance of drafted solutions. Blind simulations can be used to have gross estimates of performance and identify likely limits, but this predicates on expert judgement to identify appropriate value ranges for key model parameters. Results strongly support the case for model calibration to maximise the usefulness of the simulation. Considering the shelter provision process, the study advocates for routinely building and monitoring a transitional shelter prototype during the emergency stage of a crisis. The information collected can then be used to calibrate a model and increase the confidence in predictions not only for the prototype design but also for design variants.

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4.10 Data Access Statement

Data presented in this study are openly available at `https://doi.org/10.15125/BATH-00668` (Fosas et al. 2019).

4.11 Disclosure statement

No potential conflict of interest was reported by the authors.

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4.13 Addendum

This section was not part of the paper, but it has been included to expand and substantiate aspects that could not be directly addressed in the publication due length, complexity and relevance to core objectives.

4.13.1 On training and validation data

To calibrate the model presented in the paper, observed experimental data was divided into two groups, training and validation with a 70 % to 30 % split, respectively. The 70 % to 30 % split is simply a rule of thumb (Hastie et al. 2009) that tries to maximize the opportunity to develop a model that represents the data adequately (minimize underfitting) while minimizing the model error in the training dataset (minimize overfitting). Other fractions are possible, but the fundamental idea is that any given model is only trained, at any given stage, with the same (random) fraction of the data.

It may be considered that for any given dataset, there exists an ideal training/split ratio that balance adequately underfitting and overfitting. However, to find such ideal split one would need, in practice, to train a family of models with different split ratios to find the optimum. This implies that *all* the data would be used to find the optimal average split (average because the selection is random). Thus, the idea of unseen data by the model to validate its performance is gone because the model has been informed by all the available data (an effect known as data leakage). Other arrangements are possible. For instance, it may be also recommended that the data is split in three groups to have a training, testing and validation datasets (e.g. 50 %, 25 % and 25 %, respectively). Here, the testing dataset could be used to explore how to best decide on model hyperparameters to try maximising the performance of the trained model. However, the principle remains the same: there must be a proportion of the data that is unseen by the model to maximize the chances of having an adequate model performance with unseen data.

The study not only splits the data but also considers the first 70 % to train the dataset, rather than other arrangements such as a random selection of samples. The reason is that indoor air temperatures are time ordered, and past observations influence future observations. Regardless of the capabilities of Calibro, it was considered that interpolating between training observations in unoccupied naturally ventilated buildings was an easier task for a model rather than making a longer-term prediction of future performance (extrapolate). Therefore, it was deemed appropriate to select the first 70 for training and the remaining 30 % to validate the performance of the model.

4.13.2 Timeline

The experiment presented in this chapter corresponds to the first monitoring period of an ongoing experiment that has been maintained and has been evolving since August

2018 (see section 4.1). The following details main site visits, activities and considerations regarding the monitoring and characterization of the thermal performance of these shelters, excluding overall maintenance activities and data download, which was done on every occasion.

- **August 2018:** F. Moran and D. Fosas.
    - Main activities. Setup the experiment as described in the manuscript. In addition, 5 other shelters were built but not reported in this study, namely, (1) original shelter with a desert cooler powered by photovoltaic panels, (2) shelter with a ventilated external skin, (3) insulation fitted with spacers, (4) shelter with 4 free-running earth tubes underneath the concrete slab, (5) shelter with 3 earth tubes at 1.5 m with inline fans. The shelter with the ventilated external skin was built with the double skin only on the walls due to a lack of enough material in the workshop. Lastly, a sample of the thermal insulation material of the original shelter was brought to the UK to analyse its thermal conductivity.
    - Other planned activities not conducted:
        - Infiltration test: It was planned to conduct blower-door infiltration tests of the 12 original shelters at the beginning of the experiments, but it was decided to start building the shelters straight away given time constrains.
        - Weather station: The weather station measuring air temperature, relative humidity, wind speed and global horizontal radiation could not be fit. Given the clear skies in this time of the year, it was decided to reconstruct the solar radiation from satellite observations until the following visit.
- **October 2018:** F. Moran and D. Fosas.
    - Main activities:
        - Weather station was installed at the roof the camp's headquarter.
        - It was noted on arrival that earth tube fans were off. The issue was traced to the control system of the PV panel, which was overheating after a few hours. The problem was solved by increasing the ventilation and the shading of the locker storing the equipment.
    - Other planned activities not conducted:
        - Infiltration test: It was again planned to conduct an infiltration test of the 12 shelters using the blower-door. The test was successfully conducted for the first two shelters, (1) the control and (2) the one retrofitted with the desert cooler. Shelters were leakier than expected and could not be pressurised to 50 Pa, as required by the EN ISO

9972:2015 standard (BSI 2015). The high-quality power generator used to conduct the test was then required elsewhere in the camp for the remainder of the visit and the substitute one had a peaky voltage output that would have damaged the equipment. Considering the airtightness of the shelters tested and the impossibility to carry on with the tests, it was decided to carry out an infiltration test through the CO_2 decay method on the next visit.

    * Pyrgeometer: The location is reported to have mainly clear skies during the warm season, but significantly cloudier in the cold one, especially at night. Given that an adaptive control of thermal radiation could be a promising technique in this weather and that infrared radiation is a parameter generally estimated in weather files, it was decided to include a pyrgeometer. However, the logger for the sensors was damaged during transportation and a suitable replacement could not be found on time during the visit.

- **December 2018:** F. Moran and D. Fosas.
  - Main activities.
    * Infiltration test: A CO_2 infiltration test through the decay method was conducted in every shelter. The CO_2 loggers were prepared in the UK and combined CO_2 sensors connected to the Raspberry Pi micro-computers running on individual power banks. This was an affordable alternative to off-the-shelve loggers and allowed live monitoring of the CO_2 concentrations in six shelters at the same time. One logger was installed outdoors to monitor background levels, and the shelters were tested in two groups of six, in consecutive days, with the weather station monitoring windspeed to correct the data afterwards. In the first day the shelters were prepared for the infiltration test. The test began in the following morning, and the CO_2 was released from fire extinguishers until reaching a high concentration, which was then left to decay.
    * Pyrgeometer: The pyrgeometer was finally installed and sample data obtained for the first 24 h. Maintenance instructions were left to help keeping the instrument operational between visits.
  - Other planned activities not conducted:
    * Simplified co-heating test: A simplified co-heating test to estimate roughly heat loss coefficient that had been planned for the cold season was postponed until next year due to these shelters not having access

    to power yet. Power supply to shelters in the camp was being progressively implemented and, understandably, priority was given to occupied shelters.

- **January 2019:** F. Moran.
    - Main activities:
        - ∗ Trombe wall: As part of a collaboration with a project lead by NRC looking into energy efficiency measures for shelters, a Trombe wall was installed in one of the shelters. The shelter was that with active earth tubes given it had the best solar exposure for the Trombe wall and that its building envelope was maintained in original conditions, being representative of retrofit actions.

- **June 2019:** F. Moran.
    - Maintenance visit and set up connection to the power grid.
- **September 2019:** F. Moran.
    - Main activities:
        - ∗ Internal heat gains: Given that shelters are unoccupied, free running and that the research compound has access now access to power, heaters now simulate the internal heat gains from occupants.

- **Next planned visit:** F. Moran and D. Fosas.
    - Simplified co-heating test.
- **Planned decommissioning:** F. Moran and D. Fosas.
    - Discussions not yet finalised.

Results obtained since the second visit are part of ongoing investigations by the HHftD team. These include an analysis of the air stratification inside the shelters, which was not reported in the study presented in this chapter because it was judged unlikely that practitioners would include such an effect in their analyses if they are not even making use of thermal modelling at the moment. Likewise, tests for the conductivity of the insulation sample are yet to be conducted, although in the context of annual building simulation, the building envelope is characterised through surface whose properties need to match the average conditions of the shelter as built. The range of conductivities considered in the experiment varies an order of magnitude, a range that attempts to reflect as-built performance (i.e. the equivalent effect of compressing insulation and gaps between insulation sheets).

Considering the evolution of the experiment and some of the difficulties in carrying out work on-site, it would have been highly desirable to have a shelter replica in the UK. Indeed, the HHftD project makes active use of the Building Research Park by the University of Bath at Swindon to build and test shelter prototypes. However, the project prioritised studying at this facility shelters that could not be accessed to otherwise. A further reason is that the retrofit strategies included in the study do not respond exclusively to the aims of drastic improvements of their thermal performance, but rather the combined interests of all the institutions involved. From an improved thermal performance point of view, it would have been desirable to inform every retrofit strategy with a full sensitivity analysis to identify the most promising ones rather than the simplified version based on main effects presented in (fig. 3.8). In the experiment as implemented, this was the case for the evaporative cooler and cases with improved thermal mass.

4.14 Postscript

This study evaluated the importance of thermal modelling and prototyping in the design of transitional shelters. Following a 4-stage process, blind and calibrated simulations were compared to the observed performance of prototypes and design variants. In addition, it evaluated whether the advantages of prototyping were likely to be maintained if the process was conducted in a different climate. These evaluations addressed the objectives in Research Question 3, which deal with the suitability of building simulation to predict as-built overheating. It must be stressed that these predictions are in the absence of uncertainties due to weather and occupant behaviour in order to identify intrinsic shortcomings of the approach.

The findings are that high-fidelity building performance simulation can predict indoor temperatures. However, in this simple context comprised of a single, relatively well-known thermal zone, model variants to bound the temperature had frequent temperature differences of 4 K, primarily in daily peak temperature. Even if expert judgement can bound the problem, there is significant uncertainty in the results. Calibration improves prediction substantially for both the original case and appraised design alternatives. It must be stressed that, even though ASHRAE's Guideline 14 is often quoted as a general reference to judge the success of calibration, its usefulness to judge goodness-of-fit of indoor air temperatures is limited because the range of this variable is physically constrained. Even ANSI/ASHRAE (2017a) recognises that "[t]here are no formal criteria for when results agree or disagree (…) [this] is left to the organization referencing the method of test or to other users who may be running the tests for their own quality assurance purposes" (2017a, p. 19). Thus, reporting and evaluation of the goodness-of-fit followed here the wider recommendations in Standard 140-2017 of appraising the magnitude of results, magnitude of the difference and direction of the mismatch.

The implications of these results with regard to the aim of the thesis is that overheating definition and metrics in the standards are ill-defined: they are particularly sensitive to the uncertainty inherent in every design. This aligns with the findings by Roberts et al. (2019) in the UK context for a pair of free-running test houses. In their study, the discrepancy between observed and simulated performance — through either blind or calibrated models by experienced professionals — contrasted with the requirements of standard overheating criteria. Unfortunately, results are not comparable because they focused on overheating criteria compliance whereas here the appraisal was based on the histogram of temperature differences between observations and models.

Unlike other building types, transitional shelters are ideal for prototyping and they could be incorporated during the emergency stage of a crisis. During that stage, the prototype could only be monitored for a limited amount of time. Based on the results and discussion presented in the paper, it is hypothesized that subjecting the building to stress tests for different heat and mass transfer mechanisms could reduce the monitoring time to characterize its behaviour. Several tests could better bound the many free variables that define a high-fidelity simulation model to increase the accuracy of extrapolated performance under unobserved conditions. Further to this, the model of a single-zone naturally ventilated building might not be suitable for calibration if the observed outdoor temperatures are within the experimental error of those observed indoors. In such circumstances, it could be that the thermal performance of the model is entirely driven by the weather file, not the intrinsic characteristics of the model, rendering the calibration process meaningless.

Chapter 5

Conclusions

This thesis is concerned with overheating in buildings and has examined three interconnected research gaps that underly its assessment at design stage, namely

1. the performance of mitigation-driven passive design strategies,
2. the potential impact of overheating occupant discomfort on health and wellbeing, and
3. the extent to which high-fidelity building simulation can be used to forecast indoor air temperatures.

To this end, three research questions were formulated and investigated in the contexts of selected UK dwelling types and refugee shelters.

Research Question 1: How do passive design strategies influence overheating in free-running buildings? The first study (chapter 2) focused on the emerging evidence that links improvements to building fabric as a result of energy efficiency policies to exacerbated indoor temperatures. An in-depth review pointed to differences in the reported performance of insulation in previous studies, one of the key climate change mitigation strategies worldwide. Owing to the impossibility of conducting a meta-study to resolve the question[1] and the goal of establishing a cause-effect relationship, a parametric study based on building performance simulation was conducted. The study considered dwelling types, thermal insulation levels, thermal mass, window sizes, shading conditions, internal gains, window opening rubrics, thermal comfort models, airtightness, orientations and locations in different capitals in the world.

The regression analyses through bagged trees allowed the quantification of the relative impact of every parameter in overheating (**Objective 1-A**), indicating that increased insulation levels play a minor role in the overheating response (section 2.6.1). Yet, insulation is shown to develop a two-fold behaviour that can counteract or exacerbate

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[1] This is due to wide differences in building types, number of parameters and their ranges and methods employed to account for mechanisms such as natural ventilation.

overheating (section 2.6.2). *Post-hoc* analyses through bagged classification trees revealed that this two-fold behaviour is highly sensitive to the interactions with other parameters, primarily purge ventilation. If purge ventilation is restricted, indoor overheating increases and it is exacerbated by increased insulation levels. On the contrary, if purge ventilation is available, increased insulation levels further reduces overheating (**Objective 1-B**). In addition, the underlying physical mechanism that accounts for these results was presented, leading to plausible explanations of why previous studies arrived at apparently contradictory findings. Critically, the results demonstrate that purge ventilation does not need to be maximised for increased insulation levels to counteract overheating. This account of performance was found to be consistent with subsequent computational and empirical studies presented in chapters 3 and 4 in hot arid climates.

The implications of these results are that passive strategies aimed at climate change mitigation can indeed enhance adaptation to a warmer world. However, policies should account for a broader understanding of the interactions between different design parameters to guarantee these deliver the desired effects.

The methodology employed in the study could be further reinforced and adjusted to better tackle the problem and make findings generalisable to the built environment. The question was tackled through a parametric study that explore exhaustively every parameter and case of interest. This led to a computationally-intensive design that could have been optimised to approximate results with a fraction of the number of simulations needed. For example, the Maximum Projection Latin-Hypercube Sampling employed in chapter 4 leads to a more efficient design that could dramatically reduce the running time needed to replicate the study, at the expense of increasing the complexity in the analysis given that pairwise comparisons could no longer be relied upon. In addition, the study focused on window opening behaviour based on pre-determined rules that do not reflect necessarily the real behaviour of occupants in buildings because the interest was on the intrinsic performance of building design features. Whether increased insulation levels lead empirically to lower overheating risk is yet to be explored through a study that considers the prevalence of different building types in the building stock together with occupant behaviour models that reflect those observed in practice.

Research Question 2: How can physiological models inform building design resilient to overheating? The second study (chapter 3) examined overheating evaluation methods and how they could inform a cyclic design process for improved indoor conditions in refugee housing. This is shown to be a largely overlooked — yet significant — aspect in the shelter provision process and previous studies of indoor overheating. The context for the study was the refugee camp of Azraq (Jordan) located in the Syrian desert, which approximately hosts 40 000 individuals in nearly 9000 shelters. Bounds for annual overheating in as-designed shelters were obtained based on a validated model against spot measurements of indoor air temperatures of in-use shelters. Design alternatives explored the performance of passive strategies building on the results obtained in chapter 2 and first principles for the climate at the location.

The results compared indoor air temperatures, indoor wall surface average temperatures, extrapolated annual overheating according to ASHRAE's adaptive comfort model and annual heat strain given by the DISC index based on the Pierce 2-node model (section 3.6). Simulation results for current shelters indicated that indoor temperatures were beyond 28 °C for 25 % of annual occupied time, reaching up to 45 °C, obtaining similar results for considered surface temperatures (section 3.7.2). These are shown to cause overheating that surpasses standard thresholds for frequency and severity in comfort and their considered counterpart metrics in heat strain (**Objective 2-A**). Passive strategies could deliver significant reductions in overheating, including the severest occurrences (section 3.8). In addition, these strategies were compatible with the current shelters and could be implemented as part of the considered iterative design process (**Objective 2-B**). The performance of strategies obtained is in good agreement with the previous study in chapter 2 and so are the considerations regarding the iterative process with the experiences reported in chapter 4.

The implications of these results are that a closer attention needs to be paid to the indoor environments that shelters create, especially past the housing emergency stage. Aid-agencies should consider including thermal performance assessments as part of the design process and routinely during the in-use lifetime of shelters.

Research Question 3: To what extent can high-fidelity annual building simulation predict indoor thermal conditions in free-running buildings at design stage? The last study (chapter 4) evaluated the role that white-box modelling has in forecasting indoor air temperatures acknowledging the limited information available in the design context, and the expected gap between desired specifications and built reality. In particular, motivated by the context of refugee housing, it expanded on the previous results by questioning the advantages of thermal simulation at the design stage compared to building and monitoring a prototype. To this end, the thermal performance of seven shelters in the refugee camp of Azraq was studied and then compared to predictions obtained through building simulation. Of these shelters, one reflected the implemented solution currently deployed in the camp, and the other six different thermal retrofit strategies. Their thermal performance in free-running conditions was then monitored for seven weeks during the hot season. The appraisal focused on air temperature as the key parameter of thermal conditions to avoid the ill-conditioned formulation of standard overheating criteria (appendix A).

The comparison of empirical observations to forecasted performance of models based solely on design specification and expert judgement (termed *blind models*) shows extreme deviations between −5 K to +10 K (section 4.6.1). In these circumstances, blind models can only assess the robustness of solutions against overheating provided sufficient knowledge about its operation is available (**Objective 3-A**). However, calibrated models against past observations improves predictions substantially, constraining extreme deviations to −3 K to +4 K (section 4.6.2). Overall, the tendency for calibrated models was to reduce deviations greater than ±1 K from up to 80 % of the time to 15 % of the time (**Objective 3-B**). The advantages of calibration were here observed to be maintained for the study of design variants to various degrees, depending on the number and type of changes implemented (section 4.6.3).

There are two main implications based on these results. The first is that the uncertainty involved in a blind thermal model is likely to be excessive to assess real compliance with the standard overheating criteria available, even in the absence of occupant behaviour uncertainty. Once built, indoor spaces should be monitored to inform the model and enhance predicted performance which could be used, in turn, to assess vulnerability to future weather events. Aspects to be monitored and tested should cover the fundamental parts involved in main heat and mass transfer mechanism, which necessarily depend on the specific features of the shelter being tested (e.g. indoor air and radiant temperature, surface temperatures, infiltration and ventilation tests). The second is that, further to the results presented in chapter 3, it is highly recommended that aid-agencies consider building thermal performance simulation, *together with prototyping*, for a design stage appraisal of the long-term indoor thermal conditions that will be delivered to dwellers.

5.1 Future perspectives

The work herein focused on fundamental aspects of overheating in buildings from a design perspective, where rigorous building performance simulation is seen to have a prominent place in forecasting indoor conditions. Based on the findings of this thesis, and the belief that it is audacious to impose a design on prospective occupants without at least gauging its potential adequacy, it is recommended that future investigations:

1. Ascertain overheating criteria based on long-term thermal dissatisfaction of occupants and heat vulnerability during short-term extreme hot weather events. The first could be used to evaluate limits of thermal dissatisfaction under frequent weather conditions and the second to gauge the potential impact on occupants of different types of weather events (e.g. coping with a raise in minimum temperatures, adaptation potential to multi-day events). This is thought to be a tractable problem through an online monitoring campaign of the housing stock through which monitor in real time what indoor conditions are and have occupants reporting on their thermal environment satisfaction (e.g. similar to a combination of Robinson and Haldi (2008), Vellei et al. (2016), and Gustin et al. (2018)). Qualitative interviews could be deployed when conditions are thought to be warm or when occupants report high levels of dissatisfaction to better understand what triggered such a response and how the dwelling was operated in the hours leading

to such responses (e.g. indoor heat gains, occupant behaviour). Once overheating events have been identified, this could be amenable to mathematical modelling to create a forecasting model.

2. Establish the extent to which buildings modify external conditions during extreme hot weather events in relation to its design and operation. This could be used to score the resilience of the building with respect to the thermal conditions it promotes and to inform what extraordinary adaptation measures could be deployed in such circumstances.
3. Devise a heat index for indoor environments based on a dynamic rational model that normalises cumulative physiological heat strain, possibly correlated to observed morbidity in epidemiological studies. This is thought to be dependent on socio-demographic characteristics such as age, since it is known that groups such as the elderly or children are more vulnerable to cold and hot weather events. It is speculated that, even though such an index could be symmetrical for hot and cold conditions, the limits of occupant adaptation in practice (over themselves, not over their indoor environment; e.g. clothing) may difficult finding a model with such property.

5.2 Final remark

How can building design be informed to promote adequate thermal environments for its occupants whilst not threatening the mitigation of anthropogenic climate change? Recalling the underpinning question of this work, it has been shown how overheating is a topic that requires timely attention given the untapped potential of buildings to moderate this effect.

The role of key passive design strategies was evaluated in a wide range of climates to quantify their potential in domestic buildings and demonstrate that insulation, a fundamental mitigation strategy, can also enhance adaptation to a warmer world. The work also quantified how serious current instances of overheating are and, in the refugee housing context, it has been estimated that shelters are already failing to deliver suitable thermal environments for their dwellers. Once again, passive strategies arise as low-energy resilient solution that mitigates the severest instances of overheating, even in a hot arid desert climate. It has also been demonstrated how and the extent to which building simulation and prototyping can increase the confidence in predicted thermal performance to drive the needed improvements in thermal performance of shelters.

Although our understanding of overheating is still limited, thermal comfort and physiological indicators show that poor thermal conditions are a very likely reality in significant parts of the world. Balancing the need to mitigate climate change whilst considering the adaptation to future scenarios, these findings evidenced a sustainable pathway for the building sector that delivers the indoor thermal environments we need.

