An Investigation of Scalable Solutions to Mitigate against Overheating in New Build Homes in the UK

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Abstract

Overheating in houses is a growing concern because of increases in climate change-instigated heatwaves and low energy requirements. Overheating causes discomfort to occupants with a potential for serious health risks. In the UK, avoiding overheating has become part of building regulations which indicate methods of determining the potential for overheating. Solutions are not prescribed but are open to being met in various ways. It is possible to address every house individually in its context, however, this is time consuming and expensive. For overheating mitigation to become a reality, scalable solutions (excluding air conditioning) that can be easily applied and assessed at a mass scale, are needed. This research investigates the scalability of overheating mitigation measures in new build developments in the UK to determine an evaluation framework for their effective and practical use.

To address the scalability of overheating mitigation solutions, a much more holistic analysis of not just the technical design but the home development process and occupancy expectations was considered to be necessary. This has been undertaken through multi-method and multi-disciplinary research involving the industry, occupied housing, and theoretical assessment of wider solutions. This multimethod approach involved interviewing industry stakeholders and home occupants, real time sensor monitoring of indoor temperature in 5 UK homes, dynamic simulation modelling of 5 solutions, and validation workshops with home developers.

The investigation of the UK home development process revealed unawareness in all stages of the decision-making process, that need to be addressed to mitigate against overheating in homes. Monitoring identified how the risk of overheating was created and experienced in UK homes. Overheating analyses suggest that overheating design methods are not sufficient to pick up the extent of overheating in homes. Simulation modelling showed that externally applied fabric solutions were more effective at reducing overheating risk against internal solutions. As well as effectiveness, four areas are shown to require addressing to evaluate solutions as scalable: home occupant perceptions, cost implications, supply chain resilience, and developmental procedures. Using these, a scalability framework for incorporating overheating mitigation solutions into home development processes is proposed and assessed.

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Abbreviations

AD - Approved Document

ANC - Acoustics and Noise Consultants

ANSI - American National Standards Institute

AVO - Acoustics and Ventilation Guide

ASHRAE - American Society of Heating, Refrigerating and Air Conditioning Engineers

BCIS - Building Cost information service

BREEAM - Building research Establishment Environmental Assessment Method

BRE - British Research Establishment

BREDEM - Building research establishment Domestic Energy Model

CCC - Climate Change Committee

CCRA - Climate Change Risk Assessment

CIBSE - Chartered Institute of Building Services Engineers

CMA - China Meteorological Association

DCLG - Department for Communities and Local Government

DEFRA - Department for Environment, Food and Rural Affairs

DFEE - Design Fabric Energy Efficiency

DLUHC - Department for Leveling Up, Housing and Communities

DSM - Dynamic Simulation Modelling

DSY - Design Summer year

EPBD - Energy Performance of Building Directive

EPC - Energy Performance Certificate

FHS - Future Homes Standard

FHH - Future Homes Hub

GHA - Good Homes Alliance

GISS - Goddard institute of Space Studies

GIA - Gross Internal Area

GIFA - Gross Internal Floor Area

HIU - Heat Interface Unit

HHSRS - Housing Health and Safety Rating System
HSE - Health and Safety Executive
HQM - Home Quality Mark
HUG - Home User Guide
HVAC - Heating, ventilation, and Air Conditioning
IAQ - Indoor Air Quality
IEQ - Indoor Environmental Quality
IESVE - Integrated Environmental Solutions Virtual Environment
LWC - London Weather Centre
MEP - Mechanical, Electrical and Plumbing
MEV - Mechanical Extract Ventilation
MHCLG - Ministry of Housing, Communities and Local Government
MRT - Mean Radiant Temperature
MVHR - Mechanical Ventilation with Heat Recovery
NAP- National Adaptation Program
NHBC - National House Building Council
NMA - Nonmaterial Amendments
NPPF - National Planning Policy Framework
PHPP - Passive House Planning Package
PM - Particulate Matter
PMV - Predicted Mean Vote
PPD - Predicted Percentage of Dissatisfied
RIBA - Royal Institute of British Architects
SAP - Standard Assessment Procedure
TER - Target Emission rate
TFEE - Target fabric Energy Efficiency
TM - Technical Memorandum
UKGBC - UK Green Building Council
UHI - Urban Heat Island Effect
UKHSA - UK Health Security Agency

VOC - Volatile Organic Compounds

ZCH - Zero Carbon Hub

Acknowledgement

To say that this doctoral project and thesis was a solo effort would be an injustice to the direct and indirect support I have received from many along the way.

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Dedication

I dedicate this work to the memory of my late mother, Mama Senior Deputy Archbishop Margaret Ogot Otieno.

I know you must be so proud of me right now and I am so grateful to have had you as my mom.

I love you.

I miss you.

Continue Resting in Peace.

Chapter 1: Introduction

This chapter is an overview of the thesis, and it covers the following areas: general introduction, research background, aim, objectives and research questions, scope of study, justification, summary of research design, research structure and a chapter summary.

1.1 General Introduction

Homes not only provide shelter, they are also expected to protect the health and well-being of occupants, especially because individuals, families and communities spend most of their time in their dwellings. However, residential buildings have been associated with health hazards attributable to indoor air pollution and extreme indoor temperatures. (Vardoulakis *et al*., 2015). In the case of extreme temperatures, the most vulnerable occupants such as the elderly, the young, and those with preexisting conditions suffer the most because of their reduced capacity to adapt to their environmental circumstances (Mylona, 2019). As such, homes play a significant role in population exposure to environmental health hazards (Taylor et al., 2016).

One of the many effects of global warming is the increased risk of higher temperatures and the increased likelihood of frequent and severe heatwaves for many geographical locations including more temperate areas (NOAA, 2018). The advent of global warming and climate change (IPCC, 2014) has amplified existing health risks associated with exposure to high indoor temperatures (Vardoulakis et al., 2015). This is especially critical for temperate climate homes that typically rely on user-controlled passive design measures to tackle hot weather events (Mylona, 2019). Though residential air conditioning could be a solution, its mass use will undermine climate change aspirations to reduce emissions while potentially putting more strain on the electric grid (MCHLGb, 2019).

Global concern about Greenhouse gas emissions (GHG) and their effect on climate change has led to the need to reduce energy demand and carbon emissions attributable to buildings (Zero Carbon Hub - ZCH, 2015). The built environment is responsible for approximately one third of worldwide greenhouse emissions (UNEP, 2012) and about 40% of global energy use (EPDB, 2010). This has led to the introduction of legislations and policies designed to reduce building energy use by requiring low energy buildings (Fletcher et al., 2017).

This pursuit of sustainability goals in building design has led to residential structures characterized by higher levels of insulation and airtightness (Lomas and Porritt, 2017). While this has succeeded in achieving lower operational costs regarding heating and cooling, it has increased the chances of the occurrence of high temperatures in homes (Zero Carbon Hub - ZCH, 2016). This is because higher levels of insulation and airtightness might lead to higher indoor temperatures if there is no right ventilation system in place. Additionally, the adoption of the so-called modern methods of construction with major components typically being built offsite, has led to compact dwellings with walls made of thermally lightweight materials such as thin metal, wood, plastic, and plasterboard (Lomas and Porritt, 2017). Combining this with good insulation standards has made buildings more susceptible to summertime overheating (NHBC, 2012). This is because they are more airtight, and they lack the thermal mass necessary to ameliorate the temperature swings caused by summertime internal and solar gains (Lomas and Kane, 2013). There is a need, therefore, to understand the occurrence of overheating in residential buildings better, so mitigation measures can be put in place.

1.2 Background

Until recently, overheating in houses in the UK seemed improbable. After all, the UK is an island situated off mainland Europe between 50^0 and 59^0N with relatively mild weather in winter and temperate summer conditions (Lomas and Porritt, 2017). However, it is the mild climate experienced in the UK that precipitated buildings with poor insulation where heat is lost in uncontrolled ways due to low thermal insulation levels and infiltration though gaps in the building fabric (ZCH, 2015). The UK housing stock is considered to be one of the oldest in Europe (CLG, 2007), and does not retain heat well. Therefore, overheating has historically not been a concern. In fact, the earliest building regulations since 1965 sought to set thermal envelope standards in order to minimize heat loss in the cold weather. As a result, the majority of the housing stock in the UK, about 24.2 million dwellings (MHCLGa, 2019), were built to adapt to the generally cold temperatures.

The need to reduce energy consumption and carbon emissions attributable to buildings led to the development of legislations, standards and policies designed to promote low energy buildings (Fletcher et al., 2017). In 2008, the UK adopted a target of 80% reduction in CO^2 emissions by 2050 (DEFRA, 2008a). The European Energy performance of Buildings Directive (Directive

2010/31/EU) was introduced in 2010 to reduce greenhouse emissions, increase energy efficiency and to increase the use of renewable energy. Various voluntary sustainability certifications like Passivhaus and BREEAM (Building Research Establishment Environmental Assessment Method) have also been developed and adopted widely in the UK to increase sustainability levels and reduce energy consumption in the built environment (Lomas and Porritt, 2017).

These standards and policies have changed the form and characteristics of new residential buildings by prescribing the adoption of higher levels of insulation and increased levels of airtightness to reduce energy demand as well as associated energy transmission losses (Lomas and Porritt, 2017). Though the adoption of these standards and policies was designed to reduce heat losses and make properties more cost effective to run, the risk of overheating in residential buildings (as an unintended consequence) increased especially in warmer months (Gupta et al., 2015). These changes were not always accompanied by industry-wide capacity, understanding or skills, nor by full occupant understanding of some of the new strategies and technologies (NHBC, 2015). This was worsened by the adoption of lightweight materials with low thermal mass (Frith and Wright, 2008; Beizaee et al., 2013). As a result, overheating in British homes is an increasing concern resulting in uncertainty in thermal comfort and related indoor environmental properties (Jenkins et al., 2014; Gustin et al., 2020).

Global warming brought with it the risk of warmer summers (Murphy et al., 2010; BBC, 2019) and frequent heatwaves (UKGBC, 2016). The 2003 European heatwave that lasted 10 days and led to over 2000 deaths in England could become the norm by 2040 (PHE, 2015). Circulation models of climate change project that global mean surface temperatures could increase by 1.1^0C - 6.4^0C by the end of the twenty first century (Hansen et al., 2006). Climate change predictions in the UK indicate that summertime mean daily temperatures could increase by 1.3^0C - 4.6^0C in London by 2050s and 5.4^0C in Southern England by 2080 (UKCP09). As a result, more heatwaves in greater intensity, frequency and duration are expected (Jones et al., 2008, Marvogianni et al., 2011). In July of 2019, the UK Met office confirmed one of the highest ever temperature recording at the Cambridge University Botanic Garden measuring 38.7^0C, beating the previous UK record of 38.5^0C in Kent back in 2003 (BBC, 2019). However, 2022 was the warmest year on record and was the first year when summertime temperatures above 40^0C were first recorded shattering previous records (Met office, 2022). The Met Office has warned that the multi record-breaking hot and dry weather of 2022 will become typical in the UK in under 40 years (Sky News, 2023).

This is especially critical as we spend most of our time indoors. An activity pattern study conducted in Oxford in 2007 revealed that about 95% of people in the UK spend most of their time indoors, with over 65% of that time being spent at home (Schweizer et al., 2007). The vulnerable including young children, the elderly and the sick could even be spending longer (Vardoulakis at al., 2015). Additionally, there has been an increase in people working from home. In 2018, ONS data showed that 13.4% of the UK's 32.4 million workers usually work from home. These numbers have increased in 2020, because of the government's work from home policy due to covid-19. Therefore, houses that cause or worsen health conditions cost the economy and society yearly in terms of healthy life years, reliance on healthcare services, educational attendance, work productivity and absenteeism (UK Government, 2018).

The UK Government (through the then MHCLG) recognized the overheating risk in UK homes following recommendations by the Committee on Climate Change (CCC, 2015) progress report to parliament. The government then commissioned research to understand the overheating risk in new dwellings in the UK. In October 2019 a two-phase report (MHCLG; a and b 2019) on overheating in new homes, indicated a significant risk of overheating for new homes in general if no mitigation measures were applied. The conclusion of this research was however restricted by limited evidence and small sample sizes, with a call for the need to expand research into other housing types and locations within the UK. This shows that there is still a need for research into overheating, as the extent of the problem needs to be understood.

In June 2019, the UK became the first major economy to commit to an ambitious, new carbon target that will require the UK to bring all greenhouse gas emissions to Net Zero by 2050. With this commitment came a two-part consultation to introduce a Future Homes Standard (FHS) to future-proof homes with low carbon heating and world leading levels of energy efficiency (MHCLGb, 2019). As a result of the FHS consultation, potential overheating in homes was proposed to be tackled through the introduction of a new requirement into the Building Regulations; Approved Document O: Overheating (2021). Approved Document O presents a legal requirement for all new dwellings in England to ensure that overheating considerations are made right at the onset. The regulation indicates methods of determining the potential for overheating with a focus on glazing areas, orientation, and ventilation. Solutions are not prescribed but are open to being met in various ways if the assessment method shows achievement of the standard. Current solutions tend to have a technical focus driven by the assessment method and predominantly consider modifying glazing. Addressing the solutions for every individual house in its context is time-consuming and expensive. For overheating mitigation to be a reality, scalable solutions that can be easily applied and assessed at a mass scale, are needed.

To address the scalability of overheating mitigation solutions, a much more holistic analysis of not just the technical design but the entire home development process and occupancy expectations need to be investigated. Issues involving thermal discomfort and overheating are a result of vital decision-making steps that either occur or do not occur at each stage of the home development process. They are produced by broader systems and infrastructures of politics, economics, and culture throughout the whole development process. Additionally, in solving a problem that is pertinent to health and wellbeing, housing occupants also need to be at the heart of any probable solution or strategy aimed at preventing overheating in homes. By following this holistic approach, solutions will be seen as not just removing causes to events but strategies for wider scale and for longer-term success. All stakeholders including home developers and housing associations, their supply chains and home occupants need to be involved in developing scalable solutions to mitigate the problem of overheating. Although some work has been done at the housing scale, understanding the wider and complex issues that lead to mass market solutions, would need the involvement of all stakeholders if maladaptation is to be avoided (DEFRA, 2018). Therefore, this research investigates scalable overheating mitigation measures in new build residential developments in the UK, with a focus on the UK home development decision-making processes, to understand where decisions affecting overheating are made.

1.3 Aim and Objectives

The aim of this research is to investigate cost-effective scalable solutions to mitigate overheating and improve thermal comfort in new build residential developments in the UK, from a home development process perspective.

To aide in the achievement of this aim, the following objectives were followed:

- To review the current trends (including policy and regulation) on overheating and thermal comfort in residential dwellings and understand their scale and depth in UK homes.
- To examine the UK home development processes and the influence of decision-making on overheating in UK homes.
- To conduct an overheating analysis of homes with real time indoor temperature data, using the dynamic simulation method and simplified method stipulated in Approved Document Part O Overheating (2021).
- To evaluate the performance of different mitigation strategies in new build residential developments in the UK using dynamic simulation modelling of monitored homes.
- To develop a scalability criterion for evaluating overheating mitigation measures through evaluation workshops with developers.
- To propose a scalability framework for incorporating overheating mitigation solutions in home development processes.

1.4 Research Questions

- What are the current trends in overheating and thermal comfort in residential dwellings in the UK?
- How does the UK home development process and the various decision-making actors in it influence overheating and thermal comfort in UK homes?
- How do new build residential developments perform in terms of overheating and thermal comfort?
- What criteria can be used to define scalability and which scalable solutions can be used to mitigate overheating and improve thermal comfort in new build homes in a warming climate?

1.5 Scope of study

This study focuses on the problem of overheating and thermal comfort in new residential buildings in the UK. The causes of this problem depend on factors such as location, orientation, insulation, ventilation, solar gain, and internal heat gain as well as occupants' use of their houses. Although it deals with both comfort and health issues, the wider extent of health and well-being is not considered. This research focuses on summertime thermal comfort as opposed to winter thermal comfort. Therefore, the focus of this study is on the non-heating periods of May to September when excessive temperatures are more prone to be experienced in homes. Though thermal comfort principles apply to this research, the science around thermal comfort is not the primary focus of this research. This study focuses on overheating in homes, but more so the wider contextual issues, procedures and processes which allow overheating to thrive. Building types most susceptible to overheating are focused on. This includes flats, terraced, detached and semidetached houses. However, the building types considered are dictated by available occupied homes that were provided by housing providers for monitoring. As this research focuses on "new" houses, residential buildings constructed to energy efficiency requirements contained in Approved Document L 2013 are considered new. The study acknowledges that there was an uplift to building regulations Part L as part of the Future Home Standard. However, there would not be enough housing stock built to this standard that is readily available for monitoring. Generally, the focus is on traditional brick and block residential structures, as they constitute most homes in the UK. The geographical focus of this study is the UK and in particular, the Midlands and the South. The locations of monitored homes are based on the available and accessible occupied homes provided by collaborating home providers. Nonetheless, this research also discusses and evaluates construction practices and trends that apply in other countries, to assist in developing the case for the UK. In terms of the potential solutions focused on in this research, only cost-effective solutions are considered as they are the ones with the potential of being scalable. The mention of home development processes covers all the typical RIBA stages (0 to 7) and is generalized into land purchase, planning, design, construction, and post-construction activities such as snagging, handover, and in-use.

1.6 Justification

Continuing the planet's long-term warming trend, global temperatures in 2022 were 0.89^0C above the average for NASA's baseline period (1951-1980) according to the Goddard Institute of Space Studies Surface Temperature Analysis (GISTEMP, 2023). With an increasing average rate of 0.17^0C per decade since 1970 (CO^2 Earth, 2020), it will be challenging to prevent a rise in global mean surface temperature below 2^0C above preindustrial levels, within this current century (Anderson and Bows, 2011). This shows that Global warming will increase the likelihood of the occurrence of higher temperatures in homes and therefore, the necessity to address building adaptation to a warming climate as part of the current UK carbon reduction agenda (Mavrogianni et al., 2012; Gupta and Gregg, 2013).

European heatwaves are becoming more severe and UK summers are getting warmer due to human-caused global warming. Temperatures above 35^0C are increasingly becoming common in the Southeast, while temperatures in many areas in the north are likely to exceed 30^0C at least once per decade by 2100 (Christidis et al., 2020). All this combined with urbanization and an ageing population means that many could be affected by heat-related ill health by 2050, a significant future challenge (Zero Carbon Hub - ZCH, 2015). Increased rates of heat-related mortality have already been noted in the elderly, the sick and those living in care homes in the UK (Gasparini et al., 2012). According to the Committee on Climate Change, CCC (2015), the number of heat-related deaths is projected to increase from 2000 per year (in 2015) to 7000 per year by the 2050s. The latest ONS (2023) figures based on a three-year average show that in 2022, there were 2,866 deaths on the hottest days – compared to 1,417 in 1990; this has nearly doubled. This asserts that residential buildings and the process of their construction are important regulators of population exposure to environmental hazards such as air pollution and heat (Taylor et al., 2016). Tackling the numerous health and wellbeing concerns in houses in the UK provides an opportunity to create and use buildings to promote health and well-being, save on healthcare expenses and improve productivity (White Paper, 2018).

The Introduction of the Approved Document Part O for Overheating (2021) signifies a step in the right direction for overheating mitigation in UK homes. The regulation stipulates two assessment methods that are majorly influenced by openable and glazing areas of windows, predominant orientations, and ventilation strategies. The regulation, however, does not go far enough to proscribing solutions. With an average of about 200,000 additional new homes being constructed every year in the UK since 2015 (MHCLGa, 2019), examining individual home solutions will be time consuming and expensive to identify and implement. Scalable solutions are the way to go. For overheating mitigation measures to be effective, they need to be seen to be scalable by volume builders. This is because they are the ones who produce the largest yearly portion of new homes in the UK. Scalable solutions have the potential to be easily adaptable to home developer's business models and organizational structures and are therefore substantially replicable on a much bigger playing field. Understanding scalability potential requires an investigation of the entire home development decision-making process, and the wider contextual issues ranging from business hierarchical structures, market dynamics, planning restrictions, construction processes and stakeholders involved. To ensure that solutions obtained are implementable, evaluation with home developers is crucial to investigating the practicality issues behind solutions and to make them more implementable at a wider scale. Scalable solutions can be easily integrated into home development processes without significantly distracting developers from their main goal of building adequate, future-resilient, healthy homes, against a widening housing shortage of around 300,000 homers per year (van Hoof et al., 2014). There is an urgent industry need to address this problem and from that need, this study was born. This study is co-funded by three UK home developers and a collaborating housing association. This underscores the industry-wide urgency and significance of this research. The timeliness of this study is also key, with its completion just in time for the implementation of The Future Homes Standard (FHS) in 2025. The recommendations of this research have the potential of informing key policy changes in the residential construction industry in the UK.

1.7 Research Design

The research design for this study is based on a pragmatist research philosophy that acknowledges the existence of single and multiple realities while focusing on solving real world problems rather than philosophical positioning (Davies and Fisher, 2018). The topic of overheating and thermal comfort is a problem-based topic that can be studied better using a pragmatic approach. Pragmatism allowed the methodology of this research to explore all relevant methods that be used to solve the problem of overheating and thermal comfort. To investigate the objective and subjective characteristics (multi-disciplinary nature) of this research, a mixed-methods research design involving industry, occupied housing, and theoretical assessment of wider solutions was adopted.

Addressing the scalability of mitigation solutions required an investigation of the entire home development decision-making process, and the wider contextual issues ranging from business hierarchical structures, market dynamics, planning restrictions, construction processes and stakeholders involved. Thus, solutions need to be seen as not just removing causes to events but strategies for wider scale and for longer-term success. To ensure that solutions obtained were implementable, evaluation with home developers was crucial to investigating the practicality issues behind solutions and to make them more implementable at a wider scale.

To enable this, the following method was used:

- Semi-structured interviews were carried out with 15 Industry stakeholders including housing developers, manufacturers, and building professionals, to get their contribution on key decision-making stages in the UK home development process, and how they directly or indirectly affect overheating in UK homes.

The Introduction of the Approved Document Part O for Overheating (2021) signifies a step in the right direction for overheating mitigation in UK homes. It presents a legal requirement for all new dwellings in England to ensure that overheating considerations are made right at the onset. This regulation indicates methods of determining the potential for overheating with a focus on glazing areas, orientation, and ventilation. Solutions are not prescribed but are open to being met in various ways if the assessment method shows achievement of the standard. The regulation stipulates two assessment methods that are majorly influenced by openable and glazing areas of windows, predominant orientations, and ventilation strategies. Addressing the scalability of mitigation solutions required an analysis of overheating mitigation design methods described in the new regulation. These design methods usually involve synthetic profiles of occupancy and standard weather files that may not accurately reflect real time indoor conditions. There is a need to conduct a check on overheating assessment design methods using real time data from occupied homes. As part of this user experience of overheating and adaptation measures is required.

To enable this, the following methods were used:

- Sensor monitoring was done through indoor air quality sensors in 5 occupied houses in the UK during a typical non heating period (May to September) of 2022. Two types of sensors were used: Uhoo Aura sensor in the kitchen/dining areas and the Omron sensors in bedrooms.
- Alongside monitoring, occupants of monitored homes were engaged through thermal comfort questionnaires once a month, for the monitoring duration. Questions revolved around general demographic information, normal behavioral routines (activity and clothing), thermal sensation, behavioral adaptations (and their success) and recommendations. These questions aimed to capture the social, cultural, technical, and historical interplay in overheating and thermal comfort, in line with previous studies (Fuller & Bulkeley, 2013; Hitchings, 2011).
- Overheating analysis was done using two methods stipulated in the new Approved Document Part O (2021) for overheating; the TM59 overheating assessment criteria using monitored data, and the Simplified Method using a Future Homes Hub (FHH) template.

The analysis of scalability from a development process perspective and a design method perspective, provided a basis for targeted analysis of the effectiveness of individual mitigation solutions and their scalability based on a proposed criterion.

To enable this, the following methods were used:

- Dynamic Simulation Modelling (DSM) through the Integrated Environmental Solutions-Virtual Environment (IESVE) software, was used to model replicas of monitored homes and apply 5 different mitigation solutions to study their effectiveness in reducing the number of degree hours.
- Evaluation workshops were then done to validate research claims and findings to reduce bias and ensure that participant views are not misinterpreted (Barbour, 2001; Silverman, 2015). Evaluation workshops were done on MS teams separately with the 4 main industry partners: 3 volume builders and 1 housing association.

The three sections of this research are combined to propose a scalability framework for incorporating overheating mitigation solutions into home development processes.

The research design of this study is summarized in figure 1.

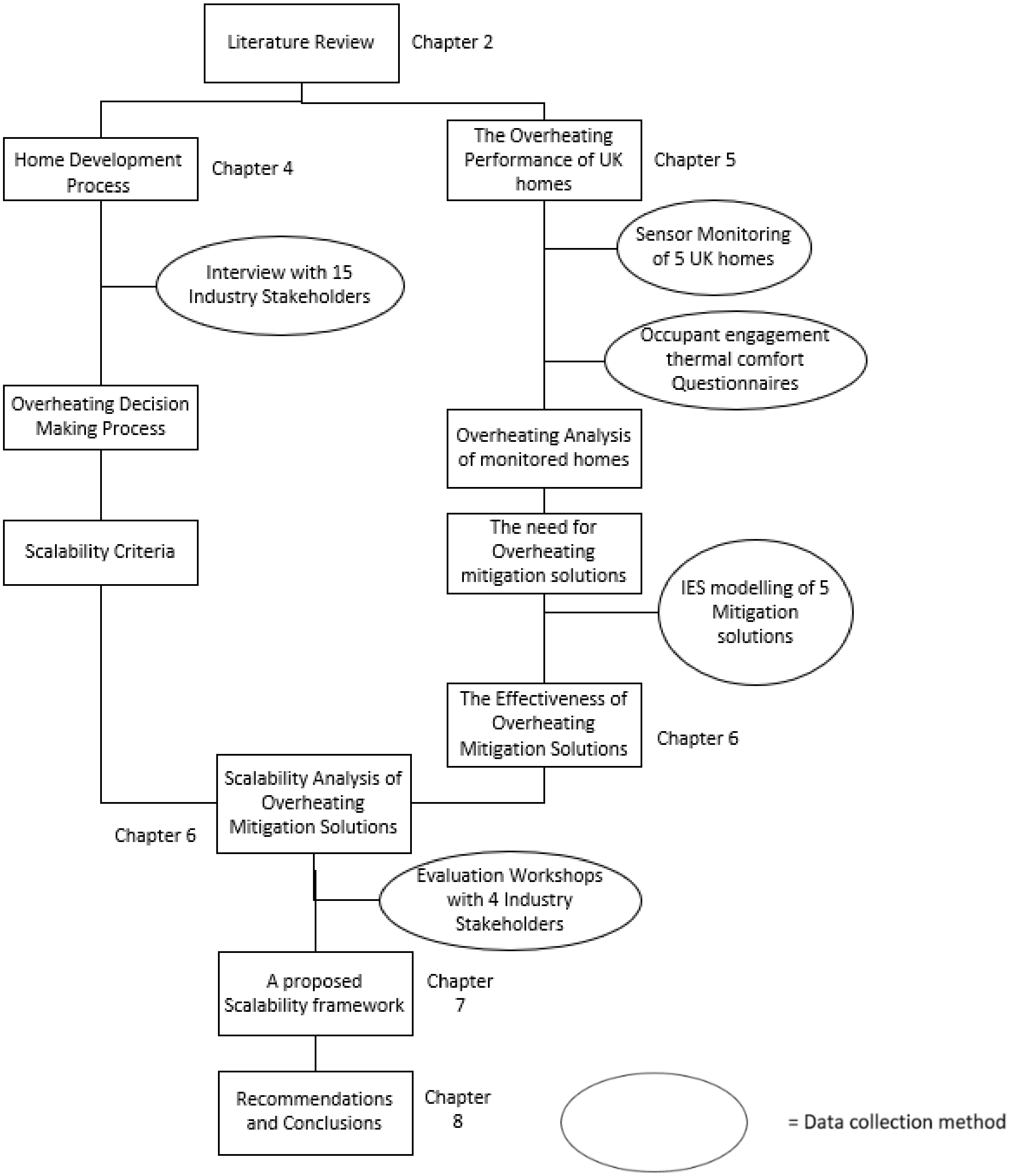


Figure 1: Summary of Research Design

1.8 Research Structure

This thesis is divided into eight chapters. A summary of the key elements in each chapter is given below.

Chapter 1 – Introduction

This chapter presents an overview of the thesis, and it covers the following areas: general introduction, research background, aim, objectives and research questions, scope of study, justification, summary of research design, summary of findings, recommendations and conclusions, research structure and finally a chapter summary.

Chapter 2 – Literature Review

This chapter critically reviews the work that previous scholars have done in overheating and thermal comfort in homes. Current trends on overheating and thermal comfort are analyzed with an aim of identifying the research gap that this research intends to explore. This section covers the following key topics: thermal comfort, overheating, assessment methods, legislation on overheating and thermal comfort in the UK, home development process, and the research gap.

Chapter 3 – Methodology

This section details the procedures and steps that were followed in carrying out this study. This section covers the following: conceptual framework, research philosophy, research design, data collection methods and instruments, participant information, data analysis and ethical considerations.

Chapter 4 – Home Development Process Analysis

This chapter presents the results of the interviews that were carried out with home developers, some of their supply chain companies and relevant home construction professionals. In this chapter, the UK home development process is analyzed to understand key decision-making steps that influence overheating in homes. The aim of this chapter is to identify aspects of the home development process that are key to developing scalable solutions to overheating in UK homes. This chapter is divided into the following sections: Thematic and conceptual visualization, UK home development decision-making processes and overheating in UK homes, discussion of results, contribution to scalable solutions and chapter summary.

Chapter 5 – Overheating Analysis using real time data.

This chapter presents temperature data obtained from air quality sensors deployed in UK homes, as well as the analysis of that data. It is divided into the following sections: summary of data sources, overview of data management and analysis strategy, monitored temperature trends, overheating analysis of sensor monitored homes and chapter summary.

Chapter 6 – Evaluation of Overheating Mitigation Solutions

This chapter presents and analyses data with the aim of evaluating overheating mitigation solutions. This is done in two steps. First is to assess the effectiveness of different overheating mitigation solutions applied to several UK housing typologies using dynamic simulation modelling. The second step presents an analysis of the scalability of overheating mitigation measures. This second step combines the results of the home development process and overheating in homes presented in Chapter 4, Overheating Analysis presented in Chapter 5, and the first part of this chapter on evaluation of overheating mitigation solutions. This chapter is broken down into the following subsections: overview of DSM procedures, DSM results for modelled houses, analysis and discussion of results, scalability of overheating mitigation measures, evaluation workshop outcomes, and chapter summary.

Chapter 7 – Proposed Scalability Framework

This chapter is the culmination of the previous chapters discussed in this study. This chapter draws from the home development process discussed in Chapter 4, the overheating analysis conducted in chapter 5, and the evaluation of overheating mitigation methods conducted in Chapter 6. In this chapter a framework to embed scalability into home development processes is presented and discussed. This chapter is broken down into the following sections, outcomes from previous chapters, proposed framework for embedding scalable overheating mitigation solutions into home development processes, and chapter summary.

Chapter 8 – Conclusions and Recommendations

This chapter contains a summary of the entire thesis, and presents the main conclusions, contribution to knowledge, and the limitations of the research. These are followed by some consideration of the potential industry implications of the research findings, particularly in relation to the implications for home developers, home occupants and government policy, as well as recommendations for future research. This chapter is subdivided into the following sections: Achievement of research objectives, conclusions of the research, research contributions, generalization of results, limitations for the study, recommendations for future research, reflecting on the research journey, and chapter summary.

1.9 Chapter Summary

This first chapter has introduced the research and provided background information. The aim, objectives and research questions have been presented, along with a scope statement and a justification. This chapter has also presented a summary of the research design and the data collection methods used in carrying out the study aims and objectives. This chapter is concluded by a research structure that shows what to expect in the preceding chapters.

Chapter 2: Literature Review

This chapter critically reviews the work that previous scholars have done in overheating and thermal comfort in homes. Current trends on overheating and thermal comfort are analyzed with an aim of laying out the research gap that this research intends to explore. This section covers the following key topics: thermal comfort, overheating, legislation on overheating in the UK, assessment methods, scalability of mitigation solutions, home development processes in the UK, the research gap and chapter summary.

2.1 Background to Thermal Comfort

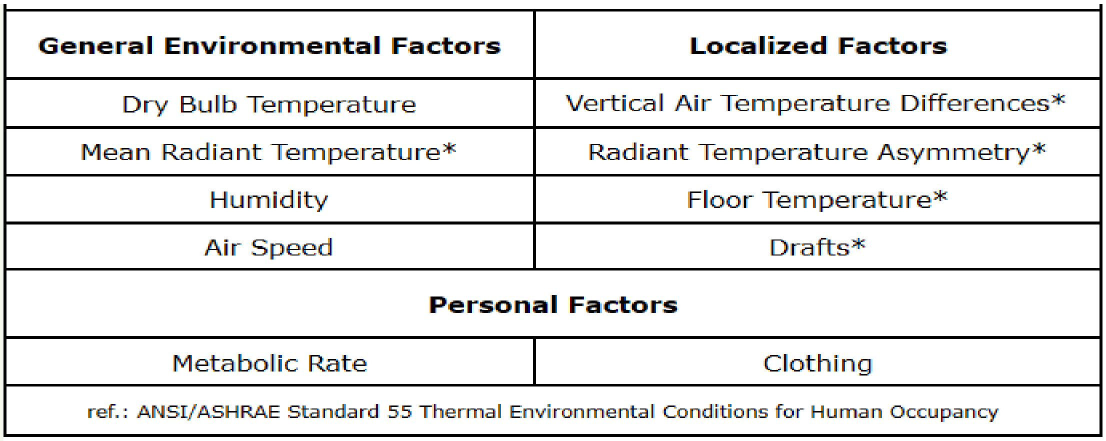
Up until the Industrial Revolution, thermal comfort was addressed by frugal means with wood or coal fires in winter and handheld fans in summer (Vadodaria, 2014). The science around thermal comfort developed in the 20th century to meet the needs of the heating, ventilation, and air conditioning (HVAC) industry (Nicol and Roaf, 2017). As such, it was dominated by engineering-led approaches that focused on measuring and producing optimal thermal conditions for building occupants. Comfort was perceived as a “product” that can be sold by the HVAC industry (Fanger, 1970). These approaches have been challenged by critiques from different directions, questioning the reductionism, simplification, and standardization inherent in such approaches (Yang et al., 2014; Jokl and Kabele, 2007; Nicol and Humphreys, 1973; Hughes and Natarajan, 2019). In recent years, thermal comfort has attracted attention mostly due to increased public discussion about climate change (Rupp et al., 2015). The study and understanding of thermal comfort moved from being a peripheral consideration where “good enough” decisions were deemed acceptable. Recent research approaches seem unconcerned with the experimental design of comfort and are leaning towards the way thermal comfort is experienced together with social and cultural aspects (Wilhite, 2009), while wrapped in technologies and policies (Shove et al., 2008). In line with this, thermal comfort is increasingly being viewed to encompass more than just buildings, heating and cooling technologies and people as bodily physiologies (Vadodaria, 2014). Understanding thermal comfort is important to provide a satisfactory condition for building occupants, have control over energy consumption and suggest and set standards (Nicol, 1993).

2.1.1 Thermal Comfort

According to the indoor environmental ergonomic definition, thermal comfort is a condition of the mind that expresses satisfaction with the thermal environment (ASHRAE 2017). It is subjective as it varies from person to person (Fanger, 1986). Chappells and Shove (2005) view thermal comfort as a socially determined notion defined by norms and expectations that change through time, place and season. According to Peacock et al., (2010), it is an amalgamation of physiological and mental response to a climatic condition. It sits at the crossroads of building physics, mechanical engineering, physiology, psychology, culture, and climate (Bean, 2012). Interestingly, a survey of indoor environmental conditions discovered that according to building occupants, thermal comfort is ranked to be of greater importance compared to visual and acoustic comfort and indoor air quality (Frontczak and Wargocki 2011).

Air temperature is the commonly used indicator of thermal comfort. Normally because it is easy to use, and most people can relate to it. However, according to the Health and Safety Executive (HSE, 2015), air temperature on its own is neither a valid nor an accurate indicator of thermal comfort. The level of thermal comfort is rather determined by a combination of personal, localized, and general environmental factors (ANSI/ASHRAE-55) as shown in Table 1. One element of thermal comfort cannot be made a proxy for the others as has been done with air temperature.

Table 1: Factors affecting Thermal Comfort (Bean, 2012)



General Environmental Factors	**Localized Factors**
Dry Bulb Temperature	Vertical Air Temperature Differences*
Mean Radiant Temperature*	Radiant Temperature Asymmetry*
Humidity	Floor Temperature*
Air Speed	Drafts*
Personal Factors	
Metabolic Rate	Clothing
ref.: ANSI/ASHRAE Standard 55 Thermal Environmental Conditions for Human Occupancy	

The general environmental factors that affect thermal comfort as in table 1 are dry bulb temperature, mean radiant temperature, humidity, and air speed. Dry bulb temperature or as it is commonly known, air temperature, is the most relatable factor that affects thermal comfort. It is the temperature of air surrounding the body and as such, it is always uneven (Thomas, 2006). Since radiation is a major source of heat perception, mean radiant temperature (MRT) is a significant factor that affects thermal comfort (Taleghani et al., 2013). MRT is the uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body is equal to the radiant heat transfer in the actual non-uniform enclosure (Senin et al., 2013). It plays a crucial role in affecting thermal comfort especially on hot sunny days. In fact, according to the HSE (2015), radiant temperature is of more influence than air temperature as regards to how heat is lost or gained to the environment.