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Appendix A

Influence of overheating criteria in the appraisal of building fabric performance

A.1 Preamble

Given the several overheating criteria available, and prior to their use in the main studies presented in this thesis, there is a need first to understand the science underpinning their definition and to test whether they are coherent between them. That different standards quantify overheating differently is to be expected based just on their formulation. Yet, it is unknown if they could play a role in identifying different *trends* when evaluating the performance of different building features. If true, this could account for qualitative discrepancies between studies that rely on different overheating criteria. A critical review of these criteria is presented together with the thermal comfort models they are based on. The outcome of the study is that current standard overheating criteria are based on expert judgement and that the changes in performance they help evaluate are not necessarily consistent between them. Therefore, the main work of the thesis disregards their use as a pass/fail compliance tool and turns to their fundamental metrics instead.

This appendix is based on the conference paper "Influence of Overheating Criteria in the Appraisal of Building Fabric Performance" presented at the "Windsor Conference 2016: Making Comfort Relevant". This study was conducted as part of the COLBE project [grant number EP/M021890/1] to understand the role overheating definitions could play in creating weather files for overheating assessments. Details about the authorship of this paper are provided in table A.1.

A.2 Declaration of authorship

Table A.1: Declaration of authorship

This declaration concerns the article entitled:
Influence of Overheating Criteria in the Appraisal of Building Fabric Performance

Publication status:
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D. Fosas, S. Natarajan, D. Coley, A. Ramallo-González, and M. Fosas de Pando (2016). "Influence of Overheating Criteria in the Appraisal of Building Fabric Performance". *Making Comfort Relevant Proceedings 9th Windsor Conference.* Windsor Conference 2016: Making Comfort Relevant. Windsor: NCEUB 2016, pp. 1078–1098.

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Candidate's contribution to the paper:
The author of this thesis has predominantly contributed to the publication (93 %). The contributions of each author are as follows:

- Formulation of ideas: D. Fosas (100 %).
- Background: D. Fosas (100 %),
- Design of methodology: D. Fosas (80 %), M. Fosas de Pando (15 %) and A. Ramallo-Gonzalez (5 %).
- Experimental work: D. Fosas (90 %) and M. Fosas de Pando (10 %).
- Analysis: D. Fosas (100 %).
- Preparation of manuscript: D. Fosas (100 %).
- Editing drafts of manuscript: D. Fosas (80 %), M. Fosas de Pando (10 %), S. Natarajan and D. Coley (10 %).

Statement from Candidate:
This paper reports on original research I conducted during the period of my Higher Degree by Research candidature.

Signed **Date** 20 December 2019

A.3 Abstract

In response to the threat of anthropogenic climate change, heating dominated countries have focused on reducing the space conditioning demand by increasing insulation and airtightness. However, given climate projections and lifespan of buildings, concerns have arisen on whether these strategies deliver resilient solutions. As overheating can be evaluated through different criteria, this paper investigates if building fabric performance is subject to bias from the assessment method chosen and account for discrepancies between previous studies.

To answer this, we modelled dwellings compliant with 1995 and 2006 UK Building Regulations and the FEES and Passivhaus (PH) standards in a consistent and realistic manner. The parametric study included different weather, thermal mass, glazing ratios, shading strategies, occupancy profiles, infiltration levels, purge ventilation strategies and orientations, resulting in 16 128 simulation models. To provide confidence in the output, the base model was first validated against data collected from a real well-insulated dwelling.

Results show that the benchmark choice is influential in the evaluation of building fabric performance as it is able to inverse overheating trends. Criteria based on adaptive comfort best represented expected behaviour, where improved building fabric is a resilient measure that reduces overheating as long as occupants are able to open windows for ventilation.

A.4 Introduction

Over the last decades, an increasing body of evidence has associated human activities as the drivers of current climate change due to the release of an unsustainable amount of Greenhouse Gases (GHG) (IPCC 2015). Among these, the building sector accounts for a notorious fraction, especially in the UK, where it represents 45 % (Pout and MacKenzie 2012). Thus, numerous initiatives have been adopted to lower and optimise the energy consumption in buildings, particularly since it has been steadily increasing (European Commission 2014). As heating is responsible for 47 % of buildings' GHG — 16 % of UK's total —, there has been a special interest in improving the building fabric, mainly through higher thermal resistance and lower air leakage.

Aligning with the interests for reduced energy consumption that arose after the oil crises, building regulations started to become increasingly strict. New dwellings are now required to achieve transmittances three times smaller than in 1970 (ODPM 2013a), whereas airtightness is expected to deliver between half to a quarter of the air leakage at that time (ODPM 2013b; CIBSE 2000). Additionally, several standards have lowered these targets further in the UK, where the FEES aims to reduce heat losses by half of what regulations require. Furthermore, the PH seeks a consumption of $15\,\mathrm{kW\,h\,m^{-2}\,a^{-1}}$, what is about 60 % less than FEES.

Another point of concern is that the climate keeps changing (IPCC 2015). Besides global warming, it is considered virtually certain that future climate will feature more extreme weather events, specially more severe and longer heat waves (IPCC 2012). These can increase morbidity and mortality as seen in the European heat wave of 2003, where over 14 000 persons died inside buildings in France (Vandentorren et al. 2006). Numerous studies have been looking at such experiences to understand and prevent these rates, where they recognised the fundamental role buildings have to alter the final indoor temperature and thus, promoting higher or lower risks. Two fundamental questions arise. Which are the limits of indoor thermal conditions? How building features affect its overheating performance?

Regarding the limits of indoor thermal conditions, a number of criteria have been proposed. These allow researchers and practitioners to quantify overheating, which, in turn, can translate into an evaluation and classification of the performance of existing buildings (Mavrogianni et al. 2012), design strategies (Porritt et al. 2012; McLeod et al. 2013) or potential impact of climate change (de Wilde and Tian 2010). Despite their usefulness, current criteria are not equally developed (ZCH 2015a), they do not identify the same amounts of overheating (Lomas and Kane 2013) and their adoption is voluntary, despite certain clauses in some building regulations (ODPM 2013a).

At the same time, there has been an increasing amount of research devoted to see if improved building fabric exacerbates temperatures during summertime in heating dominated countries. During the mentioned heat wave, it was found that higher internal temperatures were recorded in rooms without insulation. However, Orme et al. (cited by Dengel and Swainson (2012)) linked higher overheating risk with increases of insulation when assessing an update to UK's Building Regulations. The projections of the UKCIP02 allowed, at about the same time, insights of future performance, in which CIBSE (2005) concluded that the performance of increased insulation and reduced air leakage shifts depending on the hourly balance of the building. Subsequent studies have kept proving one possibility or the other, but the particular research questions, scopes, overheating standards, methods and parameters under study do not allow for comparison.

As a result, further research has been requested to clarify the role of improved building fabric together with the overheating criteria currently available (Mylona and Davies 2015; Gupta and Kapsali 2015; ZCH 2015c). The aim of this paper is to review current benchmarks and to perform a holistic assessment of overheating related to building fabric. The hypotheses that will be tested on this study are:

1. 'Different overheating criteria show inconsistent risk trends when evaluating the same buildings'. This will test the robustness of current prediction methods and will detect whether conclusions about building fabric performance can be expressed as their function.

2. ‘Dwellings built to meet low targets of heating energy demand develop lower overheating risk but are less robust’. This will characterise the performance according to current knowledge of the drivers of overheating and occupant behaviour.

The study is organised as follows. Firstly, overheating criteria background and development is reviewed. Next, the methods to test the hypotheses are described. Further, overheating criteria are applied to appraise the building fabric performance and discussed. Lastly, key findings are summarised and recommendations for future work are given.

A.5 Background

There is not yet a widely accepted definition for overheating. Intuitively, it can be said that ‘overheating is the raise of a certain temperature over a certain threshold for a certain period of time’, where further specification is subject to discussion. In addition, overheating is better expressed as a risk because temperatures depend on the energy exchange in constantly varying circumstances and is subject to occupant psychological evaluation and physiological reactions. According to what is assessed, it relates to health risks, comfort and productivity, of which only the first two are relevant for dwellings (ZCH 2015a).

The knowledge about overheating and health risks is twofold. On the one hand, the relationship on healthy adults is defined in regulations. Here, an implementation of the Wet Bulb Globe Temperature defines the threshold for the ‘heat stress index’, a metric that integrates all parameters involved. The standard ISO-7243:1989 (BSI 1994) establishes the reference method, which maintains its approach in the upcoming revision, recently opened for consultation (BSI 2015). On the other hand, the relationships for vulnerable groups — namely children, elderly and sick people — are not that developed. Despite early warnings of the IPCC (1990), it has not been until more recent experiences of heat waves (e.g. that of France in 2003) and extreme weather events projections that an increasing amount of efforts have focused on this area (Dengel and Swainson 2012). Nonetheless, there is not a framework that clarifies and quantifies these risks in relation to indoor air temperature (ZCH 2015b).

Unlike with health risks, thermal comfort features numerous schemes to assess overheating. Here, it can be reworded as ‘an unacceptable level of dissatisfaction due to excessive heat’ according to the two main theories of understanding thermal comfort: Fanger’s PMV-PPD and Adaptive Comfort Models (ACMs). Thus, they can entail explicit temperature thresholds, although it is still a risk. However, the limits of this expectation, duration and severity, do not translate directly from the PMV-PPD or the ACMs, having been proposed a number of overheating criteria based on them. The following sections focus exclusively on the thermal comfort perspective, since known health risk thresholds (i.e. healthy adults) cannot be reached in these circumstances.

A.5.1 Comfort criteria based on PMV-PPD

Two main standards implement the PMV-PPD model, the ANSI/ASHRAE (2017) and the EN-7730 (BSI 2005). The only noteworthy difference is that the American regards as acceptable a Predicted Percentage Dissatisfied (PPD) up to 10 %, whereas the European proposes categories based on degrees of satisfaction up to a PPD of 15 %. Knowing the typical situations in dwellings, an operative temperature and its dispersion can be worked out. From this, studies have consecutively supported the raising of temperatures to set limits to discomfort, where the main references are CIBSE, Passivhaus and the EN-15251.

CIBSE's TM-36 provides an illustrative fixed threshold for free-running buildings based on PMV-PPD. They argued that an assessment using ACMs — ASHRAE's model was included in the 55-2004 Standard a year ago — "results can be difficult to interpret" (CIBSE 2005, p. 9). The criteria rely in setting 'warm' and 'hot' limits — Predicted Mean Vote (PMV) +2 and +3, respectively — by adapting clothing and PPD. A building is said to overheat if 'hot' conditions are met for more than 1 % of the occupied time (reasons why 1 % not given and the cited 5 % for 'warm' is deprecated). Severity is overlooked. The limits for dwellings are derived from research and experiences in offices and schools, as usual. Although precise values for clothing and metabolic activities are not specified, the operative temperature limit in living areas is established to 25 °C ('warm', PPD $<$ 10 %) and 28 °C ('hot', PPD $<$ 20 %). Thresholds for bedrooms are adapted to 21 °C and 25 °C, respectively, according to what they considered occupant's expectations. However, Humphreys' findings support these values (CIBSE 2006), but the PMV-PPD application would result in 26–27 °C due to the lower metabolic activity, provided suitable bedding (0.9 met, 0.5–0.7 clo). For predictions, the 1 % criterion implies the use of DSYs (i.e. third Apr–Sep hottest year on average in 1983–2002) rather than Test Reference Years (TRYs) (i.e. typical year with 1976–1990 average months) so the risk is explicitly taken into account by maximizing it within 'reasonable' limits.

Built on the same grounds, Passivhaus sets the default limit to 25 °C (customizable) for a duration up to 10 % (compulsory) of the occupied time, implementing findings from Kolmetz (1996) (PI 2014). Hence, it is stricter for the temperature but more relaxed for the deviation. Here, severity is also overlooked.

The standard EN-15251 (BSI 2007) proposes a procedure to characterise comfort performance and establishes a time limit for discomfort, applicable to both PMV-PPD and the European ACM. The length of deviation is set, as an example, to 3 % or 5 %, and it has to be met simultaneously for the occupied periods at year, month, week and day levels. Then, it offers three alternatives to compute occupied hours in discomfort. The first one is a count of the time when comfort is exceeded, as seen before. The second is a degree-hours approach like in HDD-CDD according to the temperature difference ΔT_o over the limit. The third one is a PPD-weighted metric, similar to the previous but using the ΔPPD over the limit as the weighting, more suitable as this parameter does assess comfort. They point out that PPD-weightings yield greater hours, not explaining the causes. Here, they are attributed to the exponential expression of $PPD(\Delta T_o)$, common to every thermal comfort model. In fact, it can be seen that each of these methods gives higher results than the previous, potentially discouraging the use of the last two. The category of the building is the highest one that is satisfied in 95 % of its spaces. However, this can be misleading as the period and counting method are voluntary, as seen by Nicol and Wilson (2011).

A.5.2 Comfort criteria based on adaptive models

Likewise, the standards ANSI/ASHRAE (2017) and EN-15251 implement ACMs. The different databases from which they were derived — RP-884 'worldwide' (de Dear et al. 1997) and Smart Controls and Thermal Comforts (SCATs) 'Europe' (McCartney and Fergus Nicol 2002), respectively —, the methods and the assumptions involved do not allow for a direct comparison (Nicol and Humphreys 2010; de Dear et al. 2013). As explained by de de Dear et al. (1997), adaptations under PMV-PPD only accounted for about 50 % of the comfort experienced under ACMs, making adaptive models more appropriate for free-running buildings. The ANSI-ASHRAE 55 offers two limits for comfort that result in 80 % and 90 % acceptability (general and higher comfort, respectively). The EN-15251 gives three qualitative levels — I/II/III — of which the first two coincide in their intended use with the previous standard — 80 % for II and 90 % for I. Only the EN-15251 suggests how to quantify the performance of the building regarding discomfort, as explained previously. Interestingly, the concept of Adaptive Comfort Degree-Days (ACDD) for energy demand was not defined nor validated until later on by McGilligan et al. (2011).

CIBSE's TM-52 (CIBSE 2013) followed research suggestions and recommends the European ACM to appraise overheating in free-running buildings. The background summarises the state-of-the-art of this adaptive model and establishes a limit to overheating inspired in the EN-15251. It is based on three criteria and a building is said to overheat if any two are exceeded. The first one establishes a limit of 3 % on the May-September occupied hours for $\Delta T_o \geq 1\,\mathrm{K}$. The second uses the hour-degree method limited to six in any one day. The reasons given for this particular value is that it "is an initial assessment of what constitutes an acceptable limit of overheating" (CIBSE 2013, p. 14). The third one is novel and sets 4 K limit to severity, which maintains the PPD under approximately 35 %. This way, TM-52 catches up with previous critics (e.g. Nicol et al. (2012)). Additionally, it mentions that ACMs should be suitable for dwellings as adaptability premises are truer, despite being derived from offices. Moreover, it reminds that EN-15251 Category I could be used if tighter control is deemed necessary. ACMs' suitability for bedrooms is not discussed, where it might not be applicable as they were devised for a range of 1–1.3 met (offices) and sleeping is 0.9 met. The Guide A (CIBSE 2017) does mention them, setting comfort up to 24 °C and an absolute limit of 26 °C.

A.6 Methodology

The appraisal of overheating and building fabric is complex due to two main aspects. Firstly, true limits of discomfort — duration, severity and their relationship — are not yet known, especially in dwellings. Secondly, the need to cover several parameters requires pairwise models to ease the analysis, unlikely to be found in reality. However, these simulations aim to predict temperatures, requiring a careful approach (Nicol et al. 2012). Because of this and the need of knowing occupants' perception, thermal comfort research tends to focus on field studies (de Dear et al. 2013).

As a result, the methods for this study are designed to provide a balanced solution. Parametric building simulations implementing different overheating criteria better approach the hypotheses established, while concerns for such techniques are reduced by validating modelling procedures. Thus, a monitored well-insulated dwelling was chosen as the case study and confidence in the parametric simulations is provided based on the reproduction of its performance (appendix A.6.2).

A.6.1 Overheating assessment

The overheating criteria considered are PH, TM-36 and TM-52 to cover limits based on PMV-PPD and ACM theories and given their widespread adoption in both research and construction industry. They establish well-defined thresholds (table A.2) for which the following parameters are calculated:

Hours of discomfort: Count of occupied hours as defined in the criteria.

Weighted hours of discomfort: Sum of the occupied hours in overheating multiplied by the temperature deviation from the threshold.

Failure rate of rooms: This set will provide Pass/Fail summary. Additionally, it will indicate whether different criteria yield different trends among them or not.

A.6.2 Dynamic simulation modelling

The base model is a mid-terrace located next to Southampton (UK) built in the late 2000s to meet the Code for Sustainable Homes (CSH) Level 4 (fig. A.1). The election of a terrace is based on that it is the most common dwelling type prone to overheating, being ranked second to flats in overall risk (Palmer and Cooper 2013; ZCH 2015c). In this regard, studies highlight that the key difference between terraces and flats lies in the options for natural ventilation, aspect that is considered as a parameter. Within

Table A.2: Overview of selected standard overheating criteria

PH		$\geq 25\,°C$ (customizable)	for	$\geq 10\,\%$	of the occupied time
TM-36	Bedrooms:	$\geq 25\,°C$	for	$\geq 1\,\%$	of the occupied time
	Living areas:	$\geq 28\,°C$	for	$\geq 1\,\%$	of the occupied time
TM-52*	Criterion 1:	$\Delta T_{cm,max} \geq 1\,K$	for	$\geq 3\,\%$	of the occupied time May–Sep
	Criterion 2:	$\Delta T_{cm,max} \cdot time \leq 6\,K\,h$	in		any one day
	Criterion 3:	$\Delta T_{cm,max} \leq 4\,K$	for		anytime

* Under this benchmark, a building is said to overheat if any two criteria are exceeded.

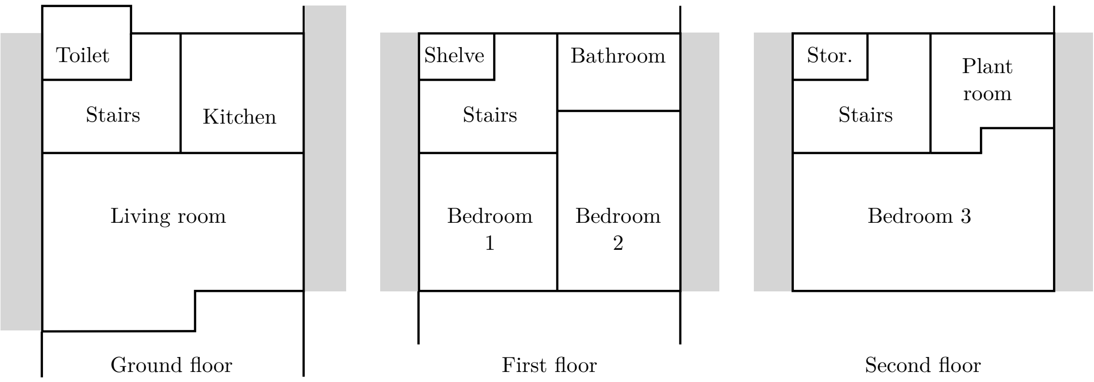


Figure A.1: Geometry of the mid-terrace

terraces, research has shown that mid ones are at higher risk for the same reason (Porritt et al. 2012; Gupta and Gregg 2013). The parametric study is done through E+ (v8.4), a robust tool extensively validated and used in research.

Base model

The house is modelled to the external side of the thermal envelope following Passivhaus conventions. Each room constitutes a zone to obtain individual temperature readings and to have better control over the definition of heat gains (e.g. the solar distribution model assigns the solar gain to the floor or the room (LBNL 2015)). Heating is provided through an ideal loads system to control the energy demand without modelling particular building services, generalizing the results.

The conditions for the elements defining each zone are:

Ground floor: Outdoors, exposed to wind. According to construction details, the house features a suspended floor with a vented cavity.

Façades: Outdoors, exposed to wind and sun.

Party walls: Adiabatic. This simplifies the analysis and is congruent with the study of high insulation levels. Nevertheless, the thermal mass of these walls is still taken into account.

Internal walls and floors: Energy exchanges through these elements are modelled to capture the effect of higher gains in certain rooms (i.e. kitchen and plant room).

Insulation

Studies have associated changes in overheating performance with high insulation levels while they are responsible for substantial space heating energy savings. In order to capture a wide range of building fabric, the modelled cases were dwellings compliant with 1995–2006 regulations and the FEES and Passivhaus standards (table A.3). Because they set the context of other parameters (e.g. ventilation systems), this had to be explicitly taken into account in the way the parametric study was carried out (appendix A.6.2).

Thermal mass

Thermal mass has been identified as a key parameter to assess the influence of insulation and airtightness on overheating. For instance, the SAP overheating check depicts a 4 K difference between low and high TMP values (Saulles 2015). Consequently, three cases were established based on TMP as it takes into account the thermally-active depth of constructions. Lightweight ones are defined as $38\,\mathrm{kJ\,m^{-2}\,K^{-1}}$ and the medium and heavyweight to $281\,\mathrm{kJ\,m^{-2}\,K^{-1}}$ and $520\,\mathrm{kJ\,m^{-2}\,K^{-1}}$, respectively (figures as per ISO-13790 method). To account for dynamic effects, the time step of the simulation was set to 10 min as a balance between accuracy and runtime.

Constructions were serialized in three groups, one per thermal mass. Lightweight constructions rely on internal insulation whereas mid and heavyweight rely on internal blocks of different properties and external insulation. Cavities are avoided to simplify the model. The insulation thickness is adapted to the year or standard of construction, according to the remaining thermal resistance. Internal areas and volumes for each of the twelve combinations were worked out and used to override automatic calculations. Thus, energy exchanges are invested in the real enclosed air. Lastly, wall thickness affects the solar heat gain model through reveals of windows, which were designed to keep recesses at 5 cm.