Relative humidity is the ratio of the amount of water vapour in the air Vis a Vis the maximum amount of water vapour that air can hold at a specific temperature (HSE, 2015). Typically, once dry-bulb temperatures above the threshold of 35^0C are hit, metabolic heat is shed via sweat-based latent cooling. At wet bulb temperatures above 35^0C, this cooling mechanism loses its effectiveness (Raymond et al., 2020). High humidity levels in indoor environments prevent the evaporation of sweat from the skin, which is the main method of heat reduction. Air speed/velocity also has a thermal effect since it can increase heat loss by convection without causing any change in temperature (Taleghani et al., 2013). Moreover, air movement can also reduce stuffiness that occurs through the buildup of still or stagnant air in built environments.

Thermal comfort can also be affected by local factors such as vertical air temperature differences, radiant temperature asymmetry, floor temperature and local drafts as shown in Table 1. This leads to what is known as local thermal discomfort. According to an experiment by Olesen et al., (2002), people do not tolerate warm head or cold feet and the impression of freshness decreases with increases in vertical air temperature differences. The asterisk * shows factors that are influenced by enclosure performance, however, dry bulb and relative humidity are co-influenced by enclosures exclusively conditioned with air-based HVAC systems (Bean, 2012).

Personal factors such as metabolic rate and clothing also affect thermal comfort. Body metabolism refers to the chemical changes that occur depending on the amount of activity being undertaken. A person's metabolic rate is also dependent on factors such as size, weight, age, fitness level and sex even when other factors are constant. Clothing levels affect thermal comfort by providing an extra layer that offers an insulating effect on the wearer. The ability to modify personal factors such as change of clothing or activity level enables individuals to find different temperatures acceptable (Cole et al., 2008).

When at a given temperature or when a combination of environmental parameters exceed a given threshold beyond which occupants experience thermal discomfort, then overheating occurs (Mcleod and Swainson, 2017).

2.2 Overheating in buildings

According to Zero Carbon Hub - ZCH (2016), overheating describes situations where the temperature inside a person's home becomes uncomfortable or excessively warm. Overheating occurs when the local indoor thermal environment presents conditions in excess of those acceptable for human thermal comfort or those that may adversely affect human health (MHCLGa, 2019). It happens when too much heat builds up in a dwelling and cannot be adequately purged. This research adopts the Zero Carbon Hub - ZCH (2016, pg.2) definition that states that overheating is *"the phenomenon of excessive or prolonged high temperatures in homes, resulting from internal or external heat gains, which may have adverse effects on the comfort, health or productivity of the occupants."* Overheating can range from thermal discomfort to conditions that could lead to heat stroke or death (DCLG, 2012). In fact, the Housing Health, and Safety Rating System (HHSRS) (2004; pg.64) states, *"High temperatures can increase cardiovascular strain and trauma, and where the temperatures exceed 25 °C, mortality increases and there is an increase in strokes."*

Although CIBSE (2013) TM52 states that overheating in buildings happens through bad design, poor management and/or inadequate services, there is overwhelming evidence that a warming climate in the recent past is also to blame (Marvogianni et al., 2011). To add to this the Department for Communities and Local Government (DCLG, 2012) describes that the increase of modern, highly insulated, and airtight homes with inadequate ventilation provision is a significant cause of overheating in UK homes.

2.3 Trends in Overheating Studies

A bibliometric analysis in Scopus (August 2023) with "overheating in homes" as the key words, produced 242 document results, mostly from engineering, energy, environmental science, physics, and social science fields. The analysis of the search results revealed trends showing that research into overheating in buildings has increased drastically in the recent past as shown in Figure 2.

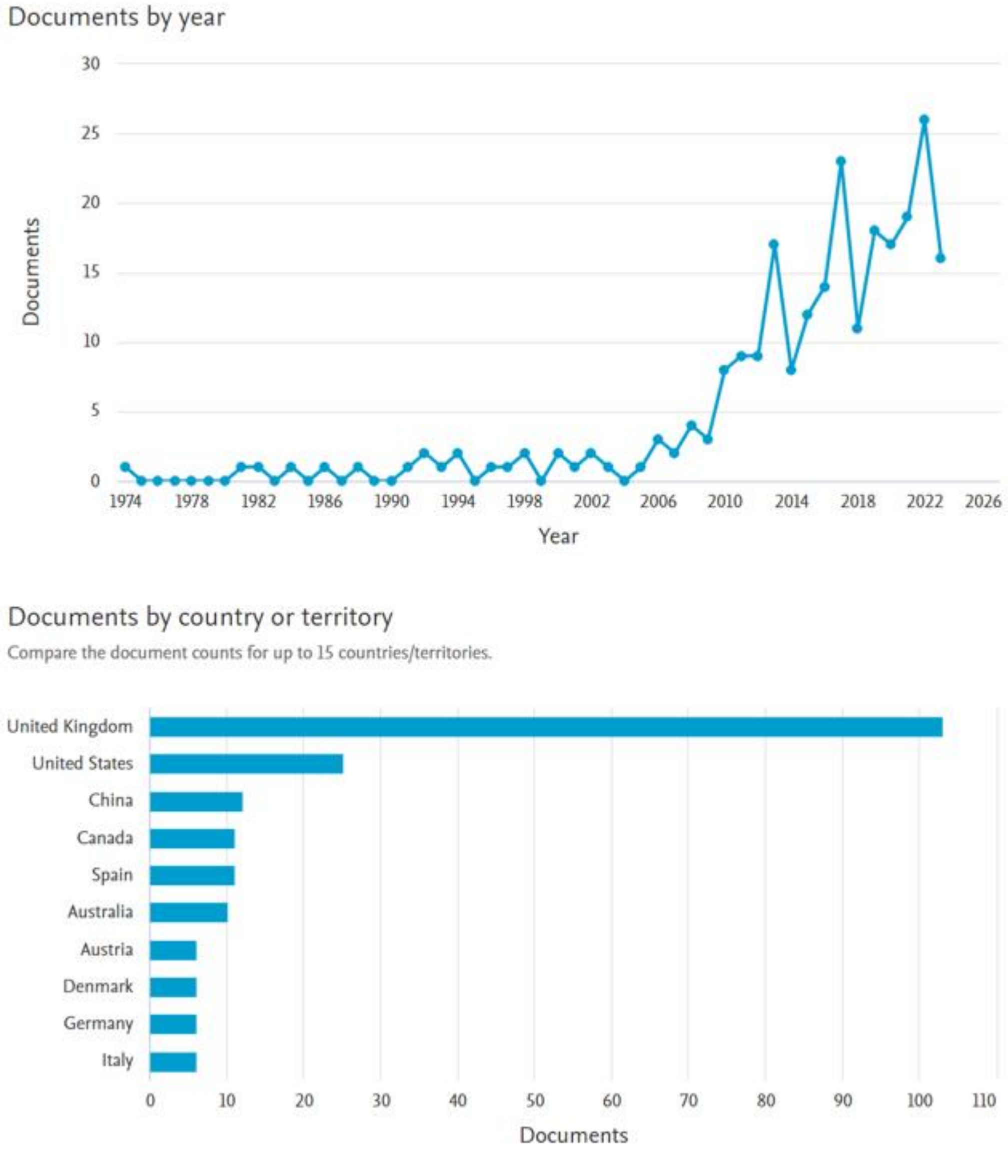


Figure 2: Bibliometric Analysis in Scopus

As can be seen in Figure 2, interest in overheating studies has increased drastically since the mid-2000s from around less than five studies a year, to about twenty-five studies a year in 2023. This shows that there has been a growing interest in this topic in the fast few years alone. In the recent few years, there have been numerous instances of climate-instigated summertime heatwaves, thereby explaining this growing interest. As Figure 2 also shows, overheating studies have been focusing on countries such as the UK, the US, China, Canada, and other European countries. The most notable of these is the UK, accounting for 103 out of 242 studies. The next section analyses overheating trends in other countries, before focusing more on the UK.

2.3.1 Overheating in the United States

Frequent and prolonged periods of high temperatures have been common in the cold semi-arid regions of America due to climate change. The frequency of heatwaves in the Eastern US is projected to increase five times from the 2002-2004 level to 2057-2059, when the average heatwave will be a day longer (Wu et al., 2014). According to the California Environmental Protection Agency, extreme heat days will more than double between 2050 and 2099 in Most California Cities, with annual heat related deaths in Los Angeles increasing from 165 in the 1990s to between 320 and 1200 in 2020 (Fisk, 2015).

Climate change not only affects outdoor temperatures but also increases air temperatures in indoor environments. A study by Dentz et al., (2014) identified that indoor temperatures in many buildings in New York were significantly higher than the required indoor temperature. The required indoor temperature being a minimum of 20 °C if the outside temperature is below 12.8 °C during the day (10:00 PM to 6:00 AM) and a minimum of 12.8 °C if the outside temperature is below 4.4 °C during the night. Research by Baniassadi et al., (2019) identifies that the current building stock in US cities is not resilient to climate change and induced warming in the absence of AC systems. However, they mention that AC is not reliable, meaning that large-scale improvement will have to depend on passive options as well.

2.3.2 Overheating in China

In recent years, summer heatwaves have frequently affected several areas of China, hotspots in cold climates as well as hot summer and cold winter climates (Wang et al., 2021). Summer in China tends to be long, hot, and humid with overheating problems often occurring in hot and humid areas. An example of those areas is Chongqing which is also known as a “furnace city” because of its high average temperatures above 20^{o}C for seven months in a year and humidity values always higher than 80% (Yao et al., 2017). Recent research (Guo et al., 2019) has revealed that heatwaves have increased significantly nationwide since the 1960s, especially in northern China. According to the China Meteorological Administration (CMA), a heat wave is a weather event with more than three consecutive days of daily maximum temperatures above 35^{o}C.

China's building design policy emphasizes on heat preservation for buildings during cold climates and heat resistance during summer. However, for areas located in heat-dominating climates, the building designs that emphasize on reducing heating demand, fail to meet the needs of mitigating overheating risk (Wang et al., 2021). Therefore, due to the combined effects of building design orientation and climate change, indoor overheating is a potential threat to the heat-dominated climate zones of China.

2.3.3 Overheating in European Countries

Most of Europe, which has traditionally temperate climates, is increasingly experiencing longer periods of days with high maximum temperatures, especially in Central Europe (Allen et al., 2018). The increasing intensity and frequency of climate change-driven heatwaves have been reported in Poland, France, Portugal, Spain, Belgium, Russia etc. in the last few years. Temperatures of up to 45^{0}C were recorded in June 2019 in Paris. Sweltering temperatures of up to 46^{0}C were recorded in the summer of 2022 in southern Spain, being the hottest summer on record since 1961. 40.2^{0}C temperatures were recorded in Angleur, Belgium in July 2019 exceeding a previous record of 38.9^{0}C in 1947. The European heatwave of 2019 also set record temperatures of up to 38.2^{0}C being recorded in Radzyn Poland. Portugal has also experienced record temperatures that have led to more than 80% of mainland Portugal being designated as "exceptional risk" to fires according to the Portuguese National Meteorological institute (IPMA). These heatwaves have resulted in many excess deaths due to heat stress. During the 2003 European heatwave, there was a 60% increase in excess deaths in France, 40% in Portugal, 8% in Spain, 14% in Italy and 7% in Switzerland, most of which occurred in homes (Cadot et al., 2007; Kovats and Hajat 2008). In Russia, a heatwave in 2010 with recorded temperature of 44^{0}C in Yashkul and 42.3^{0}C in Belogorsk resulted in 56,000 excess deaths over 44 days (Maggiotto et al., 2021). In the Netherlands, the June-July 2019 European Heatwave led to 2964 excess deaths (Vidal et al., 2020). This is because people living in these countries are less able to tolerate hot temperatures and the temperature threshold at which mortality starts to rise is lower (Allen et al., 2018). As a result, most houses in European countries have embraced mass air conditioning systems, as well as passive strategies such as fixed shading overhangs and external shutters into home designs. Ceiling fans are also popular in European homes and buildings because of this.

2.3.4 Overheating in Australia

One of Australia's most deadly natural hazards and the principal driver of peak electricity demand due to mass air-conditioning is heatwaves (Hatvani-Kovacs et al., 2016). Heat waves such the ones that occurred in February 2004 and the summer of 2009, where temperatures in excess of 40^{o}C were recorded; cause many excess deaths (Ren et al., 2014). More than a third of deaths between 1956 and 2010 in Australia are heat related deaths that occurred indoors (Coates et al., 2014), a proportion that has been rising since the 1850s. Current construction methods in Australia rely on air-conditioning, thereby increasing population dependence on it. Mass reliance on Air-conditioning in turn increases electricity demand and prices, causes occasional blackouts, and exacerbates energy poverty (Hatvani-Kovacs et al., 2016; Moore et al., 2017). There is growing awareness in Australia that understanding the performance of homes in summer conditions is vital to design dwellings which balance climate change mitigation and adaptation (Karimpour et al., 2015). Australia's energy efficiency-rating framework has been redefined and there are efforts to link improved residential energy efficiency to better health by informing public health campaigns. This is being done by acknowledging the links between residential thermal performance and summer indoor temperatures to inform policy and guide consumer choice (Willand et al., 2016).

The above sections suggest that overheating is now becoming an increasing interest even in temperate climate countries that have never had to deal with dominant hot weather events in housing design. The next section discusses overheating in the UK.

2.3.5 Overheating in the UK

UK summers are getting warmer due to human-caused global warming. Temperatures above 35^{0}C are increasingly becoming common in the Southeast, while temperatures in many areas in the north are likely to exceed 30^{0}C at least once per decade by 2100 (Christidis et al., 2020). The 2003 heatwave that lasted 10 days and led to over two thousand deaths in England could become the norm by 2040 (PHE, 2015). Climate change predictions in the UK indicate that summertime mean daily temperatures could increase by 1.3^{0}C - 4.6^{0}C in London by 2050s and 5.4^{0}C in Southern England by 2080 (UKCP09). In July of 2019, the UK Met office confirmed one of the highest ever temperature recording at the Cambridge University Botanic Garden measuring 38.7^0C, beating the previous UK record of 38.5^0C in Kent back in 2003 (BBC, 2019). However, 2022 was the warmest year on record and was the first year when summertime temperatures above 40^0C were first recorded shattering previous records (Met office, 2022). The Met Office has warned that the multi record-breaking hot and dry weather of 2022 will become typical in the UK in under 40 years (Sky News, 2023). Based on this trend, more heatwaves in greater intensity, frequency and duration are expected (Jones et al., 2008, Marvogianni et al., 2011).

According to Figure 2, most of the studies relating to overheating in homes are in the UK; 103 out of 242 documents. This is in line with the increasing trend of summertime overheating from around 2010 and the actively developing UK regulatory framework around overheating in homes, which has occurred in the last few years. As a result, there have been many overheating monitoring studies that have taken place in the UK. This signifies a growing interest among UK home development stakeholders in matters regarding overheating in homes.

Among the 103 studies on overheating in homes in the UK found in Scopus, a searching criterion was done to focus only on open-access sensor monitoring studies of homes, which were conducted from 2010 to 2023. This left fifty-seven studies to be analyzed. This was done to shed light on recent UK home monitoring studies that used the same methodology-sensor monitoring, as the one employed in this research. Table 2 contains a summary of the top 13 UK-based overheating studies, involving mass house monitoring of thermal comfort parameters in the summer periods of 2010 to 2023.

Table 2: Monitoring Studies on Overheating in Houses in the UK (2010-2023)

Studies	**Sample Type and Size**	**Period**	**Location**	**Assessment Criteria**	**Major Findings**
Mavrogianni et al., (2015)	8 social housing flats	July-September 2013	Central London	CIBSE Guide A and CIBSE TM52	The analysis of the monitored data suggests that the case study flat already experiences hours with temperatures above the recommended thresholds, even during a relatively mild summer (e.g., the summer of 2013).
McGill et al., (2017)	53 New, post-2008. Energy efficient dwellings	May-September 2012-2014	Across the UK	CIBSE Guide A, PHPP and CIBSE TM52	The results demonstrate a high prevalence of overheating in exemplary housing, indicating the need for greater efforts to ensure the effective implementation of strategies to minimize overheating and improve ventilation in low-energy homes.
Morgan et al., (2017)	26 Dwellings - 21 low energy homes and 5 Passivhaus designs	2013 Calendar year	Six sites in Scotland	Passivhaus Criteria (PHPP)	Results suggest that low-energy buildings are susceptible to overheating despite northerly latitudes, with 54% of houses studied overheating for more than six months annually, and 27% of homes overheating for less than 10% of the year.
Baborska-Narożny et al., (2017)	18 Flats in a single ten storey block	July-August 2013	Leeds, northern England	CIBSE Guide A and CIBSE TM52	Although the monitored period in summer 2013 did not exceed a daily running mean of 18.5°C, there were nevertheless significant overheating issues reported by the inhabitants.
Vellei et al.., (2017)	55 newly refurbished dwellings.	May - September 2014 and 2015	Exeter, South-west England	CIBSE Guide A and CIBSE TM52	Overheating was found to occur, particularly and disproportionately in households with vulnerable occupants in summer years that were not extreme
Gupta et al., (2017)	2 Care homes	June - September 2015	England, Four sites in north, southwest, south-east	CIBSE Guide A and CIBSE TM52	The findings suggest that overheating is a current and prevalent risk in case study schemes, yet currently little awareness or preparedness exists to implement suitable and long-term adaptation strategies (e.g., external shading).
Pathana et al., (2017)	122 Dwellings	Summers of 2009 and 2010	Greater London	CIBSE Guide A	The findings of this study indicate that London dwellings face a significant risk of overheating under the current climate.

Tabatabaei Sameni et al., (2015)	23 social housing flats built to the Passivhaus standard in the UK (18 flats and 5 houses)	August - September 2011, July - August 2012 and May - August 2013	Coventry UK	Passivhaus Criteria (PHPP)	Overheating assessment based on Passivhaus criteria, using a fixed benchmark, suggests there is a significant risk of summer overheating with more than two thirds of flats exceeding the benchmark.
McLeod and Swainson (2017)	80 unit, newly built flats in a multi-residential block	The autumn shoulder season in October 2015	England	SAP Assessment	The results suggest that the causes of chronic overheating in these modern low-energy flats are multiple, but typically share common factors stemming from poorly integrated architectural and MEP design decisions.
Energy Follow-up Survey (2013)	823 homes	December 2010 and April 2011.	England	SAP Assessment	Overall, 20% of households reported at least one room is overheated during the summer months.
Tsoulou et al., (2022)	2 care homes	June to September 2019	England	PHE 26^{0}C Threshold	The analysis of monitoring data from summer 2019 showed that almost half of indoor temperature measurements exceeded the threshold of 26 ^{0}C. Findings from thermal simulation models suggested that the risk of overheating will likely be much higher by 2050 if no cooling measures are implemented.
Gupta et al., (2021)	2 care homes	June to August 2019	London	CIBSE Guide A and CIBSE TM59	*In* both care settings, indoor temperatures were observed to exceed 30 °C during daytime hours, significantly higher than the recommended 26 °C threshold of Public Health England. Overheating was found to be prevalent and prolonged across both care settings with bedroom temperatures higher than lounges especially at night.
Toledo et al., (2016)	Four highly insulated British homes	June–August 2015	Leicester, Sandiacre, York	CIBSE Guide A (2007)	This study provided evidence that uncomfortable temperatures were recorded in all the homes under review.

The studies summarized in table 2, highlight the increasing and growing concern of overheating in UK homes. In some cases, (Marvogianni et al., 2015; Vellei et al., 2017) monitored houses were seen to have experienced significant levels of overheating even in relatively mild summers. This should raise concern given that future climate projections point towards increasing temperatures and frequent heatwave events. For example, the Zero Carbon Hub (2015) overheating survey involving housing developers found that 70% of the organizations reported experiencing at least one instance of overheating in their housing stock just in the last five years. A careful examination of drivers of change, climate change studies and modelling assessments all point towards the conclusion that overheating is becoming increasingly common in the housing stock across the UK. In fact, according to the UK trade body Zero Carbon Hub (2015), the issue of overheating together with indoor air quality will be the two predominant issues over the next 5 to 10 years for the sector. The bibliometric analysis in Table 2, shows that there is plenty of evidence of overheating in homes. What is needed is how this evidence gets into practitioners, developers, occupants etc., so that mitigation strategies can be implemented. This is why this research focuses on the home development process to analyze the wider contextual issues, processes and procedures that allow overheating to thrive and determine ways of assessing and implementing scalable overheating mitigation solutions.

2.4 Sources of Overheating

Heat is gained from both the inside and outside of a dwelling. The main source of external heat is the sun through windows, doors and other openings into dwellings (UKGBC, 2011). For double-glazed windows with low e coating, heat from the sun will be allowed in but heat will be prevented from escaping (Mohamed, 2019). Other external heat sources include cooling systems of other buildings, cars, buses, and other vehicles depending on how close they are to dwellings.

Another source of overheating is internal heat gains in dwellings (Gupta and Gregg, 2013). Internal heat gain is the sensible and latent heat emitted within an internal space from any source that is to be removed by air conditioning or ventilation, and results in an increase in the temperature and humidity within the space. This includes heat from people and pets, cooking, appliances, building lighting systems (Lapinskienė et al., 2017), internal heating and hot water distribution systems, especially when they are poorly insulated (BRE, 2016). This is summarized in figure 3.

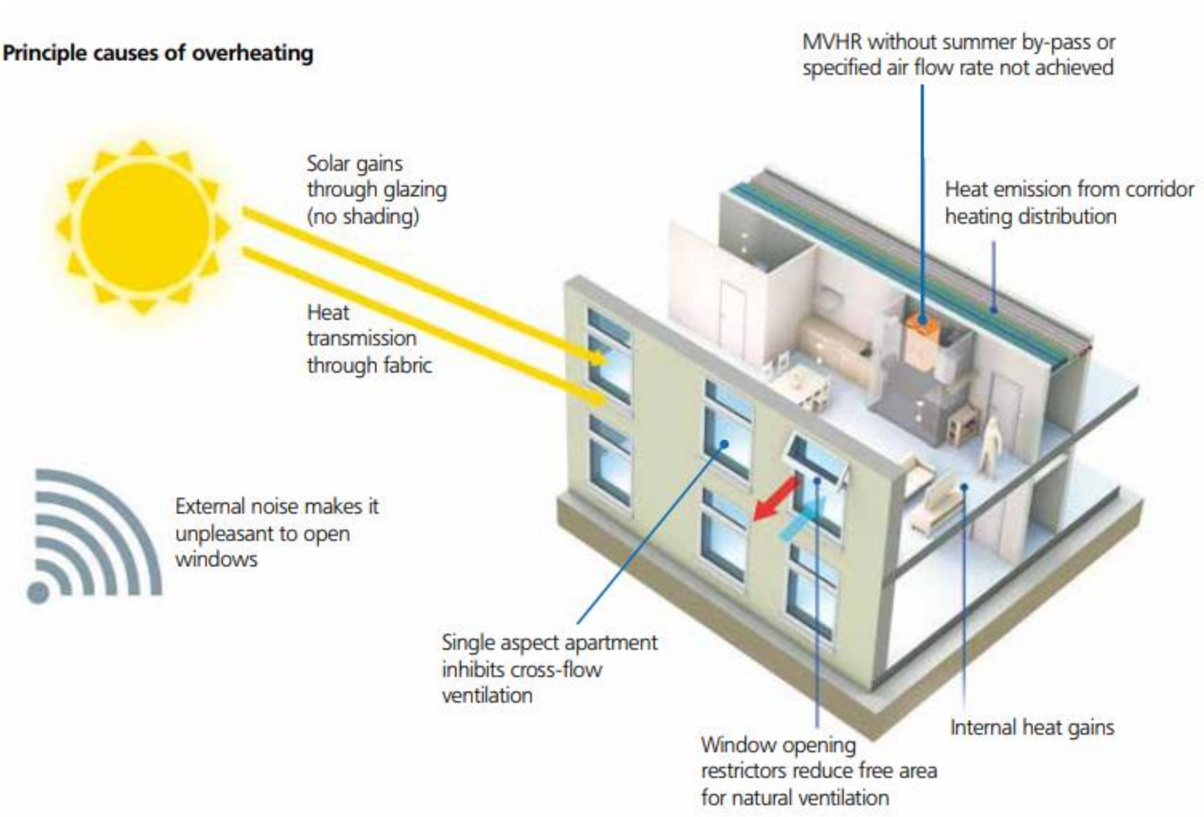


Figure 3: Main Sources of Overheating (UKGBC, 2016)

Human beings and pets lose heat to the surroundings due to their metabolic activity which depends on the level of activity being performed e.g., sleeping, dancing etc. They release sensible heat due to their higher skin temperature compared to the surrounding and latent heat through respiration and sweating (Gupta and Gregg, 2013). Lighting appliances convert some electrical energy to heat, which is then transmitted through conduction, convection, or radiation. This, however, depends on mounting position and type of the appliance (Lapinskienė et al., 2017). Other activities such as cooking are intensive heat generating activities themselves. For houses in the UK, internal heating and the accompanying hot water distribution systems including boilers and hot water storage are major contributors to internal heat gain (BRE, 2016). They all have the potential to radiate heat that may contribute significantly to overheating (NHBC Foundation NF44, 2012). This is especially true for communal occupied areas of buildings like WCs and laundry areas with large amounts of pipework in relatively small spaces. However, it is the cumulative effect of internal and external heat gains, site context factors, external temperatures, solar gains and building design features that increase the phenomenon of indoor overheating in residential buildings.

Understanding the potential sources of heat gains in residential buildings is the first step to analyzing factors that contribute to overheating in residential buildings.

The following factors influence the propensity of risks associated with overheating in residential buildings.

2.4.1 Location

The following aspects of location influence the propensity of overheating risks in buildings:

- Geographical location

Different locations experience different levels of outdoor temperatures that could determine the occurrence of overheating. This is because different locations experience different climates or microclimates. In the UK, Southern England could likely face the largest risk of indoor overheating with some of the highest recorded outdoor temperatures in the UK (DCLG, 2012a). A study by Vellei et al., (2016) investigating overheating in Exeter located in Southwest England, observed that overheating occurred even though the study period experienced no heatwaves as defined by the Met Office. This is because though it is part of the UK temperate climate, Southern England has a different microclimate with higher average temperatures than other parts of the UK. This also explains why different regions of the UK have different heatwave thresholds.

- Urban areas

Dwellings located in urban areas might be highly affected to varying degrees due to the urban heat island effect (UHI). This is a phenomenon that describes elevated temperatures felt in towns and cities more than countryside dwellings (Tomlison et al., 2012, Vardoulakis et al., 2015). It is mostly felt at night as heat retained by artificial surfaces is slowly released thereby keeping temperatures higher than countryside dwellings. According to Marvogianni et al., (2011), UHI is an inadvertent climate change modification attributed to increases in the sensible heat transfer and decreases in both the sensible and latent heat flux transfer processes occurring in the urban canopy and boundary layers. The UHI effect leads to higher night temperatures in typical cities by about 5-10^{0}C compared to the surrounding countryside (Knight et al., 2010; Tomlinson et al., 2012). In summer, and especially during heatwaves, the UHI effect may exacerbate building overheating and related health effects (Davies et al., 2008), since it prevents buildings from cooling down, particularly at night (Watkins et al., 2007). This affects 80% of dwellings in England and Scotland and 65% of dwellings located in urban areas (Capon and Oakley, 2012).

- Floor level

Overheating propensity is also determined by the floor level of a dwelling (Porritt et al., 2011). Top floor flats are more vulnerable to overheating while ground floor areas are generally cool (Capon and Hacker. 2009). This is because top floor flats receive more solar radiation than lower-level floors. Additionally, roofs are often poorly insulated and warm air from lower floors rises through the building. Bedrooms and living rooms appear to be more susceptible to high temperatures (Mavrogianni et al., 2010; Beizaee et al., 2013) because of the longer duration occupants spend in them as well as high occupancy numbers at a time for living rooms. Bedrooms are also traditionally located on upper floors that are hotter than rooms in lower floors.

2.4.2 Building Characteristics

The following building characteristics influence the overheating propensity of a residential building:

- Window properties

As the greatest source of overheating in homes is solar gains, openings such as windows play a critical role in the amount of solar ingress into homes. The size of window openings and the specification of glazing do determine the amount of solar ingress into a space (Roetzel et al., 2012; Wright and Venskunas, 2022). Larger windows allow for more area for solar gain and vice versa. Also, the specification of glazing matters. Different types of glazing; single glazing, double glazing, triple glazing do affect the amount of solar gain into a space. The more the layers of glazing, the less the sunlight that is allowed to enter a space. The g-value of glazing also matters. G-value is a measure of the solar transmittance through glazing: with a scale of between 0 -1. A high g value means full transmittance of solar energy and a low g- value means all solar energy is blocked. Most windows usually have a g-value of around 0.45. Other additional window strategies affect the amount of solar ingress into a space. These include the presence of blinds, shades, or screens that might regulate the amount of solar ingress into a space (Mohamed, 2019).

- Orientation

As solar gain is the greatest source of overheating into a space, the orientation of a building in relation to the typical sun path is critical in determining overheating in a house. Although different homes are slightly different, west facing facades are more prone to receive more sunlight than any other façade (Gupta and Gregg, 2020). Therefore, orienting homes with the predominantly glazed façade facing other directions like south, is key to reducing the overheating risk of homes. Although this is usually ideal, home orientation is limited by plot sizes and number of homes as well as planning restrictions.

- Airtightness

Airtightness of a building is a measure of the air permeability of a building's fabric. The airtightness of a building is expressed in terms of the leakage flow rate through a buildings envelope usually at 50 pascals reference pressure divided by the enveloper area. The unit is $m^3/(h\cdot m^2)$. A building with a high level of airtightness means there is no uncontrolled outward or inward leakage of air through gaps, cracks, or unintentional openings in a building (ADL1A, 2010). Airtightness in a building is usually achieved by insulation. As insulation acts as a barrier to reduce heat gain or loss from or to the interior of a building, it contributes to the air permeability of a build. It can also be achieved using polymer sprays and tapes to create an additionally barrier in sealing up small cracks. A highly airtight building means that there are limited levels of uncontrolled ventilation in a building. Though this may be good for preventing heat loss and less energy consumption in winter, it increases the risk of overheating in hot weather especially if a good means to removing excess heat is not implemented (McLeod et al., 2013). This is the reason traditional UK buildings perform better in summertime as compared to new buildings. Traditional UK buildings have high levels of air tightness as they were not built to the high levels of airtightness as per current building regulations. As a result, newly constructed houses with high airtightness levels are usually more at risk to overheating than older, less insulated homes (DCLG, 2012a).

- Ventilation strategy

The method of removing excess heat from a building is critical to its overheating performance. This is where ventilation comes in. There are two broad types of ventilation in homes: Naturally ventilated and mechanically ventilated homes. Naturally ventilated homes rely on natural means such as winds to provide for ventilation of homes. Natural ventilated homes normally rely on having openings – windows and doors on opposite ends of a building to allow for natural winds to occur. Even with adequate windows and doors, naturally ventilated homes can be affected by environmental concerns like noise and air pollution, as well as security concern. These may limit their use. Therefore, considering wider contextual factors is important for the success of natural ventilation options. Mechanically ventilated homes on the other hand rely on mechanical ventilation systems to artificially induce pressure differences to create ventilation. Most homes in the UK are naturally ventilated. However, the recent occurrences of summertime heatwaves could lead to the adoption of mechanical ventilation options. This notwithstanding, mass-residential air conditioning and other mechanical systems are not encouraged as they put more strain on the electric grid and because of their negative effects on emission reduction targets (MCHLGb, 2019).

- Building Typology

Overheating risk in homes is influenced by building typology. Compared to individual home typologies like detached, semi-detached or terraced buildings, apartments/flats are at more risk of overheating. This is because apartments usually have single aspect designs that do not allow for cross ventilation. Additionally, apartments normally have long and poorly insulated stretches of community heating pipework that runs through corridors and common areas. In such apartments, overheating is usually caused by poor ventilation and excess heat discharged from poorly insulated heating pipework (Bateson, 2017). Many community heating systems in apartments are usually operating throughout at high temperatures. This makes apartments more susceptible to overheating.

- Thermal Mass

Another build form factor that determines the occurrence of overheating in buildings is thermal mass. This is the ability of a building to store and emit heat (Mohamed, 2019). It is based on the specific heat capacity and density of fabric elements (wall, roof, and floor composition) in the structure of a building. During the day, buildings absorb heat mostly through solar gain and release it at night. The ability and rate at which heat is gained or lost in a building depends on the materials used.

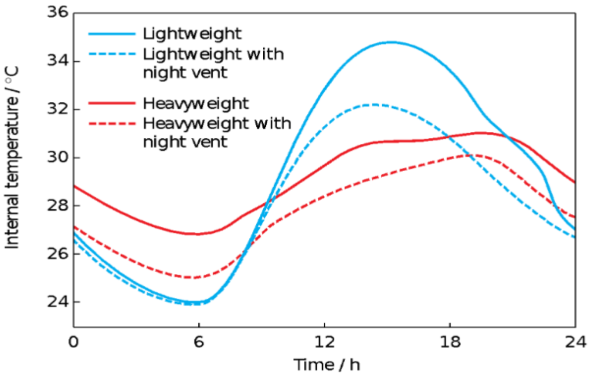


Figure 4: The Effect of Thermal Mass and Ventilation Rate on Peek Indoor Temperatures (Gagliano et al., 2016)

Although thermal mass assists in ameliorating external and internal temperature fluctuations, it can also lead to overheating especially at night. This explains why homes built of light materials like wood or PVC are more sensitive to outdoor conditions than homes built of heavy building materials like bricks (White-Newsome et al., 2012). As shown in figure 4, homes built of low thermal mass materials (materials that quickly re-emit absorbed heat into living spaces) can experience uncomfortably high day-time temperatures that could lead to overheating, making it difficult for people. Especially when purge ventilation is not possible.

2.4.3 Occupant Behaviour

When the thermal properties of dwellings of similar type and form, located in the same location are compared, occupant behaviour seems to be the biggest variable affecting the likelihood of overheating (Morgan et al., 2017). For building occupants, their susceptibility to elevated temperatures and their diverse behaviour play a significant role on the impact of overheating incidences in buildings (Lomas and Porrit, 2017). Occupants can alter indoor temperatures by adjusting ventilation and shading during hot periods using cooling systems, changing clothes, using fans, or even changing location within the home (Mavrogianni et al., 2012). These occupant actions are consistent with the Adaptive thermal comfort theory (Nicol and Humphreys, 2002, p. 564).

Their behaviour depends on their age, their sex, their metabolic rate, their thermal adaptation, socio-economic status, personal knowledge, and preferences (Wei et al., 2014). Therefore, decisions like when to open windows are spontaneously made to directly respond to experienced temperatures (Vardoulakis et al., 2015). The elderly, however, are vulnerable because of their low sensitivity when it comes to ambient conditions and physiological ability when it comes to regulating their body temperatures (Lomas and Porrit, 2017). This can even be further exacerbated by medical conditions that further reduce physiological tolerance. Apart from medical conditions and physiological vulnerability, lack of tacit knowledge in terms of overheating control practices and less access to control measures can also be to blame (PHE, 2013). This explains the findings of a recent study (Brown and Gorgolewski, 2015) that revealed that environmental control systems such as Mechanical Ventilation with Heat Recovery (MVHR) and air conditioning systems were not used by inhabitants as intended in optimized design models and this has led to significant performance failures. In a study by Morgan et al., (2017) on overheating, 46% and 15% of housing occupants stated that they did not understand or use programmatic control and thermostatic controls of HVAC systems, respectively. Additionally, the subjectiveness of thermal sensations means that adaptation can occur. Occupants that are used to hotter climates may not have the same thermal sensation as occupants that are used to cooler temperatures, even at the same temperature. This subjectivity means that occupant behaviour is a varied and complex issue.

The next section looks at strategies that can be used to mitigate against overheating in homes.

2.5 Overheating Mitigation Measures

Overheating mitigation measures can be classified into active or passive measures. Active measures consume significant levels of energy (carbon intensive systems) in order to function, while passive measures are low energy systems engrained into a building's form and envelope. Since active overheating mitigation measures are mechanically carbon-intensive systems, they produce carbon emissions that further exacerbate overheating in a vicious circle due to their contribution to climate change (BRE, 2017). Ideally, overheating mitigation measures are in line with the "fabric first" approach. This approach involves passive strategies that optimize the performance of a building's form and envelope first (low-energy measures), before considering additional secondary technologies (Oldfield, 2017). However, Mylona (2019) suggests that although passive measures could be effective under the current climate, they may not be sufficient to eliminate overheating risks in future, and active cooling strategies may become an inevitable solution for future overheating. If this happens, the electric grid could face an increased demand, and this could set industry net zero targets behind.

This research focuses on passive mitigation strategies due to their low contribution to carbon emissions. For the purposes of this research, measures that reduce the effects of overheating are broadly classified into the following groups: site assessment measures, building layout measures, ventilation strategy measures and façade design measures. These measures either limit heat gains in buildings or enhance the capacity of a building to dissipate heat.

2.5.1 Site Assessment Measures

In order to reduce the effects of the Urban Heat Island (UHI) effect Tomlison et al., (2012), and Vardoulakis et al., (2015), propose that housing construction has to consider strategies aimed at reducing heat accumulation in urban environments. Mohamed (2019) suggests the inclusion or preservation of green space areas such as parks and major blue space features such as lakes, ponds, swales, fountains, and canals in housing scheme masterplans. Trees not only provide shade, but they also cool the air around them through evapo-transpirative cooling (Moss et al., 2019), which has the potential of reducing temperatures. Such features offer opportunities to exploit shading and orientation of houses to minimize solar gains or achieving passive ventilation through mechanizing air flow. Cool infrastructure surfaces such as reflective paving and parking area surfaces can help to reflect heat rather than absorbing it. This will reduce the amount of solar energy absorbed by infrastructure around homes, and therefore reduce the heat gain into homes.

Noise assessment is important as it restricts window opening behaviours. Window opening is a key aspect of ventilation and removal of excess heat in homes. Noise assessment is even more critical for homes such as care homes that house vulnerable occupants. (AVO, 2020). For such sites, additional noise reduction measures such as additional insulation with better acoustic properties, orienting large glazing areas away from noise sources or directions and many others could be used.

2.5.2 Building Layout Measures

As the main source of heat gains in dwellings is the sun, the direction of predominant window-facing facades of houses is crucial to reducing incidences of higher temperatures. The UKGBC (2011) report suggests that west-facing windows are more prone to this, as they receive vast amounts of sunshine. Both the low-angle and high-angle positions of the sun must be factored in when deciding on the orientation of large, glazed facades because other orientations can cause problems too. East and West facing windows can bring in a lot of sun in the morning and evening in a way that is difficult to shade due to the low angle of sunlight.

Designing to allow cross ventilation is another building layout measure. Cross ventilation is achieved when there are openings (windows/doors) on opposite ends of dwellings. This strategy allows for natural ventilation to occur by allowing drafts and winds to pass through rooms from a low-pressure side to a high-pressure side, thereby cooling the dwelling. Dual aspect dwellings allow for cross ventilation. However, windows function better in positions that can allow for cross ventilation of dwellings in line with the general direction of prevailing winds in an area.

The location of bedrooms in a dwelling is another building layout measure. Home occupants spend a lot of time in bedrooms where they also sleep. Therefore, when bedrooms are located away from elevations facing major streets, it minimizes heat gains from radiant heat from nearby tarmac and pavements. For apartments, long corridors are areas where heat accumulates; atria can be preferably used to ventilate and light them.

2.5.3 Ventilation Strategy Measures

Mitigating overheating in buildings requires the use of a cooling system of which there exists three main methods: passive, mechanical and comfort cooling strategies (AVO, 2020). The ventilation strategy employed in a dwelling determines whether it is predominantly naturally or mechanically ventilated and the overheating assessment procedure it requires. Passive ventilation introduces a cooling effect without use of any mechanical means. An example for this is purge ventilation that employs the use of window opening to provide a means for cross ventilation that allows for the circulation of large amounts of air throughout a building (Mohamed, 2019). This can also be achieved by other façade openings such as balcony doors, trickle vents or atria.

Mechanical ventilation requires the use of fans to introduce external air in order to provide a cooling effect. Comfort cooling, however, uses a mechanical system to circulate air inside a room to achieve a certain user-defined temperature set point. An example of these are the Air conditioning units and Mechanical Ventilation with Heat Recovery (MVHR) systems. Ceiling fans can also be used to provide relief from overheating at a personal comfort level (Capon and Hacker, 2009). Ceiling fans are electrically powered ceiling-mounted fans with hub-mounted rotating blades to increase air speed. They improve indoor air circulation and comfort cooling by replacing stale air at a higher rate (Omrani et al., 2021). They have a physiological "wind chill" effect that is equivalent to a 20^0C drop in operative temperature in a room (CIBSE Guide A). This is because they increase the elevated air speed of rooms from around 0.1m/s to 0.8m/s. This helps to evaporate sweat.

However, the correct use of a ventilation strategy relies on the understanding of occupants on how they should be used. Therefore, occupants who are not well trained on how to use ventilation systems or are unable due to sickness or age (old or too young), are not able to fully exploit the uses of ventilation systems. For ventilation purposes, window design is important. Grussa et al., (2019) states that in urban environments, external factors such as noise, security, and noise (GHA, 2019) ought to be considered. This can be done by fitting window restrictors on window frames, or using ventilation panels, high-level windows, or noise attenuating vents.

2.5.4 Façade design measures

There are several external solutions that can be used to mitigate against overheating in homes. These are presented here:

- High albedo roofs and walls

High albedo roofs and walls are external surfaces that are applied with special coating with superficial optic-energy features (Pisello, 2015). They keep surfaces cooler by reflecting shortwave radiation back to space, thereby inducing negative radiation (Jandanghian and Berardi, 2020). High albedo surfaces have a lower solar absorption rate of up to 0.15, and higher solar reflectance rates of up to 0.75, when compared with surfaces of conventional wall and roof finishes.

- Solar control glazing

Solar control glazing allows sunlight to pass through a window but radiates or reflects away a large degree of the sun’s heat from entering a space. It involves the incorporation of special materials in glass, which have the dual effect described. This is mostly achieved by a low emissivity coating which is a microscopically thin coating of metal oxide on the internal surface of a glass. This coating reflects heat back into a space while also allowing for external light to come into a space. It can be applied to both double and triple glazing options (Pereira et al., 2022)

- Solar shading options

Solar shading enables the achievement of a balance between useful and unwanted solar gains (Mohamed, 2019). Since the sun is the major source of external heat, this measure is vital in mitigating overheating in homes. Internally, this can be done using blinds. However, external solar shading offers the most effective option in reducing solar gains that lead to overheating because it reduces heat gains before they enter a space (Grussa et al., 2019). External solar shading can be achieved by shutters, awnings, overhangs, external louvers, screens, deep external reveals, or judicious placement of balconies.

- Use of high thermal mass materials.

High thermal materials such as bricks and blocks help to regulate temperatures inside homes based on external weather patterns (Mohamed, 2019). These materials function as regulators of external and internal temperatures through ameliorating extreme temperatures. They gain heat slowly and loose het slowly.

- The use of green walls and roofs.

Green walls and roofs can mitigate against overheating in homes through their shading, evapo-traspirating, insulating and ventilating capabilities (Koch et al., 2020). They shade the underlying surface by acting as a barrier that blocks sunlight. This is largely dependent on leaf sizes and plant species. Their evapo-transpirative quality has a cooling effect that offers lower ambient temperature effect similar to shading. They provide insulation and ventilation capabilities by causing stagnant layers of air in the cavities between leaves. These act as an insulation layer, and disrupts air flow.

2.6 Scalability of mitigation measures

Homes built in the UK every year are mostly produced by home developers (private enterprises), housing associations and local authorities. A large share of these homes are built by volume builders who build on average around 150,000 homes per year and were responsible for up to 76% of total new build dwellings in the financial year 21/22 (DLUHC, 2022). For such builders, if there is need to make changes to their home development processes, the ease of making changes that can be easily adaptable to a mass scale is a critical aspect of instigating change, scalability. Scalability is the measure of a system's ability to increase its performance in response to changing system processing demands. It's the ability of a system to accommodate an increasing number of elemental change while processing growing volumes of work without failing (Bondi, 2000).

For overheating mitigation measures to be effective, they need to be seen to be cost effective and scalable by volume builders. Scalable solutions are solutions that when introduced, will still work for volume builders who aim to increase the volume of their output year on year. Scalable solutions are easily adaptable to home developer's business models and organizational structures and are therefore substantially replicable on a much bigger playing field. Additionally, these solutions must not go against the long-term plans of volume builders in relation to market share, energy targets, material sourcing protocols, net zero goals, design ethos, profit margins, and commercial reputation. Therefore, scalable solutions are seen not as just removing causes to events, but strategies for wider scale and long-term success.

Implementing passive overheating mitigation measures can be expensive (Gupta et al., 2021) and more active measures such as air-conditioning have an impact on the electric grid especially during heat waves (Mirasgedis et al., 2007). The implementation of some overheating interventions could also be difficult due to external factors such as planning constraints, visual appeal, obstruction, noise, security, and air quality (Porritt et al.,2012). Most overheating mitigation solutions highlight the common pay-off that often occurs between their ability to reduce indoor temperature, energy intensity and cooling load per m^2 (Gupta et al., 2021). Overheating mitigation solutions may require changes that will likely impact design, require commissioning, maintenance and further occupant training and education (Gupta et al.,2015). Therefore, developing scalable solutions to overheating in homes requires a holistic analysis of not just the technical design but the development process decisions and occupancy expectations.

2.7 Legislation on Overheating in the UK

Mitigating and adapting new homes to overheating now and in the future is largely dependent on thorough, well-informed, and data-backed legislations and policies that can be effectively enforced. However, it should be acknowledged that overheating is mostly under-regulated worldwide (Mulville and Stravoravdis, 2016). In some countries like Sweden, it is not regulated. In countries such as The Republic of Ireland, it is just recommended. In the countries where it is regulated, this is done in different ways. In Belgium, Denmark and France, there exists a maximum indoor temperature threshold. In Germany and Poland there exists a maximum solar gain threshold. In Hungary there exists maximum differences between indoor and outdoor temperatures which must be met during the summertime (Kontonasiou et al., 2015). However, an analysis of overheating mitigation methods, criteria, and indicators in European countries by Attia et al., (2023) revealed that most of the existing calculation methods are outdated, and do not fit climate-proof buildings.

Bean (2020) argues from a Canadian perspective that most industry organizations responsible for overheating mitigation and adaptation seem to have made the minimum requirements of building codes and regulations to be the norm, while making little or no efforts to design beyond building regulations to improve performance. A study done by Murtagh et al., (2019) on the motivations of occupants to take proactive actions to mitigate against overheating found that there existed a very low intention to take proactive action irrespective of previous overheating experience. This suggests that limited or no precautionary actions to mitigate overheating, if left to stakeholders with perceived personal and financial interests, are likely to be taken. Especially so on an issue whose adverse effects are not immediately manifest. This underlines the urgency for the industry legislation and policies discussed herein.

In the UK, there is a substantial body of policy and guidance on overheating mitigation and adaptation. These can be found in documents such as The National Adaptation Program (NAP, 2023), National Planning Policy Framework (NPPF, 2021), Planning White Paper (2020), The London Plan (2021), Adverse Weather and Health Plan (2023), The Housing Health and Safety Rating System (2004) and guidance such as The Acoustics, Ventilation and Overheating Residential Design Guide (AVO, 2020). However, these do not go far enough as they mostly contain general provisions that do not provide sufficient details on systems, controls, and assessment as regards overheating in homes. They do not contain enough information to enable building control officers to enforce overheating.

The introduction of the proposed Future Homes Standard and with it, the new Approved Document O (2021) for Overheating is a big step in the right direction. It ensures that the risk of potential overheating in new homes is not only recognized but an equal approach is used to demonstrate its compliance across the industry. It was introduced in 2021 and took effect from the 15th of June 2022 with transitional arrangements in place. As such, the structure of its use is still actively developing.

This section will explore the new overheating regulation Part O (2021) and associated guidance on overheating.

2.7.1 Building Regulations Part O (2021) Overheating

A consultation on changes to Building Regulations 2019/20 Part L and F was started in 2019 and concluded in late 2021, as part of an introduction of the Future Homes Standard (FHS). As a result of the FHS consultation, potential overheating in homes was proposed to be tackled through a new requirement in Building Regulations; An Approved Document O: Overheating (2021). This signaled the attention and priority with which the government recognized the necessity of tackling overheating in homes.

Approved Document O presents a legal requirement for all new dwellings in England to ensure that overheating considerations are made right at the onset. Requirement 01 on Overheating Mitigation states that:

“Reasonable provision must be made in respect of a dwelling, institution or any other building containing one or more rooms for residential purposes, other than a room in a hotel (“residences”) to (a) Limit unwanted solar gains in summer.

(b) Provide an adequate means to remove heat from the indoor environment.”

The requirement is aimed to protect *“the health and welfare of occupants”* by reducing instances of overheating. Based on this requirement, the overall mitigation strategy needs to take occupants into account and address the following:

- Noise at night - In areas where noise could be an issue, the overheating strategy should consider the likelihood that windows will be closed during sleeping hours from 11pm to 7am
- Pollution - Homes located near significant sources of local pollution should be designed to minimize the ingress of external air pollutants.
- Security - Only openings that can be opened securely should be considered useful to provide ventilation. This applies to ground floor bedrooms and easily accessible bedrooms that are considered vulnerable openings.
- Protection from falling - Openings designed to be left open for long durations could pose a risk of falling from heights. This could be critical for occupancies involving children.
- Protection from entrapment - Louvered shutters, railings and grills on windows and doors should not allow body parts to become entrapped. This includes adhering to certain dimensions and child safety devices.

The regulation also states that information about a building must be given to the owner to permit effective use of the overheating mitigation strategy. This regulation sets the baseline standard in standardizing an equal approach to mitigating overheating in all new dwellings in England.

2.7.2 Interaction with other Building regulations

This regulation also considers its interaction with other currently existing Building Regulations.

- Approved Document B Fire Safety

Where escape windows are designed in compliance with Approved Document B, the impact of extra glazing should consider the removal of excess heat requirement in Approved Document O

- Approved Document F Ventilation

Where openings are used, the amount of ventilation for removing excess heat is likely to be higher than the purge ventilation required for Part F. The higher amount of ventilation applies.

- Approved Document J Combustion Appliances and fuel storage systems

Ventilation fans might cause combustion gases to spill from open-flued appliances and fill the room instead of going up the flue or chimney. This can occur even if the combustion appliance and fan are in separate rooms. Therefore, guidance in Approved Document J should be followed when installing and testing ventilation appliances. Also, combustion appliances must operate safely whether fans are running or not.

- Approved Document L conservation of fuel and power

Reducing summer overheating by limiting glazing areas will impact winter solar gains and therefore increase the need for space heating. Poorly insulated pipework, particularly in community heating schemes, can be a major contributor to overheating. Control of heat losses from pipework is dealt with under Part L of the Building Regulations and the guidance in Approved Document L should be followed.

- Approved Document K Protection from falling, collision and impact and M Access and use of buildings.

Where manual controls for ventilation systems are provided, they should be within reasonable reach of the occupants, to comply with Approved Documents K and M. Also, Approved Document O, gives guidance on increased levels of protection from falling from openings compared to Part K.

- Approved Document Q Security in dwellings

Approved Document O gives guidance on security considerations when providing large openings for removing excess heat. The locking systems of windows and doors should also conform to guidance given in Approved Document Q on the security of doors and windows in dwellings.

To demonstrate compliance with this regulation, two methods are proposed; the Simplified Method and Dynamics Thermal Modelling that are discussed in detail in the next section on overheating assessment.

2.8 Overheating Assessment Methods

As overheating is related to thermal comfort, health and productivity, there exists various evidence-based thresholds for assessing overheating in different disciplines, with incomparable metrics (Zero Carbon Hub ZCH, 2016). There is no internationally recognized standard of overheating because it varies depending on local and regional climatic conditions (BRE, 2016). As a result, it is difficult to obtain a precise definition of overheating (Peacock et al., 2010). This is partly linked to the complexities of assessing individuals' adaptability to external temperatures, depending on the climatic conditions they are exposed to, are used to, and their assessment of thermal comfort (Gupta et al., 2017).

In the UK, there are several overheating assessment tools that can be used. These include the Planning House Planning Package (PHPP) – (which applies to Passive Haus), and the Housing Heat Health Rating System (HHSRS) both with a fixed temperature threshold of 25^0C, the Home Quality Mark Certification Scheme (HQM, 2020), and the Good Homes Alliance early calculation tool. However, these assessment methods are not universally used and are not enshrined in regulation. This research only focuses on the two overheating methods introduced as part of Approved Document O Overheating (2021): Simplified Method and Dynamic Simulation Method.

2.8.1 Simplified Method

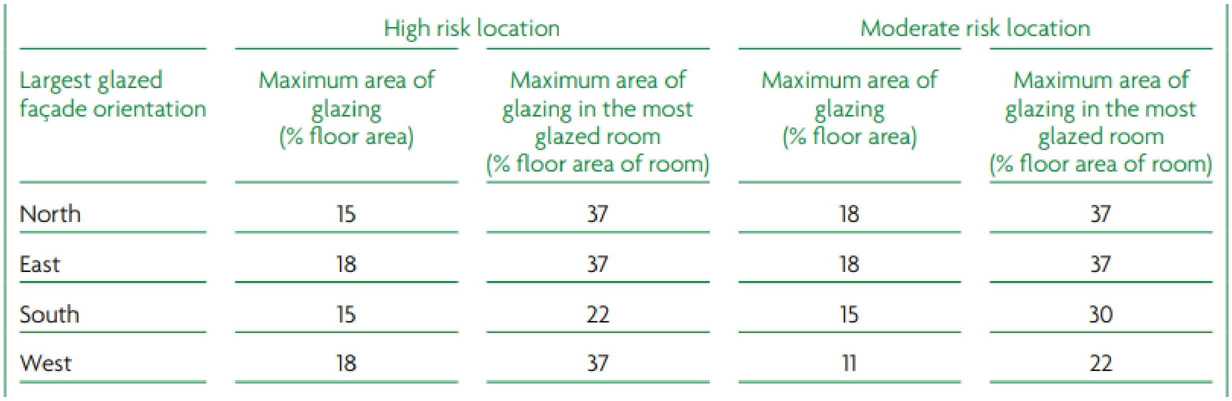
This is a new overheating methodology for demonstrating compliance, that was introduced in the new Approved Document O (2021) Overheating. Based on this methodology, a building is categorized depending on its location (in London and its suburbs or elsewhere in England) as either high risk or moderate risk, and whether it is cross-ventilated or not. These two criteria determine the overheating risk category to limit unwanted solar gains in summer and provide an appropriate means of removing excess heat from the indoor environment.

- The limiting of solar gains requirement is based on orientation. Orientation is determined by the façade with the largest glazing area. There are two aspects of this criteria: a maximum area of glazing as a percentage of the Gross Internal Area (GIA) of the floor, and a maximum area of glazing in the most glazed room as a percentage of the floor area of the room. For this criterion, the glazing area of a window is defined as the area or dimension of a glass pane excluding the frame.
- The removal of excess heat requirement is based on two aspects: a minimum free area based on the greater of the percentage of the gross internal floor area or the percentage of the total glazing area, and a bedroom minimum free area based on the percentage of the floor area of all bedrooms. For this criteria, free areas of windows are defined as the geometric open area of a ventilation opening.

For limiting solar gains, a maximum glazing area should not be exceeded and for removing excess heat, a minimum free area should be equaled or exceeded. Based on the location and cross ventilation capabilities of a home, the maximum glazing areas for limiting solar gains are found in table 3 and 4, while minimum free areas for removal of excess heat can be found in table 5 and 6, both of which are shown in section

For limiting solar gains, buildings, or parts of buildings with cross ventilation should not exceed the maximum glazing areas in Table 3

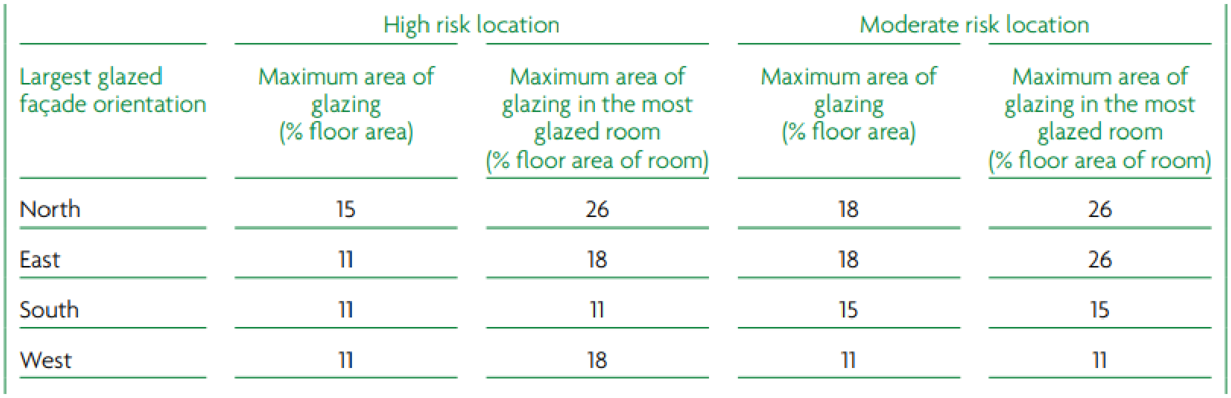
Table 3: Limiting Solar Gains for buildings or parts of buildings with cross-ventilation (Source: Approved Document O)



	High risk location		Moderate risk location	
Largest glazed façade orientation	Maximum area of glazing (% floor area)	Maximum area of glazing in the most glazed room (% floor area of room)	Maximum area of glazing (% floor area)	Maximum area of glazing in the most glazed room (% floor area of room)
North	15	37	18	37
East	18	37	18	37
South	15	22	15	30
West	18	37	11	22

For limiting solar gains, buildings, or parts of buildings with no cross ventilation should not exceed the maximum glazing areas in Table 4

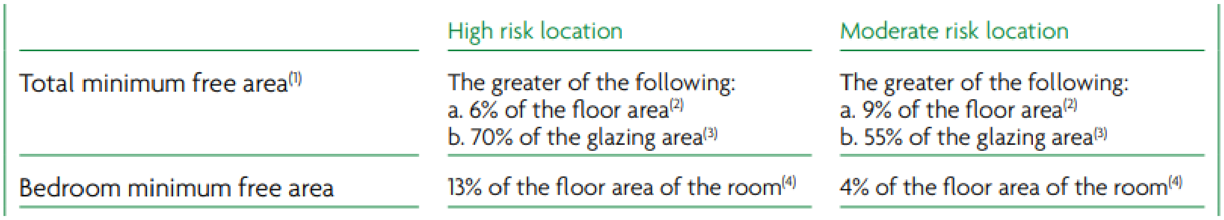
Table 4: Limiting solar gains for buildings or parts of buildings without cross-ventilation (Source: Approved Document O)



	High risk location		Moderate risk location	
Largest glazed façade orientation	Maximum area of glazing (% floor area)	Maximum area of glazing in the most glazed room (% floor area of room)	Maximum area of glazing (% floor area)	Maximum area of glazing in the most glazed room (% floor area of room)
North	15	26	18	26
East	11	18	18	26
South	11	11	15	15
West	11	18	11	11

For removing excess heat, buildings, or parts of buildings with cross ventilation should equal or exceed the minimum free areas in Table 5

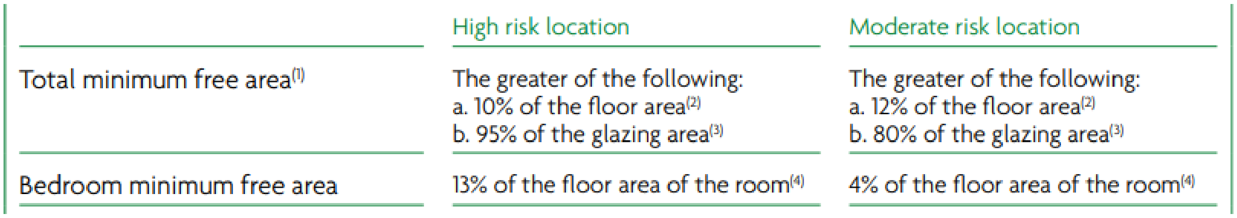
Table 5: Minimum free areas for buildings or parts of buildings with cross-ventilation (Source: Approved Document O)



	High risk location	Moderate risk location
Total minimum free area(1)	The greater of the following: a. 6% of the floor area(2) b. 70% of the glazing area(3)	The greater of the following: a. 9% of the floor area(2) b. 55% of the glazing area(3)
Bedroom minimum free area	13% of the floor area of the room(4)	4% of the floor area of the room(4)

For removing excess heat, buildings, or parts of buildings with no cross ventilation should equal or exceed the minimum free areas in Table 6

Table 6: Minimum free areas for buildings or parts of buildings without cross-ventilation (Source: Approved Document O)



	High risk location	Moderate risk location
Total minimum free area(1)	The greater of the following: a. 10% of the floor area(2) b. 95% of the glazing area(3)	The greater of the following: a. 12% of the floor area(2) b. 80% of the glazing area(3)
Bedroom minimum free area	13% of the floor area of the room(4)	4% of the floor area of the room(4)

This methodology is an alternative of two, provided in Approved Document O, in response to a government consultation on changes to Part L and F of the Building Regulations for new dwellings. For a building or part of a building to pass this methodology, both requirements for limiting solar gains and removing solar gains need to be passed.

The next section discusses the second overheating methodology in Approved Document O.

2.8.2 Dynamic Simulation Modelling

Dynamic simulation modeling (DSM) is the use of computational mathematical models to represent the physical characteristics expected or actual operations and control strategies of a building and its energy systems, through algorithms in the form of annexes (Hong et al, 2018). It is also known as Building Performance Simulation, Building Simulation, Building Energy Modelling, Thermal Modelling or Energy Simulation. DSMs are based on deterministic models (Gaetani et al., 2020) that capture an arbitrary and limited part of what essentially is a multiplicity of dynamic, stochastic, and probabilistic elements in buildings (Royapoor and Roskiily, 2015). This enables DSMs to reveal the interaction between buildings and occupants, HVAC systems and the outdoor climate while providing options for environmentally friendly design options (Clarke and Hensen, 2015). DSMs are commonly used to: perform load calculations in support of HVAC equipment selection and sizing, demonstrate the code compliance of a building by comparing the energy performance of the proposed design with the code baseline, and to identify and evaluate the best performing variant in a set of different buildings designs and operation options (Hong et al, 2018). From this, the predictions of future performance capabilities of buildings based on future climate scenarios are made possible. As regards overheating, DSMs can be used; to determine the likelihood that a design option can lead to overheating, to predict how much one design option overheats compared to another and to predict the actual hours of overheating in a methodology when same weather data and occupancy profiles are provided (Roberts et al., 2019).

Based on Approved Document O, this methodology offers designers additional design flexibility on residential buildings with very high levels of airtightness, or buildings that have very site-specific conditions that means they are not well represented by the two locations described in the simplified method. It also offers more flexibility on residential structures that are highly shaded by neighboring properties, structures, and landscapes. This methodology is recommended for dwellings that have significant noise and pollution requirements.

Demonstrating compliance with this methodology follows the guidance of CIBSEs TM 59 methodology. The Technical Memorandum TM59 (CIBSE, 2017) methodology is a modified version of the TM52 (CIBSE, 2013) with a focus on assessing overheating in dwellings. It was developed by the Chartered Institution of Building Surveyors after some shortfalls of the TM52. It was driven by the need to standardize occupancy profiles and equipment heat gains, to clarify the overheating criteria and to highlight risk assessment responsibilities, all this on the back of the insufficiency of SAP and TM52. Through this, the TM59 provides a consistent design methodology for assessing overheating risks in homes.

The TM59 overheating assessment is based on the following criteria:

1. For Living rooms, kitchens, and bedrooms; the number of hours during which $\triangle$T is greater than or equal to one-degree (K) during the period May to September inclusive shall not be more than 3% of the occupied hours (CIBSE TM52 Hours of Exceedance).
2. For Bedrooms only, the operative temperature from 10pm to 7am shall not exceed 26^{o}C for more than 1% of annual occupied hours (33 hours)

Bedrooms must meet both requirements.

Even though the introduction of the new Part O for Overheating (2021) is a big step in standardizing and enforcing overheating risk assessment in home design, with it comes new challenges. The regulation and the tools to analyze overheating are unfamiliar to many industry stakeholders. As such, there are impacts regarding how it is used in the development process to maximize its impact. This research emphasizes the need to investigate the UK home development process and the impact of decision making on overheating in homes. To enable scalable solutions as described in section 2.6, there is need to have a holistic analysis of the development process from land purchase to handover, and understand the impact of planning and design, procurement processes, policies and regulation, as well as market dynamics have on the design, assessment, and implementation of scalable overheating solutions. This next section discusses this in more detail.

2.9 Home Development Processes

The home development process in the UK, same as other construction projects in the UK, follows the 8 stage RIBA plan of works schedule. Stage 0 strategic definition, Stage 1 Preparation and Brief, Stage 2 Concept Design, Stage 3 Spatial Coordination, Stage 4 Technical Design, Stage 5 Manufacturing and Construction, Stage 6 Handover, and Stage 7 Use (RIBA, 2020). These stages can be generalized into land purchase, planning, design, construction, and post-construction activities such as snagging, handover, and in-use. This process brings together housing developers/associations and their supply chains, government ministries, local authorities and building control representatives, different professional bodies, and the wider community. Depending on the local authority, among other factors, this entire process can last about two years to over ten years. The success of this process is dependent on the critical decision-making that occurs at each stage.

Issues involving thermal discomfort and overheating are a result of vital decision-making steps that either occur or do not occur at each stage of the home development process. They are produced by broader systems and infrastructures of politics, economics, and culture throughout the whole development process. Overheating and thermal comfort in homes involves all actors in the home development process to varying degrees and it cannot be solved by individual action alone (Hamstead et al., 2016; Coseo and Larsen, 2014). Involving all industry stakeholders and partners across the housing, energy, design, and planning sectors is crucial for overheating mitigation and adaptation (Rajkovich, 2016).

The Zero Carbon Hub ZCH (2015) report highlighted several challenges in the home development process that affect overheating. To begin with, in the UK, there exists a range of different overheating standards with different sets of thresholds and parameters that can be confusing. The enforcement of these standards is sometimes unclear, as there exists lack of clarity due to overlapping metrics and whose responsibility it is to enforce them. Within the Government, the responsibilities for thermal comfort and overheating fall between different departments and different levels of government with the coordination of actions often missing (Hamstead et al., 2020). This is partly because local authorities in the UK operate under different jurisdictions in terms of policies. Housing development projects are therefore subject to different types of planning requirements depending on which part of the country they are located.

There is a need to raise understanding of the complex interactions of home development from land acquisition to the in-use phase and the effect it has on overheating. It is partly due to this limited understanding of the home building stock and its wider context as a dynamic system that makes these processes prone to failure and creates unintended negative consequences such as overheating (Janda, 2011). Given the many different actors (both up-and down the supply chain) involved in creating, operating, and maintaining the built environment, it is imperative to adopt a wider developmental evaluation, considering the different decisions that are made in these stages, to understand how housebuilders address potential overheating. The business environments in which home development takes place should be explored to identify the constraints therein and the opportunities that can be explored. The combined pressures of building regulation compliance along with market dynamics could impact their delivery (Davies & Oreszczyn 2012; Macmillan et al., 2016). Without knowing how housebuilders and their supply chains acquire, design, and construct homes, and the context in which they operate, the issues regarding overheating cannot be fully addressed. Furthermore, understanding this will be key to developing effective scalability criterion for mass market overheating mitigation strategies.

2.10 Research Gap

Overheating in houses in the UK is a result of climate change made worse by the unintended consequence of solving other problems in the industry through climate change adaptation and energy conservation. It also results from poor design and construction. Though much research has being done in this area, housing providers and the wider design community have not been adequately involved in determining mass market solutions. This research intends to explore the opportunity of involving industry partners to understand the home development process and the effects of critical decision making (at different stages) on overheating. This will involve examining their normal procedures and organizational chains of command and how decisions affecting overheating and thermal comfort are made and executed. Since housing developers and their supply chains are the ones involved in site implementation of housing projects, collaborating with them will provide new perspective to this research as to the buildability, efficiency and economic viability of potential measures and strategies. Involving them will help to develop scalable mass-market solutions and strategies to mitigate overheating and improve thermal comfort in homes. Although a lot of work has been done at the housing scale, understanding the complex issues that lead to mass market and scalable solutions, would need their involvement if maladaptation is to be avoided (DEFRA, 2018).

The Introduction of the Approved Document Part O for Overheating (2021) signifies a step in the right direction for overheating mitigation in UK homes. It presents a legal requirement for all new dwellings in England to ensure that overheating considerations are made right at the onset. This regulation indicates methods of determining the potential for overheating with a focus on glazing areas, orientation, and ventilation. Solutions are not prescribed but are open to being met in various ways if the assessment method shows achievement of the standard. The regulation stipulates two assessment methods that are majorly influenced by openable and glazing areas of windows, predominant orientations, and ventilation strategies. Addressing scalability of mitigation solutions also requires an analysis of overheating mitigation design methods described in the new regulation. These design methods usually involve standard data such as weather files that may not accurately reflect real time indoor conditions. There is a need to conduct a check on overheating assessment design methods using real time data from occupied homes.

As part of this, user experience of overheating and adaptation measures is required. In trying to solve a problem that is pertinent to health and wellbeing, housing occupants also, need to be at the heart of any probable solution or strategy aimed at preventing overheating in homes. Most research in this area rarely examines the end user perspective. When they do, human factors such as the acceptability of solutions to end users are considered less. The general approach has mostly been scientific with quantitative aspects being preferred over qualitative aspects that are known to highly influence occupant behaviour. Human beings are always treated like variables rather than for the experiences they have in their homes. Most studies involving occupants use simulation with assumed behaviours and profiles that are far from reality. As the economics of housing developments seems to be changing, there is need to focus not only on the development-cycle of houses; that is more industry led, but also reconciling it with the occupation-cycle of houses; that is more practically led, at least from housing occupants' perspective.

As a topic that is still undergoing policy review in preparation for net zero 2050, it is vital to conduct research that involves all stakeholders for better policy development. While there is some evidence on overheating in homes, what is needed now is how this evidence gets to home development stakeholders including practitioners, developers, councils, and other government institutions, not forgetting occupants, to ensure that mitigation strategies can be implemented at a mass scale. There is an urgent industry need to address this problem and from that need, this study was born. This study is co-funded by three UK home developers and a collaborating housing association. This underscores the industry-wide urgency and significance of this research. The timeliness of this study is also key, with its completion just in time for the full implementation of The Future Homes Standard (FHS) in 2025. The recommendations of this research have the potential of informing key policy changes in the residential construction industry in the UK.

2.11 Chapter Summary

This chapter has reviewed literature on overheating in UK homes. This started by an exploration of basic thermal comfort principles as the basis of understanding overheating concepts. Overheating trends in other countries as well as the UK have shown that overheating is a growing concern, that shows the significant need for this research. Sources of overheating, building factors contributing to overheating, as well as mitigation strategies have been analyzed through a vast breath of literature. Following this, the concept of scalability has been introduced and the need for scalable overheating mitigation solutions is shown. This is highlighted as one of the key threads of this research. An analysis of the actively developing regulatory framework on overheating in the UK has been shown through the analysis of the new overheating regulation Part O for Overheating (2021), and its two overheating assessment methods: Dynamic Simulation Modelling (TM59) and Simplified Method. All the previous sections have then been joined together to understand the impact of developmental decision-making processes in the UK on overheating in homes. The research gap follows to underscore the key novel contributions that this study intends to achieve. This chapter has highlighted the need for a holistic investigation of the complex issue of overheating, for scalable solutions to be achieved. The next chapter presents the methodologies used in achieving the needs of this research.

Chapter 3: Research Methodology

This section details the procedures and steps that were followed in carrying out this study. As the "underpinning" of this research (Ahmed et al., 2016), this methodology sets out the direction and implications of conducting this research as shaped by literature. The research methodology was chosen based on the research aims and objectives, norms of practice, other previous work in the research area and most importantly, the research philosophy (Buchanan and Bryman, 2007). This section covers the following: research philosophy, research design, data collection methods and analysis, evaluation workshops, and ethical considerations. Before all this, a conceptual framework that discusses all the interconnections between the elements of this research is presented.

3.1 Conceptual framework

Answering the questions of this research required an understanding of the interrelationships between different elements that are key to influencing outcomes. Developing a conceptual framework is an integral part of research as it forms the basis for analyzing interactions among concepts, their meaning and translation into practice (Sinclair, 2007), thereby aiding in data collection. Miles and Huberman (1994 page 18) define a conceptual framework as a product that "*explains, graphically or in narrative form, the main things to be studied, the key factors, concepts, or variables, and the presumed relationships among them".* A conceptual framework describes permutations between expected outcomes and predictions that can be projected based on how relationships between variables might impact outcomes. Developing a conceptual framework helps to analyze links between variables and most importantly their translation into real industry impact. A conceptual framework is a guide though the journey of developing new knowledge that contributes to industry. This conceptual framework exists on the background of literature review and an intended research gap. The development of a conceptual framework is based on a thorough literature research and review seeking adequate information about the phenomenon being studied and the various variables/concepts/factors including known and unknown relationships between them. Therefore, existing theories and models form literature are used in developing a conceptual framework. The main things being studied in this research are building characteristics and design in relation to overheating mitigation strategies, the influence of home developmental processes on overheating in homes, and occupant behaviour/expectations/experience. The next section reviews literature on the above concepts and discusses presumed interrelationships.

3.1.1 Framework Concepts

As literature review has shown, there are several overheating mitigation strategies that exist and are being used in other jurisdictions with indoor overheating related risks. These include site assessment measures, building layout measures, ventilation design measures and façade design measures (Alrasheed et al., 2023; ZCH, 2016). Each has their own potency and applicability to varied contexts. However, their applicability in UK homes is low. It is not a question of *are there overheating mitigation measures?* but rather *why are overheating mitigation measures not been implemented in UK homes?* Literature has shown that their use in UK homes is hampered by various infrastructural barriers relating to cost (Gupta et al., 2021) and general industry capacity (Porritt et al.,2012). Therefore, addressing these challenges is key, and is one of the main reasons for this research.

Through literature, this research shows how decision making in the home development processes affects indoor overheating in homes. The home development process involves complex interactions from land purchase to the in-use phase. In this complex process, overheating could be caused by decisions that are either made or not made at any stage. The home development process involves many stakeholders (Hamstead et al., 2016; Coseo and Larsen, 2014) and therefore requires collective effort. Key to understanding this is reviewing the market dynamics within which home development occurs, the barriers faced by for-profit companies and the regulations and polices that govern their conduct e.g. Approved Document Part O for Overheating (2021). This research highlights the home development process understanding as key to achieving climate resilient homebuilding.