Table A.3: Definition of the building fabric: U-values and glazing properties

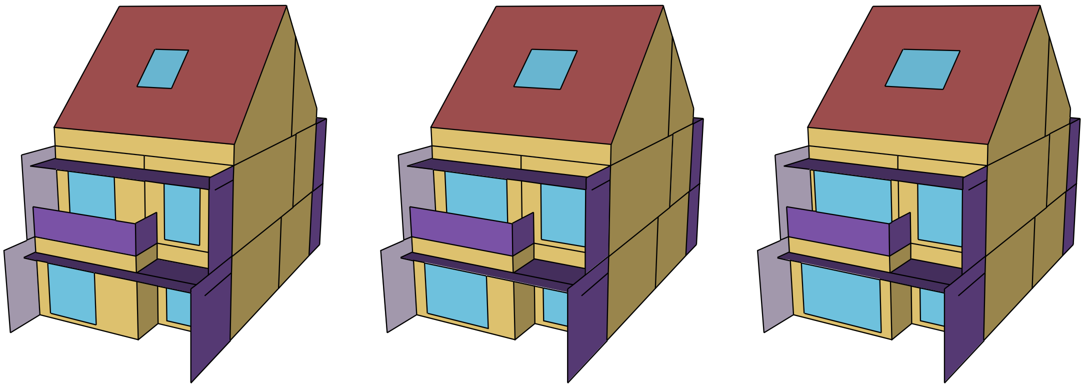
Parameter / Case	**1995**	**2006**	**FEES**	**PH**	**Unit**
U-value$_{\text{Wall}}$	0.45	0.35	0.18	0.10	$\mathrm{W\,m^{-2}\,K^{-1}}$
U-value$_{\text{Roof}}$	0.25	0.25	0.13	0.10	$\mathrm{W\,m^{-2}\,K^{-1}}$
U-value$_{\text{Ground}}$	0.45	0.25	0.18	0.10	$\mathrm{W\,m^{-2}\,K^{-1}}$
U-value$_{\text{Door}}$	3.30	2.20	1.40	0.85	$\mathrm{W\,m^{-2}\,K^{-1}}$
U-value$_{\text{Window,limit}}$	3.30	2.20	1.40	0.85	$\mathrm{W\,m^{-2}\,K^{-1}}$
U-value$_{\text{Window,BSI (2011)}}$	3.30	2.20	1.30	0.76	$\mathrm{W\,m^{-2}\,K^{-1}}$
g-value	0.74	0.70	0.60	0.59	—
Light transmission	0.80	0.76	0.76	0.69	—
Windows composition	4+6+4	4+8+4	4+16+4	5+12+4+12+5	mm

Conditional assemblies

The appraisal of a wide range of building fabrics entails different conditions and systems for each building model. Following the capabilities of E+, components were defined in separate files and only relevant combinations were assembled for the simulation. For instance, ventilation featured conditions based on regulations and standards (system type and capacity), occupancy (availability) and purge strategy (parameter and overheating criteria). Altogether, these generate 16 128 computational models.

Glazing

The original window-to-floor ratio was taken as the base case because the original house was reported to have an adequate winter–summer balance. Variations of ±5 % around the baseline were explored by modifying the geometry while keeping shading conditions (fig. A.2). Frames and dividers have been considered consistently with the way E+ takes them into account to keep solar gains constant between building fabrics, while acknowledging changes in U-value (5 cm frames in 1995–2006 and 10 cm in FEES–PH).



(a) Low 16 % (b) Medium 21 % (original) (c) High 26 %

Figure A.2: Glazing definition (wall-to-floor glazing ratio)

Shading

The knowledge of occupant behaviour (e.g. shading operation) is among the challenges of defining a model because it is still unknown (Mavrogianni et al. 2014). Thus, the original shading based on fixed elements is maintained because it was assessed to provide adequate performance by default. Northern devices were updated to meet the same shading angles as the southern ones. However, the bedroom in the loft was modelled with a shading device with optimal operation based on the indoor temperature to approximate good shading conditions because it is completely exposed to the sun. This way shading strategies remain useful regardless the orientation. This 'fully shaded' condition constitutes the best-case scenario whereas the worst one is established with no shading but that of the urban landscape where the same terrace was replicated 15 m apart.

Internal gains

Likewise shading, two cases have been considered following knowledge limitations. The first is a working family of five members where occupants are away from 09:00 to 17:00. The second is three occupants home all-day-long ('high' and 'low' scenario, respectively).

Occupancy was modelled as discrete individuals in specific rooms. Lighting and other gains such as appliances were based on a customized version of the Passivhaus methodology, informed by UK-specific data and models (Richardson et al. 2010; McLeod et al. 2013; Palmer and Cooper 2013). These established a 'budget' spent accordingly to occupancy, considering residual loads and specific appliances in the kitchen and service rooms. Resulting average gains are $3.83\,\mathrm{W\,m^{-2}}$ and $3.03\,\mathrm{W\,m^{-2}}$ for the high and low scenarios, respectively, considering their respective contributions to the thermal load.

Infiltration

Infiltration has been estimated according to studies, regulations or their specific targets (table A.4). To account for wind speed and stack effects, reference infiltrations were translated as permeability in the Walker and Wilson's model, which also considers dwelling geometry, features and suburban exposure. Additionally, flow coefficients were prorated per room according to their external envelope area. To account for the dispersion in airtightness values, high and low scenarios were taken around expected mean values.

Ventilation: purge ventilation availability and occupant behaviour

The different years of construction entail particular ventilation systems and modes of operation. These were adapted from regulations and standards to the simulation engine capabilities (table A.5). For the considered airtightness in 1995 and 2006, background

Table A.4: Infiltration definition of cases

Construction	**Case**	$\mathbf{q_{50}}$ [$\mathrm{m^3_{air}\,m^{-2}_{envelope}\,h^{-1}}$]	**n** [$\mathrm{ach\,h^{-1}}$]	**Data source for reference value**
1995	High	30	2.264*	CIBSE (2000)
	Low	10	0.755*	
2006	High	10	0.768*	ODPM (2006a) and ODPM (2006b)
	Low	5	0.384*	
FEES	High	4	0.337*	ZCH (2009) and ODPM (2013a)
	Low	2	0.169*	
PH	High	0.50*	0.042*	Cotterell & Dadeby (2012)
	Low	0.25*	0.021*	

* Data adapted from its original definition.

ventilators are advised, whereas Mechanical Ventilation (MV) is for FEES and PH, with the latter including a Heat Recovery (HR) section that is by-passed during summertime.

Real window opening behaviour is not yet well-known for building simulation purposes. As each of the overheating criteria suggests limits of discomfort, it has often been modelled to satisfy their requirements, assuming that occupants would take actions to prevent excessive overheating. Although this premise is exclusive of adaptive comfort, it has been taken into account for PH and TM-36 criteria as a traditional assumption in previous studies. Therefore, windows are opened if the following conditions are met simultaneously:

1. A trigger temperature is surpassed.
2. The external temperature is lower than the internal.
3. There are occupants in the house.

Because in adaptive comfort the first condition depends on the external running mean, the temperature trigger was implemented through hourly schedules calculated for each case. To study the impact of purge ventilation, three availability scenarios were studied:

1. Low: Purge ventilation is never available. This constitutes a worst-case scenario for control purposes.
2. Medium: Purge ventilation is available during daytime if there are occupants in the dwelling. The trigger temperature is established according to each overheating criteria as the threshold for overheating.

Table A.5: Ventilation systems summary

Case	**CO_2-oriented**	**Extract**	**Purge**
1995	Background ventilators. *Model:* Weather-driven shallow openings. *Operation:* Constant.	Specific Fan. *Model:* Extraction fan. *Operation:* On-demand, according to internal activity.	Windows, 20 % openable area. *Model:* Weather-driven wind and stack effect.
2006	Background ventilators. *Model:* Weather-driven shallow openings. *Operation:* Constant.	Specific Fan. *Model:* Extraction fan. *Operation:* On-demand, according to internal activity.	Windows, 20 % openable area. *Model:* Weather-driven wind and stack effect.
FEES	MV unit. *Model:* Ideal system. *Operation:* According to 2013 Building Regulations for mechanical systems.	Extraction to MV unit. *Model:* ideal system. *Operation:* According to supply. Airflow increased when extraction is greater due to activity.	Windows, 20 % openable area. *Model:* Weather-driven wind and stack effect.
PH	MVHR unit. *Model:* Ideal system, with HR (by-pass allowed). *Operation:* According to Passivhaus standard.	Extraction to MV(HR) unit. *Model:* ideal system. *Operation:* According to supply. Airflow increased when extraction is greater due to activity.	Windows, 20 % openable area. *Model:* Weather-driven wind and stack effect.

3. High: Purge ventilation is always available as long as there are occupants. This constitutes a best-case scenario where occupants optimize window opening behaviour. Here, occupants aim to maintain the neutrality temperature. Because in PMV–PPD this temperature would be the same, PH was modelled to 23 °C and TM-36 to 25 °C during the day and 21 °C during the night.

Orientations

Four cases, one per cardinal point, were modelled to approach results in any orientation.

Location and future projection

London was taken as the reference location. Due to the known problems with DSYs weather files, TRYs were used to carry out the simulations (Jentsch et al. 2014). To explore performance under higher external temperatures and approach the resilience of different building fabrics, the climate change projection given by Eames et al. (2011) for 2080 (high emissions scenario, 90 % percentile) was considered.

Conditional assemblies

The appraisal of a wide range of building fabrics entails different conditions and systems for each building model. Following the capabilities of E+, components were defined in separate files and only relevant combinations were assembled for the simulation. For instance, ventilation featured conditions based on regulations and standards (system type and capacity), occupancy (availability) and purge strategy (parameter and overheating criteria). Altogether, these generate 16 128 computational models.

A.6.3 Validation

The adequacy of modelling techniques is appraised through internal temperatures on free-running mode and the space heating energy demand. The first is aimed specifically to overheating performance and it is based on the original house specifications (table A.6), real occupancy derived from sensors and simulation with the real external conditions. The latter were recreated from official weather stations given the limitations of on-site external measurements (Met Office 2012; World Meteorological Organization 2018).

Table A.6: Characteristics of the monitored dwellings

Building Fabric	Opaque transmittances	0.11–0.15 $\mathrm{W\,m^{-2}\,K^{-1}}$
	Windows transmittances	0.78–1.24 $\mathrm{W\,m^{-2}\,K^{-1}}$
	Thermal Mass Parameter	250 $\mathrm{kJ\,m^{-2}\,K^{-1}}$
	Window-to-floor-ratio	$\approx$ 25 % (double sided)
	Airtightness	1.25 $\mathrm{ach\,h^{-1}}$@50Pa
MVHR unit	Airflow capacity	0.50 $\mathrm{ach\,h^{-1}}$
	Consumption	13.2 $\mathrm{kW\,m^{-2}\,a^{-1}}$
	Heat Recovery	77 %

Norms were taken to appraise the goodness of fit between the real and the simulated time series (fig. A.3). The 2-norm was used as the indicator of the average dissimilitude between signals, which, divided by that of the real one, resulted in deviations of 2.4 % ($\approx$ 0.6 K). Similarly, the ∞-norm was taken as the indicator of the peak dissimilitude, being 6.1 % ($\approx$ 1.6 K). Given the number of uncertainties, simplifications and assumptions in the process, these have been interpreted as a reasonable guarantee of the validity of the simulation. However, they are high enough to prevent accurate absolute values for a study in overheating and the results of the study will necessarily depend on the ranking of figures.

The validation of space heating demand ensures that simulations under the current weather are within reasonable limits (fig. A.4). This is done comparing the space

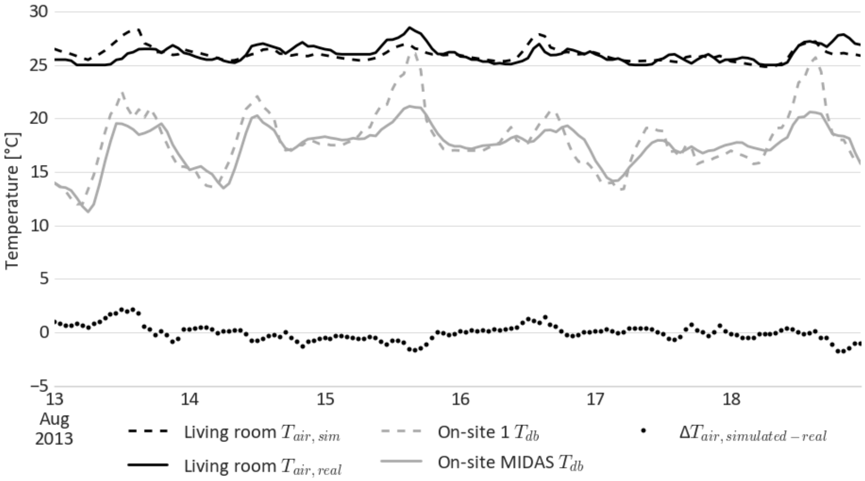


Figure A.3: Validation of the overheating model: typical summer week

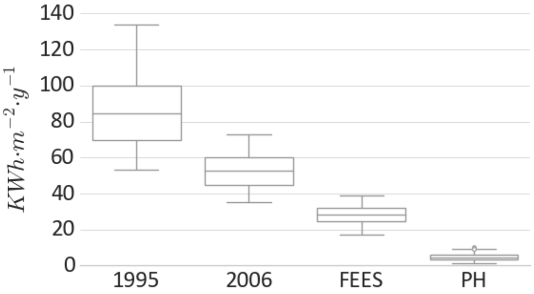


Figure A.4: Space heating energy demand intensity

heating demand intensity of the simulations with the heating energy consumption of the UK stock or FEES and PH goals. The heating energy consumption takes into account Domestic Hot Water (DHW) and the efficiency of the equipment. Considering that DHW is about 30 % of the demand and a boiler efficiency of 85 %, values would be 1.5 times greater, in the range of known values (Palmer and Cooper 2013; Shorrock et al. 2005). On the contrary, FEES and PH directly specify their heating energy demand, being the average of the locations close to the goals of 39 kW h m^{-2} a^{-1} and 15 kW h m^{-2} a^{-1}, respectively. It must be considered that FEES and PH achieve their goals by an iterative design process, meaning that the dispersion in the demand is due to the propagation of cases that have not been optimized to satisfy them.

A.7 Results and discussion

Overheating criteria appraise performance based on annual indicators, which have been computed coherently with the simulations. The exception is when purge ventilation is not available as there is no occupant behaviour involved. Here, each benchmark was applied directly to the results. Data has been stratified in equally sized samples according to the parameters of interest for each indicator, namely purge strategy, overheating criteria (linked to the opening behaviour modelled), weather, and building fabric.

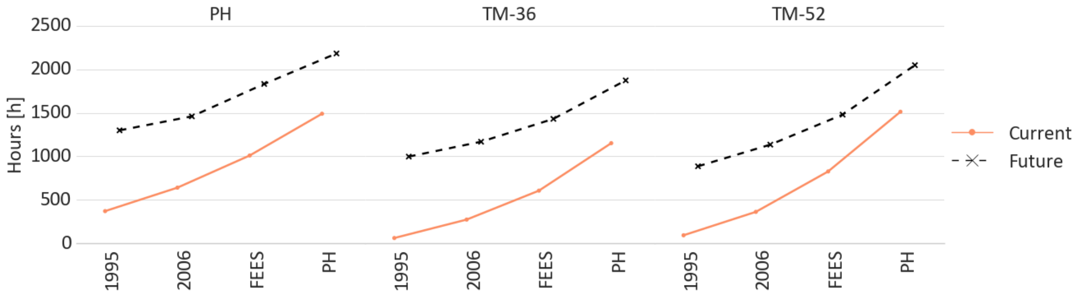
The analysis relies on pairwise comparisons given the hypotheses, the way simulations were generated and the outcome of the validation. Hence, results are presented through the average of each subset (over 5000 observations). Because rooms with very different occupancies are summarized together in this assessment, absolute figures cannot be translated directly to specific cases. Finally, each group is analysed through the Kruskal-Wallis test to appraise whether the changes observed are statistically significant or not. These are followed by the Nemenyi post-hoc tests to see which construction pairs within the same group are significantly different, if any.

A.7.1 Hours in discomfort

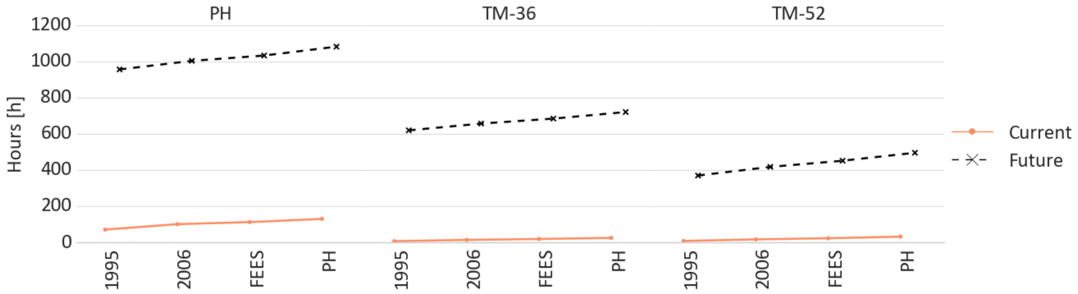
The results show the variation of overheating hours for different purge ventilation strategies and weathers (fig. A.5, table A.7). When windows cannot be opened ('low' scenario) the risk is significantly higher, reaching maximums over 2000 h ($\approx 23\,\%$ of the year). The values for each overheating benchmark differ quantitatively, as known, but with an unusual ranking. PH yields more hours than TM-36 as it could be expected from the temperature thresholds, but for TM-36 and TM-52, the latter tends to report higher values for the current weather. This is due to the definition of the thresholds and the TRY weather file. The TM-36 defines an absolute limit of 28 °C whereas the TM-52 focuses on the ΔT over the running mean. Thus, the TM-36 would result in fewer hours under circumstances prone to overheating as this one is a milder weather. For 1995, infiltration levels at 0.75–2.24 ach h^{-1} provide a major cooling mechanism because it is the only option available. Contrarily, the mechanical ventilation and infiltration in a PH gives about 0.40 and 0.02–0.04 ach h^{-1}, respectively. The result is that criteria show that improved building fabric develops higher overheating in every case. Nevertheless, overall figures suggest that this situation would be unbearable for occupants with the exception of 1995 dwellings under current weather.

The case where windows can be opened during daytime aimed to represent a 'medium' scenario where occupants, assuming a behavioural model inferred from the benchmarks, take action to keep rooms just below the thresholds. Here, absolute values are several times lower, ranging 8–180 h and 400–1100 h for current and future weather, respectively. Criteria now follow the ranking reported by previous studies, highlighting the advantages of adaptation for the climate change scenario. Improved building fabric also results in more hours above the threshold although the slope of the curve has diminished remarkably.

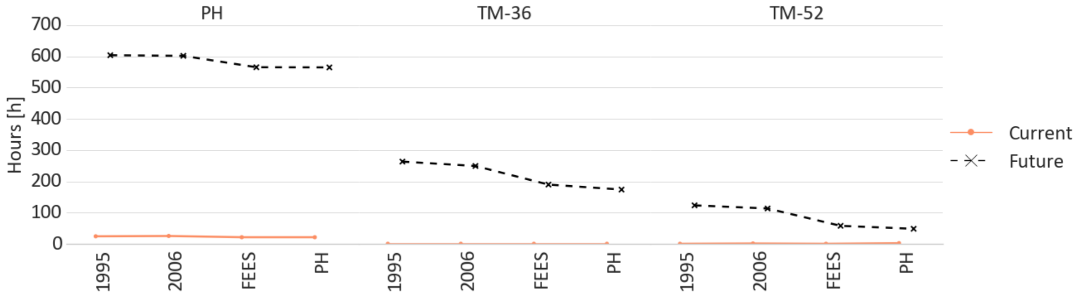
In contrast, when occupants are expected to restore neutrality, the risk diminishes over 50 % and every benchmark reports benefits from higher levels of insulation and airtightness. The temperature trigger for opening windows is lower than the threshold and indoor conditions are kept as neutral as comfort and occupancy allow. The TM-52 evaluation reports values fewer than 150 h (≈ 1.7 % of the year) for the future weather. Combined with the previous result, this indicates that there is still great potential for comfort in occupant adaptation and the external temperature daily swing. Now, improved envelopes are always beneficial although not necessarily significant between 1995 and 2006 or FEES and PH.



(a) Purge ventilation ‘Low’



(b) Purge ventilation ‘Medium’



(c) Purge ventilation ‘High’

Figure A.5: Mean overheating hours (Y-axis adapted per strategy)

A.7.2 Weighted hours in discomfort

Weighted hours are only considered in the TM-52, although they have been widely used to account for severity with a single value. The outcome provides a different perspective on what the hour count seemed to suggest (fig. A.6). The ranking of the criteria is consistent with other studies and stresses the harmful effects of sealing up dwellings when windows are kept shut. However, results for TM-52 show values several times lower even though indoor temperatures are above the threshold as often as in the other cases. Therefore, this overheating is due to lower ΔT, being about one for 1995 and two for PH.

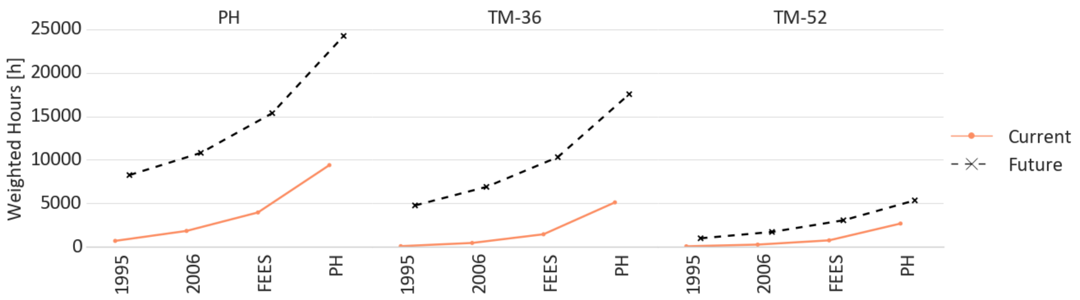
Weighted hours show different trends than before for the 'medium' purge strategy. The PH threshold of 25 °C in the current weather shows increasing overheating, from 85 h in 1995 to 116 h in PH. It decreases in the future from 3572 h to 3437 h, respectively, although only the reductions experienced by FEES are statistically significant (table A.8). TM-36 experiences the same results as PH whereas in the TM-52 trends keep growing but at a slower rate than before. Overall, the response is not the same when the maximum comfort temperature allowed varies. The comparison with the values obtained in the hour count shows that houses with a PH-based window opening algorithm had an average ΔT of 3 K, TM-36 of 2 K and TM-52 lower than 1 K. Hence, FEES and PH achieve lower overheating for high external temperatures since 1995 and 2006 reported higher weighted hours despite being less time over the thresholds, situation that does not take place in TM-52 due to its ΔT.