Occupant behavior is the third main variable in this research (Morgan et al., 2017). While many studies focus on the technical aspects of home design in addressing overheating, occupant perspective is seldom captured. Given that occupant comfort, health and wellbeing is pertinent to overheating, their involvement is key. Obtaining information on the usability of indoor comfort strategies based on lived experience could be helpful in climate resilient homebuilding. Though thermal comfort is subjective from person to person based on age, sex, health and adaptation (Wei et al., 2014), analytical approaches can be used to capture occupant information to complement other technical aspects of home design. Such information could include their awareness and knowledge of using ventilation strategies designed into their homes (Morgan et al., 2017; Brown and Gorgolewski, 2015) and their perceptions of different mitigation strategies.

These three main variables; home development processes, building characteristics and design, and occupant behaviour, are combined to form the conceptual framework of this research as shown in Figure 5.

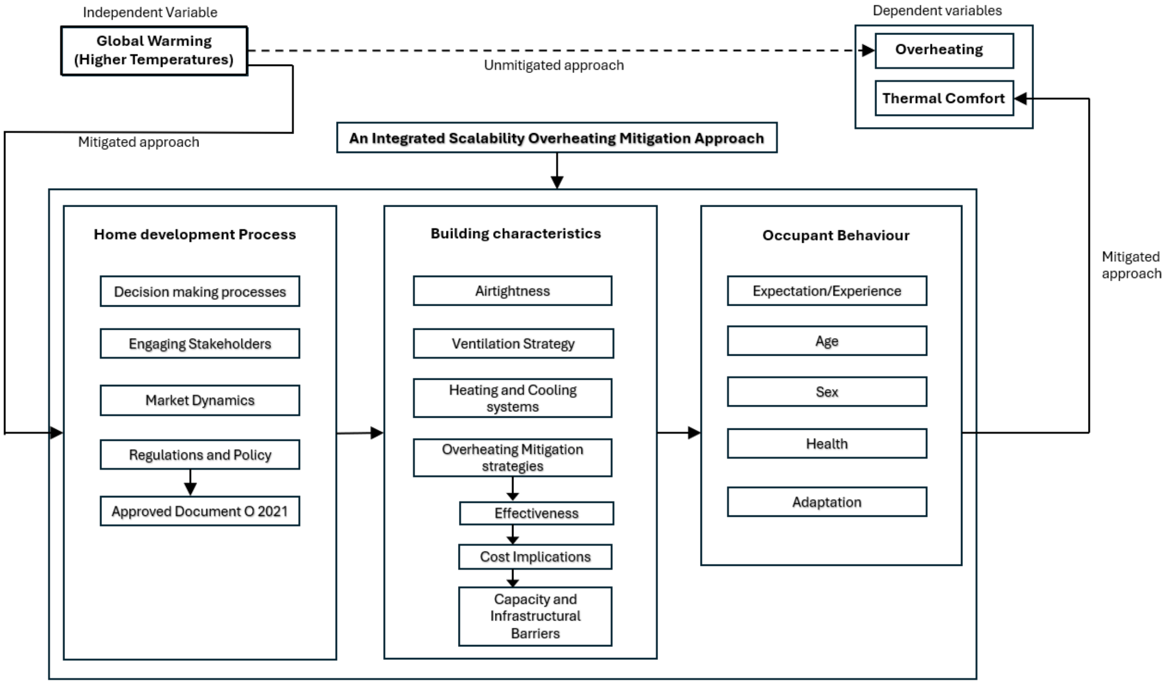


Figure 5: Conceptual framework for an Integrated Scalability Overheating Mitigation Approach in UK Homes

These three variables as shown in figure 5 are interrelated and jointly form the scalability concept that this research is aiming to achieve. This research argues the need for introducing scalable overheating mitigation solutions to UK homes. For overheating mitigation measures to be effective, they need to be seen to be cost effective and scalable by volume builders (Bondi, 2000). These solutions are easily adaptable to home development processes and are therefore mass-market solutions. However, achieving this requires a holistic analysis of not just the home development process, but a theoretical assessment of mitigation strategies and inclusion of home occupant perspectives into decision making. In doing this, solutions are seen as not just removing causes to events but strategies for wider scale and for longer-term success. This inclusion of scalability into overheating assessment will be key to achieving thermal comfort and climate resilient homes, as opposed to experiencing overheating in as ever-warming climate.

3.2 Research Philosophy

This refers to a set of assumptions concerning truth, knowledge and important education that describe different ways of viewing the world; often the basis upon which research is undertaken (Davies and Fisher, 2018). Exploring research philosophy assists in understanding the nature of research questions, aligning them to preferred methodologies and analysing data in the right way (Weaver & Olson, 2006). There are four main trends of research philosophy: positivism, interpretivism, pragmatism and realism. This research, however, is based on a pragmatist research philosophy.

3.2.1 Pragmatism

According to Creswell (2009) and Saunders et al., (2011), pragmatism is a philosophical stance that unlike other traditional perspectives, is based on actions, situations, and consequences. The pragmatist research philosophy acknowledges the existence of single and multiple realities while focusing on solving real world problems rather than philosophical positioning (Davies and Fisher, 2018). Pragmatism takes a “what works” approach to solving research problems (Patton 1990), and it relies on both qualitative and quantitative sources of data collection as the best means to answer research questions (Creswell, 2009). As it does not commit to one system of reality, it allows individual researchers to choose any research methods, techniques or procedures that best meet the purpose and needs of their research. It is a philosophical underpinning for mixed methods that focuses attention to research problems, then uses a pluralistic approach to drive knowledge about the problem (Patton, 1990).

The topic of overheating and thermal comfort is a problem-based topic that can be studied better using a pragmatic approach. Pragmatism allows the methodology of this research to explore all relevant methods that be used to solve the problem of overheating and thermal comfort. As overheating and thermal comfort principles are subjective in nature as they vary from person to person, there exists numerous overheating and thermal comfort assessment methods that need to be considered. An amalgamation of both qualitative and quantitative data collection methods are considered to be the best approach in addressing this research, a mixed-methods approach. The methods employed had to enable credible, well founded, reliable and relevant data (Kelemen and Rumens, 2008).

3.3 Mixed-Methods Research Design

Mixed methods research (MMR) is a problem-centred pragmatic approach, that involves collecting and integrating qualitative and quantitative data based on their applicability, to develop a more comprehensive understanding of a phenomena under investigation (Leavy, 2017). This approach is useful when studying complex issues that a deductive or inductive only approach cannot fully investigate.

Overheating and thermal discomfort are complex problems in the construction industry. To begin with, the definition of overheating varies from standard to standard. On the other hand, thermal comfort is a subjective matter that varies from person to person. Additionally, overheating, and thermal comfort studies sit at the crossroads of physics, physiology, psychology, culture, and climate. The parameters of overheating and thermal comfort are part of Indoor Air Quality (IAQ) metrics, which again is a section of Indoor Environmental Quality (IEQ). It draws the attention of various stakeholders including government policymaking institutions, housing developers, sustainability experts, services engineers and building occupants. The complexity of the problem around overheating and thermal comfort fits some aspects of Rittell and Webber's (1973) definition of a wicked problem. A problem that is essentially unique, so complex, less understood and that any attempt to understand it is riddled with dispute and uncertainty. Researching this topic therefore needed to employ various qualitative and quantitative methods as dictated by the nature of overheating and thermal comfort in homes.

This research on scalable overheating mitigation solutions focuses on the wider contextual issues, processes and procedures that allow overheating to thrive. This required a much more holistic analysis of not just the technical design but the home development process and occupancy expectations. Firstly, this meant engaging industry stakeholders through methods that appreciate their subjectivity, interviews and workshops. Secondly, generating evidence on overheating and understanding its scale and depth required the use of sensor monitoring and assessments methods which are objective. To complement monitoring, occupant behaviour/experience and expectation (subjective metrics) needed to be captured. Lastly, understanding the effectiveness of solutions needed a steady state simulation methodology that is based on objective metrics. Through using these mixed methods involving both qualitative and quantitative aspects, solutions would be seen as not just removing causes to events, but strategies for wider scale and for longer-term success.

Therefore, to investigate the objective and subjective characteristics (multi-disciplinary nature) of this research, a mixed-methods research design involving industry, occupied housing, and theoretical assessment of wider solutions was adopted. This research design is summarized in figure 6.

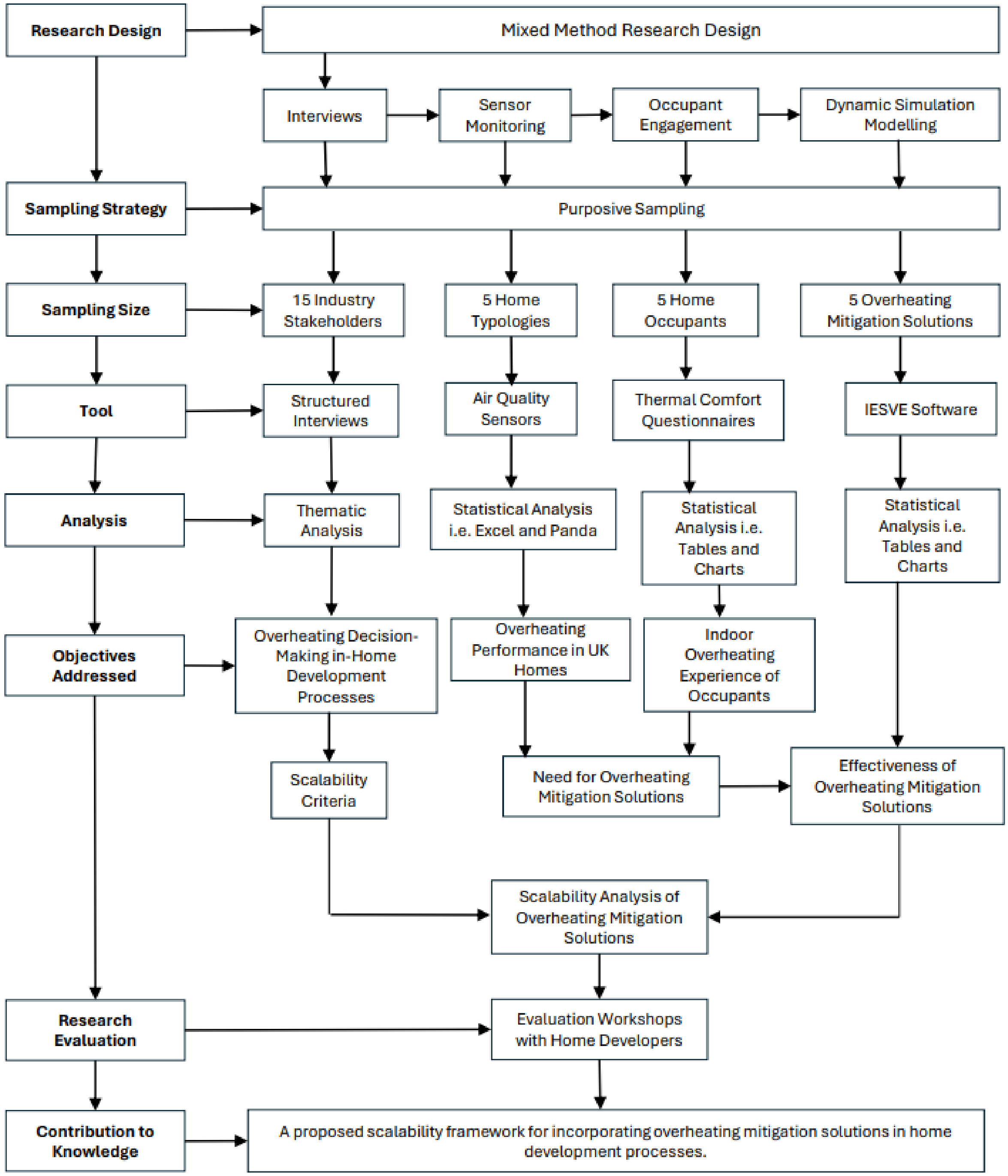


Figure 6: The Research Design used in this Study.

The research objectives of this study were met by a combination of both primary and secondary data as summarized in table 7.

Table 7: Summary of Data required to Achieve Research Objectives

	Objectives	Primary or Secondary Data
1	To review the current trends (including policy and regulation) on overheating and thermal comfort in residential dwellings and understand their scale and depth in UK homes.	Primary and Secondary data
2	To examine the UK home development processes and the influence of decision-making on overheating in UK homes.	Primary data
3	To conduct an overheating analysis of homes with real time indoor temperature data, using the dynamic simulation method and simplified method stipulated in Approved Document Part O Overheating (2021).	Primary data
4	To evaluate the performance of different mitigation strategies in new build residential developments in the UK using dynamic simulation modelling of monitored homes.	Primary and Secondary data
5	To develop a scalability criterion for evaluating overheating mitigation measures through evaluation workshops with developers.	Primary and Secondary data
6	To propose a scalability framework for incorporating overheating mitigation solutions in home development processes.	Primary and Secondary data

3.3 Data Collection Methods and Analysis

This research employed a qualitative approach; interviews, and three quantitative approaches: sensor monitoring, thermal comfort questionnaires and Dynamic Simulation Modelling (DSM), in addressing the research aim and objectives.

3.3.1 Development Process Study - Interviews

Structured interviews were carried out with housing developers, manufacturers, and building professionals, to get their contribution on key decision-making stages in the UK home development process, and how they directly or indirectly affect overheating in UK homes. Key decision-making steps that were probed revolved around environmental aspects of land purchase, policies and regulations, design decision-making, material specifications, relevant tests, assessments, simulations and calculations, skills capacity and availability, performance gap evaluations and home occupant education, among others. Probing these subjects required the need to engage with industry stakeholders through a back-and-forth approach, that was only possible through interviews.

The representatives of the industry partners collaborating with this research made up a steering committee that this research reported to around once a month. The steering committee of this research provided a rich platform to gain contact with several housing developers and their supply chain companies through purposive sampling. Purposive sampling is a non-probability sampling method whereby individuals to be sampled are chosen by the researcher based on criteria such as specialist knowledge in the research area and willingness to participate in the research (Campbell et al., 2020). The interviewees included the Technical Directors of various housing developers and other high-ranking professionals in various supply chain companies. Table 8 shows a summary of the interviews conducted, when how and with whom. Because of anonymity and ethics compliance, the companies are identified with special characters with only the type of company being listed.

Table 8: Interview Respondents

	Housing Provider	**Representative**(s) **Interviewed**	**Date**	**Means**
1	Housing Developer 1	Research and Development Manger Snr Technical Coordinator	16/03/2021	Online
2	Housing Association	Head of Construction and Quality	17/03/2021	Online
3	Housing Developer 2	Head of Group Technical	24/03/2021	Online
4	Housing Developer 3	Technical and Innovation Director	6/04/2021	Online
5	Air Crete Manufacturer	Director	26/05/2021	Online
6	Brick Manufacturer	Technical and Innovation Director	15/06/2021	Online
7	Insulation Manufacturer	Technical Director	30/07/2021	Online
8	Ventilation Manufacturer	Sales Director Regional Sales Manager Head of Research and Development Marketing Director	3/08/2021	Onsite
9	Energy Consultancy 1	Associate Director	17/08/2021	Online
10	Architectural Firm	Associate Director	23/08/2021	Online
11	Building Contractor	Design Manager	9/09/2021	Online
12	Building Control	Building Control Agent	10/09/2021	Online
13	Energy Consultancy 2	Managing Director	14/09/2021	Online
14	Building Physics Consultant	Founder/Partner	5/09/2021	Online
15	Energy Consultancy 3	Head of Technical Services	13/09/2021	Online

The interviewees were engaged through structured interviews. The interview guide was structured into the following sections as shown in table 9: land purchase, planning and design, construction, technical department, marketing and sales, and operation and maintenance. This structure was designed to follow the typical RIBA stages in the UK home development process. Each section of the semi structured interview had a set of questions that was produced based on: concepts raised from literature review, policy and regulation changes at the time, industry practice, and other areas of interest to the researcher. A pilot test was done with a fellow researcher to ascertain the clarity, flow and language of the questions while also probing for subject and concepts.

Table 9: Interview Guide Sections

Land Purchase	**Planning and Design**	**Construction**
• Land purchase process. • Site selection decision-making processes • Environmental concerns • Greenfield/Brownfield sites handling. • Planning authorities	• Tender & Procurement process • Policy and Regulation Integration • Certification systems for sustainable design principles • Covid-19’s Effects • Decisions concerning scheme orientation. • Overheating assessments and tests (Modelling, SAP)	• On-site inspection processes • Overheating mitigation strategy implementation • Engaging occupants· • Capacity to implement HVAC strategies. • Resourcing building materials • Quality assessment standards
Technical Department	**Marketing and Sales**	**Operation and Maintenance**
• Future trends • Housing typologies • Home performance measurements	• After-sale care process • Customer satisfaction and Complaints • Customer expectations and perceptions	• Commissioning of systems • Home Induction Processes • Previous issues regarding overheating • Liability procedures • Soft-landing procedures • Post-occupancy evaluation procedures

The main structured interview guide is attached in this document as Appendix 3. Interview Guide for Housing Developers. Although it was a structured interview, there was room to probe other issues that were raised depending on the answers that were provided. This allowed for flexibility in getting answers to subjects that were company specific. The standard interview guide was also adapted to make it suitable for different companies based on their specializations. Manufacturers’ questions focused more on their products and how those fit into the home development process.

Other professionals were asked specific questions about their practice and how and when they are normally engaged in the home development process.

These interviews were done between March 2021 to October 2021 with 15 different UK based companies that are directly involved in the delivery of new homes in the UK. All meetings except one were carried out online via MS Teams, and each lasted an average of about an hour. The interviews were carried out until data saturation was presumed to have been met. With their permission, all interviews were recorded and stored in a secure folder for analysis.

3.3.1.1 Data Analysis for Interviews

The interviews were recorded on MS Teams and a transcript for each interview was created and stored on a One Drive folder in a password protected laptop. Summary sheets were also created to contain brief summaries of each interview and some key points that were raised. Summaries are vital to ensure that data collection processes are systematic, and all relevant data is captured (Miles and Huberman, 1994). All interviews were analyzed in NVivo. Firstly, a word cloud of the interview transcripts was generated to identify the main and frequent words that were mentioned by the interviewees. It is useful in creating a first impression of interview transcripts and is a starting point for deeper text analyses (Lohman et al., 2015). They normally show frequent words in a text as a weighted list in either a circular, sequential, or random layout. The font sizes represent their occurrence frequency as colour, position and orientation are often varied to visually encode additional information aesthetically. To generate an accurate representation of this, all interviewers' words were removed from the transcription files. A word frequency criterion consisting of the most frequent 500 words for exact matches with a minimum length of 4 was used. Commonly used words such as "*that*", "*into*", "*then*", "*looking*" and many others were added to the stop word list, to only show words that are relevant to the research topic. This is further discussed in chapter 4.

NVivo 12 was used to create a thematic analysis framework in Chapter 4. Thematic analysis is a form of qualitative analysis that involves identifying passages of text that are linked to a common theme, allowing for the indexation of text into categories, thereby establishing a framework of thematic ideas (Gibbs, 2007). This follows a process of coding data, organizing the codes, and developing themes. Coding involves assigning labels to a passage of relevant text to reduce the amount of information and break it into digestible chunks. These codes are then arranged into categories based on similarities and patterns. These categories are then analyzed based on research aims and questions to create themes, that form the basis of analysis.

The fifteen interview transcripts were coded. A total of 142 codes were developed. Based on similarities and patterns, the codes were arranged into 36 themes. These 36 themes were then arranged based on what stage of the home development process they related to as shown in table 10. These stages are land purchase and strategic planning, design and scheme planning, construction, handover and occupation. These were developed from the typical home development processes that characterize UK home development. Also, market dynamics and business environment as well as government policy were major external factors that were mentioned significantly and were seen to resonate with the entire development process and not any specific stage. These major factors form the framework of thematic ideas on which interview data presentation and discussion are based on. A breakdown of the major factors, themes and codes is attached as an appendix to this document in Appendix 12.

Table 10: List of Themes and Codes from Interviews

Home Development Stage	**No. of Themes**	**No. of codes**	**No. of participants**
Land Purchase and strategic Planning	2	5	5
Design and Scheme Planning	15	68	15
Construction	6	17	10
Handover and Occupation	4	15	11
Government Policy and Regulation	5	19	11
Market Dynamics and Business Environment	4	18	7
Total	**36**	**142**	

3.3.2 Monitoring Study - Sensors

This method involved the collection of real time data on thermal comfort and overheating parameters in occupied houses in the UK. Monitored homes were selected through non-probability convenience and purposive sampling strategies Five homes of different characteristics (flat, detached, and semidetached) were sensor monitored. Different home typologies were considered for monitoring to cover the vast majority of UK homes and increase the transferability and generalization of obtained results to be applicable to most UK homes. The eligibility criteria for monitored homes were brick and block houses adhering to 2013 Part L regulations. Additionally, one home designed to the 2025 Future Home Standard (FHS) was monitored. These houses were provided by the home developers collaborating in this research. Monitoring was done across the non-heating period (May to September) of 2022 when most houses are free running and the effects of property characteristics on internal temperatures can be examined without the additional variable of heating. This is illustrated in Figure 7.

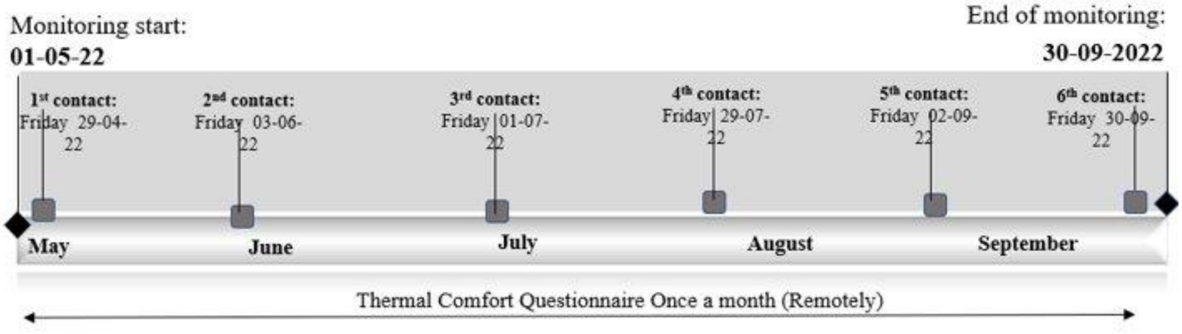
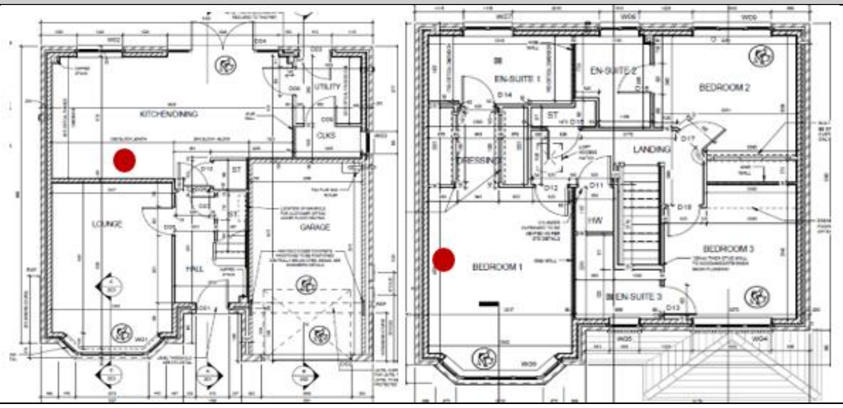


Figure 7: Monitoring Timeline

Table 11 summarises the details of the monitored homes.

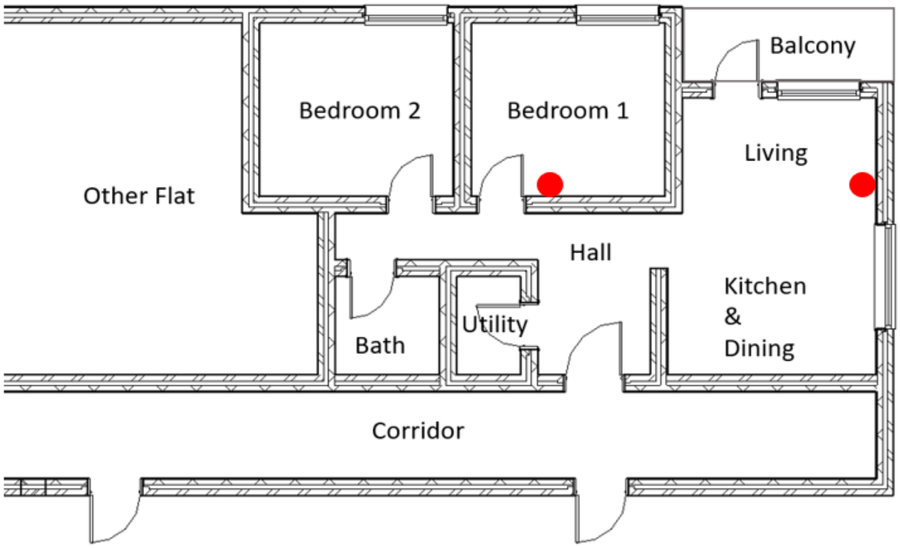
Table 11: Properties of Homes Monitored

House no. 1	
Plans	
Location	Cheshire
Type of house	Three Bedroom Detached House (Two story) (2013 Building regulations)
Household characteristics	A family of up to three – two parents, one child (no vulnerable occupants)
Type of ventilation	Naturally ventilated with extract fans in kitchen and bathroom
Monitoring duration	May 2022 – September 2022

Main window orientation	East E
Sensor details and location	One Uhoo Aura in the kitchen/Dining area, one Omron sensor in Bedroom 1 – red dots represent sensor locations
Sensor Nomenclature	CUK/D and COB

House no. 2	
Plans	
Location	Suffolk
Type of house	Four Bedroom Detached house (Two story) (2013 Building Regulations)
Household characteristics	A family of up to five people – two parents, three children (no vulnerable occupants)
Type of ventilation	Naturally ventilated with extract fans in kitchen and bathroom
Monitoring duration	May 2022 – September 2022
Main window orientation	Northeast NE
Sensor details and location	One Uhoo Aura in the kitchen/Dining area and one Omron sensor in Bedroom 1- red dots represent sensor locations
Sensor Nomenclature	SUK/D and SOB

House no. 3	
Plans	
Location	Loughborough
Type of house	Four-bedroom detached house (Two story) (2013 Building Regulations)
Household characteristics	A family of four, two parents two children (no vulnerable occupants)
Type of ventilation	Naturally ventilated with extract fans in kitchen and bathroom
Monitoring duration	May 2022 – September 2022
Orientation of front main windows	Southeast SE
Sensor details and location	One Uhoo Aura in the study room, one Omron sensor in the Livingroom area, one Omron sensor in Bedroom 1 – red dots represent sensor locations.
Sensor Nomenclature	LUS, LOL and LOB

House no. 4	
Plans	
Location	Birmingham
Type of house	Two-bedroom flat (17th floor) (2013 Building Regulations)
Household characteristics	Two people (no vulnerable occupants)
Type of ventilation	Naturally ventilated with extract fans in kitchen and bathroom
Monitoring duration	May 2022 – September 2022
Orientation of front main windows	Southwest SW
Sensor details and location	One Uhoo Aura in the Livingroom/Dining/ Kitchen area, one Omron sensor in Bedroom 1 – red dots represent sensor locations
Sensor Nomenclature	B4UL/D/K and B4OB

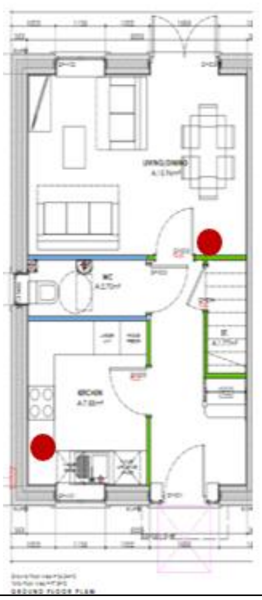
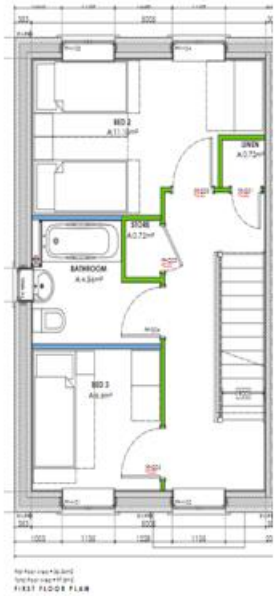
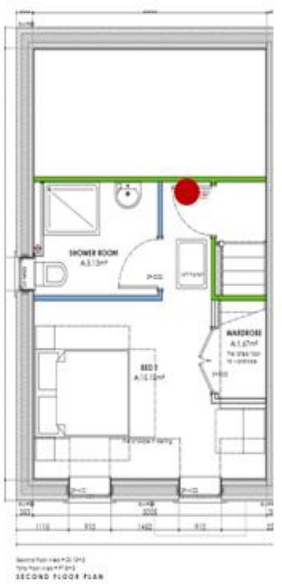
House no. 5	
Plans	  
Location	Birmingham
Type of house	3 Bedroom Semi Detached House (Future Home Standard Demo)
Household characteristics	A family of five, two parents, three children (no vulnerable occupants)
Type of ventilation	Naturally ventilated with extract fans in kitchen and bathroom
Monitoring Duration	May 2022 – September 2022
Orientation of front main windows	Southwest SW
Sensor details and location	One Uhoo Aura in the Kitchen area, one Omron sensor in Livingroom and one Omron sensor in the Top floor Bedroom – red dots represent sensor locations
Sensor Nomenclature	B2UK, B2OL and B2OB

Figure 8 shows a map of England with locations of monitored homes; Two in Birmingham, one in Cheshire, Loughborough and Suffolk.

Figure 8: England map showing monitored homes location.

3.3.2.1 Indoor Temperature Monitoring Sensors

Sensors were used to record thermal comfort / overheating parameters such as temperature and humidity. Two types of sensors were used for monitoring: the Uhoo Aura Sensor and the Omron Sensor. These sensor models were chosen based on data security, network dependability, measured metrics, and reliability. Each house had at least one Uhoo aura sensor and one Omron sensor. Two houses; Birmingham and Loughborough home had one more Omron sensor than others. This is because the main Uhoo sensor could not be placed in the main living area due to a fan noise that was coming from the sensor. It was placed in a separate kitchen for Birmingham, and a Study room in Loughborough. Therefore, an additional Omron sensor was used in these two homes to cover the main living rooms. Sensors were typically placed on eye-level shelves, away from any sources of heat, draught, and direct sun exposure.

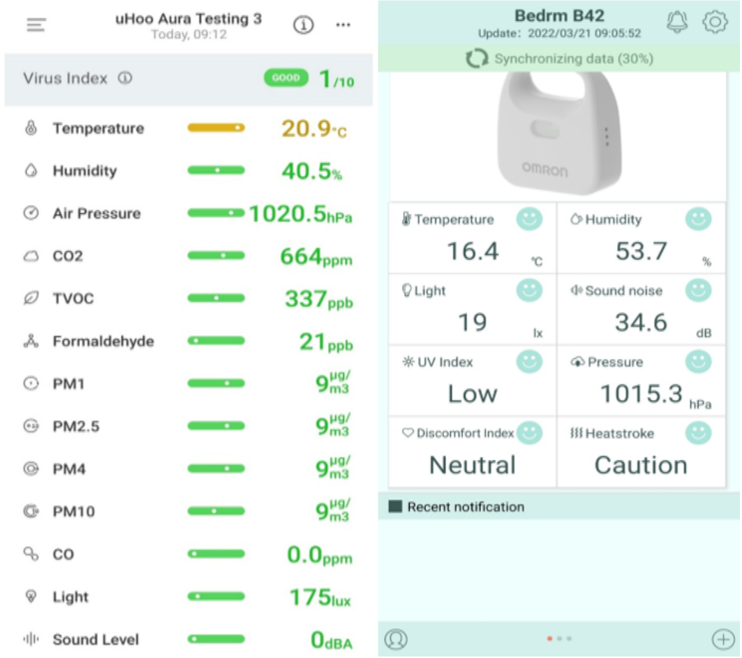
Table 12 summarizes the capabilities of each sensor.

Table 12: Summary of Sensors

	Omron Sensor	**Uhoo Aura Sensor**
		
Dimensions	Approx. 46.0 × 39.0 × 15.0 mm	200mm x 180mm x 57mm
Indoor Air quality parameters	Temperature, Humidity, Light, UV index, Barometric pressure, Sound noise	Temperature, relative humidity, carbon dioxide, various particle sizes (PM10, PM4, PM2.5, PM1), carbon monoxide, formaldehyde, volatile organic compounds (VOCs), air pressure, light, and sound
Range	Temperature: -10 to 60°C Humidity: 30 to 85%	Temperature: -40 to 85ºC Humidity: 0 – 100%
Accuracy	Temperature: ±2°C Humidity: ±5%	Temperature: ±0.5°C Humidity: ± 3%
Connectivity	Bluetooth® low energy	Wi-Fi
User Interface	Mobile App	Web Dashboard and Mobile app
Data log Interval	15-minute intervals	Minute by minute intervals
Power Supply	3 VDC (Lithium battery CR2032 × 1)	Main Power Source 5V/2A USB adapter Backup Power Source 3250mAh @ 3.6V lithium-ion battery

According to TM59, operative temperature is recommended for indoor temperature monitoring However, for this research, air temperature that is recorded by these sensors, is used because of the challenging nature of long-term measurement of operative temperature in occupied homes. The Uhoo and Omron sensor are likely to record an undefined mix of air and operative temperature as well as surface temperature from conduction through a mounting surface (Quigley, 2017). Studies

(Lomas et al., 2018; Lomas and Giridharan, 2012; Beizaee et al., 2013 and Marvogianni et al., 2014, Gupta et al., 2021) have shown that air temperature sensors (such as the ones used in this study), could record a temperature closer to the one occupants' experience, more than pure bulb temperature.



uHoo Aura Testing 3
Today, 09:12

Virus Index	GOOD 1/10
Temperature	20.9°C
Humidity	40.5%
Air Pressure	1020.5hPa
CO2	664ppm
TVOC	337ppb
Formaldehyde	21ppb
PM1	9µg/m3
PM2.5	9µg/m3
PM4	9µg/m3
PM10	9µg/m3
CO	0.0ppm
Light	175lux
Sound Level	0dBA

Bedrm B42
Update: 2022/03/21 09:05:52
Synchronizing data (30%)

Temperature	16.4 °C
Humidity	53.7 %
Light	19 lx
Sound noise	34.6 dB
UV Index	Low
Pressure	1015.3 hPa
Discomfort Index	Neutral
Heatstroke	Caution

Recent notification

Figure 9: Uhoo Aura and Omron Sensor Dashboards

The Uhoo aura sensor has a dashboard (Figure 9 left) that relays data over Wi-Fi. For this, the temperature data was downloaded remotely every month, into a secure one drive account file. The Omron sensor allows data transfer through Bluetooth to a dashboard (Figure 9 right). This was done at the end of the monitoring camping in September 2022.

3.3.2.2 External Temperature Data Collection

In addition to monitoring indoor temperature, outdoor temperature of monitored locations was obtained from available weather files from the UK Met Office - Daily Weather Summary database (2022). Figure 10 shows the weather station locations from the Met Office database.

Figure 10: Weather Station Locations (Met Office)

The weather stations closest to the locations of monitored homes were considered in the following order, the Bedford weather station data (24) for Birmingham (82 miles away), the Wattisham weather station data (27) for Suffolk (5 .9 miles away), the Shawbury weather station data (22) for Loughborough (78 miles away) and the Crosby weather station data (19) for Cheshire (33 miles away). From these weather station databases, two daily temperature datapoints (00:00 and12:00), were obtained for the months of May to September 2022.

3.3.2.3 Data Analysis for Monitoring

To prepare data for analysis, all the sensor data was extracted from the sensors first. The Uhoo sensor has an online dashboard from which all the sensor data was downloaded per month, in minute-by-minute intervals from May to September 2022. The files in csv formats were then arranged into folders corresponding to each home and uploaded to one drive for data security. Data from the Omron sensors was downloaded using a Bluetooth connection via an android app. This process was arguably slow due to low Bluetooth capability. The downloaded data was in 15 minute-intervals with varying start and end dates as some data was lost due to the nature of the sensors. However, sufficient data was obtained to enable sufficient analysis of the homes monitored. Previous studies on overheating such as Baborska-Narożny et al., (2017), Gupta et al., (2017), Toledo et al., (2016) and Gupta et al., (2021), have used similar or even shorter periods of monitoring for overheating assessments. The duration of the data captured from both sensors is presented in table 13.

Table 13: Available Sensor Data Timelines

Home	Sensor Nomenclature	Available data
Cheshire	CUK/D	1st May – 30th September
	COB	20th July – 30th September
Suffolk	SUK/D	1st May – 30th September
	SOB	24th July – 30th September
Loughborough	LUS	1st May – 30th September
	LOL	8th June – 15th September
	LOB	17th July – 30th September
Birmingham Flat	B4UL/D/K	26th May – 13th August
	B4OB	17th May – 24th August
Birmingham	B2UK	1st May – 21st September
	B2OL	8th June – 19th August
	B2OB	1st May – 11th August

For ease in analysis, data from both sensors was cleaned to remove other sensor parameters that were recorded as well. For the Uhoo sensor, this included 14 other parameters and for the Omron sensor, 5 other parameters. This only left the temperature parameters in both sensors for longitudinal analysis. Microsoft Excel software was used for this. Since the data from the Uhoo sensor was only downloadable per month, all the months were manually combined such that all data files for each sensor started at the beginning of May and ended at the end of September. Although data from the Omron sensor was month by month data, there was an empty row after every month's data. This was removed manually for all the sensors to reduce the percentage of missing cells.

Panda, a statistical software for analyzing time series data, was used to produce a profiling report on the reliability of the excel data files from all sensors. Panda is a statistical software library written for the Python Programming language. Its data structures and operations allow for the analysis of time series data and manipulation of numerical tables (McKinney, 2022). Table 14 shows the dataset characteristics of the sensor data files of the 5 monitored homes developed from the Panda software.