Previous considerations towards the maximum comfort temperature also arise in the 'high' purge ventilation strategy. Aiming for neutrality improves the behaviour of better building fabric but the specific temperatures generate similar ΔT. Altogether, these results indicate that FEES and PH stabilise temperatures in a smaller range than the others. They report less overheating for large deviation from their limits, but not for the small ones. Additionally, they improve results if they are given margin as in the 'high' case. 1995 and 2006 benefit from higher infiltration and conduction when the weather is colder than their thresholds, but they are no longer beneficial given the temperature increment by 2080.

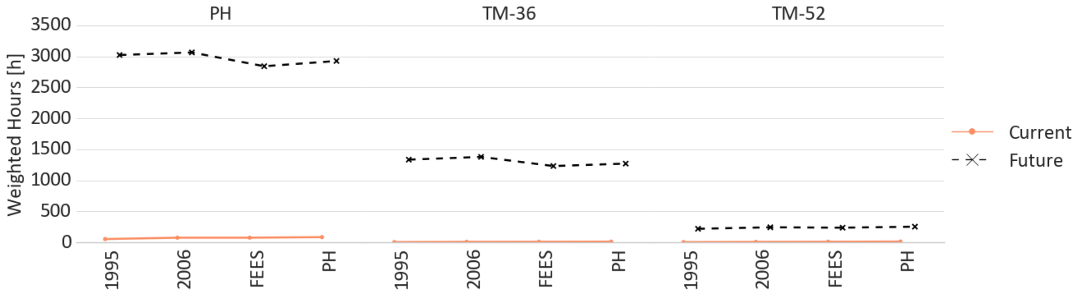
A.7.3 Overheating criteria

Figure A.7 shows the overall results of the benchmarks. It has to be considered that the approach through extreme cases — low-high parameter values — make large proportions of the simulations prone to overheating. The lack of purge ventilation shows a steep evolution towards 100 % for current weather as building fabric changes and a complete failure for the future scenario. The only noteworthy difference is that TM-52 depicts lower values than TM-36 despite figures obtained in the hour count. The reasons are that TM-52 implements three criteria of which two need to be failed to report overheating. Moreover, the hour count is done for $\Delta T \geq 1$ K and the other two allow for restrained deviations, even though the maximum comfort threshold is met before 28 °C.

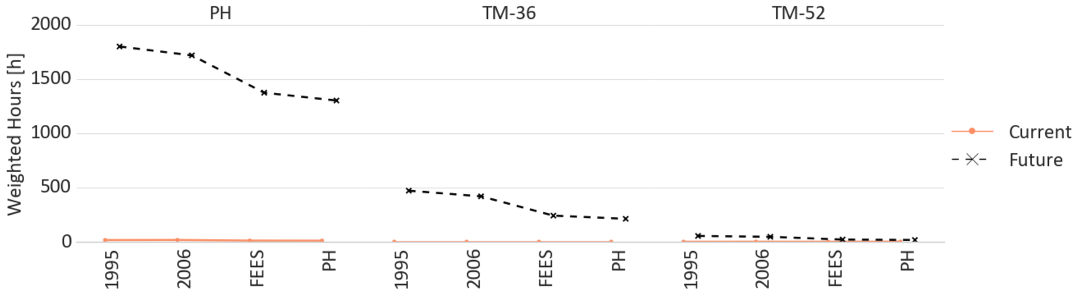
Inconsistencies and limitations between criteria are evident in fig. A.7(b). PH and TM-36 report trends as in the hour breakdown, but now TM-36 has a higher failure rate under current weather. This is because the relationship between the temperature



(a) Purge ventilation ‘Low’



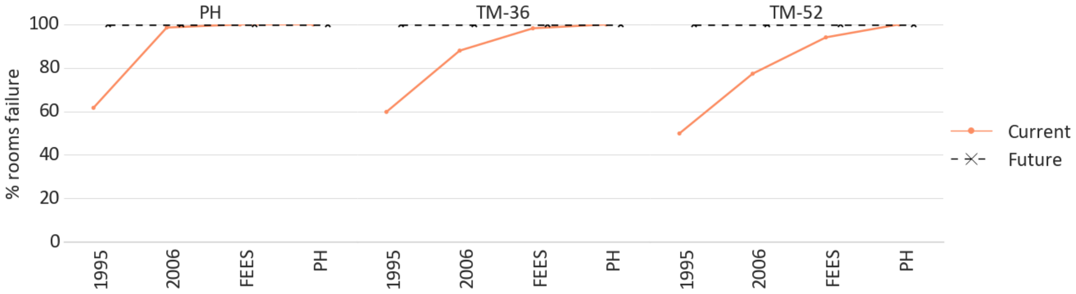
(b) Purge ventilation ‘Medium’



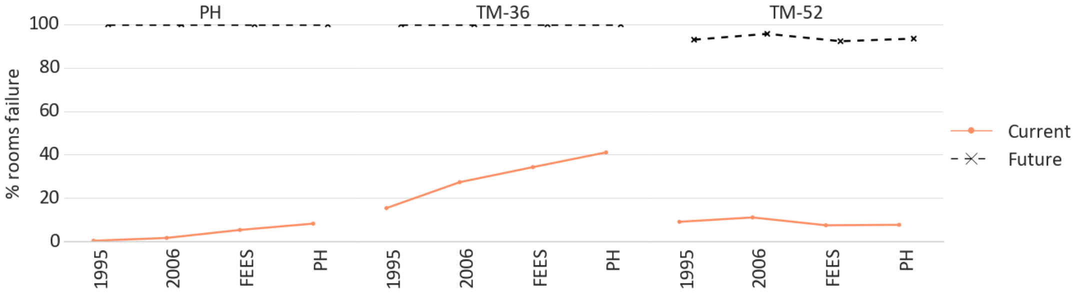
(c) Purge ventilation ‘High’

Figure A.6: Mean overheating weighted hours (Y-axis adapted per strategy)

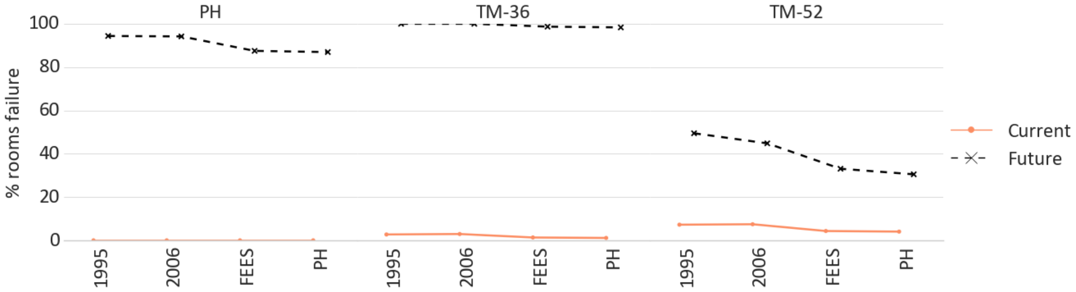
limit and the amount of time is unfavourable (28 °C–1 % of the occupied time against 25 °C–10 %). Remarkably, and unlike the previous, TM-52 captures reductions in the risk with improved building fabric under current climate. Nevertheless, only those by FEES are statistically significant in the future scenario (table A.9). These results contrast with the indicator breakdown shown earlier because small overheating is neglected in TM-52. This further reinforces that FEES and PH tend to maintain better indoor temperatures for $\Delta T \geq 1\,\mathrm{K}$ whereas they are more sensitive to smaller ones. Lastly, ‘high’ purge ventilation results also support these conclusions. The temperature offset from the maximum threshold not only lowers the risk substantially but also inverses trends in PH and TM-36 while demonstrating the effectiveness of better building envelopes.



(a) Purge ventilation ‘Low’



(b) Purge ventilation ‘Medium’



(c) Purge ventilation ‘High’

Figure A.7: Percentage of room per group failing their overheating criteria

A.7.4 Conclusions

Given past experiences of heat waves and the projections of climate change, researchers and practitioners need to be able to quantify their impact in the thermal environment. However, there is a lack of agreement in the methods to use. At the same time, the role of building fabric in overheating risk has been subject of numerous studies that have arrived at apparently contradictory conclusions. This paper has examined the criteria provided by PH and CIBSE to appraise the performance of four building envelopes and tested their coherence and suitability in the quantification of overheating.

The results demonstrate that available criteria can identify different overheating trends, depending on the considered occupant window opening behaviour and constructions. The TM-52 is deemed the most appropriate among the benchmarks considered because it was specifically derived from comfort evaluations in free running buildings and recommends sensible limits to duration and severity of discomfort. Nonetheless, none of them seem advisable as the only metric to appraise performance and further efforts are deemed necessary to improve the evaluation and communication of overheating risk. Moreover, it remains essential a better understanding of the properties of discomfort and health risks as assessment procedures rely heavily on them.

Results regarding overheating and building fabric are twofold. The combination of insulation, airtightness and ventilation for 1995 translates in lower overheating risk when purge ventilation is not available since the external temperatures are below the maximum comfort threshold most of the time. However, better building fabric arises as the best option against severe overheating or when windows are operated to reach the neutrality temperature in both current and future climates. Although further studies should extend these findings to other dwelling types, they suggest that the goals of lowering carbon emissions and the delivery of resilient and comfortable dwellings can align through improved building fabric.

A.8 Acknowledgements

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A.10 Appendix

Table A.7: Significance of statistical tests for hour count in fig. A.5

Purge	**Standard**	**Weather**	**Kruskal-Wallis**	**2006-1995**	**FEES-1995**	**PH-1995**	**FEES-2006**	**PH-2006**	**PH-FEES**
Low	PH	Current	***	***	***	***	***	***	***
Low	PH	Future	***	***	***	***	***	***	***
Low	TM-36	Current	***	***	***	***	***	***	***
Low	TM-36	Future	***	***	***	***	***	***	***
Low	TM-52	Current	***	***	***	***	***	***	***
Low	TM-52	Future	***	***	***	***	***	***	***
Medium	PH	Current	***	***	***	***	***	***	***
Medium	PH	Future	***	**	***	***	*	***	*
Medium	TM-36	Current	***	***	***	***	***	***	***
Medium	TM-36	Future	***	***	***	***	**	***	**
Medium	TM-52	Current	***	***	***	***	**	***	***
Medium	TM-52	Future	***	***	***	***	***	***	***
High	PH	Current	***			.	*	**	
High	PH	Future	***		***	***	***	***	
High	TM-36	Current	***		***	***	***	***	
High	TM-36	Future	***		***	***	***	***	
High	TM-52	Current	***			***		***	***
High	TM-52	Future	***		***	***	***	***	

p-values: $0 < \ast\ast\ast \leq 0.001 < \ast\ast \leq 0.01 < \ast \leq 0.05 \leq . < 0.1$

Table A.8: Significance of statistical tests for weighted hours in fig. A.6

Purge	**Standard**	**Weather**	**Kruskal-Wallis**	**2006-1995**	**FEES-1995**	**PH-1995**	**FEES-2006**	**PH-2006**	**PH-FEES**
Low	PH	Current	***	***	***	***	***	***	***
Low	PH	Future	***	***	***	***	***	***	***
Low	TM-36	Current	***	***	***	***	***	***	***
Low	TM-36	Future	***	***	***	***	***	***	***
Low	TM-52	Current	***	***	***	***	***	***	***
Low	TM-52	Future	***	***	***	***	***	***	***
Medium	PH	Current	***	***	***	***		**	**
Medium	PH	Future	***		**		***	**	
Medium	TM-36	Current	***	***	***	***	.	***	***
Medium	TM-36	Future	***	.	*		***	*	
Medium	TM-52	Current	***	***	***	***	*	***	***
Medium	TM-52	Future	***	***	***	***		*	**
High	PH	Current	***		**	***	***	***	
High	PH	Future	***		***	***	***	***	
High	TM-36	Current	***		***	***	***	***	
High	TM-36	Future	***	.	***	***	***	***	
High	TM-52	Current	***			***		**	***
High	TM-52	Future	***		***	***	***	***	

p-values: $0 < \ast\ast\ast \leq 0.001 < \ast\ast \leq 0.01 < \ast \leq 0.05 \leq . < 0.1$

Table A.9: Significance of statistical tests for percentage of rooms failing in fig. A.7

Purge	**Standard**	**Weather**	**Kruskal-Wallis**	**2006-1995**	**FEES-1995**	**PH-1995**	**FEES-2006**	**PH-2006**	**PH-FEES**
Low	PH	Current	***	***	***	***			
Low	PH	Future	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Low	TM-36	Current	***	***	***	***	***	***	
Low	TM-36	Future	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Low	TM-52	Current	***	***	***	***	***	***	**
Low	TM-52	Future	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Medium	PH	Current	***		***	***	***	***	***
Medium	PH	Future	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Medium	TM-36	Current	***	***	***	***	***	***	**
Medium	TM-36	Future	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Medium	TM-52	Current	**				**	*	
Medium	TM-52	Future	**	*			**		
High	PH	Current	n/a	n/a	n/a	n/a	n/a	n/a	n/a
High	PH	Future	***		***	***	***	***	
High	TM-36	Current	***		.	*	*	**	
High	TM-36	Future	***		***	***	***	***	
High	TM-52	Current	***		*	**	**	**	
High	TM-52	Future	***	.	***	***	***	***	

p-values: $0 < \ast\ast\ast \leq 0.001 < \ast\ast \leq 0.01 < \ast \leq 0.05 \leq . < 0.1$

Appendix B

Overheating and health risks in refugee shelters: assessment and relative importance of design parameters

B.1 Preamble

This work examines the role rational human thermal models could play in evaluating overheating given the shortcomings identified in the standard overheating criteria (appendix A). The goal is to expose alternative ways to quantify overheating through rational models and indices conceived for thermal stress and health risks. These are then applied to the evaluation of building features to show how these could inform the design process.

This appendix is based on the paper “Overheating and Health Risks in Refugee Shelters: Assessment and Relative Importance of Design Parameters” presented at the “PLEA International Conference: Design to Thrive” in 2017. This study was conducted as part of the HHftD project [grant number EP/P029175/1] to explore evaluation frameworks that could help inform shelter design decisions by governments, aid-agencies and dwellers. Details about the authorship of this paper are provided in table B.1. The corrigendum (appendix B.10) lists known issues with the publication, none of which influence the outcomes of the study.

B.2 Declaration of authorship

Table B.1: Declaration of authorship

This declaration concerns the article entitled:
Overheating and Health Risks in Refugee Shelters: Assessment and Relative Importance of Design Parameters

Publication status:
Published

Publication details:
D. Fosas, D. Albadra, S. Natarajan, and D. Coley (2017). "Overheating and Health Risks in Refugee Shelters: Assessment and Relative Importance of Design Parameters". *Proceedings of the 33rd PLEA International Conference: Design to Thrive.* PLEA International Conference: Design to Thrive. Ed. by L. Brotas, S. Roaf, and F. Nicol. Vol. 3. Edinburgh: NCEUB 2017, pp. 3746–3753.

Copyright status:
I hold the copyright for this material.

Candidate's contribution to the paper:
The author of this thesis has predominantly contributed to the publication (93 %). The contributions of each author are as follows:

1. Formulation of ideas: D. Fosas (85 %) and D. A. Coley (15 %).
2. Background: D. Fosas (80 %) and D. Albadra (20 %).
3. Design of methodology: D. Fosas (100 %).
4. Experimental work: D. Fosas (100 %).
5. Analysis: D. Fosas (100 %).
6. Preparation of manuscript: D. Fosas (100 %).
7. Editing drafts of manuscript: D. Fosas (85 %), D. Albadra (5 %), S. Natarajan and D. A. Coley (10 %).

Statement from Candidate:
This paper reports on original research I conducted during the period of my Higher Degree by Research candidature.

Signed **Date** 20 December 2019

B.3 Abstract

There are now more than four million refugees living in camps around the world. The majority of such camps are within inhospitable environments, often with extreme climates. This paper focuses on the thermal conditions of shelters in the Azraq refugee camp (Jordan), subject to an arid climate with high temperatures during the hot season. Due to political and other sensitivities, whole-, or multi-year monitoring of occupied shelters—and hence the empirical determination of overheating—is difficult. Instead, internal conditions in the shelters were monitored for three weeks in summer and used to validate computer models of the accommodation. These models were then used to generate annual predictions of overheating assessed through overheating criteria based on thermal discomfort and physiological indicators of heat stress. Building on these results, the performance of alternative designs specifications or shelter operation strategies were investigated through parametric analysis. The results show maximum indoor temperatures over 45 °C. Overheating thresholds were exceeded for more than 20 % of the year and physiological indicators suggest the possibility of health-threatening conditions. The use of alternative designs and strategies reduced overheating to nearly 2 % of the year, with a steep reduction of severe heat stress indicators.

B.4 Introduction

The current number of forcibly displaced population in the world is among the highest on records of which a third, 20 million, are refugees (UNHCR 2017). The refugees from the Syrian Arab Republic alone represent 23 % of the total refugee population with 4.9 million people. As part of the response to this crisis, they are often hosted in camps in neighbouring countries such as Turkey, Lebanon and Jordan. Given the location of camps and the severe conditions experienced in Jordan's climate, this paper investigates overheating discomfort and potential heat stress risk of refugees in these circumstances.

The thermal performance of shelters, and the indoor conditions they deliver, is a subject with a limited number of studies. One of the key concerns is the actual provision of a shelter as a humanitarian response. This constitutes a challenging task of paramount importance as it needs to deliver rapidly a scalable housing solution to an unexpected crisis of unknown duration. Among the few studies that focused on the thermal performance of shelters, there has been a greater number of studies dealing with cold environments (e.g. Crawford et al. (2005)) than hot ones (e.g. Cornaro et al. (2015)). This results in an underdeveloped area of research considering the number of people involved and the potential risks associated, especially for vulnerable occupants as children, one of the major refugee groups worldwide.

Consequently, this study evaluates the overheating risk in the Azraq refugee camp in Jordan (31.90°N, 36.58°E). Firstly, the application of different overheating metrics for discomfort and heat stress in the built environment is explored. Then, previous

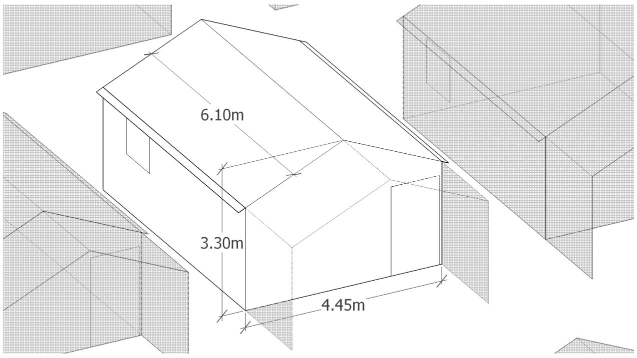

Figure B.1: Description of the T-Shelter in Azraq refugee camp

Figure B.2: Example of shelter interior

metrics are applied in the Azraq context to evaluate whether refugees are exposed to excessively hot indoor conditions regarding discomfort and heat stress. Lastly, the potential of passive strategies to reduce excursions from neutrality conditions to inform potential design improvements to current shelters is quantified. To accomplish these goals, the following hypotheses are established:

1. Refugees in considered shelters are exposed to indoor conditions outside the acceptable range established in the ASHRAE Std. 55 (2017).
2. Refugees in considered shelters are exposed to indoor conditions outside the recommended ranges for heat stress in the Pierce 2-node and PHS physiological models.
3. Current shelters cannot be optimized to avoid overheating discomfort through the passive measures considered.
4. Current shelters can be optimized to avoid severe heat stress through the passive measures considered.

B.5 Methodology

The study focuses on the Azraq refugee camp because of its exposure to the 'hot desert climate' (Köppen-Geiger zone BWh) and because it is based on a well-defined shelter design (figs. B.1 and B.2). As of April 2017, the camp hosts 53 914 refugees, of whom 57 % are under 18 years old. Due to security concerns —among other considerations—, the structure of the camp and the arrangement of shelters cannot be modified. Owing to these considerations, the study was conducted in two phases. The first is a three-week field study, during which surveys and spot measurements of environmental conditions were collected. The second extrapolates annual overheating conditions via building and human thermal simulations.

B.5.1 Field study

The field study was carried out from 31st August to 23rd September 2016. Here, randomly selected families completed a thermal and a social survey ($n = 36$). The thermal survey included ASHRAE Std. 55 (2017) guidelines whereas the social one focused on factors such as perceived security, privacy or adaptation opportunities. Shelter units were documented 'as built' to track any discrepancies between the original specification and their actual conditions (e.g. shading devices, openings, insulation location, actual occupation…).

B.5.2 Simulation

The data collected during the field study was used to calibrate and validate the base shelter simulation. The model is based on the design specification (UNHCR 2016), where the findings of the social survey and shelter inspections completed missing information (e.g. occupancy patterns) or overrode contradictory ones (e.g. as-built thermal insulation conditions).

The spot measurements of different shelters were combined into a single time series and split into two groups, one to calibrate the model and another one to validate it. Uncertainties regarding model inputs were constrained to the following variables: infiltration (unknown; bounds estimated following construction details), ventilation effectiveness (unknown; e.g. surroundings influence on wind speed or discharge coefficients), occupation (variable between shelters) and U-value (bounded range of conductivity and thickness). A set of 72 simulations were used to calibrate these parameters and then validated with the remaining monitored data (fig. B.3, E+ 8.6, NREL (2017)). The goodness of fit was evaluated through the peak and mean dissimilarities and the root mean square indicators (2.38, 0.36 and 1.47 K, respectively). Given the between-shelter variability and the uncertainties in parameters such as ventilation and infiltration, these results were regarded as adequate for the purposes of this study.

The validated model was then used to extrapolate annual overheating performance. Given the limitations to monitor typical external conditions throughout the year in this location, the weather files for surrounding ones were used to derive plausible ranges (Guriat (Saudi Arabia), Queen Alia International Airport (Jordan) and Safawi (Jordan)). In addition, the validated model forms the basis from which to explore design alternatives and shelter operation strategies (table B.2):

- 'Orientation' and 'Shading' focus on a different arrangement of shelter units that alters their solar heat gains globally.
- 'Insulation thickness', 'Thermal mass', 'Thermal mass location', 'Infiltration' and 'Opening effectiveness' address different design specifications. In the case of thermal mass, the baseline is the original lightweight construction (IBR sandwich

Table B.2: Parameters and cases to explore for the shelter design improvements (weather file: Guriat)

Parameter	**Cases**	**Comments**
Orientation [-]	[N, E, W, S]	One per cardinal direction.
Insulation [cm]	[1, 5, 10, 15]	Conductivity: $0.04\,\mathrm{W\,m^{-1}\,K^{-1}}$.
Thermal mass [-]	[light, heavy]	Light: current shelter composition. Heavy: 215 mm perforated brick and plaster.
Thermal mass location [-]	[internal, external]	Relative position to the indoor space.
Occupancy [p]	[6, 12]	Original shelter design aims for 6 p and surveyed occupation frequently reached 12 p.
Shading [-]	[none, full]	None: current solar exposure (see fig. B.1). Full: completely block solar radiation.
Ventilation strategy [-]	[daytime, always]	Daytime: as needed during 7–23 h. Always: as needed (constant occupation).
Infiltration [-]	[original, reduced]	Original: current shelter estimated infiltration. Reduced: 25 % of the previous value.
Opening effectiveness [%]	[10, 40, 70]	Multiplicative factor for opening areas. 10 % is the fitted value in the calibration and 70 % a value around illustrative reference levels (ASHRAE 2013).
Total	**3072 models**	Every parameter-case combination.

panel with 15 mm insulation). The alternative is a heavyweight envelope with a decrement delay[1] of 12 h which aims to take advantage of the diurnal swing in desert climates.

- ‘Occupancy’ and ‘Ventilation strategy’ assume the same building characteristics but with different occupancy densities or operation modes. A minimum ventilation of $8\,\mathrm{L\,s^{-1}\,p^{-1}}$ is considered despite the purge ventilation strategy.

B.5.3 Human thermal models

Refugees do not have access to electricity and the main cooling strategy at building level is natural ventilation. The social survey highlighted that coping mechanisms against

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[1] The time difference between external and internal peak temperatures in a 24-hour period.

heat were mainly to shower, to pour water onto themselves with their clothes on and to spray water on the floor. Other parameters such as clothing were adjusted within certain ranges (average summertime clothing insulation between 0.50 ± 0.07 clo (male) and 0.93 ± 0.05 clo (female)).

Annual overheating is first evaluated via the adaptive comfort model according to ASHRAE Std. 55 (2017), calculating the running mean as the exponential moving average of outdoor temperature, $T_{rm}(\alpha = 0.8)$. Discomfort is evaluated through the temperature difference between the internal operative temperature and the adaptive comfort upper limit ($T_{lim} = 0.31 \cdot T_{rm} + 21.3$). Illustrative limits of discomfort are established at 1 % and 3 % of the annual occupied time since the ASHRAE model does not suggest one. These values are on the lines of European recommendations (BSI 2007; CIBSE 2013) for temperature differences greater than 1 K over the adaptive comfort upper limit.

Heat stress is evaluated through two rational thermal physiological models:

1. Pierce 2-node model: This is the updated version of the Pierce 2-node model (Gagge et al. 1971; Fountain and Huizenga 1997). It considers air and radiant temperatures, relative humidity, activity level, work efficiency, clothing and air velocity. The DISC is used to report heat strain as this index normalizes the effect of the inputs on the thermoregulatory system in a 7-point scale (-3 severe cold strain, 0 neutrality, $+3$ severe heat strain).

2. PHS: ISO method (BSI 2004) to evaluate heat strain through required sweating and changes in the deep body temperatures presented by Malchaire et al. (2001).

The Pierce 2-node and the PHS models present technical barriers for their adoption in building simulation studies. Although the first one is included in E+, the user must introduce time-varying values for air speed and certain assumptions cannot be adjusted. The PHS is not part of building simulation suites and its implementation is computationally intensive for annual studies in large parametric analyses.

To overcome these issues, the models were implemented and validated numerically in a standalone application. For this study, the air speed has been estimated through the time-varying natural ventilation air flow divided by the cross-section of the shelter unit and fed into the calculation of operative temperatures (CIBSE 2013). Regarding clothing, the aforementioned average of 0.93 clo has been considered as a representative value.

B.6 Results

B.6.1 Current shelters

The results for extrapolated annual overheating in current shelters under typical weather conditions are presented in fig. B.4 (discomfort), fig. B.5 (Pierce 2-node) and fig. B.6

(PHS). For the first two, severity is reported in the X axis (binned) and duration is reported in the Y axis for the three locations[2]. The PHS model follows an independent assessment scheme[3].

The discomfort evaluation (fig. B.4) shows that the adaptive thermal comfort upper limit is surpassed for more than 20 % of the time, well beyond the maximum 1 % (annual) or 3 % (seasonal) illustrative limits. Of special concern is that more than 12 % of the time the overheating is severe ($\Delta T \geq 4\,°\mathrm{C}$), a trend that is consistent in the three locations considered.

The heat strain measured via the discomfort index in the Pierce 2-node model (fig. B.5) indicates an unacceptable indoor environment from the physiological perspective, with a cumulative average greater than 20 %. Unlike the previous, votes follow a diminishing progression towards greater strain. However, durations in the severest bins are well beyond what is deemed appropriate for comfort conditions.

The PHS provides greater insights to evaluate potential health risks. Here, each day of the annual building simulation is considered independent and simulated from 9 to 17 h (a best-case scenario since physiological indicators are reset for the following day). Figure B.6 shows the percentage of days where limits for each variable are surpassed. Despite occupants were considered adapted to hot conditions and able to drink water as required, the water loss due to sweat is evaluated excessive for 95 % of the population for more than a third of the year and greater than 2.5 % for the mean subject. A complementary indicator is the change in rectal temperature. Here, the upper limit of 38 °C ($\Delta T = +1.2\,\mathrm{K}$) is surpassed in the three locations (≈0.28 %, one day, for Queen Alia). Therefore, the evaluation indicates that indoor conditions cause both excessive water loss and changes in the deep body temperature in the refugee shelters under typical weather conditions.

B.6.2 Relative importance of design parameters

The main effects for each of the 23 parameter-case in the 3072 model variants are presented in fig. B.7 for discomfort duration and ranges of internal temperatures in fig. B.8. Although this is an overview of performance, it is noticeable how 18 out of the 23 parameter-case span the wide minimum–maximum value range (≈2.5 % and ≈20 %, respectively). This indicates that shelters can be greatly optimized to cope with the hot desert climate despite the limited passive strategies considered.

Of paramount importance are insulation thickness, thermal mass and shading: they have a determining impact no matter the values of remaining variables. Additionally, they constitute robust solutions that do not depend on occupant behaviours. Changing insulation from 1 cm to 5 cm onwards almost halves the maximum overheating, although 1 cm can deliver 3 % overheating if care is taken in every other design parameter. The

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[2] GU: Guriat (Saudi Arabia), QA: Queen Alia International Airport (Jordan), SA: Safawi (Jordan).

[3] T_{re}: Rectal temperature limit surpassed, S_X: Sweating limit surpassed for X% of the population.

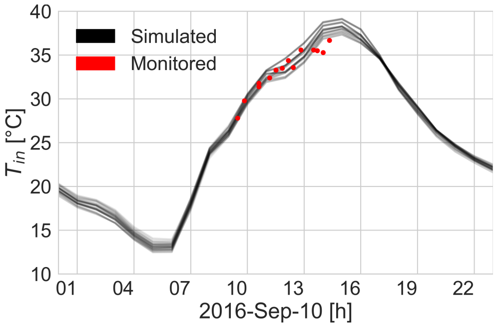

Figure B.3: Current shelters: example of measured indoor conditions (red, $n = 14$) and simulated models (black, $n = 72$) over 24 h

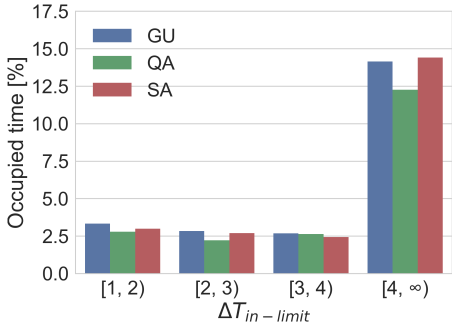

Figure B.4: Current shelters: extrapolated annual overheating according to the Adaptive Thermal Comfort model (ANSI/ASHRAE 2017)[2]

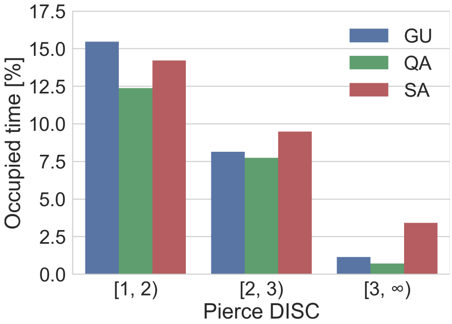

Figure B.5: Current shelters: extrapolated annual overheating according to Pierce 2-node DISC[2]

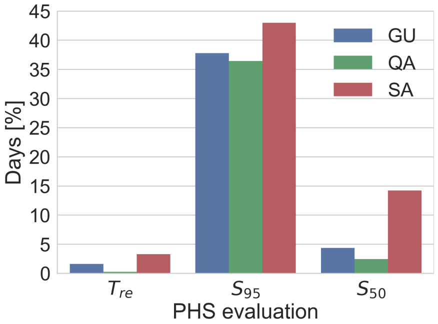

Figure B.6: Current shelters: extrapolated annual overheating according to PHS[2,3] (n.b. Y axis scale)

provision of sufficient thermal mass as to achieve a 12 h decrement delay proves to be the most effective solution—even for 12 p occupancy (high internal gains)—, whereas the theoretical maximum shading performs similarly to 5 cm insulation. Lastly, the fact that external thermal mass scores a minimum of 4 % suggests that retrofitting shelter envelopes from the exterior could be an effective overheating countermeasure; notwithstanding, internal thermal mass is preferable.

The best, median and worst cases (table B.3) are analysed in the same way as the current shelters. Figure B.9 highlights how the best case can diminish overheating duration to 2.2 % while avoiding severe overheating ($\Delta T \geq 4\,\mathrm{K}$). The heat strain (fig. B.10) features an equivalent reduction in overheating, with the median model avoiding the range $[3, \infty)$. Lastly, excessive water loss due to sweating can be completely avoided for the mean subject or greatly diminished for the 95 % population and changes in the deep body temperature can be kept below the recommended threshold in every case throughout the year (fig. B.11).

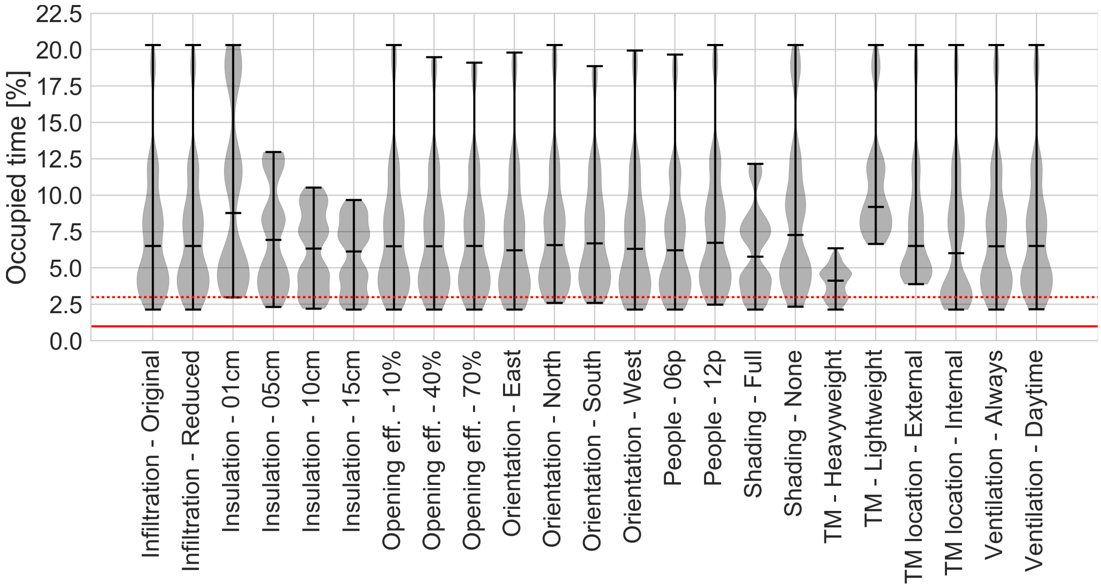

Figure B.7: Overheating discomfort in proposals: main effects (plot indicates minimum, median and maximum (black segments) and variable distribution (shaded area); illustrative overheating thresholds in red: 1 % and 3 %)

Table B.3: Proposals: best, median and worst cases according to annual overheating discomfort duration

Orientation	Insulation [cm]	Thermal mass	Thermal mass location	People [p]	Shading	Ventilation	Opening effect. [%]	Infiltration	Overheating time [%]
E	15	Heavyweight	Internal	6	Full	Always	40	Original	2.2
S	1	Heavyweight	External	12	None	Daytime	70	Reduced	6.4
N	1	Lightweight	Internal	12	None	Daytime	10	Reduced	20.3

B.7 Conclusions

The provision of adequate shelter for refugees is becoming an even more pressing issue than ever before given the increasing number of people involved worldwide. Owing to different humanitarian crises, refugees are often allocated in camps subject to harsh environments that can represent a threat to their health and wellbeing. Therefore, this paper presented the study of indoor thermal conditions in the Azraq refugee camp (Jordan) to evaluate the annual overheating risk of refugees from a discomfort and health risk perspective. Based on a three-week field study during summertime in the camp, overheating exposure was evaluated through adaptive thermal comfort and physiological models for heat stress. Extrapolated annual conditions via building and human thermal simulation suggest that refugees are subject to overheating for more than 20 % of the year, surpassing recommended physiological thresholds for heat stress. Building on

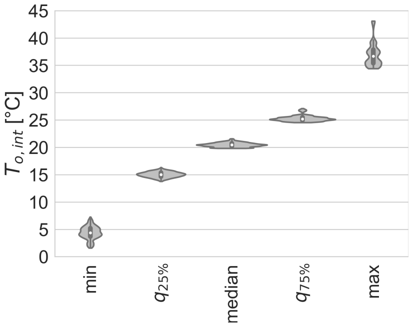

Figure B.8: Proposals: indoor operative temperature ranges ($n = 3072$; values computed independently for each case and aggregated into each violin plot).

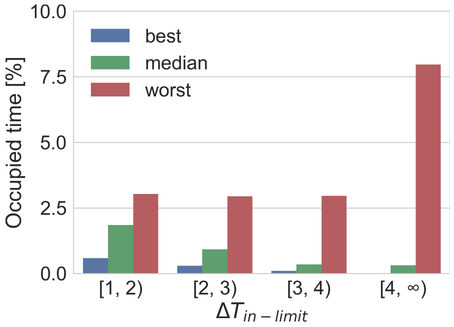

Figure B.9: Proposals: extrapolated annual overheating according to the Adaptive Thermal Comfort model (ANSI/ASHRAE 2017).

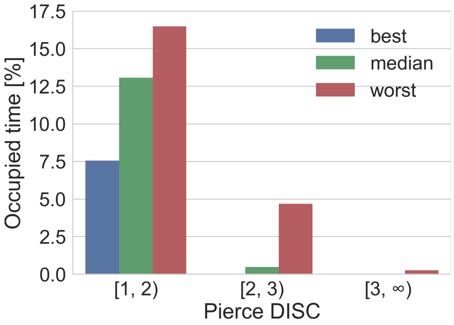

Figure B.10: Proposals: extrapolated annual overheating according to Pierce 2-node DISC

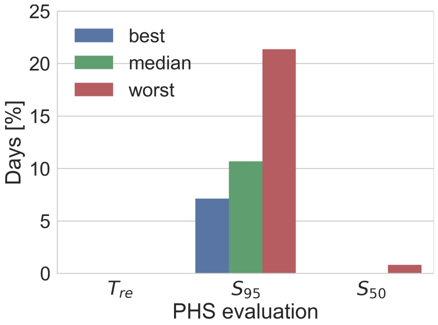

Figure B.11: Proposals: extrapolated annual overheating according to PHS[3] (n.b. Y axis scale) the efforts of involved agencies, the study presented a parametric analysis of passive strategies in 3072 shelter variants. Results indicate that considered measures can reduce overheating to 2.3 % of the year, with a drastic reduction in associated heat stress.

B.8 Acknowledgements

This research was funded by the Engineering and Physical Sciences Research Council (EPSRC) [grant number EP/P029175/1] and was conducted in collaboration with the Princess Sumaya University for Technology (PSUT) in Jordan, the UNHCR Jordan and the NRC Jordan. We thank the families surveyed and all those who facilitated the study, including Prof Abdullah Alzoubi, Dr Omar Bani-Ahmad Otum, Ahmad Otum, Ahmad Muhaisen, Zain Aboabeid and Shaghayegh Mohammad. Daniel Fosas appreciates the support of the ‘EPSRC CDT in the Decarbonisation of the Built Environment (dCarb)’ [grant number EP/L016869/1] and the ‘laCaixa’ Foundation. This research made use of the Balena HPC service at the University of Bath.

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B.10 Corrigendum

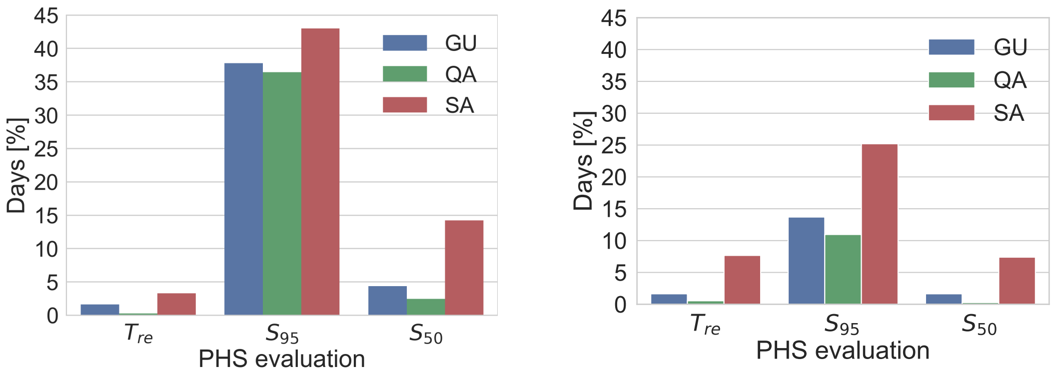
The following errors have been detected in the study:

1. Occupant parameters of the PHS model (table B.4) were not propagated correctly throughout the calculations, which affected the quantification of heat stress according to the PHS model. The original and corrected versions are reproduced together for clarity (figs. B.12 and B.13). As shown, the overall results still portray severe heat stress and does not affect the conclusions of the study.

2. The Discomfort index (DISC) is reported as a "7-point scale (−3 severe cold strain, 0 neutrality, +3 severe heat strain)" (appendix B.5.3) whereas it should have read a "5-point scale, with 0 describing comfortable conditions and 5 intolerable" as properly indicated in the journal publication (section 3.6.2).

Table B.4: Occupant parameters for the PHS model

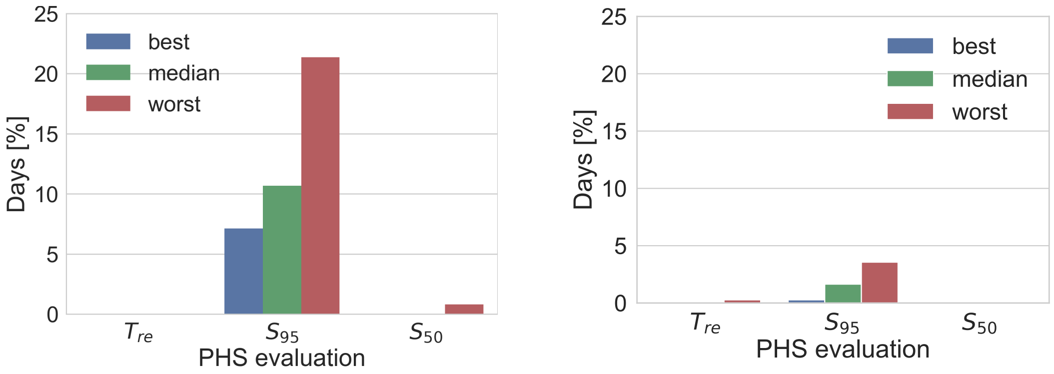
Parameter	**Units**	**Value**
Drink	—	True
Weight	kg	66
Height	m	1.6
Met	$\mathrm{W\,m^{-2}}$	80
Work	$\mathrm{W\,m^{-2}}$	0
Posture	—	Standing
Clothing insulation	clo	0.93
Clothing – permeability index	—	0.38
Walk speed	$\mathrm{m\,s^{-1}}$	0
Walking direction	—	Omnidirectional
Acclimatised	—	True



(a) Original (as published)

(b) Correction

Figure B.12: Corrections to fig. B.6 – “Current shelters: extrapolated annual overheating according to PHS^{2,3} (n.b. Y axis scale)”



(a) Original (as published)

(b) Correction

Figure B.13: Corrections to fig. B.11 – “Proposals: extrapolated annual overheating according to PHS^{3} (n.b. Y axis scale)”

Appendix C

Weather files for remote places: Leveraging reanalyses and satellite datasets

C.1 Preamble

Weather files constitute a fundamental input for the evaluation of building thermal performance through simulation, markedly so in the case of overheating studies. Despite its importance, there used to be a poor world coverage of publicly available weather files. As argued in the study, the reasons were a limited spatio-temporal coverage of weather stations with complete weather records at the right frequency — usually hourly for thermal performance studies. In this study, reanalysis and satellite-based datasets are explored to fill in the gaps of historical weather station data for the location of interest. These provide an emerging resource that combines direct on-site and remote observations with climate models for a homogeneous spatio-temporal coverage potentially apt for the simulation of building thermal performance.