Table 14: Dataset characteristics of the sensor data files – from Panda

Home	**Sensor Nomenclature**	**Variables** **Date and Time – Categorical** **Temperature - Numeric**	**Observations**	**Missing Cells**		**Duplicate Rows**	
				No.	**%**	**No.**	**%**
Cheshire	CUK/D	Date &Time, Temperature	219680	0	0.0%	4	<0.1%
	COB	Date &Time, Temperature	9636	784	12%	1	<0.1%
Suffolk	SUK/D	Date &Time, Temperature	220199	0	0.0%	7	<0.1%
	SOB	Date &Time, Temperature	9634	903	10.6%	1	<0.1%
Loughborough	LUS	Date &Time, Temperature	220038	0	0.0%	6	<0.1%
	LOL	Date &Time, Temperature	9656	294	1.0%	1	<0.1%
	LOB	Date &Time, Temperature	9566	707	13%	1	<0.1%
Birmingham Flat	B4UL/D/K	Date &Time, Temperature	113818	0	0.0%	16	<0.1%
	B4OB	Date &Time, Temperature	9655	294	1.0%	1	<0.1%
Birmingham	B2UK	Date &Time, Temperature	206002	0	0.0%	2	<0.1%
	B2OL	Date &Time, Temperature	6959	213	1.0%	1	<0.1%
	B2OB	Date &Time, Temperature	10571	321	1.0%	1	<0.1%

As can be seen in table 14, all the Uhoo sensors located in most kitchens/living areas (containing the letter U in the sensor nomenclature), registered high numbers of observations as compared to the Omron sensors (with the letter O in the sensor nomenclature). This is because the Uhoo sensors recorded temperature data in minute-by-minute intervals, while the Omron sensor was set to record data in 15-minute intervals to preserve the battery life and storage. Low numbers of missing cells were reported especially by the Uhoo sensors that reported 0 missing cells. Additionally, all the sensor data files recorded negligible duplicate rows of less than 0.1% based on their observations.

It can therefore be concluded that all the sensor data files are reliable and sufficient for data analysis.

Once data from all sensors and all houses were cleaned and organized, they were presented in steps. In the first instance, the general temperature trends for all the houses are presented in a graph alongside a table that includes measures of central tendency for each house and sensor. This is followed by an in-depth look at temperature trends for each house factoring in their locations and house types.

Overheating Analysis

The recorded temperature data and the specification of the monitored homes formed the basis of more in-depth overheating analysis. Two methods were used to assess overheating risk in the five homes monitored: The Technical memorandum (TM) 59 and the Simplified method. These two methods were chosen due to their significance as being introduced in the new overheating regulations in Approved Document O (2021) for overheating. This helped to draw a comparison between the two methods.

The TM59 overheating assessment.

This methodology is based on the following criteria:

1. For Living rooms, kitchens, and bedrooms; the number of hours during which ΔT is greater than or equal to one-degree (K) during the period May to September inclusive shall not be more than 3% of the occupied hours (CIBSE TM52 Hours of Exceedance).
2. For Bedrooms only, the operative temperature from 10pm to 7am shall not exceed 26^{o}C for more than 1% of annual occupied hours (33 hours)

Bedrooms must meet both requirements.

The occupied hours are assumed to be the same as stipulated in the TM59 methodology. Bedrooms assume a 24-hour occupancy profile while kitchens and living rooms are unoccupied during sleeping hours and occupied for the rest of the day (08:00 to 21:00). For a 24/7 period from May to September, bedroom occupied hours should total 3672 hours and 1989 for living rooms and kitchens. No difference between weekdays and weekends is considered.

Although the TM59 is intended for home design and modelling using annual data as opposed to measured data from monitoring, it can still be applied. The percentage thresholds for annual occupied hours can be converted to actual hours. The analysis therefore provides indicative results for TM59 rather than definitive results as annual data is not available. Analysis from this methodology has and is being used in overheating studies (Gupta et al.,2021; Wright et al.,2018) and in practice. This enables the results of this research to be located within an emerging industry-wide discussion.

The Simplified Method

The Simplified Method is a new overheating methodology for demonstrating compliance. It was introduced in the new Approved Document O (2021) Overheating. Based on this methodology, a building is categorised depending on its location (in London and its suburbs or elsewhere in England) as either high risk or moderate risk, and whether it is cross-ventilated or not. These two criteria determine the overheating risk category to limit unwanted solar gains in summer and provide an appropriate means of removing excess heat from the indoor environment. For limiting solar gains, a maximum glazing area should not be exceeded and for removing excess heat, a minimum free area should be equaled or exceeded. More detail on the simplified method of overheating analysis has been discussed in section 2.8.1 of this research.

3.3.3 Thermal Comfort Questionnaires

To include the important aspect of human behaviour in this thermal comfort and overheating study, questionnaires were issued to occupants. This method harnesses the subjective nature of overheating and thermal comfort on individuals and their thoughts on personal experiences; phenomenology (Hess-Biber and Leavy, 2011). Thermal comfort questionnaires (an example attached as Appendix 4), were sent to the occupants of homes used for sensor monitoring. Questions revolved around general demographic information, normal behavioral routines (activity and clothing), thermal sensation - Likert scale, behavioral adaptations (and their success) and recommendations. These questions aimed to capture the social, cultural, technical, and historical interplay in overheating and thermal comfort, in line with previous studies (Fuller & Bulkeley, 2013; Hitchings, 2011). The questionnaires were structured and involved 7 closed-ended questions and 2 open ended questions on one page. The questionnaire was built off the one used for a similar study on overheating (Appendix 3 - Oikonomou et al., 2020). These questionnaires were administered online through email and sent to home occupants through obtained email addressed, during the monitoring period from May to September, on the first day of each month as shown in figure 6 on page 59 as “contact”.

3.3.3.1 Data Analysis for Questionnaires

These were analyzed through tables to map out the thermal perceptions of occupants during the periods of high temperatures, the effects of temperatures perceived, the actions they took, and the success or failure of those actions, alongside recommendations. This data was vital to complement the monitored data. This triangulation of sensor monitoring data and thermal comfort questionnaire data produced complementary insights and a more comprehensive understanding of overheating and thermal comfort. Though thermal comfort questionnaires were done for five months of monitoring, only the responses for the June, July and August periods were analyzed. It was during these three months that there were significant and prolonged periods of high temperatures. Additionally, it was during these months that high questionnaire response rates were received; 5 for June 5 for July and 4 for August. Only one occupant did not submit their questionnaire in August. This high response rate signifies the high priority that occupants of monitored homes give to understanding their indoor thermal environments.

3.3.4 Solution Study - Dynamic Simulation Modelling (DSM)

DSM was used to understand other aspects of overheating that cannot be satisfied by sensor monitoring alone. This involved analyzing the performance of different mitigation strategies under certain assumptions. The research used the Integrated Environmental Solutions-Virtual Environment (IESVE) software – 2022 version. IESVE is a renowned software with a suite of various building performance analysis applications and tools designed for energy modelling and compliance, buildings, and systems design with BIM Interoperability. It is used by designers and engineers to analyze different design and system options, identify passive solutions, analyze low carbon and renewable technologies. It can also be used to draw conclusions on energy consumption, occupant comfort and carbon emissions. Its integrated central data model has direct links to other software such as SketchUp, Revit, as well as IFC and dxf imports. This tool was chosen for its whole building energy simulation capabilities, solar shading, climate and weather analysis, daylight simulation, lighting design and compliance to UK and Ireland Building Regulations like the Applications Manual (AM 11, 2015) for Building performance Modelling. IESVE is also a renowned tool that is well recognized in industry by both research and practice communities, with extensive historical testing and verification. It has been used in several projects such as the Spinning fields building in Manchester and studies such as Gupta et al., (2015), Wright and Venskunas (2022) among others.

The five monitored homes were modelled following the TM59 protocol as designed by CIBSE. This procedure is outlined below:

- Building geometry was created in the IESVE tool Model IT. This involved creating floor plans, elevations and thereby a 3D representation of the five monitored homes. Also, the rooms in the homes were organized into groups following a TM59 room profile. The drawings and specification details of each home were obtained from the collaborating home developers. These are the five homes that were sensor monitored.
- Thermal data from relevant CIBSE TM59 thermal templates were assigned to the models in the IESVE tool Apache. These include internal gains, occupant gains, equipment loads, occupancy profiles, air flow rates etc. To enable this, when creating the file for each home, a CIBSE TM59 template was chosen as it came with all thermal data already prepopulated.
- Constructions and glazing data were assigned to models in Apache. This includes fabric details such as fabric elements and thicknesses, U-values, and g-values, for walls, roofs, floors, windows, and doors.
- The opening criteria for windows and doors was modelled in the IESVE tool Macroflow. The opening profiles entailed in section 2.6 of Approved Document O (2021) were assigned.
- Weather and location data was assigned to all models under AP locate. For simulations, a London location, and a London Weather Center (LWC) CIBSE Design Summer year (DSY) 2020 high emission 50th percentile weather file was used. This is because the London weather file has higher overheating possibilities due to Urban Island effect (UHI). Considering how simulations would perform in such a location, provides a good overheating scenario under which to study the effectiveness of solutions.

- Dynamic Simulation Modelling was run in ApacheSim, and the results viewed in IESVE tool VistaPro.

Figure 11 shows the axonometric view of the five modelled homes as viewed in IESVE. These images show that they are representative replicas of their monitored versions in real life.

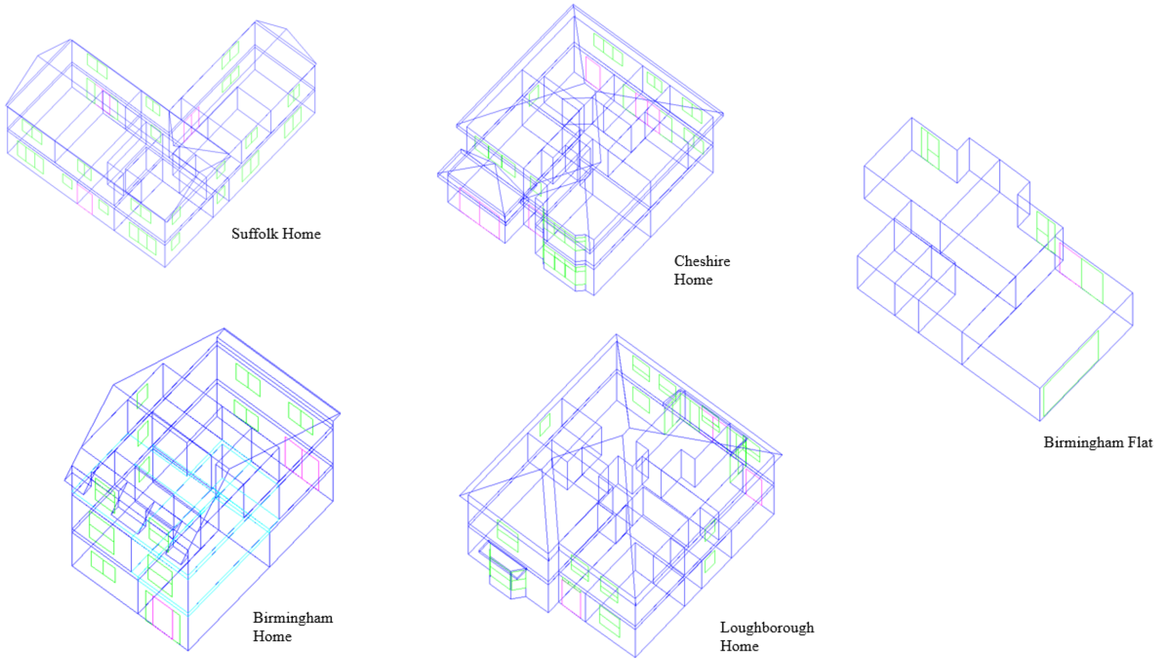


Figure 11: Axonometric View of Modelled Homes in IESVE

Five overheating mitigation solutions were modelled for each of the five homes considered. These solutions include high albedo walls and roofs, ceiling fans, external shutters, low e-double glazing, and fixed shading overhangs. These solutions were obtained from various literature studies, publications, and response from thermal comfort questionnaires with occupants of monitored homes.

- High Albedo walls and Roofs

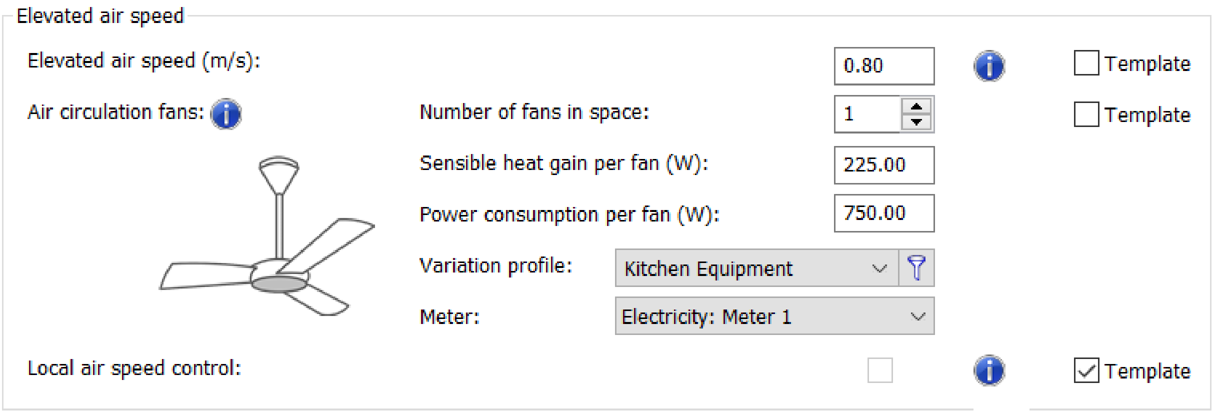
High albedo roofs and walls are surfaces that have a special coating as shown in figure 12, with superficial optic-energy features applied (Pisello, 2015). They keep the surface cooler by reflecting shortwave radiation back to space, thereby inducing negative radiation (Jandanghian and Berardi, 2020).

Figure 12: High Albedo reflective paint coating (Manufacturer website)

High albedo surfaces were modelled in IESVE through creating new roof and wall constructions with solar absorption changed from 0.7 to 0.15, and the solar reflectance from 0.25 to 0.75 to reflect the application of light-coloured, heat reflective external coating.

- Ceiling fans

Ceiling fans are electrically powered ceiling-mounted fans with hub-mounted rotating blades to increase air speed. They improve indoor air circulation and comfort cooling by replacing stale air at a higher rate (Omrani et al., 2021). Figure 13 shows the elevated air speed settings for ceiling fans in Apache.


Elevated air speed

Elevated air speed (m/s): 0.80 ☐ Template

Air circulation fans: Number of fans in space: 1 ☐ Template

Sensible heat gain per fan (W): 225.00

Power consumption per fan (W): 750.00

Variation profile: Kitchen Equipment

Meter: Electricity: Meter 1

Local air speed control: ☐ ☑ Template

Figure 13: Ceiling Fan Setting in IESVE

Ceiling fans were modelled by increasing the elevated air speed of main occupied rooms such as kitchens, bedrooms and living areas from 0.1m/s to 0.8m/s. One fan was selected for each individual room regardless of size, and the variation profile for each room was selected as appropriate. For example, Kitchen equipment profile for kitchens.

- External Shutters

External shutters as shown in figure 14, are external- louvered window elements whose major aim is to block sunrays from getting inside a building. They exist in different forms (vertical, horizontal, decorative, roller, with or without radiation control, mechanically operated - rod crank or spring-loaded). They are normally made from wood aluminum, steel, plastic, composites polyester laminates, glass fiber and resin.

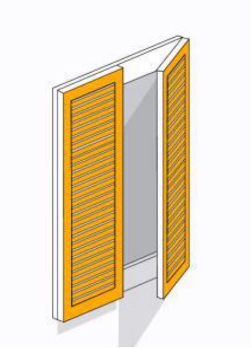
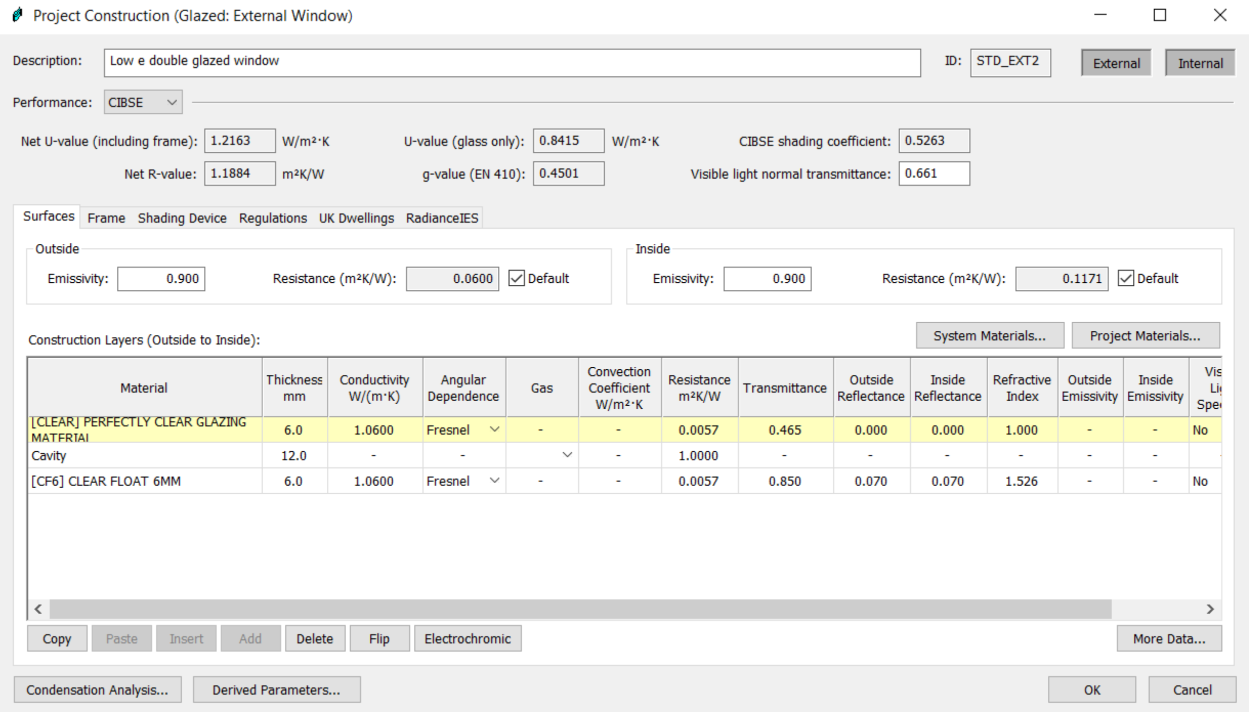


Figure 14: Example of External Shutters (Mohamed, 2019)

External shutters were modelled by creating a new window construction with external shutters (under the shading device – external shade) with the same operation profile as the window opening criteria assigned in section 2.6 of Approved Document 0 (2021).

- Low e - double glazing

This type of glazing is characterized by two sheets of glass, one with a low emissivity (low e) coating and a gap between them. Low e glass has a microscopically thin coating of metal oxide on one of the internal glass surfaces. This coating reflects heat back into a space while allowing for external light to come into a space. In IESVE, these windows were modeled by a glazed window construction as shown in Figure 15.



Description: Low e double glazed window

ID: STD_EXT2

Performance: CIBSE

Net U-value (including frame): 1.2163 W/m²·K

U-value (glass only): 0.8415 W/m²·K

CIBSE shading coefficient: 0.5263

Net R-value: 1.1884 m²K/W

g-value (EN 410): 0.4501

Visible light normal transmittance: 0.661

Outside

Emissivity: 0.900

Resistance (m²K/W): 0.0600 ☑ Default

Inside

Emissivity: 0.900

Resistance (m²K/W): 0.1171 ☑ Default

Construction Layers (Outside to Inside):

Material	Thickness mm	Conductivity W/(m·K)	Angular Dependence	Gas	Convection Coefficient W/m²·K	Resistance m²K/W	Transmittance	Outside Reflectance	Inside Reflectance	Refractive Index	Outside Emissivity	Inside Emissivity	Vis Li Spe
[CLEAR] PERFECTLY CLEAR GLAZING MATERIAL	6.0	1.0600	Fresnel	-	-	0.0057	0.465	0.000	0.000	1.000	-	-	No
Cavity	12.0	-	-		-	1.0000	-	-	-	-	-	-	
[CF6] CLEAR FLOAT 6MM	6.0	1.0600	Fresnel	-	-	0.0057	0.850	0.070	0.070	1.526	-	-	No

Figure 15: Low e double glazing inputs in IESVE.

Low e double glazing modelled in IESVE had an outer pane made of 6mm perfectly clear glazing, a 12mm cavity, and a 6mm inner pane made from clear float. It also had a U-value of 1.2163 (from 1.6), a g value of 0.45 (from 0.39) and a cavity resistance of 1.0m^{2}K/W. The U value and g value were obtained by changing the thermal conductivity of material elements and changing the transmittance of material elements respectively. As the special coatings for almost all low e glazing systems face into the cavity, the low emissivity coating was considered via an increase in the cavity resistance.

- Fixed shading overhangs

Overhangs are fixed and mostly horizontal surfaces protruding above a window. They can appear in a variety of forms such as cantilever additions, jettied storeys, balconies, verandas, or porticoes (Stevanovic, 2022). Overhangs were modelled by creating new window constructions.

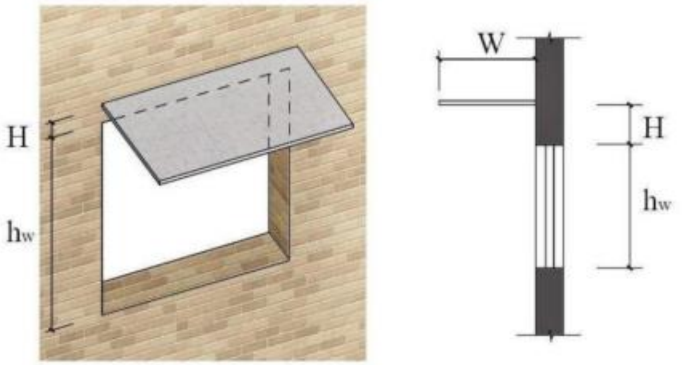
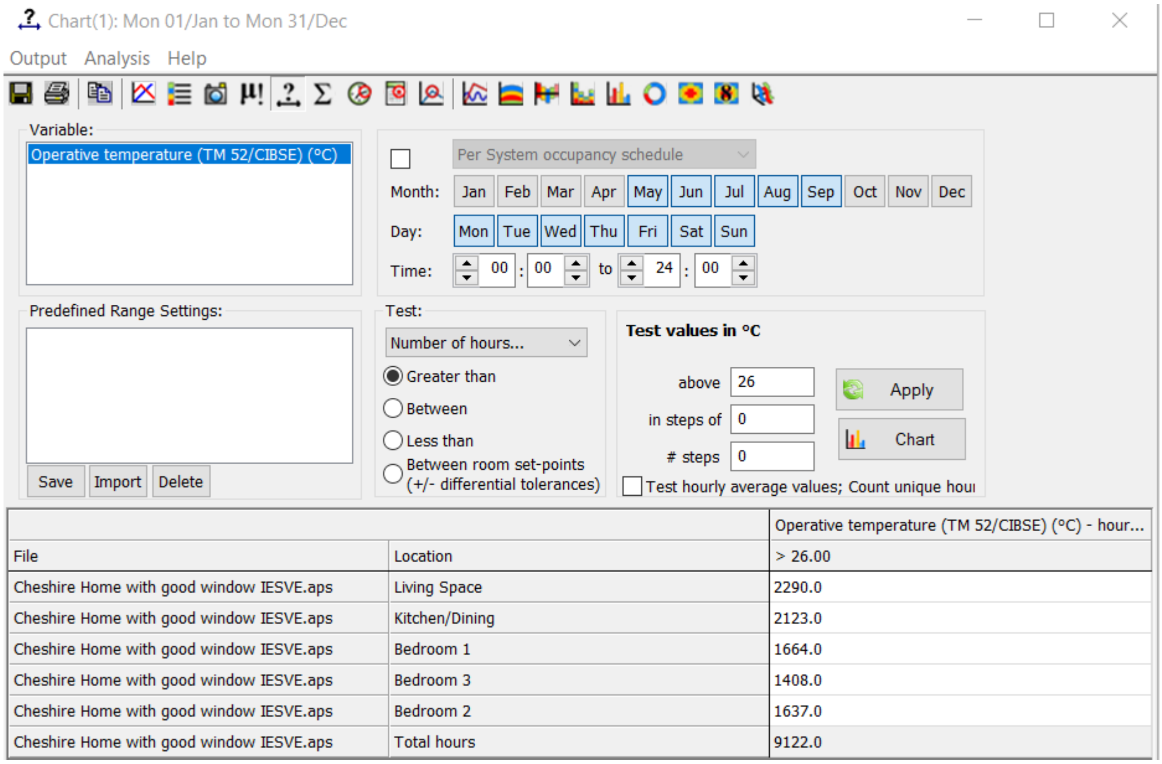


Figure 16: Overhang design in IESVE

In IESVE, overhang design can be represented as shown in figure 16, with W representing the width of the shading device (corresponding with overhang projection in IESVE) and H representing the distance from the lower edge of the shading device to the upper edge of the window (corresponding with overhang offset in IESVE). In IESVE, the created window construction for overhangs had the overhang projection at 1m with a normal <2m window depth overhang type and the overhang offset at 0.

3.3.4.1 Data Analysis for Dynamic Simulation Modelling

Each of these solutions (including the base model that is based on 2013 fabric properties) were simulated in Apachesim, with the Suncast and Macroflow links enabled, and the results viewed in VistaPro. For each house and each solution, all four orientations were considered. In total, 120 simulations were conducted. Each simulation took around two minutes hence the possibility. In VistaPro, a range test was done on the operative temperature of main occupied rooms (kitchens, bedrooms and living areas) for the number of hours above 26^0C for the period of May to September. This was repeated for all 120 simulations to determine the effectiveness of the different solutions. An example range test in vista pro is shown in figure 17.



Variable: Operative temperature (TM 52/CIBSE) (°C)

Predefined Range Settings:

☐ Per System occupancy schedule

Month: Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

Day: Mon Tue Wed Thu Fri Sat Sun

Time: 00 : 00 to 24 : 00

Test: Number of hours...

● Greater than
○ Between
○ Less than
○ Between room set-points (+/- differential tolerances)

Test values in °C

above 26

in steps of 0

steps 0

☐ Test hourly average values; Count unique hou

		Operative temperature (TM 52/CIBSE) (°C) - hour...
File	Location	> 26.00
Cheshire Home with good window IESVE.aps	Living Space	2290.0
Cheshire Home with good window IESVE.aps	Kitchen/Dining	2123.0
Cheshire Home with good window IESVE.aps	Bedroom 1	1664.0
Cheshire Home with good window IESVE.aps	Bedroom 3	1408.0
Cheshire Home with good window IESVE.aps	Bedroom 2	1637.0
Cheshire Home with good window IESVE.aps	Total hours	9122.0

Figure 17: Range test View in IESVE

The operative temperature figures for each solution (including base model) in each room, in each house, and all four different orientations were produced. From these, horizontal bar graphs were created in python to analyze the different solutions. The length of each horizontal bar represents the number of overheating hours attributable to each case. The result for each solution in each home is presented in chapter 6.

3.4 Evaluation Workshop with Developers

Owing to the levels of subjectivity involved in analyzing the qualitative aspects of this research, there was a need to verify the results and findings (Merriam, 2014; Silverman, 2015). The same qualitative dataset can be interpreted differently by different researchers (Burbard et al., 2008). As such qualitative accounts cannot straightforwardly represent the social world. Qualitative accounts could contain highly prejudicial information that when taken arbitrarily, could lead to invalid results (Ashworth, 1993). A rigorous analytical approach is needed to evaluate research claims and findings to reduce bias and ensure that participant views are not misinterpreted (Barbour, 2001; Silverman, 2015). Evaluation is achieved based on how accurately the results among study participants represent true findings that can be generalized to a wider audience. To test the appropriateness of a qualitative account, Ashworth (1993), suggests participant evaluation, asking the research participants themselves. Participant evaluation means returning to respondents with initial data analyses to validate or refute researchers' interpretation of the data (Burnard et al., 2008; Yin, 2013). However, care should be taken to ensure respondents accounts are not romanticized at the expense of clear research interpretations (Atkinson, 1997).

Participant evaluation in this research was done through validation workshops. Validation workshops are collaborative sessions where industry partners and stakeholders review and confirm the requirements, assumptions, and constraints of a project. Validation workshops were done with the 4 main industry partners: 3 volume builders and 1 housing association. These were done separately on MS Teams and the sessions were recorded after permissions were obtained. Table 15 shows the main participants involved and the dates when these workshops were carried out.

Table 15: Evaluation Workshops

Industry partner	Date	Representatives involved	Means and duration
Housing developer 1	13/07/2023	• Head of Research and Technical Innovation	MS Teams - 1 hour
Housing developer 2	14/07/2023	• Head of Group Technical • Technical manager	MS Teams - 1 hour
Housing developer 3	10/07/2023	• Technical and Innovation Director • Snr Technical Innovation Coordinator • Group Technical Innovation Manager	MS Teams - 1 hour
Housing Association	02/08/2023	• Head of Construction, Quality, and Innovation	MS Teams - 1 hour

Participant validation workshops involved PowerPoint presentations of the preliminary results and analysis of this research and answering any questions the participants had. These included the results from interviews on home development process, sensor monitoring of occupied homes, and dynamic simulation analysis of overheating mitigation measures. The participants were then presented with the scalability criteria and analysis of overheating mitigation solutions to ensure their views had not been misrepresented. The validation workshops followed an unstructured approach with open-ended questions. This meant that the workshop followed a conversation-like approach (Blackman, 2002) and made it easy to conduct. All aspects of the five-scalability criteria for overheating mitigation solutions were probed to capture accuracy, hierarchy of priority, real-time practicality issues and general perceptions. To enhance this, validation workshop participants were emailed copies of the preliminary research results and analysis days earlier, to ensure they understood the questions and had a chance to seek clarification in advance.

3.5 Ethical Considerations

Since this research involves many different stakeholders and commercial concerns, high ethical standards were followed to ensure that research participants were treated with professional courtesy and with sufficient care. Approval was obtained from the University's Research Ethics Committee on the 19th of January 2021, upon submission of this research's detailed ethical report. A copy of the obtained University Ethics Permission is attached to this document as Appendix 1.

Interview participants were obtained through recommendations from the four main industry collaborators. Interview participants were emailed using official university email accounts to ascertain credibility. Interviews were scheduled on MS Teams according to participants' availability. The main questions asked were based on an interview guide as shown in Appendix 3. This was then tailored to each interviewee based on their specialization. MS Teams is recommended as a secure site for conducting university related studies. Interviews were recorded and transcribed with the permission of the participants; all of them were happy with this.

Since monitoring involved accessing people's homes, informed consent was obtained beforehand using a Home Occupant Information leaflet as shown in Appendix 2. The respondents were informed of the benefits and risks of engaging in this research as part of the voluntary nature of participation, through a leaflet and consent form. Data security is another aspect that was guaranteed to the research participants. The participants were openly informed of the purpose of any data obtained from their homes to ensure anonymity, confidentiality and that their participatory rights are upheld. This involved using sensors with localized data storage and secure cloud storage capabilities. Communication with research participants was done through official university email accounts to ascertain credibility.

Given the fact that this research involved working with various housing developers, clarity, confidentiality, and consent was maintained to safeguard the image of the university and the reputation of the housing developers as well. At the end of this research, research findings and recommendations were made available to the stakeholders based on request.

3.6 Chapter Summary

This chapter started by reviewing the conceptual framework that analyzed the conceptual interactions of research ideas, thereby creating a base for data collection. A pragmatic philosophical positioning of the research was presented, and this was used to justify a mixed methods research design as the most appropriate choice for this research. Four data collection methods namely interviews, monitoring, thermal comfort questionnaires, and dynamic simulation modelling were presented. Details of the data collection methods presented included research participants – interviewee details, monitored homes and occupants, simulation software, alongside a justification of sample sizes, detailed steps, and data analysis protocols for each method. Evaluation workshops were also carried out with home developers to ensure participant data was not misrepresented. This chapter is then summarized by a run-through of the various ethical considerations that were made to enable the success of the research methodology.

Chapter 4: Home Development Process Analysis

Addressing the scalability of mitigation solutions requires an investigation of the entire home development decision-making process, and the wider contextual issues ranging from business hierarchical structures, market dynamics, planning restrictions, construction processes and stakeholders involved. Thus, solutions need to be seen as not just removing causes to events but strategies for wider scale and for longer-term success. To ensure that solutions obtained are implementable, evaluation with home developers is crucial to investigating the practicality issues behind solutions and to make them more implementable at a wider scale.

This chapter presents the results of the interviews that were carried out with home developers, some of their supply chain companies and relevant home construction professionals. The results presented are based on thematic analysis conducted in NVivo software. In this chapter, the UK home development process is analyzed to understand key decision-making steps that influence overheating in homes. The aim of this chapter is to identify aspects of the home development process that are key to developing scalable solutions to overheating in UK homes. This chapter is divided into the following sections: Thematic and conceptual visualization, UK home development decision-making processes and overheating in UK homes, discussion of results, contribution to scalable solutions and chapter summary.

4.1 Thematic and Conceptual visualization

Figure 18 shows a word cloud of the interview transcripts that was generated in NVivo as preliminary analysis of the interviews with developers, their supply chain companies, and relevant professionals.

Figure 18: Word Cloud for Interviews

The generated word cloud shows that the most common words mentioned in the interviews were people 245, building 207, planning 173, house 188, site 191, design 137, ventilation 133, time 117, overheating 112, products 112, quality 94, windows 74, system 75, just to mention a few. This gives a perspective into what was more emphasized by the interviewees, and it shows the word clusters that were commonly used in discussing this research area. As shall be explained later, these main words have a relationship with the key decision-making stages in the home development process, that do affect overheating in homes.

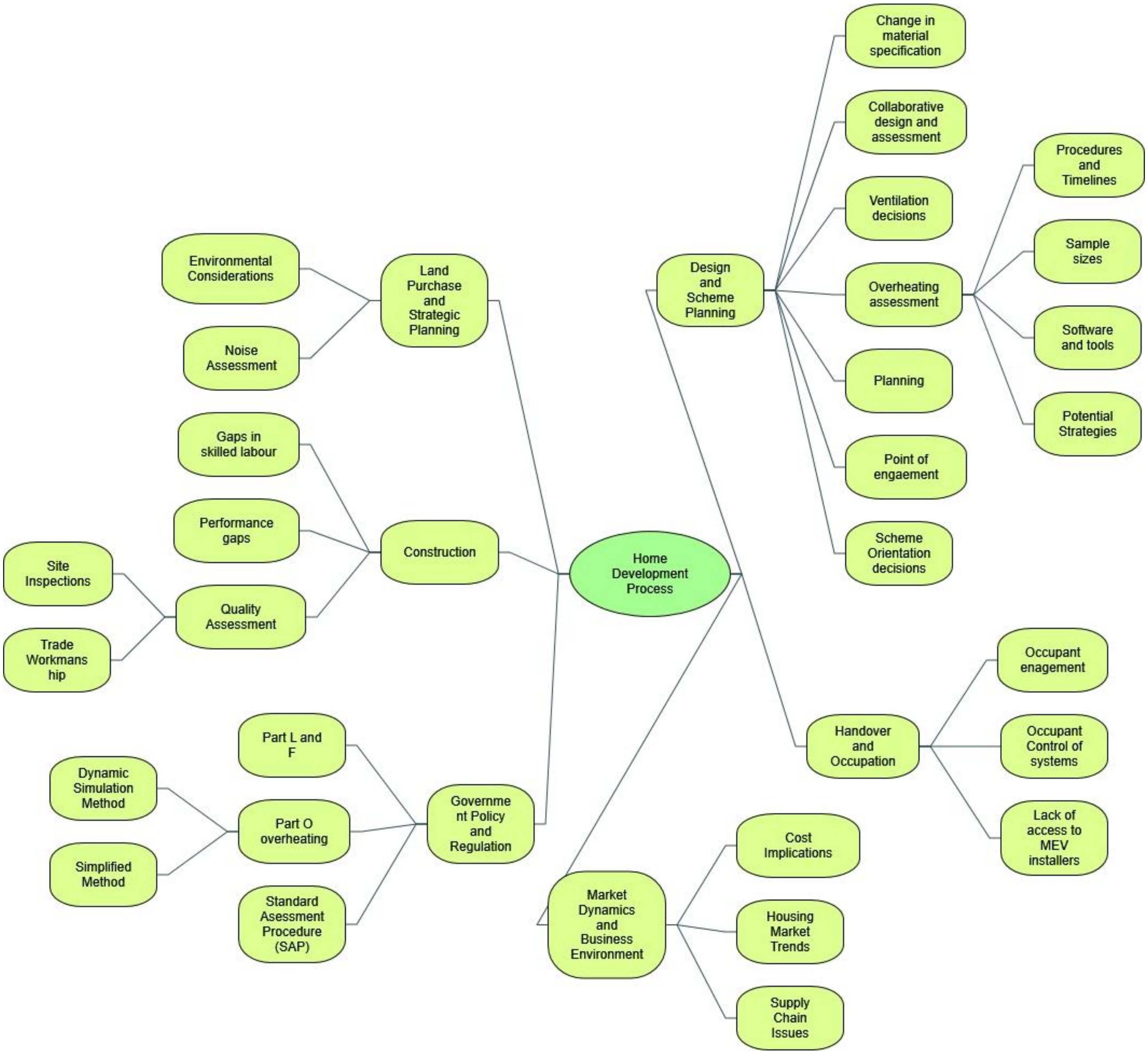


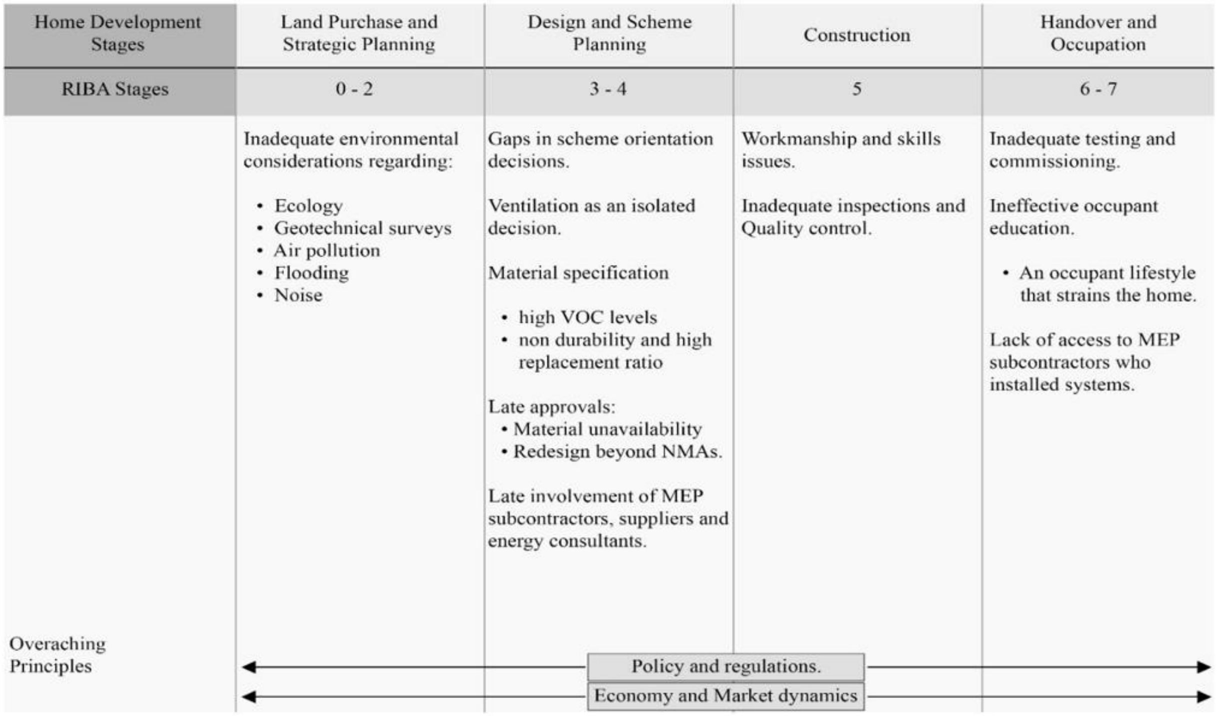
Figure 19: Mind Map of Interview Themes and Codes from NVivo

Figure 19 shows a mind map of themes and codes developed in the qualitative analysis software NVivo. There are 6 main themes: land purchase and strategic planning, Design and scheme planning, construction, handover and occupation, government policy and regulation, and market dynamics and business environment. Each of the 6 main themes branch into codes and sub-codes that are related to the theme. These results and discussion of the interviews are structured according to the main themes in figure 19.