Overall, this can be understood as an ephemeral problem considering the increase in the number of active weather stations worldwide. For instance, Crawley and Lawrie (2019) released an unprecedented number of weather files with a largely improved global land coverage using weather station data between the years 2003 and 2017. Yet, reanalyses and satellite-based datasets could still provide useful historical data that spans several decades, which could then be used to reconcile past observations of building thermal performance.

This appendix is based on the paper “Weather Files for Remote Places: Leveraging Reanalyses and Satellite Datasets” presented at the “1st International Conference on Data for Low Energy Buildings” in 2018. This study was conducted as part of the COLBE project [grant number EP/M021890/1] and the HHftD project [grant number EP/P029175/1] to explore ways in which weather files for camps far from publicly available weather stations could be defined. Details about the authorship of this paper are provided in table C.1. The corrigendum (appendix C.11) lists a known issue with the publication which does not affect the outcomes of the study.

C.2 Declaration of authorship

Table C.1: Declaration of authorship

This declaration concerns the article entitled:
Weather Files for Remote Places: Leveraging Reanalyses and Satellite Datasets

Publication status:
Published

Publication details:
D. Fosas, M. Herrera, S. Natarajan, and D. A. Coley (2018e). “Weather Files for Remote Places: Leveraging Reanalyses and Satellite Datasets”. *1st International Conference on Data for Low Energy Buildings.* 1st International Conference on Data for Low Energy Buildings. Murcia: Diego Marín, Murcia, pp. 14–19.

Copyright status:
I hold the copyright for this material.

Candidate’s contribution to the paper:
The author of this thesis has predominantly contributed to the publication (95 %). The contributions of each author are as follows:

- Formulation of ideas: D. Fosas (100 %).
- Background: D. Fosas (90 %) and M. Herrera (10 %).
- Design of methodology: D. Fosas (90 %) and M. Herrera (10 %).
- Experimental work: D. Fosas (100 %).
- Analysis: D. Fosas (100 %).
- Preparation of manuscript: D. Fosas (100 %).
- Editing drafts of manuscript: D. Fosas (90 %), M. Herrera, S. Natarajan and D. A. Coley (10 %).

Statement from Candidate:
This paper reports on original research I conducted during the period of my Higher Degree by Research candidature.

Signed **Date** 20 December 2019

C.3 Abstract

Weather files capture the time-varying conditions under which buildings perform and, as such, they constitute one of the fundamental inputs for building performance simulation. In theory, the creation of weather files only requires collecting data at a certain frequency for a key number of variables during the time of interest. In practice, several problems arise. Direct measurement on a project basis can be a costly operation considering the site accessibility and the number of instruments needed to collect complete weather observations. Sometimes, this is simply impossible if a study requires historical data. These issues are traditionally overcome using the weather data collected at a nearby public weather stations, but this can be equally challenging, or even impossible, depending on how far away the station is and the frequency and completeness of observations.

Arising from the need to simulate the thermal performance of buildings at remote locations, this study presents an approach to generate weather files based on satellite imaging and reanalysis datasets. Given the good agreement with local station's observations, it is shown how these publicly available datasets can be combined to create weather files suitable for building performance simulation. This is applied to a case study to compare the performance of a building and its systems against traditional weather files. The work quantifies and discusses the discrepancy obtained between the different sources. Overall, results indicate that satellite and reanalysis datasets constitute a suitable resource to create weather files for building performance simulation.

C.4 Introduction

One of the fundamental roles buildings have is the provision of indoor environments in which human activity can thrive, given a changing outdoor environment that is frequently uncomfortable and, at times, even inhospitable. This requires buildings that mediate successfully the energy exchange between these environments, a task they can accomplish through two mechanisms: passive energy transfers and active energy counterbalances. Among others, the former involves adequate envelope characteristics and occupant behavior; the latter fueled systems that, in the pursuit of adequate indoor environments, currently account for 10 % of the total energy consumption in the world (IEA/OECD 2013; IEA 2018). Therefore, and regardless of the mechanism employed, the external environment is at the core of the energy exchanges that drive building design, operation and energy consumption (CIBSE 2017).

In the last decades, Building Performance Simulation (BPS) has been established as a prominent tool for researchers, policy makers and professionals due to the influence buildings have not only on occupants' health and well-being, but also on the economy and carbon emissions (Clarke 2001; CIBSE 2015). Following a conceptualized model of the mechanisms that arise in real life, one of the central inputs for BPS is a representation of the environment surrounding building components (Clarke 2001; Crawley et al. 2001). This has been, over time, parameterized in the so-called ‘weather files’, files that describe the most basic and relevant environmental variables in a model (e.g. air temperature, relative humidity, solar radiation, wind characteristics) (Crawley et al. 1999; Herrera et al. 2017).

Despite the role weather files play, one of the barriers yet to overcome is their worldwide coverage and availability. The creation of weather files requires collecting data for the essential variables for the problem at hand, and at a certain frequency, with weather stations (CIBSE 2017; Crawley et al. 1999; Herrera et al. 2017; ASHRAE 2017). This is typically achieved using weather stations of the World Meteorological Organization (WMO) (Smith et al. 2011) given the difficulties and costs associated with private weather monitoring. However, the spatial and temporal distribution of these stations — and the suitability of the data they collect to create weather files — vary greatly. A weather station might not be close enough to the location of interest to accurately describe weather conditions, there might be missing variables or values (e.g. solar radiation), the frequency of records might be unsuitable for BPS (e.g. daily means), there might even be no records at all for the time span of interest, or a combination of all the previous.

These issues have motivated a large body of research to maximise the amount of usable weather information for weather files (e.g. Hensen and Lamberts (2011), Perez et al. (1990), Ineichen et al. (1992), NREL (2018a), and Underwood and Yik (2004)). Research projects and organizations have analyzed data resources and applied a variety of models and assumptions to this extent, but their land coverage still features serious limitations, depending on the location of interest, and often require a paid licence (CIBSE 2017; ASHRAE 2017; Thevenard and Brunger 2002a; Thevenard and Brunger 2002b; Meteonorm 2018). Building on these efforts, and thanks to the collaboration of many institutions, the United States of America Department of Energy (DOE) offers one of the most popular services that index freely available weather files (NREL 2018b; Crawley and Lawrie 2018). An overview of this resource shows a total number of 2590 weather files, that is, a world average of 1 weather file per a 227-kilometer-side square in land (NREL 2018b; World Bank 2018). This is clearly insufficient to capture the weather variability between locations. Yet, these figures largely depend on the country under consideration. For instance, the USA features 1478 weather files (57 % of the dataset), while other countries a have a substantially smaller coverage, if any.

Parallel to these developments and discussions, there has been active monitoring campaigns of the Earth’s climate. As a result, there are products available that have resulted from direct and indirect measurements, local and remote, or derived through the new and refined models based on these campaigns. The promising advantages of these resources are their vast spatio-temporal coverage, consistency, quality assurance and public availability. However, routinely applications to weather files as a whole in BPS could not been found in the surveyed literature, albeit notable exceptions: the use of satellite solar radiation data (ASHRAE 2017; Hensen and Lamberts 2011; Meteonorm 2018), ASHRAE's numerical model to adjust weather observations (Qiu et al. 2015) and the work by Lundström for Northern Europe based on mesoscale datasets (Lundström 2016; Lundström 2017). Unfortunately, it is unknown if and how weather files can be generated based on these kinds of datasets and how they compare to the traditional approach based on weather stations.

Due to these limitations and opportunities, this work hypothesizes that large-scale datasets resulting from the Earth's monitoring campaigns and models can be used to create weather files for BPS. In particular, the objectives are to discuss the creation of weather files based on these datasets and their comparison against traditional weather files from public and private resources. A case study is carried out based on a residential model and the needs of the Healthy Housing for the Displaced project (HHftD) to simulate the performance of buildings that are often located in remote locations.

The work is organized as follows. Firstly, the creation of weather files for a common BPS engine is discussed, suitable data resources are identified, and the case study is introduced. Next, the results and discussion are presented and structured around three aspects: (1) the comparison of weather observations between the local weather station of the Healthy Housing for the Displaced (HHftD) project and those found in the new resources, (2) the application of the nearest publicly available weather files against their independent recreation with the new datasets and (3) overall performance of the new weather files for the remote location against seven weather files from two independent sources. Lastly, appendix C.7 presents the concluding remarks.

C.5 Methodology

C.5.1 Weather files for building performance simulation

Among all the available options, EnergyPlus Weather file (EPW) constitute the most popular weather file format for BPS (Herrera et al. 2017) and is thus taken as the reference format for this study. The EPW format was proposed in 1999 to overcome the limitations already experienced with previous approaches, and it established the weather file format for two open-source and well-validated BPS engines widely used in research, ESP-r and E+ (Crawley et al. 1999). Besides these, nowadays other BPS software accept this weather file format, either directly or indirectly via conversion (e.g. IES, TRNSYS, DesignBuilder, TAS).

The EPW specification is open and based on a loosely defined schema implemented as a comma-separated value text file. Therefore, EPW files are transparent to the user and can be readily inspected. Internally, the file is divided into two sections, a 'header' and a 'body'. Components and fields are identified by the position they occupy since most are unlabeled (Crawley et al. 1999; NREL 2018a).

The header comprises the first 8 lines of the EPW and it describes: (1) the location of the weather file, including name, region, country, type of weather file, WMO station ID, latitude, longitude, time zone and elevation; (2, 3) a brief description of design and typical/extreme weather conditions, which could be used, for example, to size building systems; (4) thermal characteristics of the ground and its monthly average temperatures; (5) a description of holidays and daylight saving periods; (6, 7) space reserved for arbitrary comments; (8) a summarized description of the data in the second section, the ‘body’.

The body spans from line 9 onwards and it describes the actual observations time series. These are provided for variables that can change significantly between timesteps, together with source and uncertainty metadata. For example, the body includes variables such as air temperature, solar radiation and wind, whereas ground temperatures are described in the header with monthly values. The frequency and number of observations are flexible, although hourly observations over a year is a common choice (i.e. 8760 or 8784 records for leap and non-leap years, respectively). The minimum number of variables (columns) in the body is 33 and the maximum 35, where the last 3 columns provide complementary information for selected variables (see Crawley et al. (1999) and NREL (2018a) for a comprehensive list).

Two key remarks are important for this work. Firstly, not all the information present in a weather file is necessarily used by a BPS software. Secondly, missing values can be specified for selected fields. This means that the actual interpretation of an EPW file unavoidably relies on the BPS engine used. Here, the engine E+ is chosen to continue the discussion and carry out the study, given the widespread use this software has in research and commercial applications, its open-source code and its tight integration with the EPW format.

As of the latest stable version available at the time of this work (version 8.9), the following observations can be made regarding the use of EPW and the aims of this study. These are based on the documentation, cross-checked with the source code and tested with sample cases and selected EPW files from ASHRAE. Whenever missing or contradictory information was found, the source code version prevailed.

1. The information in the EPW header can be overwritten by the E+ model as they often depend on the building or site characteristics rather than the weather’s.

2. The following time series variables are used by E+: (1, 2) Date and time information; (3) dry bulb temperature; (4) dew point temperature; (5) relative humidity; (6) atmospheric pressure; (7) horizontal infrared sky radiation (if missing, it can be estimated through the opaque sky cover); (8, 9) direct and diffuse solar radiation; (10, 11) wind direction and wind speed. In addition, surface convection and reflectance models need to know if surfaces are wet and if there is snow on the ground. If present, this information is derived from one or more of the following

columns: (12) present weather observations, (13) present weather codes, (14) snow depth and (15) liquid precipitation depths. Otherwise, E+ defaults to dry surfaces and no snow conditions.

C.5.2 Alternatives to weather station data for weather files: the MERRA-2 and CAMS datasets ('ReaSat')

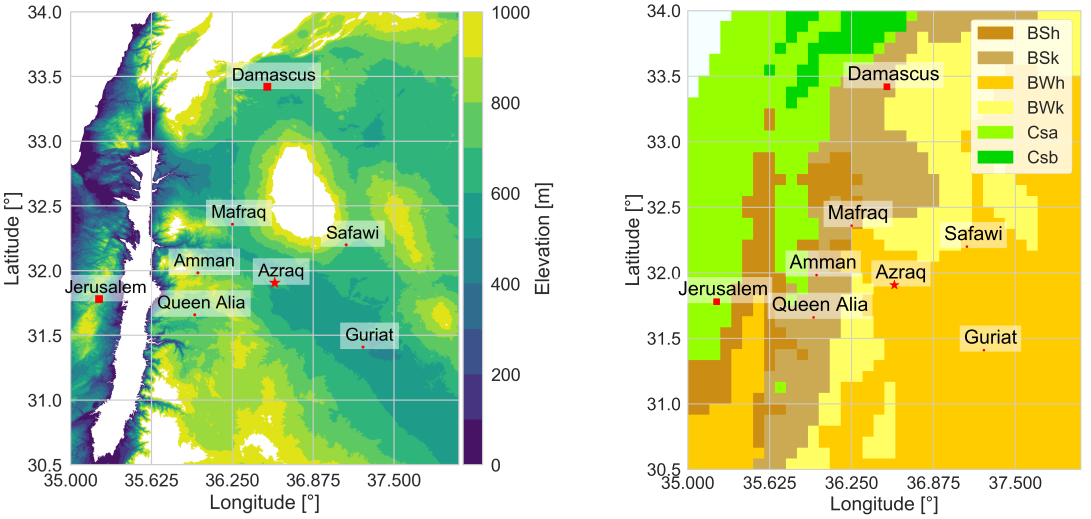
Given the information required, two products have been identified to construct the essential information for EPW files in E+. The first is the MERRA-2 presented by Gelaro et al. (2017). MERRA-2 is a comprehensive reanalysis of a wide number of observing systems. This means that different observations are integrated into a resource that, via a forecast model, produce a coherent dataset with homogeneous spatial coverage (Gelaro et al. 2017). MERRA-2 data is publicly available, and it features worldwide gridded variables at about 50 km, in hourly intervals since 1980 (Global Modeling and Assimilation Office 2015). The following variables are directly obtained: air temperature, relative humidity, atmospheric pressure, wind direction, wind speed, rainfall and snow depth. The dew-point is then obtained through phsychrometric relationships. Lastly, the present weather observations and codes are adjusted according to rainfall and snow depth.

The second product identified for the creation of weather files is the 'Copernicus Atmosphere Monitoring Service' radiation service version 3 (here referred to as 'CAMS') (Qu et al. 2017). This service integrates satellite observations through a series of models to create a comprehensive dataset for solar radiation, and atmospheric composition (Schroedter-Homscheidt et al. 2017). Data is available from February 2002 onwards, and the spatial coverage of this service is roughly the area comprised between ±66° for both longitudes and latitudes in a 3-kilometer grid. For this study, data at 1 min intervals were used to obtain the remaining variables for the EPW file. The variables retrieved here are: global, diffuse and direct solar radiation, cloud coverage and albedo. It must be noted that not all of them are strictly required for the EPW. Yet, the cloud coverage allows the calculation of the horizontal infrared sky radiation, the albedo informs inputs for the BPS model surroundings and the global horizontal radiation can be compared to weather station observations, as shown in the next sections. The main limitation is that the albedo and cloud coverage are derived variables from solar radiation observations and they are not available at night time. As an approximation, they were filled in via linear interpolation.

C.5.3 Case study

To fulfill the aims of this work, a case study is devised based on the location of the refugee camp of Azraq (Jordan, fig. C.1). The weather at this location is partly monitored by the HHftD project given that the nearest WMO weather stations are approximately 60 km away. Commercial weather files are available based on those WMO stations, which fill any gaps in observations through a number of models (Meteonorm 2018). Lastly, the closest freely available weather files for this location are those of Jerusalem and Damascus (approximately 130 and 180 km away from Azraq, respectively; International Weather for Energy Calculation (IWEC) EPW files (Thevenard and Brunger 2002a; Thevenard and Brunger 2002b)).

Despite the large number of variables captured in weather files, they do not impact building performance equally. Bearing in mind that MERRA-2 and CAMS are routinely validated, the interest here lies in quantifying how different is the performance of a building under weather files derived from these sources (here termed ReaSat weather files) when compared against traditional approaches (weather files around the location of interest). For this, the detached house prototype at DOE (U.S. Department of Energy 2013) was adapted to E+ v8.9 and simulated under these different weather file versions. The selected model version was that for the 2006 International Energy Conservation Code, located in Phoenix (Arizona) and with a heat pump. The reasons for this choice are that Phoenix's climate (BWh) is the same as Azraq's and that the heat pump provides both space cooling and heating. Therefore, this allows the comparison of building performance in cold and hot seasons and avoids the modelling complexities of naturally ventilated buildings.



(a) Elevation (values clipped to 0–1000 m range, out-of-range values in white; elevation data from Jarvis et al. (2008))

(b) Köppen Geiger climate zone classification (climate zone data from Kottek et al. (2006) and Rubel et al. (2017))

Figure C.1: Locations considered in the study (symbols: the 'star' indicates the location of interest; 'dots' the closest commercial weather files; 'squares' two of the closest publicly available weather files; plot grid as per MERRA-2 structure)

C.6 Results and Discussion

C.6.1 ReaSat versus on-site and nearby weather stations

Both MERRA-2 and CAMS are gridded datasets at 50-km and 3-km intervals, respectively. Hence, the first potential concern is their spatial representativeness within a grid cell. Although data could be adjusted in several ways, it is still of interest their comparison against on-site observations.

The results on fig. C.2 compare observations for two of the most important weather variables in BPS. In fig. C.2(a), the ReaSat version provides a better fit for the local observed values than the one obtained with 'nearby' WMO station (near Safawi). Noting that the WMO station is further into the desert (fig. C.1), this disagreement is deemed reasonable. Traditional goodness-of-fit metrics allow quantifying the disagreement between two signals. The MBE, a measure of the overall average disagreement, yields 1 % for the 'ReaSat-Local' pair, and 8 % for the 'Nearby-Local' one. Similarly, the CV(RMSE) provides a measure of the disagreement of values at time-step level, resulting in 4 % for 'ReaSat-Local' and 9 % for 'Nearby-Local' pairs.

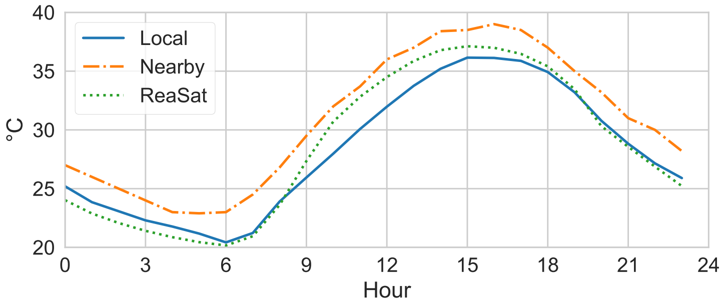
Figure C.2(b) shows a frequent situation where solar radiation data is not available in a nearby weather station. Yet, the agreement between the on-site monitored values and those obtained for the ReaSat version is remarkable (MBE ≈0 %; CV(RMSE) ≈14 %) and better than those typically accepted in modelled solar radiation for weather files to decompose global horizontal into diffuse and direct components (Ineichen et al. 1992).

Although the on-site monitoring period is limited (10 d), these results indicate good agreement between local measurements and the MERRA-2/CAMS observations. Overall, the latter was a preferable alternative to WMO station data.

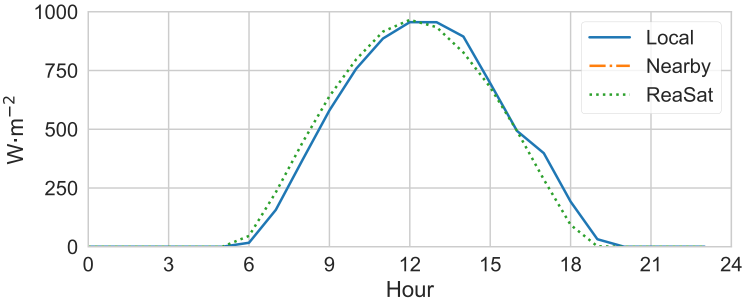
C.6.2 ReaSat versus selected IWEC weather files

A second test for the new weather files is the recreation of existing ones. Figure C.3 shows the results for the two cases under consideration, Jerusalem and Damascus. The same kind of weather file (IWEC) was chosen for both locations to simplify the analysis. IWEC files are one of the many approaches to create 'typical year' weather files: files that attempt to capture average weather conditions for a location based on a mixture of observations from several years. For this study, the main problem is that these files are based on historical weather data prior to 2002 and is thus outside CAMS temporal coverage. An alternative approach is taken based on 13 individual weather files corresponding to the years 2005–2017. Assuming IWEC files faithfully represent a typical year, the closer the 2005–2017 ReaSat simulation are to that of the IWEC one, the greater the confidence in the new weather file generation framework.

Results are twofold. Those for Jerusalem show a poor agreement with the reference IWEC weather file (fig. C.3(a)) whereas those for Damascus show a good overlapping



(a) External dry bulb temperature (ReaSat values from MERRA-2)



(b) Global horizontal radiation (n.b. missing data for 'nearby' case, ReaSat values from CAMS)

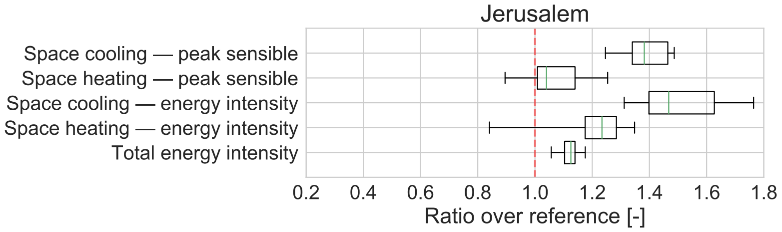
Figure C.2: Comparison of time series summarized in an 'average day' (monitoring period: from 2017-08-10 until 2017-08-20; 'local': on-site weather station, 'nearby': nearest WMO station (WMO 402650, 60 km away from the location), 'ReaSat': obtained from MERRA-2 and CAMS data).

between the ReaSat 2005–2017 range and the reference values (fig. C.3(b)). Reasons for this outcome can be given on fig. C.1. There, it is shown how site characteristics within the MERRA-2 grid cell for Jerusalem vary greatly. The elevation spans a wide range, from negative altitudes in the Dead Sea to elevations around 800 m (fig. C.1(a)). Likewise, the climate classification features two different main climatic zones in the same grid cell (fig. C.1(b)). Contrarily, the case of Damascus benefits from more homogeneous characteristics within its grid cell, although it is influenced by the Anti Lebanon mountain range in the North.

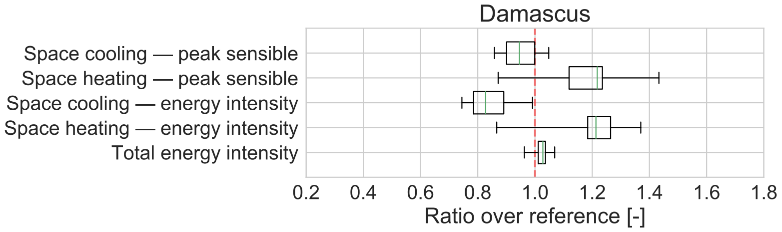
Up until now, results suggest that MERRA-2 displays a reasonable approximation for average weather conditions, but care must be taken in heterogeneous grid cells. This could be tackled in several ways, like the application of spatial interpolation techniques, but this falls out the scope of this study.

C.6.3 ReaSat weather files for remote locations

Figure C.4 presents the comparison of the model performance under ReaSat weather files to the ones obtained with conventional nearby weather files. Having shown that ReaSat can provide useful observations for weather files, this addresses a common



(a) Jerusalem



(b) Damascus

Figure C.3: ReaSat 2005–2017 vs nearby IWEC weather files (boxplot convention: bar within the box represents the median, the box the range between first and third quartile and the whishkers the min-max range; data normalize with the performance obtained for the original IWEC weather file for the variable at hand)

issue for BPS modelling: the building at hand is at considerable distance of the closest available data sources. Three basic strategies are usually employed: (1) choosing the closest freely available weather file (here, Jerusalem), (2) choosing the closest freely available weather file under a similar climate (here, Damascus) or (3) turn to commercial options (here, the remaining locations shown in fig. C.1 around Azraq).

Although the total energy intensity is reasonably consistent across locations, this is not necessarily the case for its breakdown (fig. C.4). For example, Jerusalem has notable differences in performance when compared to every other case. The smaller values for space cooling energy intensity and peak cooling power can be understood in fig. C.4, as it is shown that Jerusalem belongs to an entirely different climate zone with cooler temperatures. In this sense, the performance of the multi-year ReaSat version of Azraq closely agrees with that of Damascus, where boxplot ranges overlap for every metric. This emphasizes the preferable match of climatic conditions when choosing a weather file rather than blind direct proximity.

The performance obtained in Guriat and Safawi can also be attributed to geographical differences. These locations are at a lower elevation than Azraq, and deeper within the desert. The result is a remarkable higher cooling energy intensity and power requirements. Likewise, Queen Alia, Amman and Mafraq show substantial differences with Guriat and Safawi in these regards. This is especially noteworthy because all these weather files are of the same type and generated by the same procedures.

Overall, the general pattern obtained for ReaSat weather files in Azraq can be deemed reasonable, especially considering the different weather file types involved in the analysis. The 13-year simulation appears to capture a weather variability that compares in magnitude to the differences obtained across every other location. In addition, this range overlaps well with the arguably most similar locations to Azraq. Given the choices modelers need to make for BPS in these circumstances, no fundamental reasons are found to discourage the careful use of reanalysis and satellite-derived datasets.

C.7 Conclusions

This study presents a novel framework to create weather files for building simulations based on satellite imaging and reanalysis datasets. Motivated by the need to estimate the thermal performance of buildings in remote locations, this approach promises greater freedom for the creation of weather files than their counterparts based on weather station data.

The method is thus compared to on-site and off-site weather observations, and a series of building simulation experiments quantify the effects of the new weather files against traditional ones around the location of interest.

The analysis that underpins this framework stresses the importance weather files have in building performance simulation, and exposes aspects often neglected due to the limitations in data availability. Unless weather observations are made at the very location under study, there is room for large variations. In this sense, weather files with this new framework appear as a reasonable approach if the conditions within the grid cell are sensibly homogeneous. In these circumstances, the inter-agreement of the new weather files is not only coherent with that of similar locations but also with on-site measurements. In addition, it provides a closer fit to that obtained from the off-site public weather stations considered in this study. If conditions in the grid cell are heterogeneous, there are several ways to continue forward. For instance, common techniques in environmental sciences could be applied to localize observations to the very point of interest.

Nevertheless, and despite its simplicity, the framework can be regarded as a starting point to enhance current input data practices in building performance simulation. The duplicity of sources would then mean a greater confidence in weather files (un)certainties that modelers can leverage to inform decisions to help deliver buildings that do perform as intended.

C.8 Sponsors

EPSRC projects HHftD [grant number EP/P029175/1], and COLBE [grant number EP/M021890/1]. Daniel Fosas gratefully acknowledges the financial support by the ‘laCaixa’ foundation and the University of Bath.

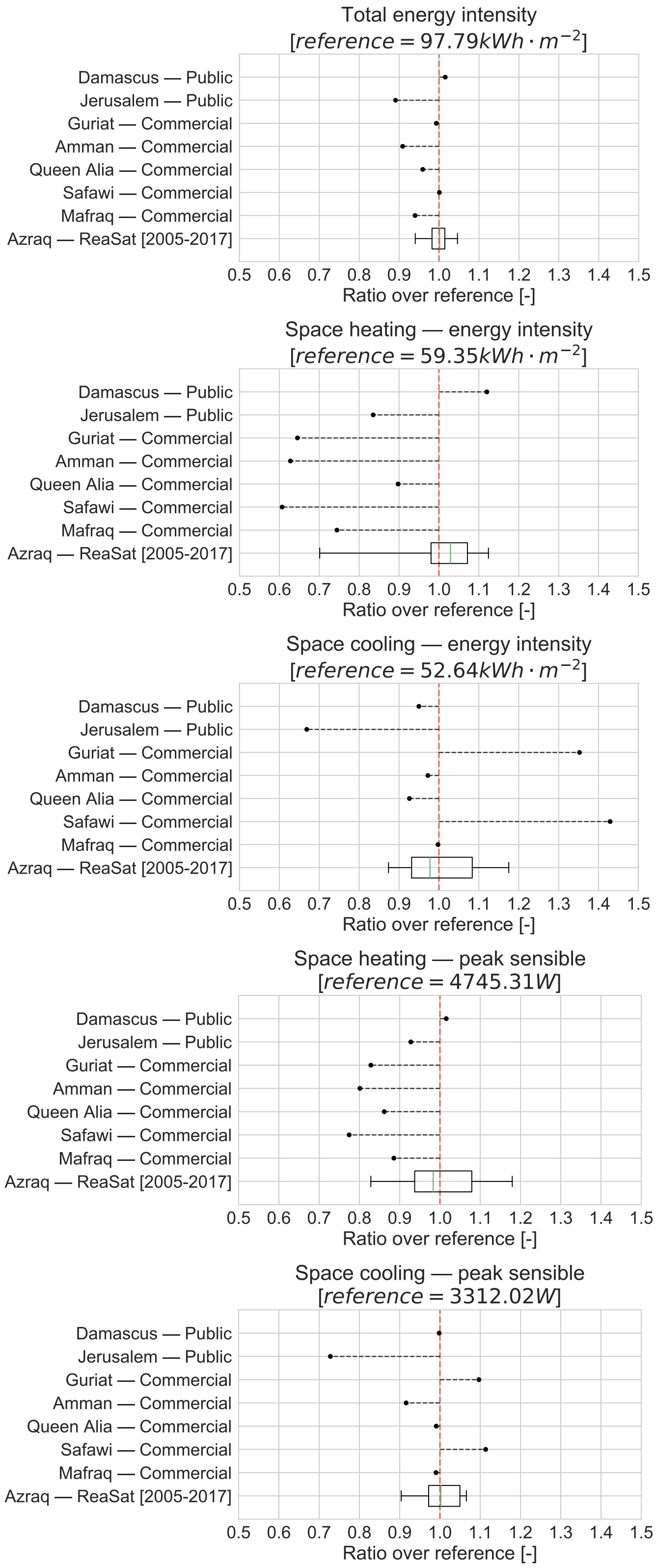


Figure C.4: Building performance comparison under different weather files (the reference taken to normalize values in each plot is the average of the multi-year simulation of the ‘Azraq — ReaSat [2005–2017]’ case; see fig. C.3 for boxplot conventions)

C.9 Acknowledgements

We thank Shaghayegh Mohammad and Dima Albadra for their help in acquiring local weather data in Jordan, and Nick McCullen for the computational resources used in this study. Local weather station monitoring in Azraq conducted in collaboration with PSUT in Jordan, UNHCR Jordan and NRC Jordan. Besides the referenced work, the study was conducted thanks to open-source software, specially E+, Python and NumFOCUS projects, and the outstanding communities behind them.

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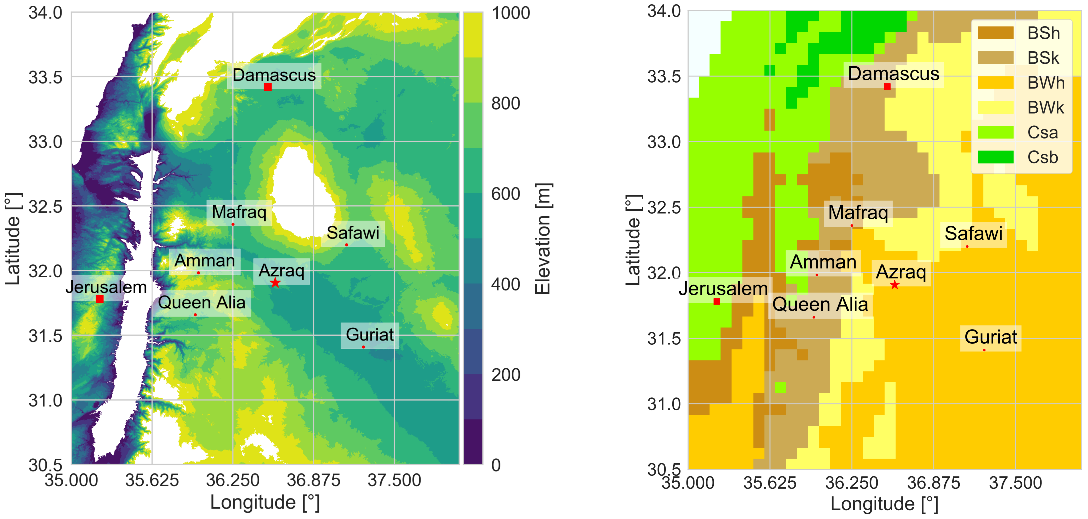
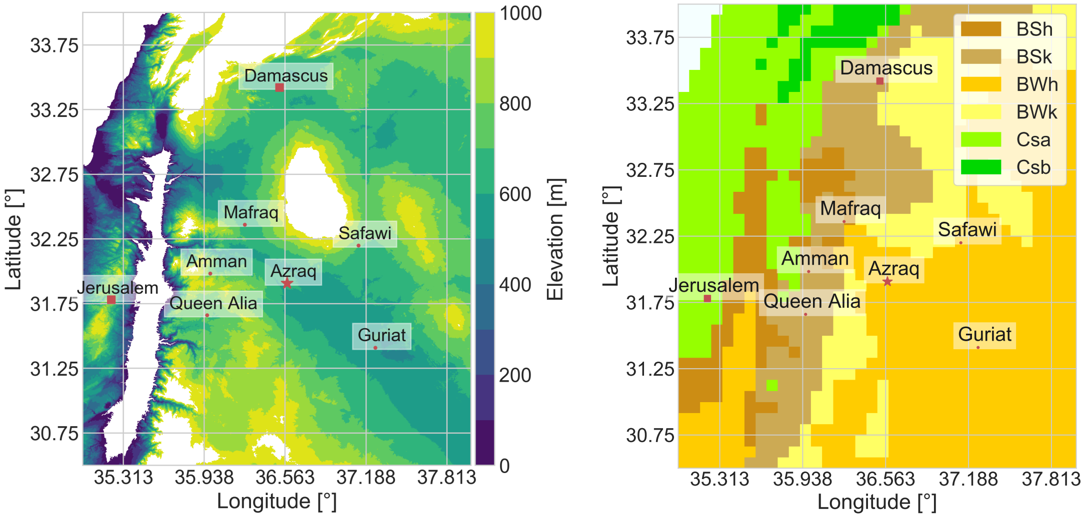
C.11 Corrigendum

The MERRA-2 grid overlay in fig. C.1 was not offset appropriately according to its definition. This did not affect the content of the study. The original and corrected versions are here reproduced together for clarity (fig. C.5).



(a) Elevation (Original)

(b) Köppen Geiger climate zone classification (Original)



(c) Elevation (Corrected)

(d) Köppen Geiger climate zone classification (Corrected)

Figure C.5: Corrections to fig. C.1 – "Locations considered in the study (symbols: the 'star' indicates the location of interest; 'dots' the closest commercial weather files; 'squares' two of the closest publicly available weather files; plot grid as per MERRA-2 structure)"

Appendix D

Reclaiming refugee agency and its implications for shelter design in refugee camps

D.1 Preamble

The work presented in this thesis only tackled but a narrow aspect of the shelter provision process, namely indoor overheating. The study of the thermal performance of shelters allows identifying pathways for an improved design process that, as shown, could operate as a drop-in replacement for current practices in the sector. However, the topic of healthy housing for the displaced interweaves climate, social and political environments. As such, it is complex and cannot be constrained to a single aspect, let alone a single discipline.

As complementary perspective to the technical accounts presented in the main studies, this work reflects on how encamped refugees live and alter the shelters they dwell. Two cases are presented based on the findings of the HHftD project through interdisciplinary work at the Department of Social & Policy Sciences and the Department or Architecture & Civil Engineering at the University of Bath. As shown in adaptive comfort theory, the pathways to improve indoor thermal conditions would be ultimately constrained by the wider opportunities for adaptation, which should not be considered in isolation from cultural norms and interactions with the surrounding environment.

This appendix is based on the paper “Reclaiming Refugee Agency and Its Implications for Shelter Design in Refugee Camps” presented at the “International Conference on: Comfort at the Extremes: Energy, Economy and Climate” in 2019. This study was conducted as part of the HHftD project [grant number EP/P029175/1] to reflect on how refugee agency shapes the environments camp dwellers live at and how it could be the cornerstone of an improved design process that successfully reconciles the views of all the actors involved. Details about the authorship of this paper are provided in table D.1.

D.2 Declaration of authorship

Table D.1: Declaration of authorship

This declaration concerns the article entitled:
Reclaiming Refugee Agency and Its Implications for Shelter Design in Refugee Camps

Publication status:
Published

Publication details:
N. Paszkiewicz and **D. Fosas** (2019). "Reclaiming Refugee Agency and Its Implications for Shelter Design in Refugee Camps". *Proceedings of the 1st International Conference on: Comfort at the Extremes: Energy, Economy and Climate.* International Conference on: Comfort at the Extremes: Energy, Economy and Climate. Dubai: Ecohouse Initiative Ltd, pp. 584–594.

Copyright status:
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Candidate's contribution to the paper:
The author of this thesis has contributed to the publication (38 %). The contributions of each author are as follows:

- Formulation of ideas: N. Paszkiewicz (50 %) and D. Fosas (50 %).
- Background: N. Paszkiewicz (90 %) and D. Fosas (10 %).
- Design of methodology: N. Paszkiewicz (60 %) and D. Fosas (40 %).
- Field work: N. Paszkiewicz (100 %).
- Thermal Analysis: D. Fosas (60 %) and N. Paszkiewicz (40 %).
- Proposals: N. Paszkiewicz (50 %) and D. Fosas (50 %).
- Preparation of manuscript: N. Paszkiewicz (60 %) and D. Fosas (40 %).
- Editing drafts of manuscript: N. Paszkiewicz (50 %) and D. Fosas (50 %).

Statement from Candidate:
This paper reports on original research I conducted during the period of my Higher Degree by Research candidature.

Signed **Date** 20 December 2019

D.3 Abstract

Refugee agency refers to the notion of decision making exercised by forced migrants, and their efforts aimed at improving life in the context of displacement. As such, it has emerged as a useful concept to channel discussions about the challenges of current refugee encampment practices, which we argue encompasses consequences for the design and provision of shelter solutions. Building on the evidence collected in selected refugee camps of Jordan and Ethiopia, we suggest that acknowledging and incorporating the voices of refugees can not only enhance their well-being in climatically, socially and politically challenging environments, but it could also be beneficial to other actors such as humanitarian agencies and host governments. While we recognize the constrains arising in these contexts, we focus on the importance of adaptations and customization of shelters that we found to be the leitmotiv and, more critically, a fundamental humanizing factor of refugee experience in camps. The refugees' freedom to make choices about their own shelters can then be used to rethink how to deliver better environments in which camp inhabitants can live in dignity. Although engineering design can only facilitate agency, rather than give it, it could help build the consensus about the pre-requisites of what constitutes truly 'appropriate' shelters.

D.4 Introduction

In the area of refugee studies, the term refugee agency has been juxtaposed against the cultural representation of displaced people as voiceless and passive victims portrayed as the objects of humanitarian interventions, rather than the subjects capable of making choices and taking control of their life trajectories, albeit in very difficult situations. The first narrative depicts refugees as oppressed by institutions, in this case, by camp management, whereas the one that emphasizes the strategies used by them to oppose this domination tends to romanticize the encampment. Both approaches, however, reveal a degree of interpretative bias by either underestimating the autonomy of refugees whilst demonising role of the humanitarian sector, or by exaggerating the refugee's capacity to resist institutional, legal and political structures embedded in the refugee administration (Fresia 2007).

Humanitarian sector is often seen as overtly preoccupied with technical solutions given the requirements of dealing with emergency situations, as well as the character of funding, namely that donors tend to be more generous at the beginning of a crisis, with funds dwindling with time passage. The often-ad hoc, rushed, and therefore not including consultations with refugees, response of the sector to a crisis can be interpreted as geared towards control and surveillance (Agier 2010). Furthermore, the lack of participatory approach has led to erroneous aid programmes (see Zetter (1991) and Crisp (2001) for an overview) and the call to embed refugees' views in implementation of aid is not new; multiple studies have shown that refugees are agents capable of articulating their own needs and seeking solutions to challenges that they face (Essed et al. 2004; Dona 2007; Harrell-Bond and Voutira 2007; Brun and Lund 2010). Wilson (1992, p. 226) points out that refugees suffer the most not when less than average level of assistance is provided, but when their own survival and adaptation strategies have been particularly limited by authorities and/or relief agencies in the name of concerns for security and control, or merely for the purpose of administering aid more smoothly. On the other hand, it is evident from interviews that we carried out with humanitarian staff in Jordan that leaving refugees to their own devices might lead to technically inappropriate solutions, and consequently, possible risks of fire, flooding and other hazards. A third perspective, aiming to combine the aforementioned approaches, recommends that humanitarian interventions should explicitly include refugees in their programming, fully recognising their agency and potential to ameliorate their living standards in the situation of displacement (Harrell-Bond 1986; Harrell-Bond 1989; Allen 1996; Hyndman 2000; Chimni 2009).

In our interdisciplinary project Healthy Housing for the Displaced (HHftD), we argue that detangling those complex relationships between refugees, humanitarian actors and host countries can lead to enhancing the sustainability of aid initiatives, as well as to fostering refugees' ownership of programmes implemented by the sector. Not only is the project multivocal due to its interdisciplinary character, but also because we work with all the actors engaged in camp governance, namely refugees, UNHCR and other UN agencies and INGOs, as well as representatives of host governments. Up until now, the project identified shelter performance shortcomings and characterised the thermal needs of camp dwellers in Jordan (Albadra et al. 2017) and proposed consequent design solutions (Fosas et al. 2018). Furthermore, it has suggested negotiating a consensus which challenges the current dichotomy (McGrath et al. 2018), calling all actors to work together in order to improve shelters for displaced populations (Albadra et al. 2018). Building on these efforts, we advocate here for refugee agency to be the fundamental guiding principle of the shelter provision process. In this context, refugee agency is a factor that guarantees dignity of camp dwellers and, entails certain design practices as emanating from the field work conducted in this project.

D.5 Institutional framework

Refugee camps are regulated settings governed by bodies representing a host state; the UNHCR; and other UN agencies alongside INGOs, as well as small local organizations. Shelters in refugee camps are loosely regulated housing units. Their dimensions are defined by the The Sphere project (2011) and follow the requirement that each shelter should provide a minimum three-and-a-half square meters of covered living space to every resident. In many cases, this is not implemented in practice; for example, in the Hitsats camp (Ethiopia) an average of five to nine persons live in one concrete block house which is only 4 m × 5 m. Some regulations are vague, and therefore either not followed at all, or easy to negotiate, for example the requirement “where possible” to provide shelter that is acceptable “socially and culturally” to its intended occupants (The Sphere project 2011, p. 258). To the best of our knowledge, there is no institutional actor responsible for making shelters culturally appropriate for a particular group of people, and it is either ignored or left to largely unstructured consultations with refugees such as those carried out by UNHCR in some Ethiopian camps (UNHCR and ARRA 2017).

Discussion on refugees’ agency in refugee camps inevitably involves the aspect of time, namely the alleged dichotomy between temporariness and permanency. The often-quoted average time of 17 years that refugees spend in camps is actually inaccurate; it does not refer to camps — majority of refugees live in urban areas — and it is limited to the duration of displacement situations, not the time that people stay in exile (Devictor and Do 2016). The length of protracted refugee situations does however last decades, with oldest refugee camps dating back to 1947 (Cooper’s Camp in India, following the partition) and 1948 (Palestinian camps in the Levant set up after the establishment of Israel). What we often saw in the course of our research was a narrative that permitting refugees to improve their shelters will influence their decision to stay in the camp for longer; therefore, those adaptations are undesirable from the perspective of host states and donors, and sometimes refugees themselves, as the homemaking process may be seen as undermining their claims for long term solutions to displacement. Under this discourse, ensuring that refugee camp remains a transient space would, for instance, facilitate an easier management of possible returns, the preferred UNHCR durable solution to refugee crisis. This argument is built on the assumption of a rigid dichotomy between temporariness and permanency, and consequently, the association of shelter enhancement with permanency. We argued elsewhere (Hart et al. 2018) that it is lack of alternatives, and/or ongoing conflict in the country of origin, rather than degree of satisfaction experienced in a camp, that impacts refugees’ decision to relocate.