4.2 UK Home Development Decision-Making Processes and Overheating in UK homes.

This section presents results on key decision-making processes in the home development process that affect overheating according to the interviews. This section is arranged according to the framework of thematic ideas developed in NVivo. These include land purchase and Strategic planning, design and scheme planning, construction, handover and occupation, and market dynamics and business environment.

From the interview results, figure 20 summarizes the key decision-making points that contribute to overheating across the typical UK home development stages.



Home Development Stages	Land Purchase and Strategic Planning	Design and Scheme Planning	Construction	Handover and Occupation
RIBA Stages	0 - 2	3 - 4	5	6 - 7
	Inadequate environmental considerations regarding: • Ecology • Geotechnical surveys • Air pollution • Flooding • Noise	Gaps in scheme orientation decisions. Ventilation as an isolated decision. Material specification • high VOC levels • non durability and high replacement ratio Late approvals: • Material unavailability • Redesign beyond NMAs. Late involvement of MEP subcontractors, suppliers and energy consultants.	Workmanship and skills issues. Inadequate inspections and Quality control.	Inadequate testing and commissioning. Ineffective occupant education. • An occupant lifestyle that strains the home. Lack of access to MEP subcontractors who installed systems.
Overaching Principles	Policy and regulations. Economy and Market dynamics			

Figure 20: Factors that contribute to overheating in the UK Home Development Processes

4.2.1 Land Purchase and Strategic Planning

In this stage, data from interviews shows that decisions regarding environmental assessments such as noise can impact overheating in homes. Participant 14, the founder of a Building Physics Consultancy mentioned that "*my instinct is that there are sites that are too noisy to build homes on. It just isn't a good site for a home. That is too noisy, I don't think it's human to live in a place where you can't open the windows.* Also, when asked about limitations to overheating mitigation strategies, she talked about the importance of noise reports. She mentioned that *"the other big problem comes in when it's a noisy site and you've got an acoustic report that says it's really noisy, it's on a main road, we're recommending that you don't rely on openable windows to prevent overheating. At that point it all gets really hard."* The sequence and frequency in which environmental reports regarding noise pollution are done varies from one developer to another, but the interviews reveal that this needs to improve. Respondent 4, a technical and innovation director for housing developer 3 revealed that *"now it is involved earlier on because it's mostly legislation driven."*

4.2.2 Design and Scheme Planning

In the design stage, the interviews show that ventilation is not a high priority. Respondent 10, a seasoned architect, and an Associate Director stated that *"I think it is a consideration, but probably not as much, not as much as it should be."* Respondent 8, a sales director of a major manufacturer of ventilation systems in the UK stated that *"ventilation is always considered last"* and that ventilation decisions always seem to be *"an isolated decision."*

Additionally in the design stage, the interviews show that gaps in scheme orientation decisions also affect overheating. In explaining the complexity of scheme orientation, Respondent 4 from Housing Developer 3 states that it involves *"a dichotomy argument of wanting as much daylight through windows but not as much heat in summer"*. A Senior Technical Coordinator for Housing Developer 1 states that there are specific requirements on other factors of scheme design such as distance between houses, rear garden lengths and defensible space *"but there are no hard rules on orientation."* He further adds that *"most of the time in terms of orientation, you know, we don't really think about that too much."* Respondent 8, a sales director of a major ventilation manufacturer in the UK, adds that "*I'm not sure that it would yet occur to specifiers that orientation and positioning on the plot would impact building services further down the design process."*

The interviews show that material specification can also affect IEQ. Respondent 11 mentioned this when talking about carpet thickness. He stated that *"the one thing I've had on a couple of things where we think there's been an issue was installing carpets that are too thick, so that they've blocked the air gap underneath the doors to bathrooms, so they don't get cross ventilation. So, that's one thing to watch is the thickness of the, the floor, compared to the gap underneath the* *door. Because obviously the bathroom doors you probably get them shut for a majority of the time, isn't it?"*

The respondents all expressed their frustrations with the planning process with words like *"absolute nightmare", "it's the worst I've known it"*, *"protracted"* and *"expensive."* One respondent described the planning process as *"a mixture of politics and planning as a science."* Planning influences overheating in homes when other factors such as material availability and supply are considered. Respondent 11, a design manager described how late approvals led to challenges on site when certain building materials specified in the planning application were unavailable due to late approvals. These included certain bricks and windows with a g-value of 0.35 that were specified for overheating reasons. This also reveals that once planning approvals are obtained, introducing changes that might be necessary for mitigating overheating, beyond non-material amendments (NMAs), is something that many home developers might not want to put themselves through. As Respondent 10 states *"if you've already got planning, then that's just an extra layer of complexity."*

The interviews show that the point of introduction of critical MEP supply chain companies and consultants into the home development process and their inclusion in planning and design is an important factor to overheating. The respondents of this research include representatives from an Aircrete, Insulation and MEP manufacturer and supplier alongside various Energy and Sustainability Consultants. When asked at what point they are introduced into home developments, they mostly agreed, not early enough. Respondent 13 an Energy Consultant said, *"It's probably RIBA stage three or four"* Respondent 14, a Building Physics Consultant reports that *"It varies quite a lot right from early doors and Stage 1-2 through to probably too late when we're in stage, three, four, and it's a bit too late to make a difference, you know, post planning…"* Respondent 8, an MEP manufacturer when asked how often they are engaged early on in a project said, *"I'd say less, not massively."* Respondent 8 mentioned that in most situations, it is mostly the Architect or the M & E engineer requesting for their most suitable product that ticks several boxes, without engaging them in the design process. He stated that, *"we are treated more as a supplier…like here is the sort of lane…. tell us which products you offer, which tick these boxes."* Stakeholders' point of involvement into the home development process as shown by the interviews, is summarized in figure 21.

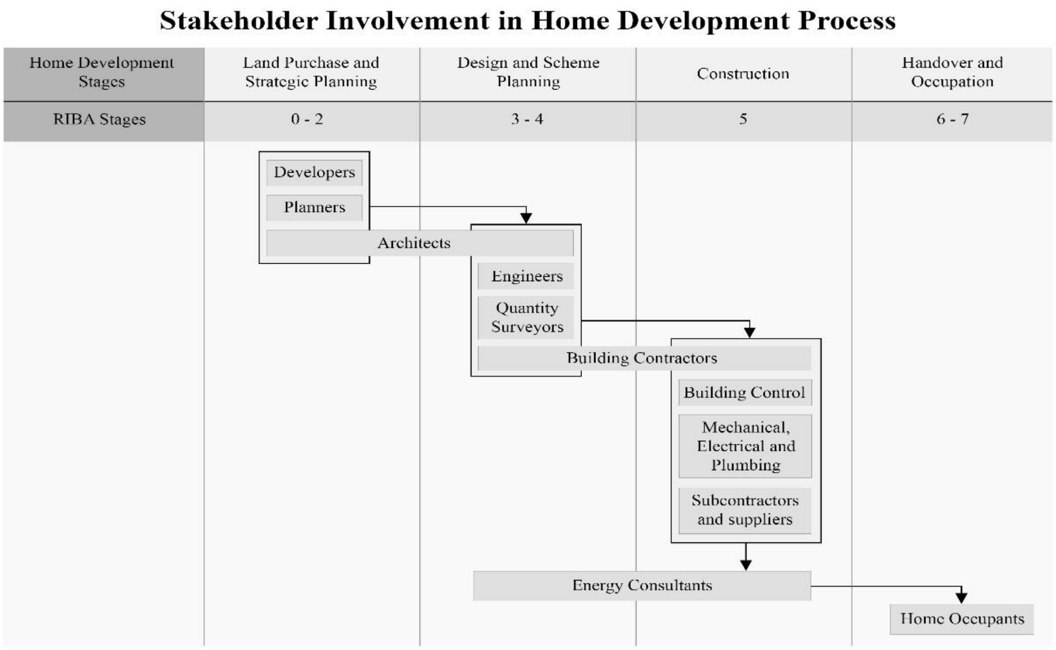


Figure 21: Stakeholder Involvement in the Home Development Process

4.2.3 Construction

In the construction stage, the interviews show that skills could be an issue. Respondent 3 when asked about the availability of skilled labour, said that *"we do up to a point. I think as the zero-carbon agenda comes forward; we won't have enough."* Respondent 2 adds that *"I would doubt we could roll out these new systems through our build without workforce challenges."* Additionally, the interviews mention that failures in quality control and inspections play a role. Respondent 9 from Energy Consultancy 1 states that *"you would very often find that if a planning target is set in the planning condition, like let's say ten percent carbon or 90 percent carbon or you have to, you have to achieve a certain Target, there's no follow-up at the as build stage from the planners in wanting to know the as-built performance on paper."* In relation to this, there was concern raised about a potential performance gap in reporting SAP information back to assessors to produce as-builts SAPs and EPCs. When asked about the accuracy of information they receive from developers for as-built SAPs and EPCs, Respondent 1 stated that *"it's you relying on them to tell you whether they've made any changes. If they choose not to tell you then we wouldn't know."* Respondent 13 from Energy Consultancy 2 adds that *"you know, evidencing the installation of products correctly as to the manufacturers guarantees and warranties…. there's not enough of it. Greatly…. you know, building control can only do so much you know."*

4.2.4 Handover and Occupation

The interviews show that Failure to include home occupants by properly educating them on the use of systems in their homes could lead to poor indoor environmental quality. When talking about MVHR systems, participant 14 mentions that “*I think there's a lot of Education around MVHR needed because I think still it's the case that a lot of them don't work very well and people don’t understand how they're supposed to work and don't understand when their filters need changing or how to change them.”* Respondent 12, a Building Control Agent further explains that *“what you'll never regulate for you is that you walk away from a building on a Monday by Friday the first tenant might have moved in, had the windows changed, all the trickle vents been different. They might have blocked up the air vents because there's a draft and might have disabled the fans because they don't like the noise then very quickly, you end up with a building that is nothing like it was designed to perform, as sometimes education will help, sometimes people don't care. So, we will design, we will see the construction off, we will sign off a building that is compliant, but ultimately the use will affect that quality of air”* Most new home occupants are provided with a Home User Guide (HUG) or a handover pack. However, its effectiveness is being questioned. Respondent 12 explains that “*they’ll look at it at the back and make sure it’s been signed, put it in the drawer and never read it.”* Respondent 8 adds that *“obviously then you’ve got the first wave of residents coming in, you’d hope there would be some kind of handover pack with our user guides in and things like that to explain to the resident what the unit does and everything, but you know in reality they are just gonna put that in a drawer and forget about.”*

The interviews also suggest that the lack of a direct relationship between occupants and the MEP suppliers and installers who were involved in building their homes influences their interaction with the heating and cooling systems in their homes and thus their indoor thermal comfort conditions. Respondent 8 an MEP manufacturer explains that due to this lack of direct contact, *“there will be plenty of homes where the resident, the end user won’t know what is installed in their house, what it is, where it is.”* Respondent 9 further adds that currently in most developments that they are involved in, their *“expertise if it was ever on site, it is almost gone at the point the occupant takes ownership.”*

4.2.5 Government Policy and Regulation

Throughout the home development process, one theme that cuts across all stages is the role of government policy and regulation. When asked why overheating concerns are going high up the agenda for home developers, Respondent 4 of Housing Developer 3 states that *“it is becoming more legislation driven.”* Respondent 1 of Housing developer 1 adds that *“we're a heavily regulated industry rightly so and a lot of the stuff that we need to do is in response to the regulations.”* When asked how policy and regulation affects the delivery of products and services in the UK housing market, Respondent 15, an Energy Consultant explained that *“it has to be led by proper legislation, it has to be built into part L. When you give people the option, it comes down to pennies and if it's going to cost the developer another pound to build, they're not going to do it, they are not going to do it unless they are forced to. I think that's the real problem with the building industry. Unless they have to do it, they won’t.”*

However, respondent 7 described what he felt as political unwillingness to take a leap and that regulation was not keeping up to sentiment. He further added that *“we're talking about, you know, sustainability, about embodied energy. These are things that are beyond regulation. Regulations are just, they're old news really.”*

4.2.6 Market Dynamics and business Environment

Another factor that cuts across the home development process is market dynamics and business environment related matters. At numerous points, the respondents mentioned how the competitive nature of the housing market is a barrier to implementing proper overheating mitigation in UK homes. This was expressed with expressions such as *“cost comes into play always”, “it’s a competitive market”, “some clients are just about money”, “but yeah, we live in a commercial world”* among others. This could be the reason why overheating is not given as much priority as explained by Respondent 10, *“it’s like considered normally a little bit too late….. after it's already set, then you've got someone around the table go, right, so you how are we gonna prevent overheating, and then you start looking at the G values and sort of like the specifications of the glass.”* Respondent 15 adds that *“air tightness was talked about quite a bit; overheating has not been considered to the same extent in the market.”* To this, Respondent 8 the MEP manufacturer adds *“ventilation was sort of the forgotten part of any sort of the element of the build.”* Respondent 15 explains that *“you know, the attitude we get to the major house builders is literally, can we* *build the same house at 20% improved specification for the same money?"* Respondent 15 when asked about potential barriers explained that *"it's really cost concerns, you know, the nature of our industry is, it's all about value engineering or cost-cutting, and we can do calculations properly, we can provide the correct materials on the site, but if it's out of their budget, people take shortcuts, you know, that's the biggest barrier to providing real good performance on site."* In explaining the reason as to why only a few sample homes are chosen for SAP assessment, respondent 9 explains that *"it's a competitive market so you sometimes want to do more samples than you actually getting paid for, you know".*

In trying to explain the business environment, Respondent 1 from Housing Developer 1 explains that *"because we have a housing shortage in, in the UK, it is always, at the minute the main concerns are going to be location and price. Almost everything else is secondary to those concerns."* He adds that *"the housing market, in my view, isn't something that customers drive. It's something that because of the supply issues, if you build something, it's going to sell"* Respondent 9 adds that *"people don't have another choice and if it's not done in the first place, then people might just go around and buy it."* To this Respondent 7 further adds that *"the nature of the construction sector in the UK is that we do not build our own homes, most people do not have a say in the types of homes, the performance of the homes that are going to live in, people buy because of location, because of price, you know."*

4.3 Discussion of Results

The discussion section is divided into the following five subsections: Planning and design, Procurement processes, Government Policy and Regulation, Market dynamics and Business Environment, and End User Education and home induction process. These five subsections cover the full extent of the UK home development process from land acquisition through to the completion and delivery of new housing stock.

4.3.1 Planning and design

Planning is central to the home development process and is it one of the biggest national challenges for home developers (PwC, 2019). In contrast, there are exceptional planning and development projects, but far too often, this is the exception rather than the rule, as it is hindered by several problems with the system as it stands (MHCLGa, 2020). Decades of planning policy reform have built complexity, uncertainty, and unnecessary delay (MHCLGa, 2020). In a study conducted by the NHBC (2014) surrounding challenges of the house development process, the main concerns about the planning process includes among others the length of time it takes to achieve a decision. Receiving late planning approvals can lead to challenges on site when certain building materials specified in the planning application become unavailable due to supply issues. Additionally, once planning approvals are obtained, introducing changes that might be necessary for IEQ, beyond non-material amendments (NMAs), is something that many home developers might not want to put themselves through.

Design is another important stage when critical overheating decisions are made or not made. Each home developer has their own design ethos with words like creating great spaces, occupant centered design, creating thriving and healthy communities etc., attached with their own design score cards. However, overheating mitigation is not a high priority in the design process, as revealed by the interviews (when they were carried out in 2021). One critical aspect of design that affects overheating in homes is ventilation. The interviews suggest that ventilation is more of an afterthought in home design. As building regulations continue to push for more airtight homes in response to climate change adaptation and energy conservation measures, ventilation is key to preventing unintended consequences such as potential overheating. The depth to which ventilation considerations are embedded into the design process affects the delivery of overheating in homes. Ventilation is always assumed to be limited to physical products such as MEVs, MVHR, filter-less fans etc. However, it is much more than that. As respondent 8 explains *"It is as much about the physical product but also very much about the methodology, the expertise, the understanding."* Ventilation decisions have implications on the sizes, number and orientation of windows and doors, cross ventilation capabilities, the inclusion of mechanized cooling systems and their infrastructure, energy strategy and planning limitations. Home developers must address the complex interaction between design, ventilation system operation, and human behaviour to mitigate overheating in airtight homes. As such, building professionals such as building services engineers, in collaboration with other design team members, are responsible for creating healthy, safe, and comfortable buildings when exposed to the varying conditions outdoors. Designing safe thermal environments in homes requires the integration of a holistic view of design inclusive of ventilation, and in close collaboration with other design team members.

Still in design, scheme orientation decisions are vital in mitigating overheating in new homes. Scheme orientation determines the direct intake of sunlight into rooms, the positioning and sizing of ventilation infrastructure such as windows, doors, exhausts and intakes and the intake of pollution from adjacent sources among others. Housing scheme designs are made through site visits, planning, pre-application meetings, consultations with the local planning authority and community. However, it all comes down to clients who would prefer as many houses on site as possible and unit density requirements in planning requirements. Orientation is limited by these. Respondent 11, a design manager explained that to reduce potential overheating in a recent project, *"different orientations were considered but restricted by planning and unit density."*

The choice of materials in home development could have an impact on overheating in new homes. Most home developers have a construction specification standard that could be slightly different depending on the local authority jurisdiction. In these, they have negotiated deals with different manufacturers and suppliers as per their need. However, Corsi (2011) argues that new materials are being introduced at a rate that exceeds the current ability to evaluate them properly, their long-term thermal performance in buildings, and their effects on building occupants.

4.3.2 Procurement processes

The interviews show that the point of introduction of critical MEP supply chain companies and consultants, into the home development process and their inclusion in planning and design is an important factor to overheating in homes. The capabilities of specialist consultants and MEP subcontractors can only be fully captured when there is still scope to influence design. Around RIBA stage 1 or 2 when planning applications have not yet been completed. However, MEP subcontractors are mostly engaged once designs have been done and planning permissions obtained. This denies them the opportunity to contribute to the buildability of design based on their onsite experience over the years. The typical procurement process is normally to tender to different suppliers and manufacturers to obtain different quotes and select the suitable one. By tender stage, most of the drawings have already been signed off thereby limiting the chance of tenderers influencing the designs. Designs are already completed so that quotes for tendering to different subcontractors can be produced. However, the preference is to bring the contractors on board as early as possible, to give feedback on design. Which comes first?

Changes should be made to introduce critical supply chain companies early enough to maximize their benefits on design buildability. As Respondent 14 puts it, *“you need enough of the design kind of in place, but you need there still to be the scope to influence it.”* Regarding overheating control measures, Respondent 13, an energy consultant, described how the results of an overheating assessment they were asked to do was limited as they were introduced into the project post planning. As a result, better, more impactful, and cheaper recommendations could not be possible. This leaves only reactive measures that are counterintuitive, rather than proactive measures. Simple and effective measures such as change in orientations, window sizing – (glazing and free areas) and cross-ventilation design, to more expensive and complicated options like mechanical ventilation. The procurement process should ideally allow for specialist consultants and MEP subcontractors to be introduced at a point where they can influence the design. In home development projects, material-related activities from sub-contractors (e.g., ventilation, building materials) contribute more than half of the total cost and have huge effects on the project schedule (Ho et al., 2007). Thus, efficient approaches to interact with suppliers/subcontractors at the early stage is imperative in integrating them into projects right from planning and design, etc. (Emiliani, 2000; Envirowise, 2001).

4.3.3 Government Policy and Regulation

The Home Development Industry in the UK is characterized by tightly governed policies and regulations that are ever evolving and a competitive business environment with tight margins. As a result, industry organizations may just aim to meet minimum requirements for building codes and regulations, with little or no efforts to design beyond building regulations to improve performance (Bean, 2020). Moreover, issues like overheating, whose adverse effects are not immediately manifest, if left to stakeholders with perceived personal and financial interests, can easily be neglected (Murtagh et al.,2019). Therefore, government policy and regulation are key precipitators for positive change in UK home development.

However, the ability of government policy to influence home development decision making through legislation, alongside the impact of broader structural changes in the economic, demographic, and political contexts of housing provision, means that many diverse factors can shape building outcomes and thus overheating outcomes. This may go some way to explaining why issues of home development remain so difficult to address.

Policy and regulation, however, must be in-keeping with current trends and targets especially regarding climate change adaptation and Net Zero targets that do have an impact on overheating. To some stakeholders in the home development process, regulation and policy seems to be moving quite fast, while to others within the sector, it’s the opposite. This creates a unique challenge for policy makers and regulators to ensure they strike a balance that carries along both sides.

Even with proper legislation, ineffective enforcement could still lead to failure. New Building Regulations (Part L and F 2021) aim to remove this performance gap by introducing a change in terms of providing photographic evidence. However, this provides a major challenge in terms of staff needed as well as training and deploying them. Effective enforcement of proper legislations and policies will be key to mitigating overheating in homes.

4.3.4 Market dynamics and Business Environment

The interviews reveal that the housing market is characterized as a competitive business environment. This can influence whether to adopt strategies that could be helpful in mitigating overheating in homes. Cost-cutting tendencies affects the number and quality of SAP assessments performed, as well as sample sizes for overheating-related tests. Same as other industries, when consultants compete on the housing market for jobs, this is often done based on costs. Same goes to sample sizes for overheating assessments such as simplified method and dynamic simulation methods. The number and quality of overheating assessments done on a housing development has an impact on the performance of a home. These tests cover issues to do with glazing specifications, ventilation rates, air permeability rates, solar gains and sun path calculations, internal gains, fabric U-values, energy consumption rates etc. All these have a potential to affect overheating in homes.

The backdrop of a housing shortage has not helped. Bramley (2018) approximates that 4.75 million households across Great Britain are either homeless or living in precarious and unsuitable accommodation and that 380,000 new homes need to be built every year for the next 15 years.

Demand for homes is still very high. As such, cost and location are still the most dominating factors in the market. Customers are largely limited by these. Therefore, it could be argued that whether extra measures to mitigate overheating are implemented or not, homes still sell.

The housing market is not quick to adopting change. Overheating in homes is a subject that is slowly gaining momentum as the effects of climate change become more apparent and consumers become more aware of what they want for their indoor thermal environments. This is however still not being reflected in the housing market as affordability and location still dominate. For better thermal comfort in homes, the housing market and its stakeholders must embrace new technology, methods, materials, and systems that help mitigate overheating in homes.

4.3.5 End User Education and home induction process.

The Home development process does not end at least until occupants are inducted into their new homes and defects corrected within the warranty period. Therefore, measures required to mitigate overheating must include the occupant cycle of home development. Failing to include home occupants by properly educating them on the use of systems in their homes could lead to overheating. Recent studies (Gupta, & Chandiwala, 2010; Toftum, 2010; Atkins, 2017; Seabra et al.,2021) agree that involving end users in the development process, though rarely seen, can highly assist in improving the performance of indoor environments. Involving home occupants in understanding the design of their houses will help to give them proper control of their indoor environments.

Regarding indoor environments especially, there should be a direct relationship between occupants and the MEP manufacturers who were involved in the build. This will ensure occupants have access to vital information to effectively control the ventilation, cooling and heating systems that are in their homes. Having that direct access to occupants means that they can provide more tailored support to occupants regarding the heating, ventilation, and cooling systems in their home. Through this direct relationship, occupants can gain access to the full potential of the systems installed in their homes. Without this relationship, home occupants are deprived of the opportunity to improve their indoor environments by maximizing the potential of the heating, cooling and ventilation systems and features installed in their homes. As occupant health issues due to extreme thermal conditions cost the economy as well as occupant's lives (BREb, 2015), it is imperative to educate occupants on the health risks of overheating, through effective and engaging home induction practices.

This discussion is summarized in figure 22 which shows the UK Home Development processes and its relationship with overheating in UK homes.

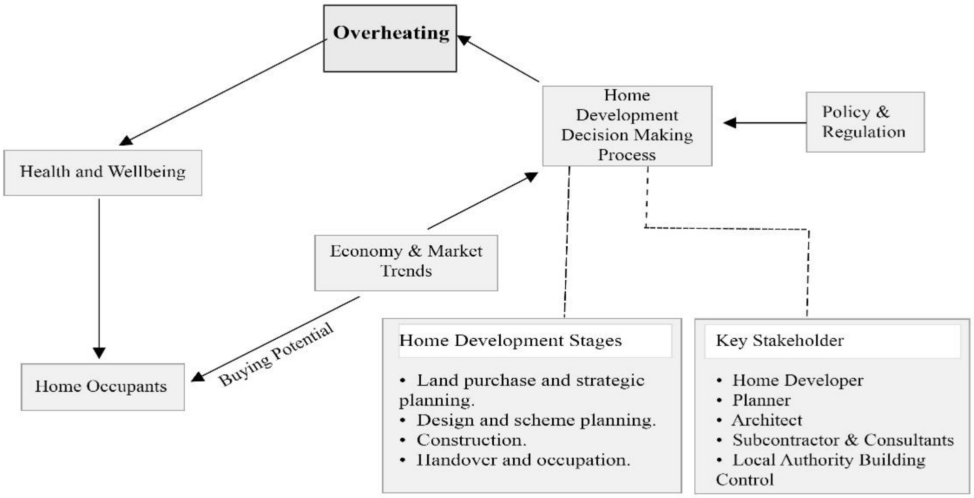


Figure 22:Relationship between the UK Home Development Processes and Overheating in UK Homes

As illustrated in figure 22, the home development decision making process is a constituent of the different developmental stages and the main stakeholders involved in it. This process is in turn affected by external factors such as policy and regulation, economy and market trends. The home decision making process does in turn affect overheating in homes, which in turn affects the health and wellbeing of occupants.

4.4 Contribution to Scalable solutions

The analysis of the home development process and decisions therein that affect overheating in homes is vital to understanding the scalability of overheating mitigation solutions. This analysis has revealed key aspects of the development process that are key for UK home developers to adapt changes that lead to scalable overheating solutions at a mass scale. The following five factors have been identified as key to developing scalable mass market solutions for overheating mitigation in UK homes: Cost implications, point in the development process when a decision needs to be made and who needs to be involved, the resilience to supply chain dynamics, and occupant perception.

Home developers operate in competitive business environments in a market whose dynamics are ever-changing. Therefore, cost becomes an important factor in assessing the scalability of changes. Studies (Gupta et al., 2021; Porritt et al., 2012) show that implementing overheating mitigation solutions has cost implications. As such evaluating the cost implications of different overheating solutions is key to determining whether they can be easily adopted by home developers on a mass scale. Additions of changes worth hundreds of pounds per home, could amount to millions per year for volume builders who build around 20,000 homes a year.

The analysis of the home development process has also revealed that the developmental stage when a decision is made is important to its effectiveness. Decisions regarding overheating mitigation solutions that affect the fabric and design of homes, can only be made at the planning and design stage. Making these decisions at this stage means that more effective and less expensive solutions such as orientation analysis, can be made. Further along the development process, the only overheating solutions that can be implemented are cosmetic solutions such as mechanical cooling. These are normally less effective and more expensive. Analyzing the points when decisions regarding overheating mitigation solutions are made is key to making them scalable.

Additionally, the point of introduction of critical MEP supply chain companies and consultants into the development process is an important factor to overheating in homes. The interviews have shown that MEP subcontractors are mostly engaged once designs have been done and planning permissions granted. This limits their capabilities to influence design as there is limited scope to influence design. For scalable solutions to overheating, to be a reality, specialist MEP subcontractors as well as energy, overheating, acoustic and sustainability consultants need to be engaged in early design changes.

Another key contribution of this developmental analysis to scalable solutions is the resilience to supply chain dynamics. These solutions might require certain materials, fabric elements and skills that might not be easily available if mass implementation is to be considered. Solutions that rely on international supply chains could be susceptible to changing market dynamics and thus affect delivery timelines. Additionally, these solutions might require training for industry to adapt to new methods and strategies that they may not be used to. As such, resilience to supply chain dynamics is key to developing scalable solutions.

Finally, this developmental analysis has revealed that occupant perception, engagement and education is important for any overheating mitigation solution to work. For overheating mitigation solutions to be scalable, home occupants must be convinced that these changes do not adversely affect the architectural appeal of their homes, reduce the floor space of their homes, increase their energy bills, or be difficult to operate. Since these factors inform their priorities when purchasing homes, home developers will be keen on this to not influence their share of the market.

These factors form the backbone of a criteria that this research proposes is key to developing scalable overheating mitigation solutions.

4.5 Chapter Summary

At present, UK home development processes are not perfectly suited to deliver against manifold building non-performance attributes such as potential overheating. A methodological look across the home development process in the UK has revealed gaps in the decision-making process, that should be improved to mitigate overheating in homes. The inclusion or not of environmental concerns in planning, the handling of ventilation design, the possibilities of making needed changes after obtaining planning requirements and decisions around material selection, have been argued as key factors in indoor thermal performance of homes. This is further influenced by the point of introduction of critical MEP supply chain companies and consultants as well as logistical issues around construction materials and skilled labour. The competitive nature of the housing market alongside harsh realities such as housing shortage means that home development is mostly cost driven, a key factor in indoor thermal performance in homes. As such government policy and regulation is mostly relied upon as a driver that provides a common ground across the market.

Overheating in homes is rising in the agenda more recently as home development stakeholders including councils and planning authorities are taking an interest. Home developers and Housing associations are beginning to include overheating mitigation more into their proposed requirements. Governance models and institutionalization of indoor environmental quality standards are still actively developing ahead of the flagship Future Home Standard (FHS) regulation (2025) and Net Zero 2050. This should have a trickle effect in home development decision making processes, for better outcomes on mitigating overheating.

Most importantly, the exploration of decision making in UK home development and overheating provides great insight into developing scalable solutions to overheating in homes. This exploration has revealed five keys aspects that are key for home developers to adapt changes that lead to scalable overheating solutions at a mass scale. These factors include cost implications, point in the development process when a decision needs to be made and who needs to be involved, the resilience to supply chain dynamics, and occupant perception. This research proposes these five factors developing a scalability criterion for overheating mitigation solutions in UK homes.

Chapter 5: Overheating Analysis using Real time data.

An analysis of overheating design methods is key to ensuring accuracy and reliability. The introduction of the Approved Document Part O for Overheating (2021) signifies a step in the right direction for overheating mitigation in UK homes. It presents a legal requirement for all new dwellings in England to ensure that overheating considerations are made right at the onset. This regulation indicates methods of determining the potential for overheating with a focus on glazing areas, orientation, and ventilation. Solutions are not prescribed but are open to being met in various ways if the assessment method shows achievement of the standard. The regulation stipulates two assessment methods that are majorly influenced by openable and glazing areas of windows, predominant orientations, and ventilation strategies. Addressing scalability of mitigation solutions requires an analysis of overheating mitigation design methods described in the new regulation. These design methods usually involve synthetic profiles of occupancy and standard weather files that may not accurately reflect real time indoor conditions. There is a need to conduct a check on overheating assessment design methods using real time data from occupied homes. As part of this, user experience of overheating and adaptation measures is required.

This chapter presents monitored temperature data obtained from air quality sensors deployed in UK homes, as well as the analysis of that data. It also presents data on user comfort in relation to the experience of overheating and adaptation measures. It is divided into the following sections: summary of data sources, monitoring results and analysis strategy, monitored temperature trends, overheating analysis of sensor monitored homes, implications of overheating analysis and chapter summary.

5.1 Summary of Data Sources

Indoor temperature data was collected via two types of air quality sensors (discussed in section 3.3.2) that were deployed in 5 homes across the UK during the non-heating period of 2022 (May to September). The details of the 5 homes have been summarized in table 16. Indoor temperature data from these 5 homes is presented and assessed for overheating. Alongside sensor monitoring data, thermal comfort questionnaires were deployed to the occupants of the monitored homes. This was done once a month for each home from May to September. Data from these questionnaires is used to complement data from sensors. External temperature was also obtained from selected weather station databases from the UK Met Office - Daily Weather Summary database (2022).

Table 16: Details of 5 Sensor Monitored Homes in England

House No.	**1**	**2**	**3**	**4**	**5**
Location and house type	Cheshire - Three Bedroom Detached House (Two story) (2013 Building Regs)	Suffolk - Four Bedroom Detached house (Two story) (2013 Building Regs)	Loughborough - Four-bedroom detached house (Two story) (2013 Building Regs)	Birmingham - Two-bedroom flat (17th floor) (2013 Building Regulations)	Birmingham - 3 Bedroom Semi Detached House (Future Home Std Demo)
Household Characteristics	Single family of up to two people (no vulnerable occupants)	Multiple family of up to five people (no vulnerable occupants)	Multi-family of up to five people (no vulnerable occupants)	Single family of up to two people (no vulnerable occupants)	Single family of up to five people (no vulnerable occupants)
Type of Ventilation	Naturally ventilated with extract fans in kitchen and bathroom	Naturally ventilated with extract fans in kitchen and bathroom	Naturally ventilated with extract fans in kitchen and bathroom	Naturally ventilated with extract fans in kitchen and bathroom	Naturally ventilated with extract fans in kitchen and bathroom
Monitoring Duration	May 2022 – September 2022	May 2022 – September 2022	May 2022 – September 2022	May 2022 – September 2022	May 2022 – September 2022
Orientation of front main windows	East E	Northeast NE	Southeast SE	Southwest SW	Southwest SW
Sensor Details	One Uhoo Aura in the kitchen/Dining area, one Omron sensor in Bedroom	One Uhoo Aura in the kitchen/Dining area and one Omron sensor in Bedroom 1	One Uhoo Aura in the study room, one Omron sensor in the Livingroom, one Omron sensor in Bedroom 1	One Uhoo Aura in the Livingroom/Dining/ Kitchen area, one Omron sensor in Bedroom 1	One Uhoo Aura in the Kitchen area, one Omron sensor in Livingroom and one Omron sensor in the Top floor Bedroom
Sensor Nomenclature	CUK/D and COB	SUK/D and SOB	LUS, LOL and LOB	B4UL/D/K and B4OB	B2UK, B2OL and B2OB

5.2 Monitoring Results and Analysis Strategy

The results for the sensor monitoring campaign are presented in the following steps:

In the first instance, the general temperature trends for all the houses are presented in a graph alongside the results from the thermal comfort questionnaires from occupants of monitored homes. This is followed by an in-depth look at temperature trends for each house factoring in their locations and house types and an analysis of a table that includes measures of central tendency for each house and sensor.

Most importantly, more in-depth overheating analysis is done using two overheating assessment methods highlighted in section 3.4. This is the TM59 overheating criteria (2.8.2) and the simplified method (2.8.1). A determination of whether monitored homes have failed the overheating assessment is made. This is followed by a discussion of the implications of the assessments.

5.3 Monitored Temperature Trends

Figure 23 visualizes outdoor temperature trends for monitored locations as obtained from the UK Met Office - Daily Weather Summary database (2022). As can be seen in figure 23, there were three notable peak periods (circled in blue), when outdoor temperatures neared or exceeded 30^{0}C across monitored locations. These peak periods coincide with heatwave periods experienced in the UK in the summer of 2022. A publication by the ONS and UKHSA (2022), confirms these heatwave periods (circled in blue) as the 16th - 19th of June 10th - 25th of July, and 8th - 17th of August respectively.

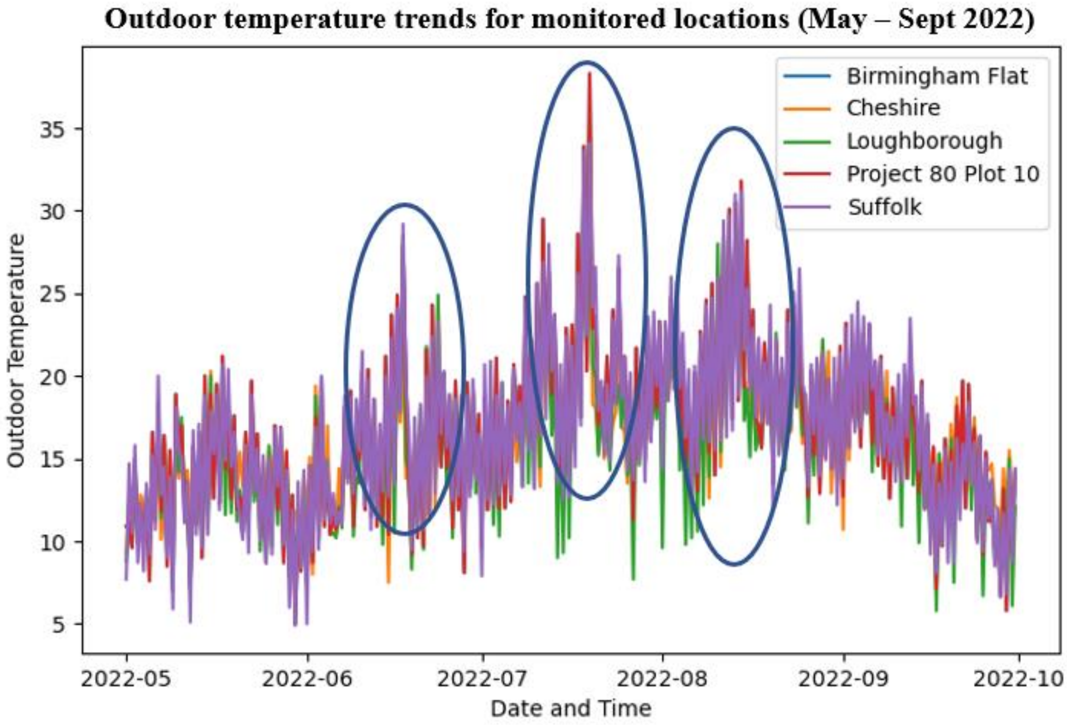


Figure 23: Outdoor Temperature trends for Monitored Locations (May - Sept 2022)

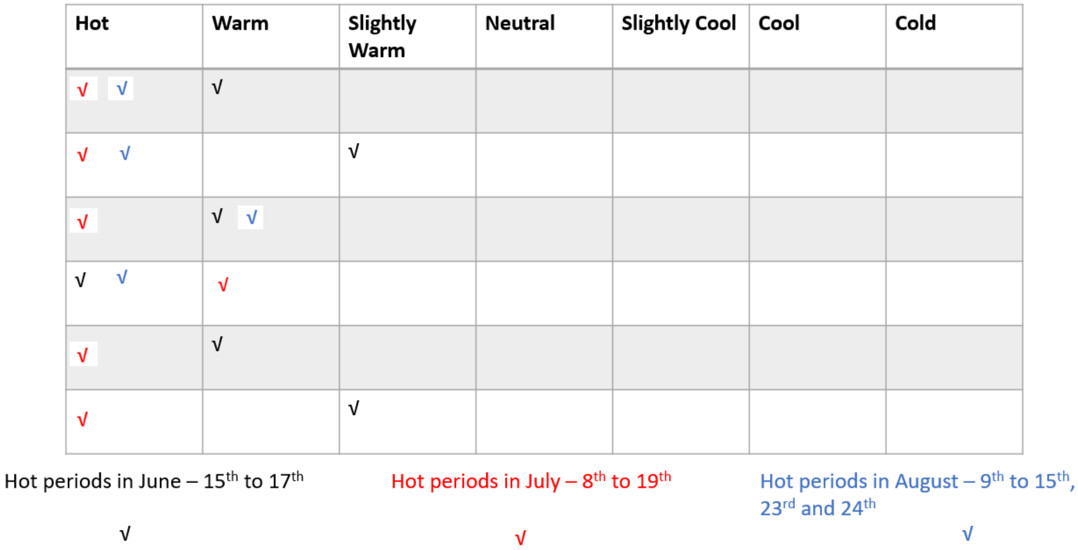
During the June peak periods, peak outdoor temperatures were the following: 24.2^{0}C in Cheshire, 28.5^{0}C in Loughborough, 27.9^{0}C in Birmingham and 29.2^{0}C in Suffolk. The July peak periods had the highest temperature recordings of 35.4^{0}C in Cheshire, 35^{0}C in Loughborough, 38.3^{0}C in Birmingham and 34.1^{0}C in Suffolk. In the month of August high temperatures of 27^{0}C, 29.5^{0}C, 31.8^{0}C and 31.3^{0}C were recorded respectively. July seems to have been the hottest month recording peak temperatures of above 34^{0}C across all monitored locations, with the highest temperature recording of 38.3^{0}C in Birmingham on the 19th of July 2022.

Thermal Comfort Questionnaire Results

As part of the monitoring exercise, home occupants of monitored homes were provided with thermal comfort questionnaires (as shown in Appendix 4) on each month of the monitoring period. Questions revolved around general demographic information, normal behavioral routines (activity and clothing), thermal sensation - Likert scale, behavioral adaptations (and their success) and recommendations.

Table 17 presents the results of the thermal perceptions of occupants during the monitoring period from June to July when there were significant heatwaves. This table is based on a Likert scale of 7 options from hot to cold.

Table 17: Thermal Perception of Occupants during Monitoring Period



Hot	Warm	Slightly Warm	Neutral	Slightly Cool	Cool	Cold
√ √	√					
√ √		√				
√	√ √					
√ √	√					
√	√					
√		√				

Hot periods in June – 15th to 17th
√

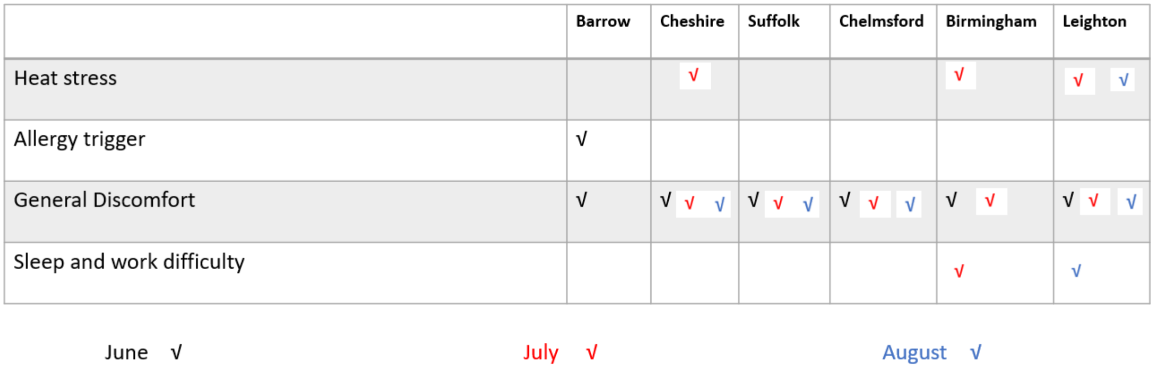
Hot periods in July – 8th to 19th
√

Hot periods in August – 9th to 15th, 23rd and 24th
√

As can be seen in table 17, the thermal perception in June was averagely warm and mostly hot in July and August. This coincides with the three heatwave periods with higher and prolonged temperatures recorded during the July heatwave period, followed by August, then June. During the July heatwave period, one occupant described their thermal perception as *"you are feeling like* *in a sauna”.* Another occupant described it as *“It was too hot to bear the heat”.* This shows the effect of significant heatwave periods on the indoor thermal perceptions of home occupants.

Table 18 summarizes the outcomes of the thermal perceptions experienced by occupants during the monitoring periods.

Table 18: Effects of Thermal Conditions by Occupants



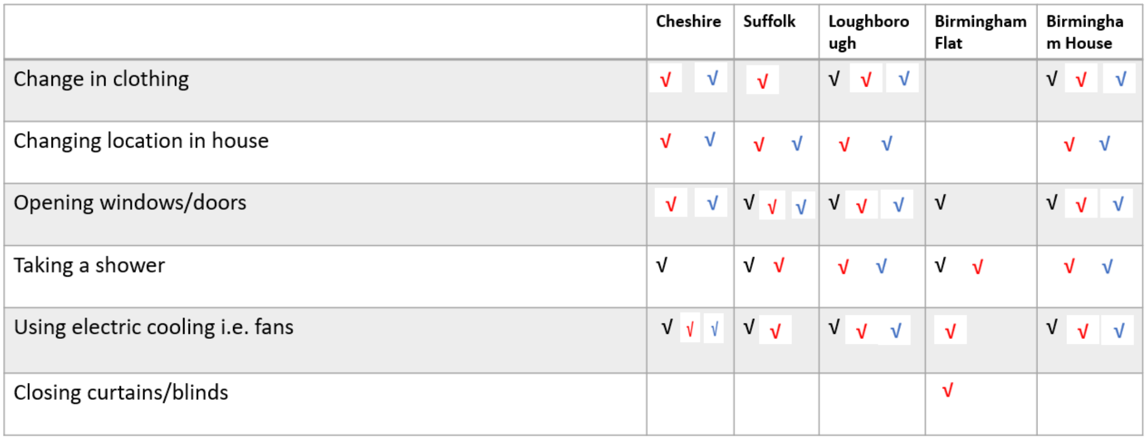
	Barrow	Cheshire	Suffolk	Chelmsford	Birmingham	Leighton
Heat stress		√			√	√ √
Allergy trigger	√					
General Discomfort	√	√ √ √	√ √ √	√ √ √	√ √	√ √ √
Sleep and work difficulty					√	√

June √ July √ August √

As can be seen in table 18, the occupants mostly recorded general discomfort conditions in the June heatwave period. However, in the July and August heatwave periods that were more intense and prolonged, occupants recorded heat stress effects and sleep and work difficulty, on top of general discomfort conditions. This shows how extreme heat conditions affects occupants. There were no vulnerable occupants (sick and the elderly) in the five homes monitored. However, obtaining such results from mostly healthy home occupants is still significant.

Table 19 shows how the occupants of the five monitored homes responded to the perceived thermal conditions during the three months of monitoring with significant heatwave periods.

Table 19: Response to Thermal Conditions



	Cheshire	Suffolk	Loughborough	Birmingham Flat	Birmingham House
Change in clothing	√ √	√	√ √ √		√ √ √
Changing location in house	√ √	√ √	√ √		√ √
Opening windows/doors	√ √	√ √ √	√ √ √	√	√ √ √
Taking a shower	√	√ √	√ √	√ √	√ √
Using electric cooling i.e. fans	√ √ √	√ √	√ √ √	√	√ √ √
Closing curtains/blinds				√	

June √ July √ August √

As can be seen in table 19, the responses during the June heatwave periods mostly involved opening windows and doors, taking showers and the use of electric cooling fans. The Cheshire home occupant mentioned in their response that *"opening the patio doors kept the downstairs cool. Had to keep windows open through the night in the bedroom"*. However, as more extreme, and prolonged heatwaves came in June and July, other additional responses included change in clothing, changing locations at home, and closing curtains and blinds. During the July heatwave period, Birmingham flat occupant mentioned that she *"spent a lot of time on the balcony, wanted some air and couldn't stay inside because it was too hot"*. However, the occupants mentioned that their responses were limited and ineffective most of the time. The Suffolk home occupant mentioned that *"it helped but didn't always improve to a normal temperature"*. The Loughborough home occupant mentioned that *"wearing shorts and opening windows did cool interior slightly, so partially but at 40^{0}C there is only so much you can do without air con"*. Finally, the Birmingham home occupant mentioned that their response was *"mainly effective, but difficult to sleep at night. Bedroom gets a lot of sun in the evening and takes a long time to cool down overnight"*. The limitations of their responses offers insight into the inadaptability of current home designs to extreme heat conditions and justifies the need for scalable solutions to overheating in homes. In fact, four of the five home occupants involved in these questionnaires recommended the need for external shading options, low e glazing windows, blinds, and internal fans.

Outdoor temperatures were reflected in monitored indoor temperatures. The next section presents an in-depth look at temperature trends for each monitored home.

5.3.1 Cheshire Home

Figure 24 shows monitored temperature trends for the Cheshire home. The three-line graph represents the indoor temperature sensor in the Kitchen/Dining area (CUK-D) and the bedroom (COB), together with the outdoor temperature (Outdoor) form the UK Met Office - Daily Weather Summary database (2022).

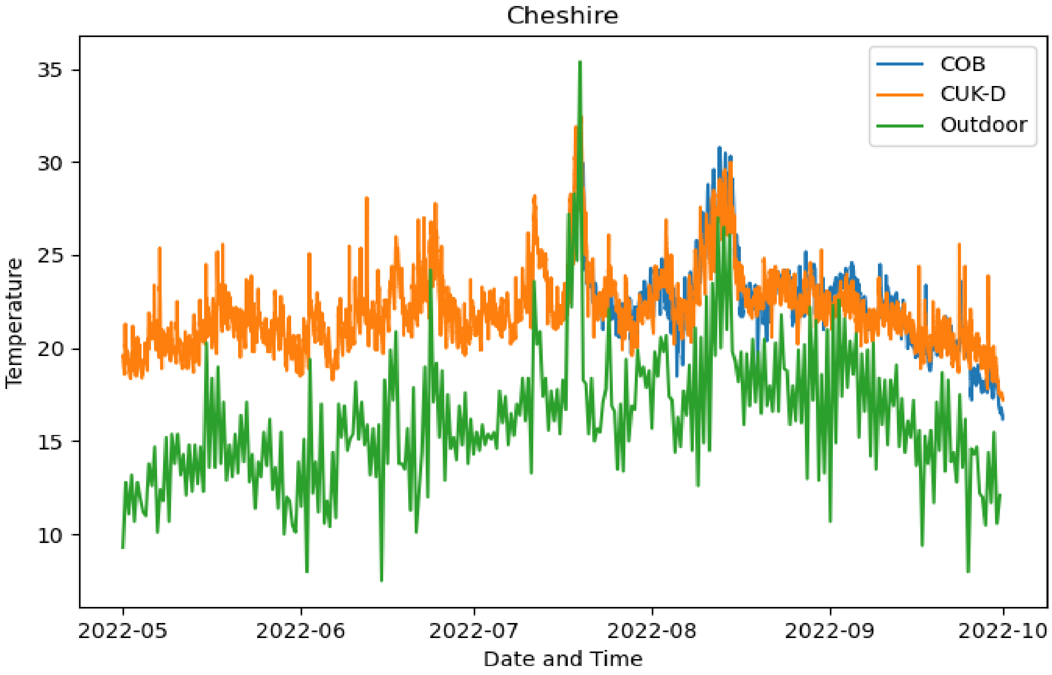


Figure 24: Cheshire Monitored Temperature Trends

The Cheshire home recorded maximum temperatures of 32.5^{0}C in the Kitchen/Dining area and 30.8^{0}C in the Bedroom. This difference in temperature can be largely explained by possibly higher internal loads in the kitchen. The indoor temperature sensor in the Kitchen/Dining area (CUK/D) had a mean of 22.01^{0}C for the whole period, the lowest amongst all monitored kitchen/dining areas. It also recorded a maximum temperature of 32 .5^{0}C on the 19th of July 2022. The lowest mean temperature amongst kitchen/dining areas in other monitored homes could be due to its northerly location as compared to other monitored homes and therefore lesser in temperature. The indoor temperature sensor in the Bedroom area (COB) had a mean of 22.43^{0}C, the lowest amongst all monitored bedrooms, and a recorded maximum temperature of 30 .8^{0}C on the 19th of July 2022.

The lowest mean temperature amongst bedrooms in other monitored homes could be due to its northerly location as compared to other monitored homes and therefore less in temperature.

Frequency histograms shown in figure 25 were produced in the Panda statistical software. The frequency histograms represent temperature readings with higher frequencies by the height of vertical bars. The temperature frequency histograms in figure 24 show that most of the temperature readings for CUK/D sensor were recorded between 18 and 24^{0}C, while that for COB sensor were between 20 and 24^{0}C.

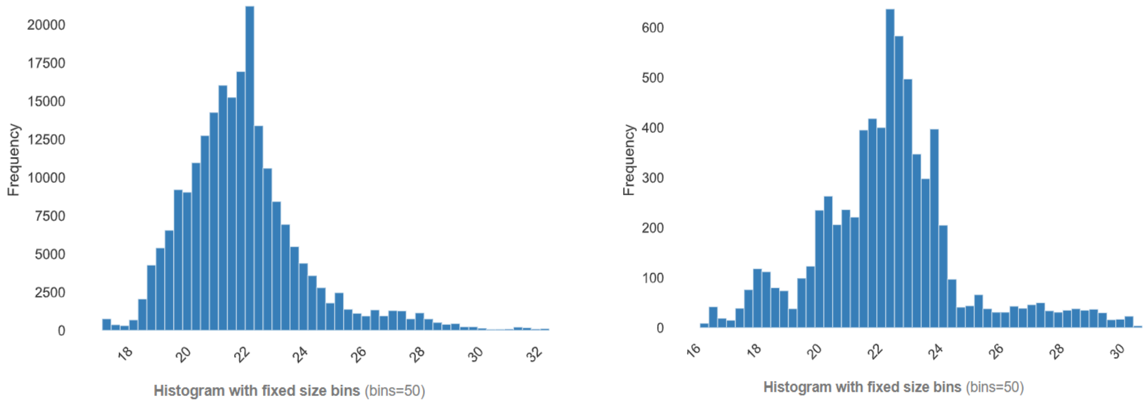


Figure 25: Temperature Frequency Histogram (CUK/D left) (COB right)

For CUK/D, these were still significantly higher temperatures recorded with the top 10 maximum temperature recordings of more than 31^{0}C being recorded 388 times. Most of these occurred during the hotter periods of the monitored summer duration. The maximum 10 temperature values recorded for the COB sensor, had the following frequencies 30.8^{0}C once, 30.7^{0}C once, 30.6^{0}C twice, 30.5^{0}C thrice, 30.4^{0}C four times, 30.3^{0}C 16 times, 30.2^{0}C 8 times, 30.1^{0}C 4 times, 30^{0}C 5 times and 29.9^{0}C 6 times. Based on this, the bedroom temperatures in the Cheshire home are the lowest amongst all monitored homes.

5.3.2 Suffolk Home

Figure 26 shows monitored temperature trends for the Suffolk home. The three-line graph represents the indoor temperature sensor in the Kitchen/Dining area (SUK-D) and the bedroom (SOB), together with the outdoor temperature (Outdoor) from the UK Met Office - Daily Weather Summary database (2022).

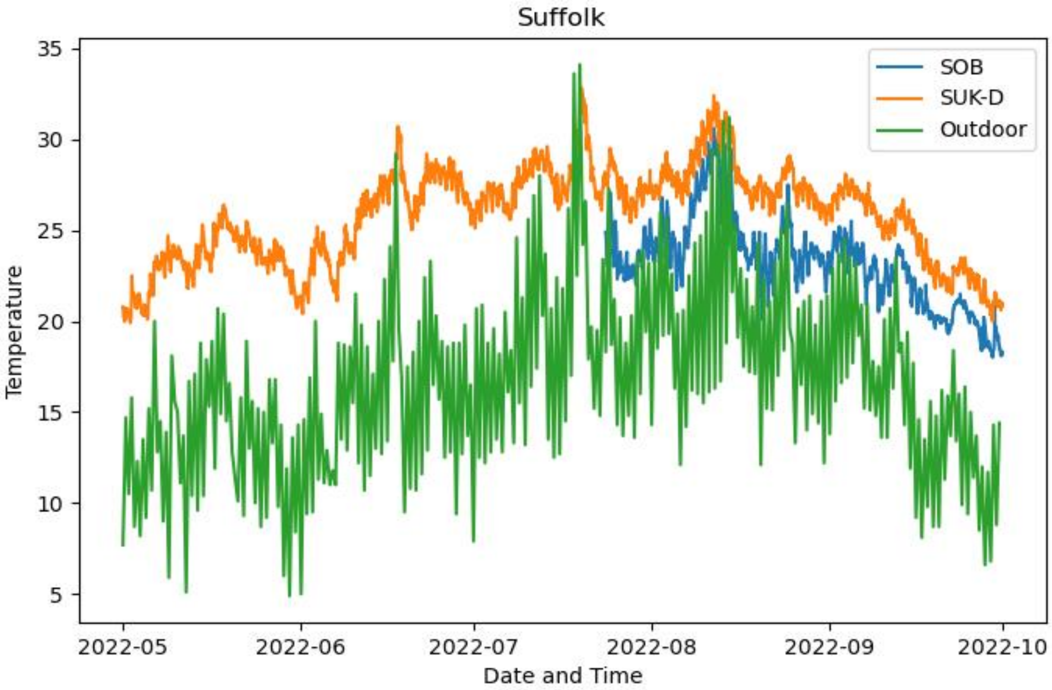


Figure 26: Suffolk Monitored Temperature Trends

The Suffolk home recorded maximum temperatures of 32.8^{0}C and 30.6^{0}C in the kitchen/Dining area and bedroom respectively. The indoor temperature sensor in the Kitchen/Dining area (SUK/D) had a mean of 25.83^{0}C, the highest amongst all monitored homes, and a recorded maximum temperature of 32.8^{0}C on the 19th of July 2022. The indoor temperature sensor in the Bedroom area (SOB) of the monitored Suffolk home had a mean of 23.3^{0}C, and a recorded maximum temperature of 30.6^{0}C on the 19th of July 2022.

As figure 27 shows, most of the temperature readings for SUK/D exceeded 26^{0}C with a substantial number of them above 30^{0}C, while that of SOB averaged around 22 to 25^{0}C.

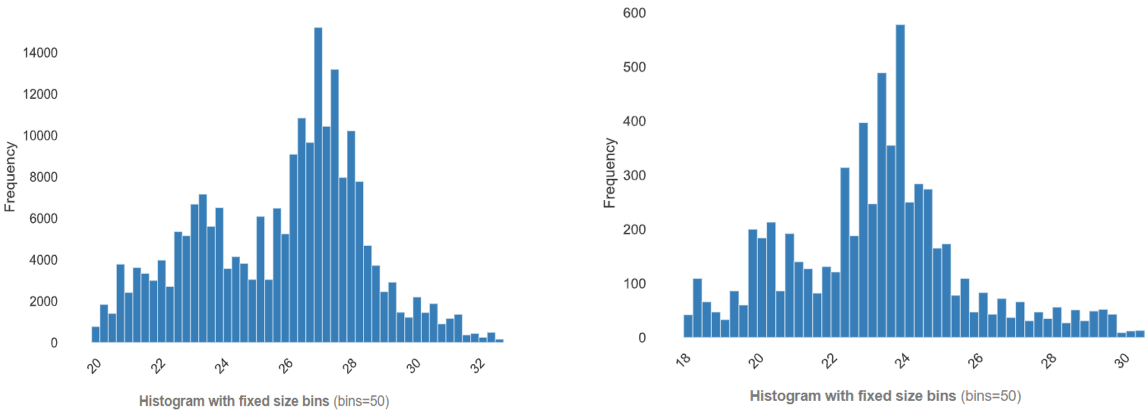


Figure 27: Temperature Frequency Histogram SUK/D (Left) and SOB (Right)

The most recorded temperature value for SUK/D was 27^{0}C with a frequency of 5479 times. The top 10 recorded maximum values were all above 31.9^{0}C with a total frequency of 1220 times. These readings suggest that well above average temperatures were recorded in the kitchen/dining area of the Suffolk home during the summer of 2022. The top 6 maximum values recorded by SOB were all above 30^{0}C with the following frequencies: 30.6^{0}C 6 times, 30.5^{0}C 4 times, 30.4^{0}C 3 times, 30.3^{0}C 6 times, 30.2^{0}C 2 times and 30.1^{0}C 4 times.

5.3.3 Loughborough Home

Figure 28 shows monitored temperature trends for the Loughborough home. The four-line graph represents the indoor temperature sensor in the bedroom area (LOB), living area (LOL), study area (LUS), together with the outdoor temperature (Outdoor) form the UK Met Office - Daily Weather Summary database (2022).

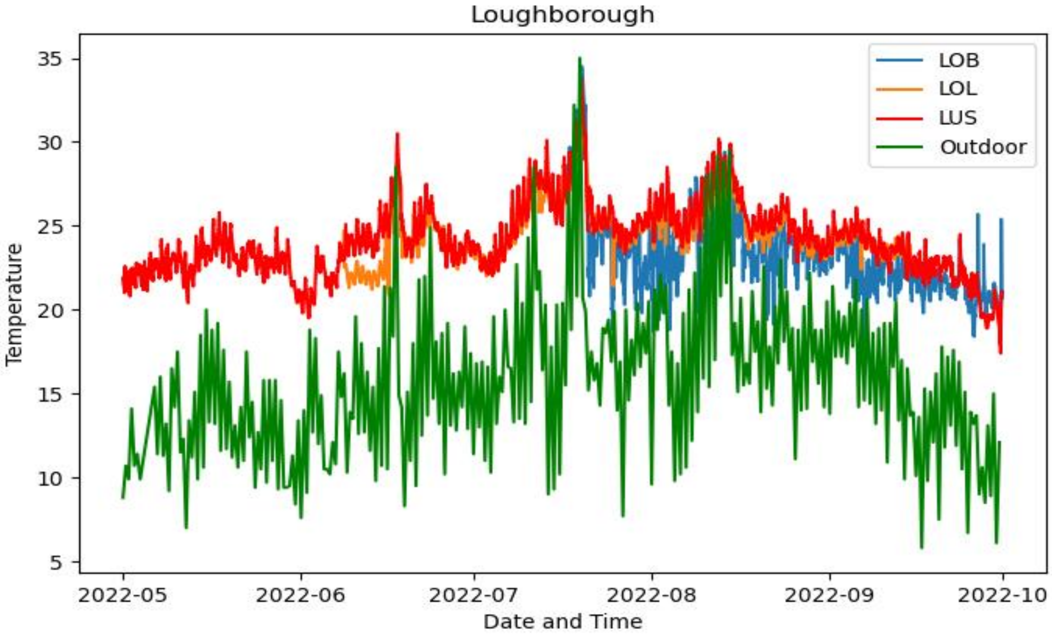


Figure 28: Loughborough Monitored Temperature Trends

The Loughborough home recorded maximum temperatures of 33.8^{0}C, 31.6^{0}C and 34.5^{0}C in the study room, living room and bedroom respectively. The indoor temperature sensor in the Playroom area (LUS) had a mean of 24.2^{0}C and a recorded maximum temperature of 33.8^{0}C on the 19th of July 2022. The indoor temperature sensor in the Livingroom area (LOL) had a mean of 24.73^{0}C and a recorded maximum temperature of 31.6^{0}C on the 19th of July 2022. The indoor temperature sensor in the Bedroom area (LOB) had a mean of 23.45^{0}C and a recorded maximum temperature of 34.5^{0}C on the 19th of July 2022 around 4pm. This is the highest maximum temperature recorded among all monitored homes.

As the Temperature frequency histogram in figure 29 shows, most of the temperature readings for LUS were between 22.5^{0}C and 27.5^{0}C, between 23^{0}C and 26^{0}C for LOL and between 20 to 25^{0}C for LOB. It is worth noting that sensor LOL recorded the highest minimum temperature value of all recorded homes at 20.8^{0}C

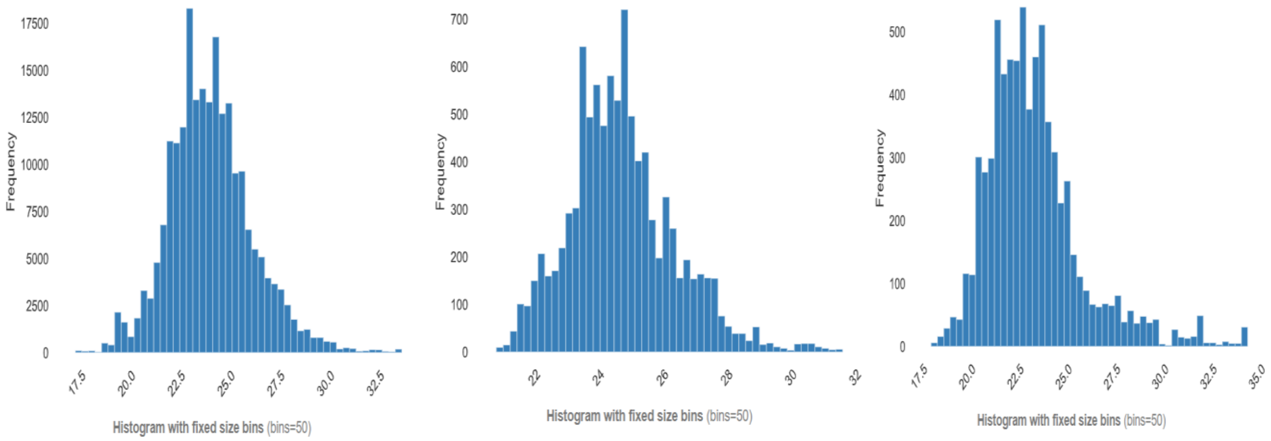


Figure 29: Temperature Frequency Histogram for LUS (left), LOL (middle) and LOB (right)

The top 10 recorded maximum temperature values for LUS were all above 32.9^0C with a total frequency of 325 times. These readings suggest that well above average temperatures were recorded in the study area of the Loughborough home during the summer of 2022. The 10 maximum recorded temperature values for LOL were all above 30^0C and with the following frequencies: 31.6^0C twice, 31.5^0C thrice, 31.4^0C once, 31.3^0C thrice, 31.2^0C twice, 31.1^0C 4 times, 31^0C 4 times, 30.9^0C 5 times, 30.8^0C 6 times and 30.7^0C 8 times. The 5 maximum recorded temperature values for LOB were all above 34^0C with the following frequencies: 34.5^0C 19 times, 34.4^0C 4 times, 34.3^0C 5 times, 34.2^0C thrice and 34.1^0C twice. These represent the highest temperature recordings in all monitored bedrooms and overall monitored rooms. Most of these recordings were made on the hottest day of the year, 19th of July 2022. These high temperatures could also be due to several factors namely, local temperature, occupant behaviour such as opening and closing of windows among others.

5.3.4 Birmingham Flat

Figure 30 shows monitored temperature trends for the Birmingham Flat. The three-line graph represents the indoor temperature sensor in the bedroom area (B4OB), living/dining/kitchen area (B4UL-D-K), together with the outdoor temperature (Outdoor) form the UK Met Office - Daily Weather Summary database (2022).

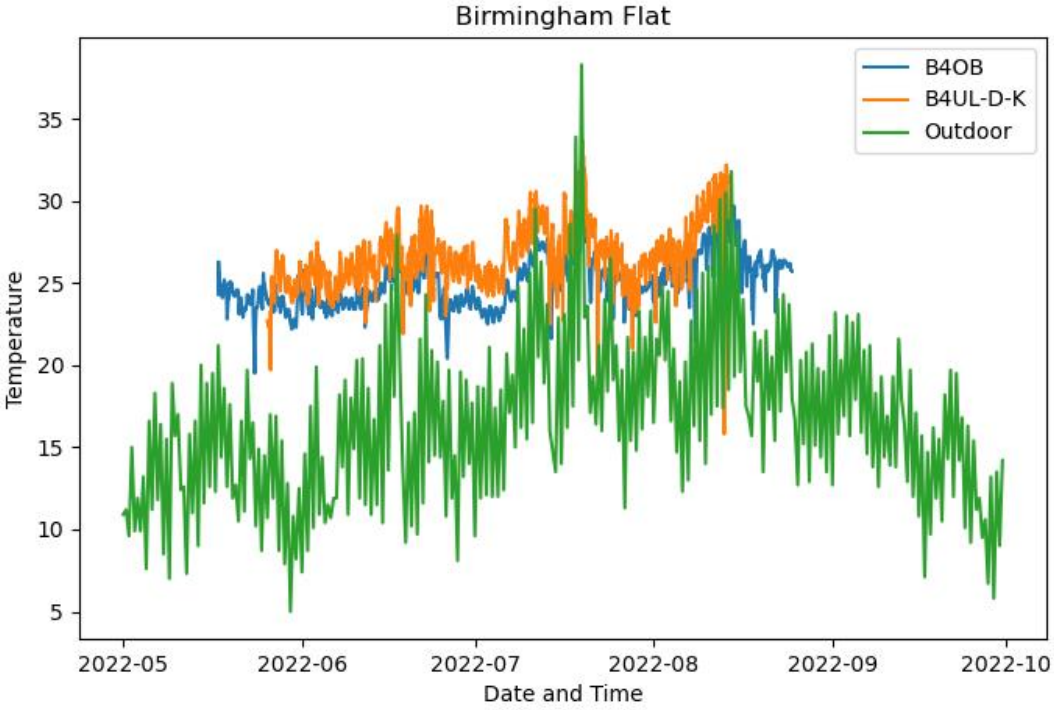


Figure 30: Birmingham Flat Monitored Temperature Trends

The Birmingham Flat recorded maximum temperatures of 33.7^{0}C and 30.5^{0}C in the kitchen/Dining area and bedroom respectively. The indoor temperature sensor in the Kitchen/Dining/Living area (B4UL/D/K) had a mean of 26.7^{0}C and a recorded maximum temperature of 33.7^{0}C on the 19th of July 2022. The indoor temperature sensor in the Bedroom area (B4OB) had a mean of 25.01^{0}C, the highest average temperature of all bedrooms monitored. It also recorded a maximum temperature of 30.5^{0}C on the 19th of July 2022.

As figure 31 shows, most of the temperature readings for B4UL/D/K exceeded 25^{0}C with a substantial number of them above 30^{0}C, while most of the temperature readings for B4OB averaged around 25^{0}C with a few of them above 30^{0}C.

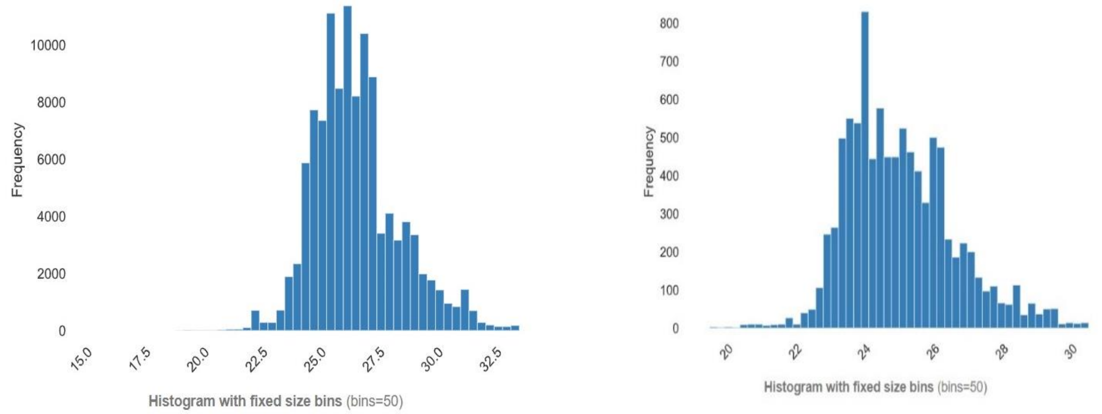


Figure 31: Temperature Frequency Histogram for B4UL/D/K (Left) and B4OB (Right)

The recorded maximum 10 values for B4UL/D/K were all above 30^0C and with high frequencies. These include 33.7^0C 44 times, 33.6^0C 36 times, 33.5^0C 40 times, 33.4^0C 60 times, 33.3^0C 37 times, 33.2^0C 34 times, 33.1^0C 31 times, 33^0C 39 times, 32.9^0C 58 times and 32.8^0C 66 times. All this considering a minute-by-minute interval. This suggests that considerably high indoor temperatures were monitored in the kitchen, dining, and living area of the Birmingham flat monitored. The maximum 5 values recorded by the B4OB sensor were above 30^0C with the following frequencies: 30.5^0C 2 times, 30.4^0C 7 times, 30.3^0C 5 times, 30.2^0C 4 times and 30.1^0C 8 times. This is based on 15-minute interval readings. Still, this suggests a more than average temperature recording for the bedroom area of the monitored Birmingham flat.

5.3.5 Birmingham Home

Figure 32 shows monitored temperature trends for the Birmingham Flat. The four-line graph represents the indoor temperature sensor in the bedroom area (B2OB), the living area (B2OL), the kitchen area (B2UK), together with the outdoor temperature (Outdoor) form the UK Met Office - Daily Weather Summary database (2022).