Depending on the political context, host states impose a different set of their own rules, for example in relation to buildings materials. The Jordanian authorities forbid usage of concrete in Syrian refugee camps as it symbolically signifies the permanence of camps and recalls the Palestinian presence in the country largely composed of different refugee groups that have previously blended into the Jordanian nation-state. On the other hand, in Hitsats, Eritrean refugee camp in North Ethiopia, all shelters are essentially permanent and built of bricks, and there are no restrictions in relation to adaptations made by refugees. Overall, camp administration policies and practices are not rigid, even though they often strive at appearing so; they may change their position over time, and this tends to fluctuate towards relaxing the rules (Hart et al. 2018). For example, residents of Zaatari camp in Jordan were initially provided with communal kitchens and bathrooms. People did not want to use them, and eventually were given private facilities instead. In a more regulated Azraq camp refugees repetitively plant trees outside their shelters in the night, even though they are then removed by the authorities in the daytime. The assumption is that one day the governmental authorities will turn a blind eye to this practice (and probably they will). In Hitsats refugees are not allowed to keep dogs as a precaution against rabies outbreak, but in one instance a puppy was hidden during the day and roamed freely in the night; by the time she grew up, no one seemed to remember about the regulation that was forbidding dogs in the camp. Therefore, it seems that the relationship between refugees and actors managing the camp often takes form of a cat-and-mouse game, an unspoken testimony of refugees' autonomy battling against the institutional odds.

D.6 Refugee's agency and shelter adaptations

Drawing on the anthropology of architecture, we argue that through the production of material forms, such as dwellings, people define and order socio-cultural relationships in the process that mutually constitutes one another, subjects and objects (Vellinga 2007, p. 761). In other words, one could coin a dictum, "how the things that people make, make people" (Küchler and Miller (2005, p. 38) as cited by Vellinga (2007)) which very much resonates in the context of displacement camps, effectively in the state of constant re-making by refugees.

D.6.1 The case of Zaatari and Azraq camps in Jordan

A very good example of this mutually constitutive relationship is the construction of *al madafah*, space for receiving guests. None of the surveyed shelter solutions accounted for guestrooms in their design, and refugees have themselves built spaces needed to welcome visitors. The primary function of such spaces is to offer a comfortable setting for the very important cultural practice of visiting, serving food and drinks to one's guests, a prerequisite to harmonious communal life. Islamic Sharia law explicitly recommends that hospitality should be a principle guiding the design of dwellings in the Muslim context (Othman et al. 2015). The guestroom also allows to uphold one's social status and family honour, and therefore re-asserts social identity after experiencing the rupture caused by conflict and forced migration.

Taking Zaatari as an example, the conditions in the camp allowed for an unintended exercise of ownership by the refugees over their shelters. Given that these are highly portable caravans, refugees could relocate within the camp and freely arrange their shelters to create the spaces they needed (Albadra et al. 2018). Some people have over time developed, depending on their skills and financial situation, very elaborate guestrooms that included bird towers, water fountains and small gardens, providing refuge from the summer heat. According to our interviews with UNHCR staff in Jordan, at least 50 % of the camp was effectively re-made by refugees themselves. From the institutional actors' perspective this led to health and safety hazards; for example, people were moving caravans in the way that was blocking the access to roads in case of emergency.

On the contrary, Azraq camp opened at a later stage, and was ready for inhabitation prior to the arrival of refugees. Azraq designers seem to have considered the shortcomings of Zaatari camp from a care-giver's perspective — rather than from the refugees' perspective — into a highly organised plan based on villages, districts, blocks and shelters[1]. Focusing on the shelter solution, the design did not take advantage of the climate at the location (fig. D.1(a)), being mainly constrained by cost, speed of construction, structural and fire safety. These resulted in a single-room lightweight shelter made of steel where the only heavyweight element of the construction is the concrete slab, which uses the internal walls as the formwork (fig. D.1(b)). As such, the shelter cannot be reconfigured in the same ways the caravans were in Zaatari, and the main space is used as a bedroom during night time and a guestroom during daytime.

The current in-use state of the shelters clearly highlights the shortcomings of the original design and the ways in which the owners adapted the space (fig. D.1(c)). People inhabiting these shelters report high levels of thermal discomfort as assessed in field studies (Albadra et al. 2017), since the lightweight construction follows closely the wide range of daily external temperatures (fig. D.1(a)). This causes, for example, internal condensation in winter and surfaces becoming too hot to touch in the summer. At present, many shelters have been retrofitted with an extra layer of 15 mm insulation in the internal walls besides people's own adaptations including hanging fabrics. In many instances, the inhabitants have even opened new windows to enhance natural ventilation. The reasons are that the ventilation pipes provided cannot be operated by the occupants and cause excessive sand ingress, and that privacy is not preserved with the window on the same side of the entrance to the shelter. The concrete floor is usually carpeted and sprayed with water in the summer to provide some evaporative cooling. Since the walls are drilled to the structure and anchored into the ground, the shelter can only expand in-between other units, an appropriation not foreseen in the design and not allowed by the camp management. This space allows to cook outdoors to minimise the heat gain inside the shelter or to grow a small garden which is a cherished aspect of Syrian culture. The modification attempted by the owners in this regard is to enclose this space with an additional wall on one side or tarpaulins as an improvised roof. Overall, even though Azraq camp benefitted from pre-planning the infrastructure and the shelter design, it did not build on the unintended success of Zaatari in terms of refugee agency and the refugees' ownership of their shelters.

D.6.2 The case of Hitsats camp in Ethiopia

The case of the Hitsats refugee camp in Ethiopia depicts a different scenario both culturally and climatically. For instance, Eritreans socialize around coffee ceremony,

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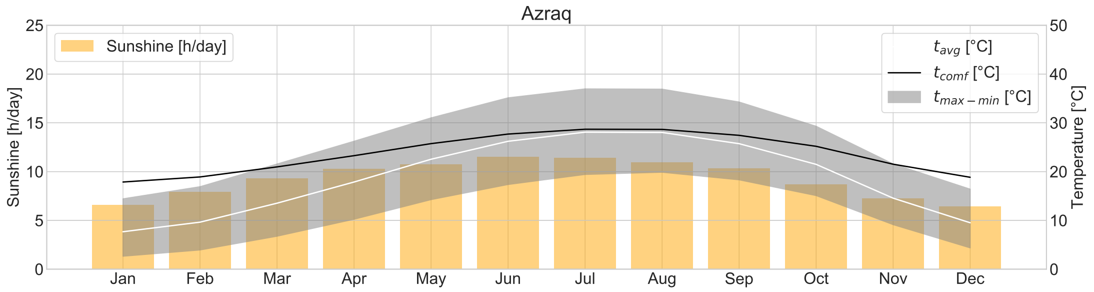
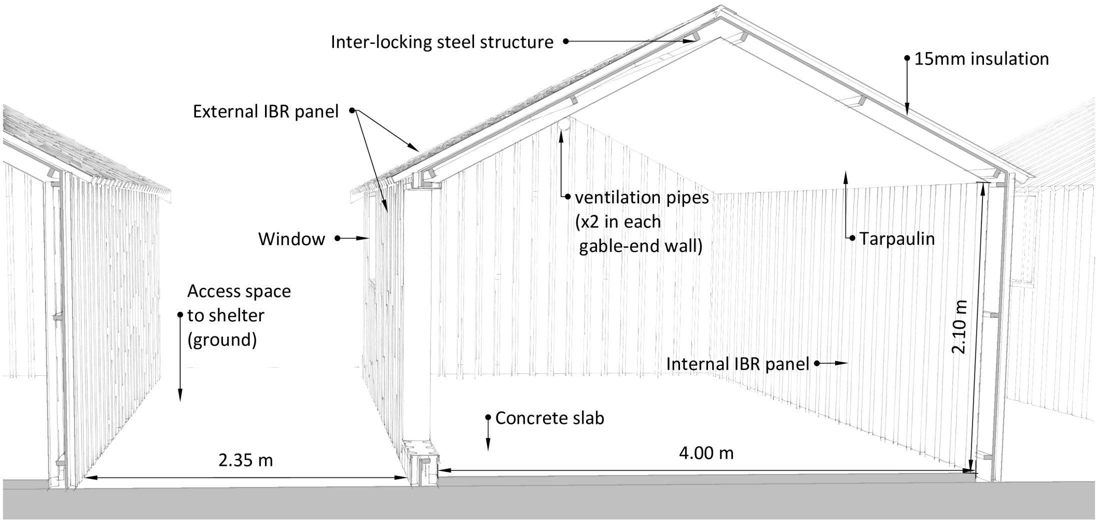
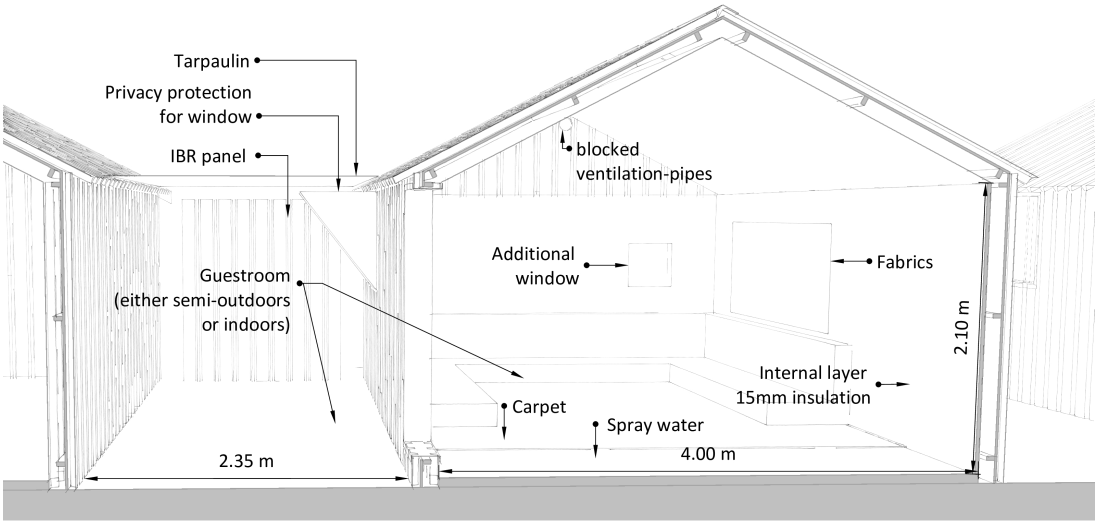
[1] See Dalal et al. (2018) for a discussion on the planning of Zaatari and Azraq.



(a) Climate overview – Nicol graph (data: Gelaro et al. (2017) and Schroedter-Homscheidt et al. (2017))



(b) Shelter as designed



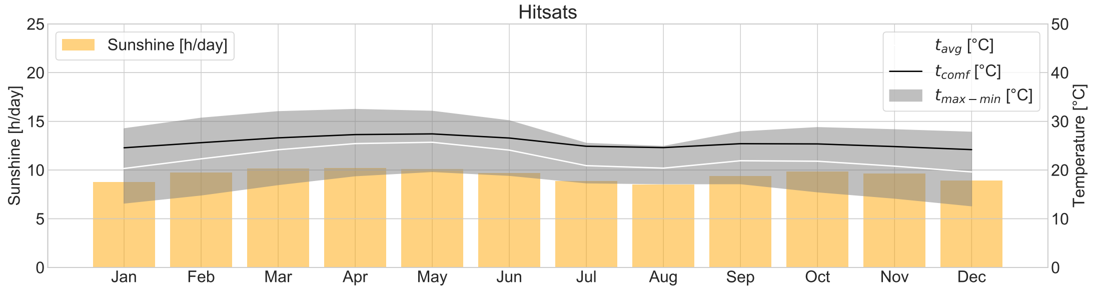
(c) Shelter as used

Figure D.1: Azraq case study (Jordan, latitude 32°N) *buna jebena*, which involves roasting raw coffee beans and takes on average 1–2 h to prepare. It is traditionally performed 3 times a day, usually only by women, and a guest should drink three cups of freshly brewed coffee in order not to offend the host. Gender norms, and consequently, the understanding of privacy, are more relaxed in Hitsats than among Syrian refugees so in most cases we did not see any partitions inside the dwellings, even when these were inhabited by young single people of both sexes, who are the dominant demographic group in the camp. Young men and women living in one shelter tended to say that they are friends, and that they trust each other. They also shared household chores, with men bringing firewood and women preparing food. This is also due to the impact of indefinite compulsory military service in Eritrea: people aged 16–18 leave their family for military training, and friendship bonds acquire significant cultural meaning.

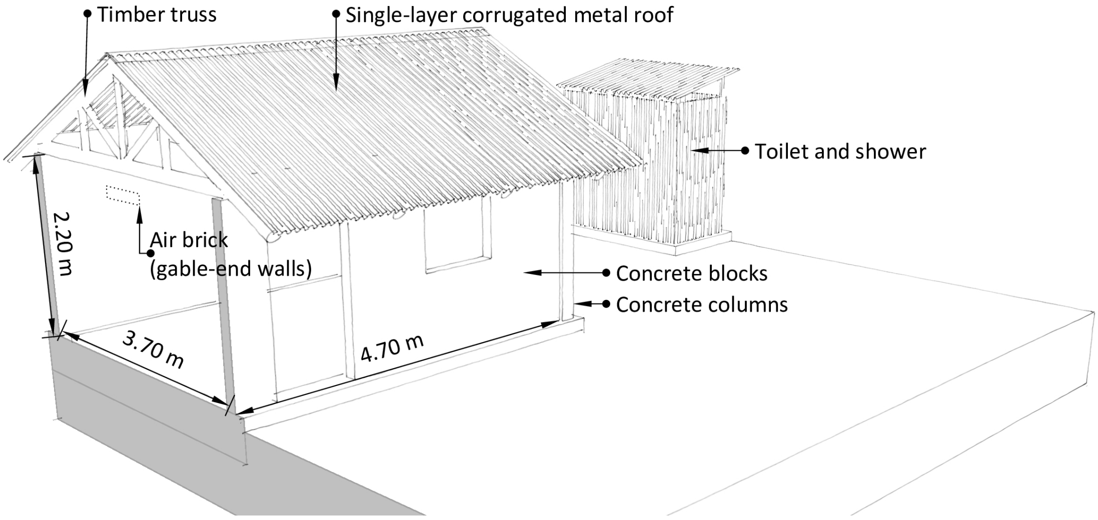
In terms of climate, Hitsats depicts relatively warm conditions, with temperatures in the range of 15–35 °C, and daily temperature swings of 15 °C approximately (fig. D.2(a)). As hinted by the temperature drop between June and September, there is a wet season that features not only high humidity but also strong rainfalls and wind gusts. The shelters here are made of concrete blocks for the walls and corrugated metal sheets of timber trusses for the roof (fig. D.2(b)). It is erected over flattened raised ground to minimise water ingress. The interior is an unfurnished single space of 17 m^2 with single-side ventilation through the door and the window, although gable-end walls include air bricks. The unit also features an external bathroom unit with a toilet and a shower detached from the shelter.

The adaptations performed by the camp dwellers are done on three levels (fig. D.2(c)). At interior-space level, it is the construction of mud furniture, mainly beds inside the shelters which recreates a sensory memory of home, given that people would not normally sleep on the floor in Eritrea. At shelter level, the main adaptations are to build a double roof because of water leaks and to paint the outer walls to repel insects. At plot-level, owners that can afford it build an outdoor sitting space to receive guests and perform the coffee ceremony because the single-sided ventilation system of the shelter does not provide enough ventilation to purge the smoke and the heat.

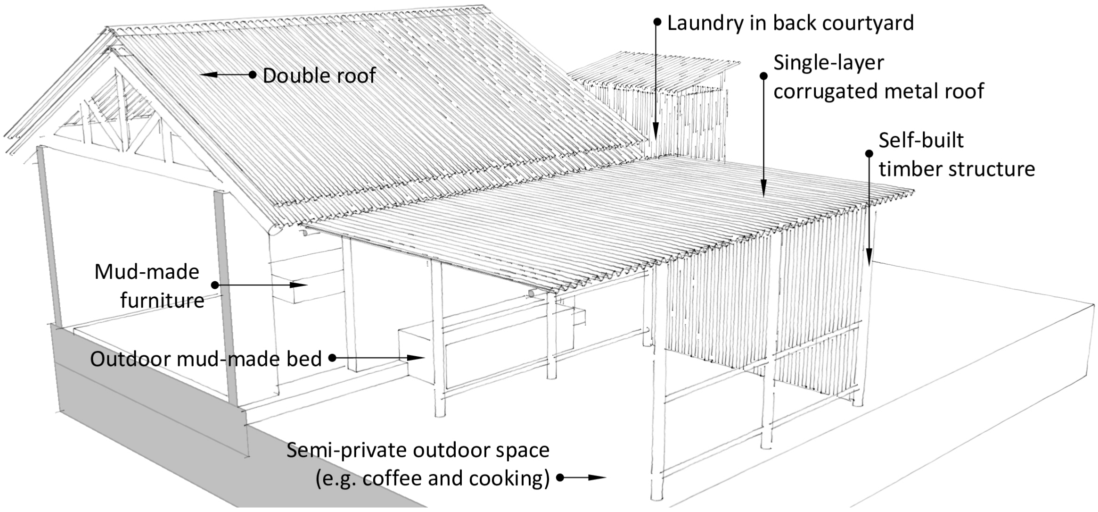
Prior to a formal thermal comfort study, a similar social survey to that performed in Azraq was conducted in Hitsats. Residents reported thermal comfort to be the highest concern when asked about their accommodation. Given that the comfort temperature is in general well within the mild external temperatures and that the shelter provides some thermal mass thanks to the bricks, this is speculated to be due to the single roof, lack of appropriate ventilation regimes due to single-sided ventilation, overcrowding of the shelter and heat gains due to cooking and related activities.



(a) Climate overview – Nicol graph (data: Gelaro et al. (2017) and Schroedter-Homscheidt et al. (2017))



(b) Shelter as designed



(c) Shelter as used

Figure D.2: Hitsats case study (Ethiopia, latitude 14°N)

D.7 Discussion

We have seen how cultural norms and practices play a fundamental role in how the affected populations adapt, modify and enhance their dwellings, not only in the case studies presented but also in the course of our fieldwork in other refugee camps and internally displaced people's settlements (Bangladesh, Nepal and Turkey). Whilst the importance of culture is nowadays generally acknowledged in the humanitarian sector's programming, it is an aspect that does not seem to inform current shelter solutions yet. Participatory approach tends to be applied to livelihoods and protection activities in refugee camps, rather than to shelter sector. We are calling for those efforts to be extended to shelter design, thereby reclaiming refugee agency as a fundamental aspect that should not be neglected in this process. The case studies presented here portray not only shortcomings that would have been overcome by an improved design methodology, but also how refugees do exercise decision-making to shape their environments, regardless of, and sometimes clearly at odds with the institutional constraints of encampment. This ability of humans to choose and to act autonomously is a prerequisite for dignity:

> "To be an agent, in the fullest sense of which we are capable, one must (first) choose one's own path through life — that is, not be dominated or controlled by someone or something else (call it 'autonomy'). [...] And having chosen, one must then be able to act; that is, one must have at least the minimum provisions of resources and capabilities that it takes (call all of this 'minimum provision') [...] so others must not forcibly stop one from pursuing what one sees as a worthwhile life (call this 'liberty')." (Griffin 2008, p. 33).

Since refugees in camps are unable to enjoy full control over their lives, a combination of the top-down approach and bottom-up approach would be an initial step forward. This could combine the expertise of discipline-specific designers to establish the technical requirements and efficient use of resources of technical solutions with structured consultations carried out with refugees as soon as feasible. The preparation stage for transitional shelters should include a portfolio of culturally appropriate solutions in different contexts which could be developed with help of anthropologists. This would provide a basic framework to ignite conversations with refugees, not to impose those preconceived technocratic solutions on them.

Besides the discussions about the overall design of camps and the particular shelter solutions, we would like to draw the attention to how those two scales are articulated. As seen in these case studies, the immediate outdoor space to a shelter plays a fundamental role to support semi-private/public activities of special significance to camp dwellers. This suggests that shelter surroundings need to be explicitly accounted for in the planning of the camp as a space that can foster the agency of refugees. Although

UNHCR does use the concept of 'plot' in their camp masterplans in some locations, what we recommend is to consider how the shelters can be expanded within such plots by refugees themselves.

It might be useful for all actors to think how the funds provided by donors at the onset of a crisis can be invested to establish camp infrastructure and agree with the refugees what the basic shelter provision needs to fulfil (e.g. private bedroom space, individual toilet facilities). Camp dwellers would then take over to maintain and extend their shelters into this space to further support the continuation of cultural practices of neighbourliness and forging a community in the new location. Such a strategy would combine the technical requirements of institutional actors with the much-needed agency practice by camp dwellers.

D.8 Conclusions

This paper explores the idea of how agency not only humanizes the refugee experience but also how it can help tackling design challenges in complex situations of refugee crisis characterised by pressures faced by humanitarian agencies and demands articulated by host governments. We do not wish to neither normalize nor romanticize encampment in our attempt to reclaim refugees' agency towards improving current shelter practices. We acknowledge the precarity of life in a refugee camp, but we would like to draw attention to agency amidst the constraints that we observed in Zaatari and Azraq Syrian refugee camps in Jordan, as well as in Hitsats, Eritrean refugee camp in Ethiopia. We call for a dialogue between agencies and residents, in order to find a consensus between refugees' need for flexibility and the authorities' focus on manageability in the context of scarce resources and political constraints.

From the design perspective, it is crucial that designers support camp inhabitants in their efforts to improve the shelters through understanding of architectural settings in which social relations are conducted in a given culture with solutions that are not just technically and climatically relevant. An explicit acknowledgement of agency in the encampment situation would allow refugees to acquire a sense of control over their lives, while making an efficient use of limited resources available to those who govern refugee camps.

D.9 Acknowledgements

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