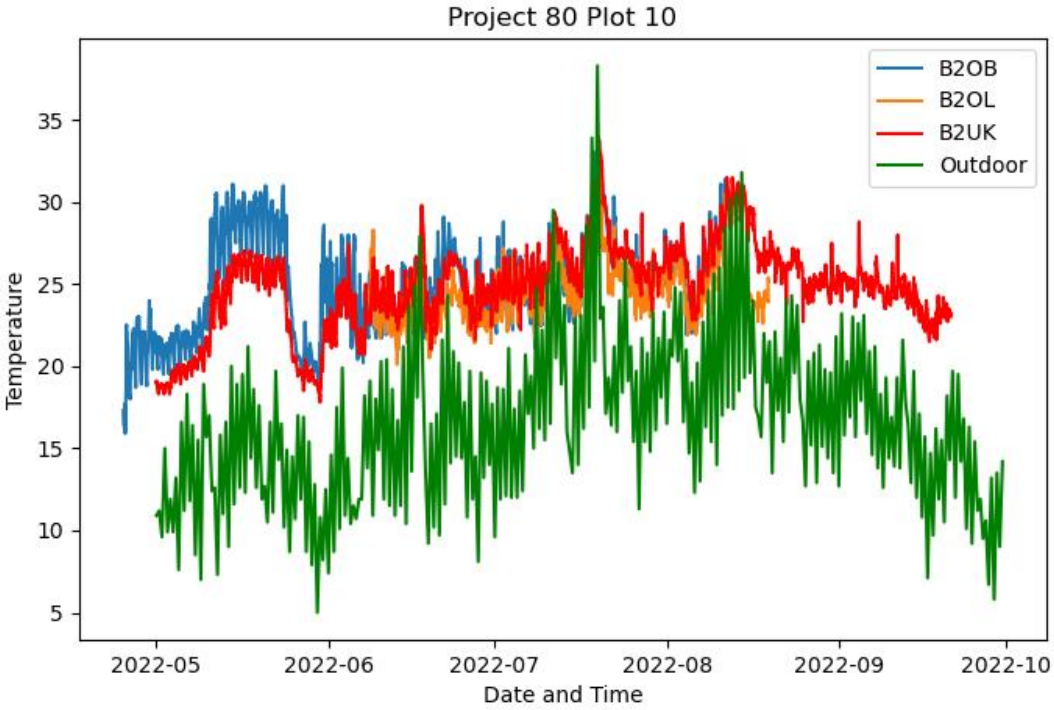


Figure 32: Birmingham Home Monitored Temperature Trends

The Birmingham home recorded maximum temperatures of 33.8^{0}C, 32.1^{0}C and 34.0^{0}C in the kitchen, living room and bedroom respectively. The indoor temperature sensor in the Kitchen area (B2UK) had a mean of 24.86^{0}C. It also recorded a maximum temperature of 33.8^{0}C on the 19th of July 2022. The indoor temperature sensor in the Livingroom area (B2OL) had a mean of 24.61^{0}C and a recorded maximum temperature of 32.1^{0}C on the 19th of July 2022. The indoor temperature sensor in the Bedroom area (B2OB) had a mean of 24.76^{0}C and a recorded maximum temperature of 34^{0}C on the 19th of July 2022. This is the second highest maximum temperature recording in all monitored homes.

As the temperature frequency polygon in figure 33 shows, most of the temperature readings for B2UK averaged around 23 and 28^{0}C with a few of them above 30^{0}C. For B2OL, most of the temperature readings were between 22^{0}C and 26^{0}C while for B2OB, most of the temperature readings were between 22^{0}C and 27^{0}C but with a significant portion above 27^{0}C.

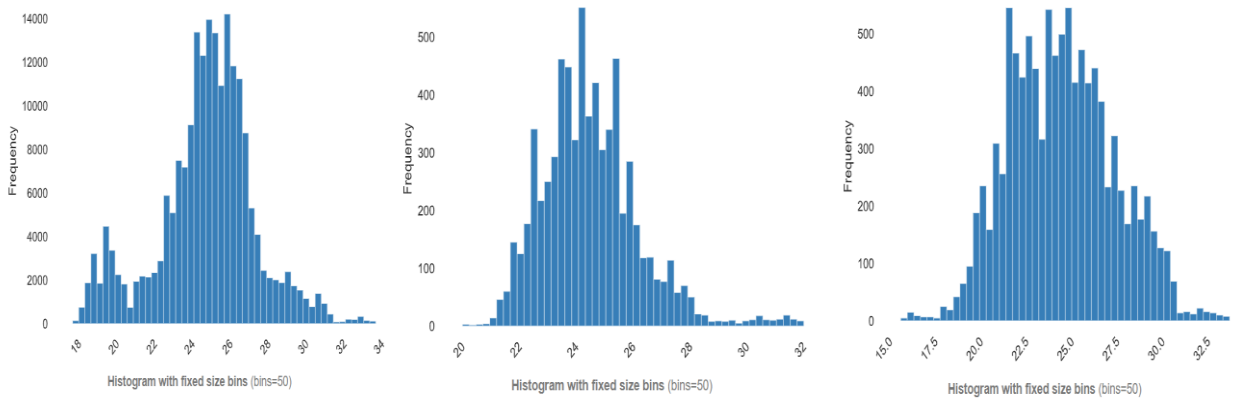


Figure 33: Temperature Frequency Histogram for B2UK (left), B2OL (middle) and B2OB (right)

The maximum 10 temperature recorded values for B2UK were above 32.9^0C with the following frequencies: 33.8^0C 41 times, 33.7^0C 31 times, 33.6^0C 26 times, 33.5^0C 20 times, 33.4^0C 38 times, 33.3^0C 65 times, 33.2^0C 45 times, 33.1^0C 61 times, 33^0C 178 times and 32.9^0C 93 times. This is based on 15-minute interval readings. This suggests a more than average temperature recording for the kitchen area of the monitored Birmingham home. The 10 maximum temperature recordings for B2OL were all above 31.2^0C with a frequency of 52 times. For B2OB, 26.1^0C was the most common temperature recording with a frequency of 196 times. Also, the 10 maximum recorded temperature values were above 33.1^0C with a frequency of 24 times.

Table 20 provides a summary of the descriptive statistics of indoor temperatures across all monitored homes. It includes measures of central tendency such as mean, median, maximum, and minimum temperatures of the monitored homes.

Table 20: Descriptive statistics of monitored homes.

	Location	House Type	Room Monitored	Sensor Nomenclature	Duration Monitored	Mean	Median	Max.	Min.
1.	Cheshire	Three Bedroom Detached House (Two story) (2013 Building regulations)	Kitchen/Dining	CUK/D	1st May to 30th September	22.01	21.8	32.5	17.5
			Bedroom	COB	20th July to 30th September	22.43	16.8	30.8	16.5
2.	Suffolk	Four Bedroom Detached house (Two story) (2013 Building Regulations)	Kitchen/Dining	SUK/D	1st May to 30th September	25.83	26.4	32.8	19.9
			Bedroom	SOB	24th July to 30th September	23.3	18.7	30.6	18
3.	Loughborough	Four-bedroom detached house (Two story) (2013 Building Regulations)	Study Room	LUS	1st May to 30th September	24.2	24.1	33.8	17.4
			Livingroom	LOL	8th June to 15th September	24.73	23.0	31.6	20.8
			Bedroom	LOB	17th July to 30th September	23.45	19.8	34.5	18.1
4.	Birmingham	Two-bedroom flat (17th floor) (2013 Building Regulations)	Livingroom/Dining /Kitchen	B4UL/D/K	26th May to 13th August	26.77	26.5	33.7	15.8
			Bedroom	B4OB	17th May to 24th August	25.01	26.1	30.5	19.5
5.	Birmingham	3 Bedroom End of Terrace House (Future Home Standard Demo)	Kitchen	B2UK	1st May to 21st September	24.86	25.1	33.8	17.8
			Livingroom	B2OL	8th June to 19th August	24.61	24.2	32.1	20.1
			Bedroom	B2OB	1st May to 11th August	24.76	27.6	34.0	15.9

The highest indoor temperature recorded was in the bedroom of the Loughborough home with a high of 34.5^{0}C on the 18th of July 2022. The Birmingham flat had the highest mean temperature across the monitoring period at 26.77^{0}C in the Kitchen/Dining area, followed by a mean temperature of 25.83^{0}C in the Kitchen/Dining Area in the Suffolk home. This seems to suggest that flats experience higher temperatures than typical homes and that southerly locations in the UK could be experiencing higher temperatures than other parts of the UK. Additionally, window glazing area and direction seems to play a part in this. The lowest mean temperatures were recorded in the Kitchen/ Dining and bedroom of the Cheshire home at 22.01^{0}C and 22.43^{0}C respectively. Both the Loughborough and Birmingham homes experienced higher maximum temperatures in the Bedrooms than in the other two monitored rooms in each house. Notably as well, the living rooms of the Loughborough and Birmingham homes experienced higher minimum temperatures of 20.8^{0}C and 20.1^{0}C.

5.4 Overheating Analysis of sensor monitored homes.

This section seeks to complement the monitored sensor data in relation to different standards of overheating assessment. These are the TM59 methodology and the simplified method.

5.4.1 TM59 Overheating Analysis

This methodology is based on two criteria, one for hours of exceedance based on a changing external mean temperature and one based on a static threshold for bedrooms only for specific hours.

Criterion 1

For this first criterion, the following formula applies (From TM59):

$$\Delta T = Top - Tmax$$

Where Top is the actual operative temperature in a room

The TM52 (a subsidiary of TM59) states that though operative temperature should be measured with a 40mm globe thermometer, air temperature can also be used in long term measurements; hence the use of the air temperature parameter from sensors – Page 13, TM 52 (CIBSE, 2013))

Where T*max* is the maximum acceptable temperature

Tmax is derived from the following formula (From TM59):

$$Tmax = 1.33Trm + 21.8$$

Where T*rm* is the (monthly) running mean of outdoor temperature

Using the monthly running temperature means for monitored locations (Trm), the following Tmax figures in table 21 are obtained for each month.

Table 21: Trm and Tmax figures for monitored locations.

	May		**June**		**July**		**August**		**Sept**	
	T_{rm}	**T_{Max}**	**T_{rm}**	**T_{Max}**	**T_{rm}**	**T_{Max}**	**T_{rm}**	**T_{Max}**	**T_{rm}**	**T_{Max}**
Birmingham	13.21	26.16	15.34	26.86	19.47	28.22	19.75	28.32	15.12	26.79
Cheshire	13.48	26.24	15.03	26.76	17.77	27.66	18.56	27.92	15.66	26.97
Suffolk	13.08	26.12	15.66	26.96	19.21	28.14	20.00	28.4	15.25	26.83
Loughborough	12.78	26.02	14.9	26.71	17.66	27.63	18.41	27.87	14.56	26.60

The Tmax figures are then used to calculate ΔT using the formula from TM59:

$$\Delta T = Top - Tmax$$

The Tmax figures from table 24 were used in the excel files for recorded temperature (Top) and the number of times ΔT was more than 1^0C was counted. This was done for the five main sensor files (Uhoo sensors) for the occupied homes.

For criterion 1, the number of times Δ T is greater than or equal to 1^0C, should not be more than 3% off occupied hours. Based on TM59, occupied hours are as follows: 3672 hours for bedrooms and 1989 hours for living rooms and kitchens.

$$For\ Bedrooms = \frac{3}{100} \times 3672 = 110.16$$

$$For\ Livingrooms\ and\ Kitchen = \frac{3}{100} \times 1989 = 59.67$$

For this criterion to be passed, the number of hours above the threshold should not be more than 110.16 for bedrooms and 59.67 for living rooms and kitchens. Table 22 presents the hours of exceedance criterion for the five Uhoo sensors in the kitchen-dining areas of all monitored homes with a monthly breakdown.

Table 22: TM59 Criterion 1 Hours of Exceedance for monitored locations.

Sensor Nomenclature	**May**		**June**		**July**		**August**		**September**				
	Total Hours	**Hours above**	**Total Hours**	**Hours Above**	**Total Hours**	**Hours above**	**Total Hours**	**Hours above**	**Total Hours**	**Hours above**	**Total Hours above**	**% 3672 or 1989**	**Pass/Fail**
SUK-D (Suffolk)	744	0	720	140	744	94	744	147	720	1.3	382	19.2%	**Fail**
B2UK (Birmingh)	744	0	720	11.5	744	60	744	92	484	184	348	17.8%	**Fail**
LUS (Loughbor)	744	0	720	17	744	69	744	22.4	720	0	108	5.43%	**Fail**
CUK-D (Cheshir)	734	0	670	7.7	744	25.8	744	13	720	0	46	2.31%	Pass
B4UL-D-K (Bir)	141	0	720	59.1	744	82.2	303	89.6	-	-	230	11.56%	**Fail**

As can be seen from table 22, all the homes failed the TM59 Criterion 1 except for one; Cheshire. The highest fail rates were noted in the living/kitchen area of the Suffolk home at 19.2%, the Kitchen area of the Birmingham home at 17.8% and the Living/Dining/Kitchen area of the Birmingham flat at 11.56%. Most of these failures were due to many hours recorded above the threshold in June, July, and August. The Cheshire home was the only home that registered a pass for criterion 1 for TM59 in the Kitchen/Dining. However, it is worth noting that the analysis for the Birmingham flat could have been influenced by missing data for the month of September. The TM59 overheating standard recommends a period of May to September. However, previous studies have carried out TM59 analysis with shorter monitoring periods (Lomas et al., 2018; Lomas and Giridharan, 2012; Beizaee et al., 2013 and Marvogianni et al., 2014, Gupta et al., 2021). In these instances, results are seen as more indicative rather than definitive. Therefore, the missing data for the Birmingham flat sensor is deemed acceptable as the results are intended to be indicative. Also, only the rooms with the Uhoo sensors (mostly kitchen-dining areas) were used in this analysis because of significant missing data for the other rooms with Omron sensors. This analysis acknowledges that this is a retrospective TM59 analysis using monitored data of homes that are in different locations and involve different occupancy profiles. As such, they are not exactly similar comparisons, but largely indicate the overheating performance of different homes based on real time data.

Criterion 2

In checking for criterion 2, sensor data from bedrooms was truncated to limit it to temperature recordings between 10pm to 7am. As is seen in table 20, all sensors have different start and end dates and therefore a difference in hours monitored. Based on the criteria, recorded bedroom temperature between 10pm to 7am should not exceed 26^0C for more than 1% of occupied hours.

$$Total\ occupied\ hours\ in\ a\ year$$

$$= 365\ days\ \times 9\ hrs\ (10pm\ to\ midnight: midnight\ to\ 7am) = 3300\ hours$$

$$Therefore\ 1\%\ of\ total\ occupied\ hours = \frac{1}{100} \times 3300 = 33hrs$$

Based on this calculation, the criterion is passed when the maximum number of hours for which temperatures above 26^0C are recorded does not exceed 33 hrs. for the period of May to September. Table 23 shows the results of criterion 2 of bedrooms of monitored homes.

Table 23: Criterion 2 of TM59 for monitored locations.

Sensors locate in bedrooms	**Total Hours Monitored**	**Hours above 26^0C threshold**	**Pass/Fail 33hrs. max**
Birmingham Flat B2OB 01/05/2022 – 08/08/2022	917 hrs.	260 hrs.	Fail
Birmingham Home B4OB 17/05/2022 – 24/08/2022	884 hrs.	139 hrs.	Fail
Cheshire Home COB 20/07/2022 – 30/09/2022	650 hrs.	53 hrs.	Fail
Loughborough Home LOB 17/07/2022 – 30/09/2022	677 hrs.	56 hrs.	Fail
Suffolk Home SOB 24/07/2022 – 30/09/2022	614 hrs.	55 hrs.	Fail

As can be seen on table 23, all bedrooms of monitored homes fail this criterion with all recording more than 33 hours when temperatures exceed the 26^0C threshold. Though the monitored hours for each of the bedrooms are different due to variable missing data from sensors, the standard threshold of 33 hours still applies. Compared to the other bedrooms, the bedrooms in Birmingham locations fail the most with B20B exceeding 227 hours and B4OB by 106 hours. Although this is influenced by the higher recorded hours for these bedrooms, there could be explanations for this.

For B4OB, this can be explained by the fact that it is a flat and flats do experience higher temperatures due to their nature. Flats experience more internal temperatures due to their characteristics in relation to poor cross ventilation, poorly insulated and longer heating pipework systems, solar reflections from other buildings, Urban heat Island (UHI) effect among others (Bateson, 2017). However, for B2OB it could be due to its higher fabric standards and dwelling specifications. Different from other homes, the Birmingham Home is a Future Homes Demonstrator project with higher U values and airtightness levels for its fabric elements as compared to the other 2013 Building regs homes. It had the following U values: 0.11 for floors, 0.13 for walls, 0.1 for roofs, 1.2 for windows and doors. This is compared with the following U values for 2013 building regs homes 0.13,0.18,0.13,1.4 and 1.2 respectively. These specifications affect the thermal performance of a home by its ability to reduce the transfer of heat through building fabric.

5.4.2 Simplified Method

This is a relatively new assessment method that was introduced in 2021 as part of Part O overheating compliance for new homes (Approved Document O, 2021). Based on this methodology, a building is categorised depending on its location (in London and its suburbs or elsewhere in England) as either high risk or moderate risk, and whether it is cross-ventilated or not. Homes located in London and its suburbs are considered high risk, while homes located outside London and its suburbs are considered moderate risk. Cross ventilation is achieved when a dwelling has openings on opposite sides. These two criteria determine the overheating risk category to limit unwanted solar gains in summer and provide an appropriate means of removing excess heat from the indoor environment as explained in section 2.8.1. For limiting solar gains, a maximum glazing area should not be exceeded and for removing excess heat, a minimum free area should be equaled or exceeded.

- The limiting of solar gains requirement is based on orientation. Orientation is determined by the façade with the largest glazing area. There are two aspects of this criteria: a maximum area of glazing as a percentage of the Gross Internal Area (GIA) of the floor, and a maximum area of glazing in the most glazed room as a percentage of the floor area of the room. For this criterion, the glazing area of a window is defined as the area or dimension of a glass pane excluding the frame.

- The removal of excess heat requirement is based on two aspects: a minimum free area based on the greater of the percentage of the gross internal floor area or the percentage of the total glazing area, and a bedroom minimum free area based on the percentage of the floor area of all bedrooms. For this criteria, free areas of windows are defined as the geometric open area of a ventilation opening.

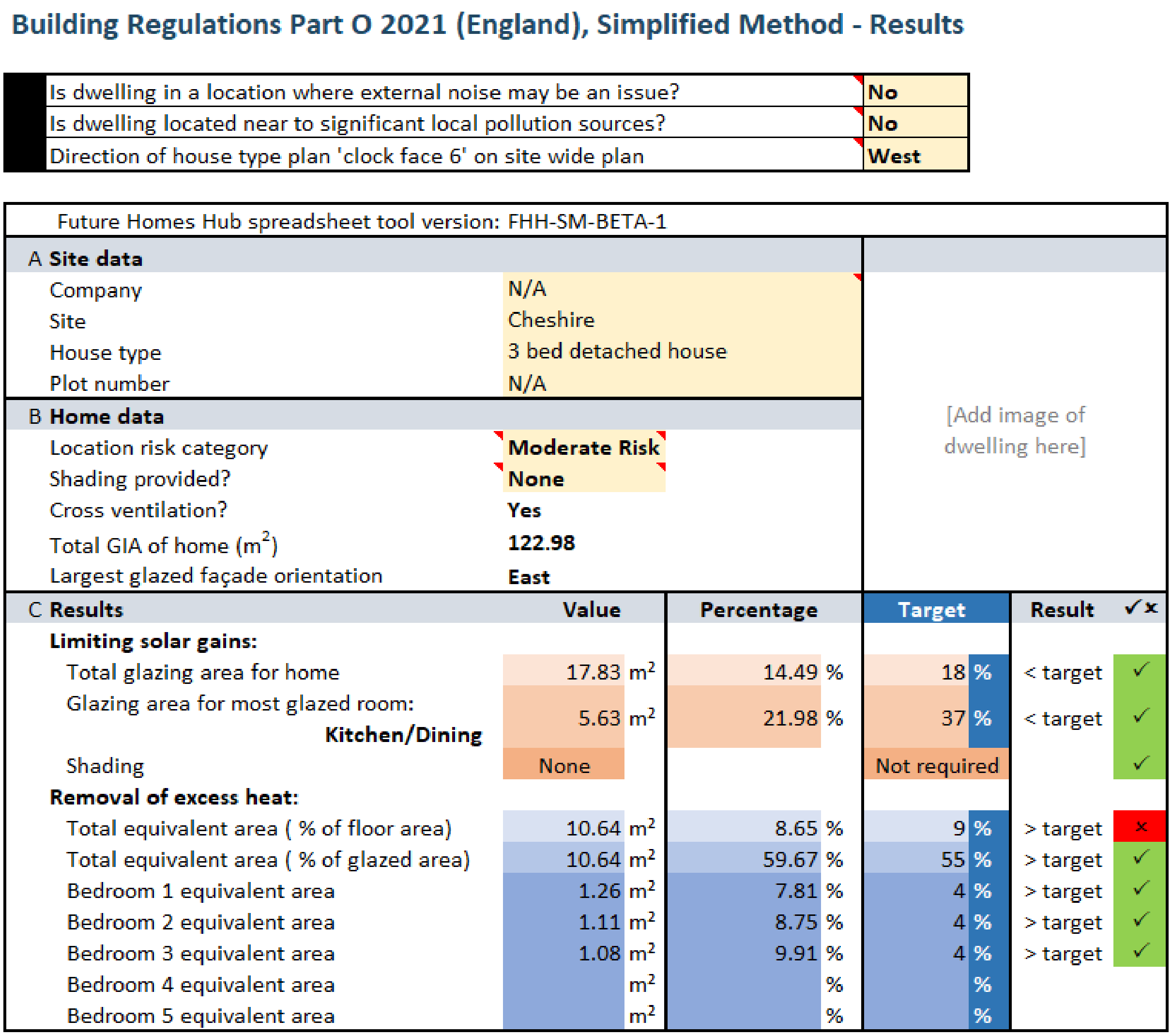
Based on the location and cross ventilation capabilities of a home, the maximum glazing areas for limiting solar gains are found in table 3 and 4, while minimum free areas for removal of excess heat can be found in table 5 and 6, all of which are shown in section 2.8.1. The noise and pollution requirements affect the window opening requirement and restrict the use of this methodology. Therefore, dwellings with significant noise and pollution requirements can only be assessed for overheating by the more comprehensive Dynamic Simulation Method that is based on TM59 criterion.

The Future Homes Hub (FHH) has produced a template to aid in calculation of the method. This excel workbook template is used in this research (appendix 5 to 9) to standardize the calculation and reporting of this overheating assessment method.

5.4.4.1 Cheshire Home

Figure 34: 4 Elevations of Cheshire Home

As can be seen in figure 34, the house meets the criteria for cross ventilation as it has windows on opposite facades. The site is in Cheshire and is therefore considered to be a “moderate risk locations” for Part O. The floor area (Gross Internal Area - GIA) of the home is 122.98m^2. The following details of the house were entered into the Future Home Hub Excel worksheet, to produce a simplified method calculation. These include the GIA of the home, cross ventilation capabilities, location, window and external door details, room floor areas, orientation of the building, house type, shading requirements, noise, and pollutions considerations. With these details entered, the FHH workbook generated a simplified method overheating result as shown in Figure 35. An extended excel spreadsheet capturing the window and door input data that was used to generate results in figure 35 is attached in appendix 5 of this research.



Building Regulations Part O 2021 (England), Simplified Method - Results

Is dwelling in a location where external noise may be an issue?	No
Is dwelling located near to significant local pollution sources?	No
Direction of house type plan 'clock face 6' on site wide plan	West

Future Homes Hub spreadsheet tool version: FHH-SM-BETA-1

A Site data		
Company	N/A	[Add image of dwelling here]
Site	Cheshire	
House type	3 bed detached house	
Plot number	N/A	
B Home data		
Location risk category	**Moderate Risk**	
Shading provided?	**None**	
Cross ventilation?	**Yes**	
Total GIA of home (m^2)	**122.98**	
Largest glazed façade orientation	**East**	

C **Results**	**Value**		**Percentage**		**Target**		**Result**	**✓✗**
Limiting solar gains:								
Total glazing area for home	17.83	m^2	14.49	%	18	%	< target	✓
Glazing area for most glazed room: **Kitchen/Dining**	5.63	m^2	21.98	%	37	%	< target	✓
Shading	None				Not required			✓
Removal of excess heat:								
Total equivalent area (% of floor area)	10.64	m^2	8.65	%	9	%	> target	✗
Total equivalent area (% of glazed area)	10.64	m^2	59.67	%	55	%	> target	✓
Bedroom 1 equivalent area	1.26	m^2	7.81	%	4	%	> target	✓
Bedroom 2 equivalent area	1.11	m^2	8.75	%	4	%	> target	✓
Bedroom 3 equivalent area	1.08	m^2	9.91	%	4	%	> target	✓
Bedroom 4 equivalent area		m^2		%		%		
Bedroom 5 equivalent area		m^2		%		%		

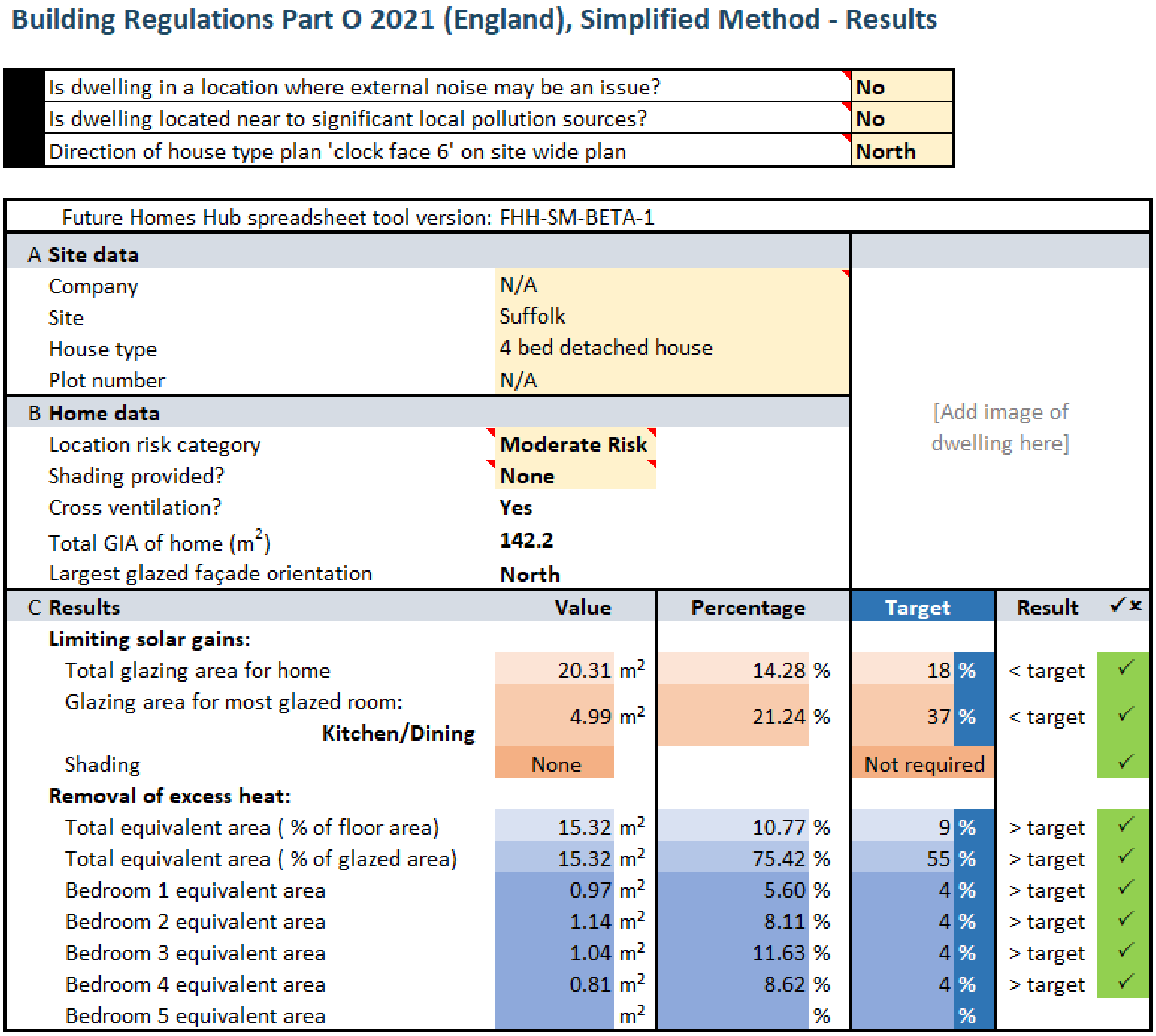
Figure 35: FHH Format of Simplified Method Results for the Cheshire Home

The results shown in figure 35 show that the home failed the simplified method of overheating assessment. This is shown by one red colored checkmark on the results tab. For the limiting solar gain criteria to be met, the actual percentage need not exceed the target. From figure 35, the total glazing area for the home was 17.83m2, 14.49%, lower than the 18% target for a west facing house plan type. The glazing area for the most glazed room (Kitchen/Dining), was 21.98%, lower than the maximum value of 37%. For the removal of excess heat criteria, the percentage of equivalent areas should be more than stipulated targets in the target column. This is where the criterion fails. The total equivalent area (10.64m^2) as a percentage of the floor area was slightly below the 9% target at 8.65%. This represents a failure. However, the floor area as a percentage of the glazed area exceeded the minimum target of 55% at 59.67%. Additionally, the equivalent areas for bedrooms 1, 2 and 3 all exceeded the minimum percentage of 4%, with values of 7.81%, 8.75% and 9.9% respectively. With noise, security, and pollution considerations, the result demonstrates that the Cheshire home failed the simplified method for overheating assessment as per Approved Document O (2021) for Overheating.

5.4.4.2 Suffolk Home

Figure 36: 4 Elevations of Suffolk Home

Figure 36 shows that the Suffolk home meets the cross-ventilation criteria due to openings on opposite facades. As it is in Suffolk, it is considered as a “moderate risk” location for Part O. The home details including the gross internal area (GIA), window and door details, room floor areas, orientation, shading requirements, noise, and pollution considerations, were entered into the Future Home Hub’s (FHH) workbook to generate a simplified method overheating result as shown in figure 37. An extended excel spreadsheet capturing the window and door input data that was used to generate the results in figure 37 is attached in appendix 6 of this document.



Building Regulations Part O 2021 (England), Simplified Method - Results

Is dwelling in a location where external noise may be an issue?	**No**
Is dwelling located near to significant local pollution sources?	**No**
Direction of house type plan 'clock face 6' on site wide plan	**North**

Future Homes Hub spreadsheet tool version: FHH-SM-BETA-1

A **Site data**		
Company	N/A	
Site	Suffolk	
House type	4 bed detached house	
Plot number	N/A	
B **Home data**		[Add image of dwelling here]
Location risk category	**Moderate Risk**	
Shading provided?	**None**	
Cross ventilation?	**Yes**	
Total GIA of home (m^2)	**142.2**	
Largest glazed façade orientation	**North**	

C **Results**	**Value**	**Percentage**	**Target**	**Result**	**✓×**
Limiting solar gains:					
Total glazing area for home	20.31 m^2	14.28 %	18 %	< target	✓
Glazing area for most glazed room:	4.99 m^2	21.24 %	37 %	< target	✓
Kitchen/Dining					
Shading	None		Not required		✓
Removal of excess heat:					
Total equivalent area (% of floor area)	15.32 m^2	10.77 %	9 %	> target	✓
Total equivalent area (% of glazed area)	15.32 m^2	75.42 %	55 %	> target	✓
Bedroom 1 equivalent area	0.97 m^2	5.60 %	4 %	> target	✓
Bedroom 2 equivalent area	1.14 m^2	8.11 %	4 %	> target	✓
Bedroom 3 equivalent area	1.04 m^2	11.63 %	4 %	> target	✓
Bedroom 4 equivalent area	0.81 m^2	8.62 %	4 %	> target	✓
Bedroom 5 equivalent area	m^2	%	%		

Figure 37: FHH format of Simplified Method results for the Suffolk Home

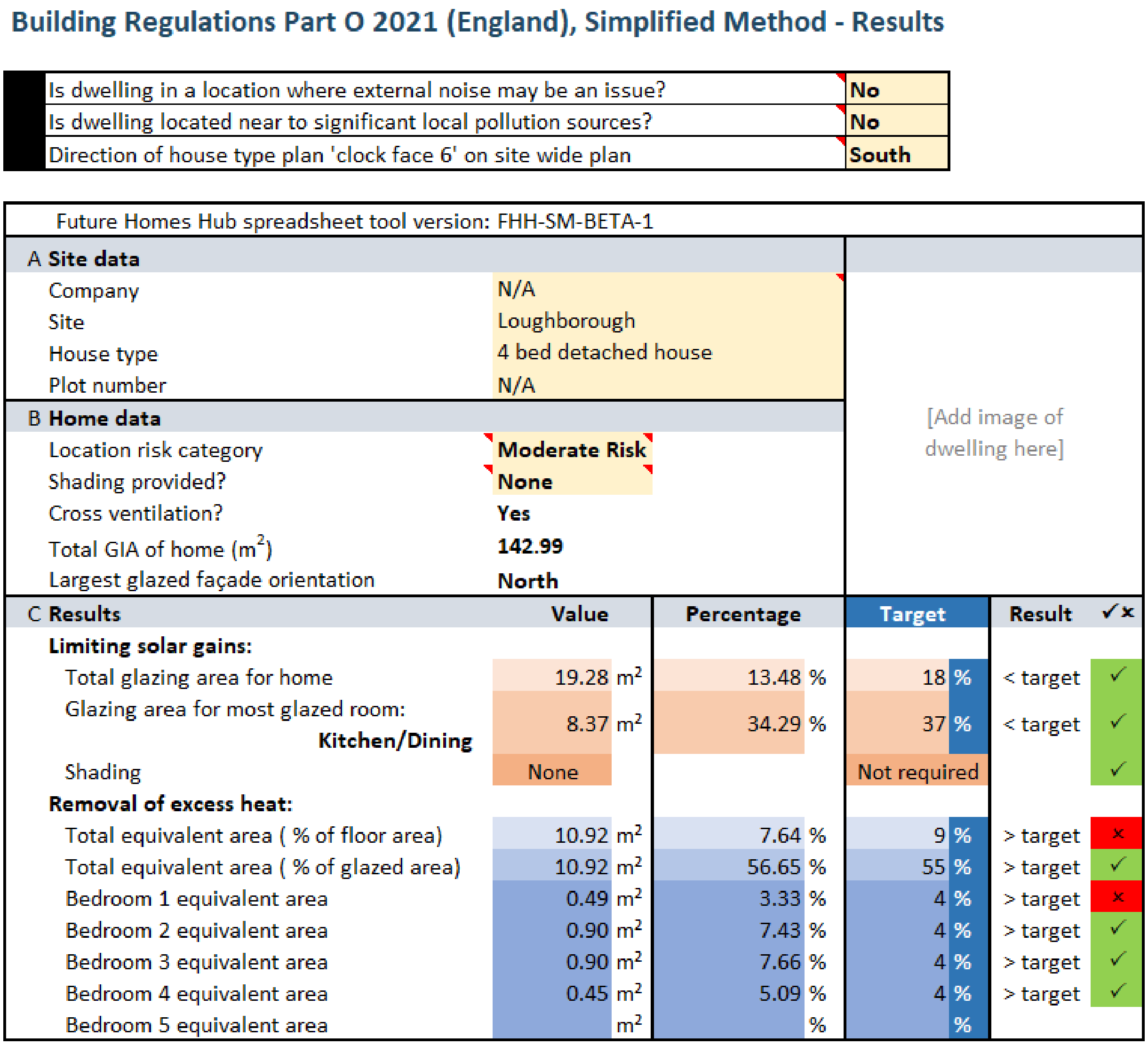
As shown in figure 37, the Suffolk home has passed the simplified method overheating assessment method as can be seen in the result column. For limiting solar gains, the total glazing area 20.31m^2

is 14.28% and less than the maximum of 18%. The glazing area of the most glazed room (Kitchen/Dining at 4.99m^2), is 21.24% and below the 37% upper limit as dictated by the north orientation of the largest glazed façade. For the criteria for removal of excess heat, the total equivalent area is 15.32m^2. This is 10.77% of the total floor area and 75.42% of the total glazed area. Therefore, it passes the 9% and 55% lower limit of the equivalent area criteria. Additionally, all 4 bedrooms exceed the 4% lower limit of equivalent area at 5.60%, 8.11%, 11.63% and 8.62%. With the noise, pollution and security considerations shown in the workbook, the Suffolk home passes the simplified method for overheating assessment as per Approved Documents O (2021) for Overheating.

5.4.4.3 Loughborough Home

Figure 38: 4 Elevations of Loughborough Home

Figure 37 shows that the Loughborough home meets the cross-ventilation criteria due to openings on oppo8ite facades. As it is in Loughborough, it is considered as a “moderate risk” location for Part O. The home details including the gross internal area (GIA), window and door details, room floor areas, orientation, shading requirements, noise, and pollution considerations, were entered into the Future Home Hub’s (FHH) workbook to generate a simplified method overheating result as shown in figure 39. An extended excel spreadsheet capturing the window and door input data that was used to generate the results in figure 39 is attached in appendix 7 of this document.



Building Regulations Part O 2021 (England), Simplified Method - Results

Is dwelling in a location where external noise may be an issue?	**No**
Is dwelling located near to significant local pollution sources?	**No**
Direction of house type plan 'clock face 6' on site wide plan	**South**

Future Homes Hub spreadsheet tool version: FHH-SM-BETA-1

A **Site data**					
Company	N/A				
Site	Loughborough				
House type	4 bed detached house				
Plot number	N/A		[Add image of dwelling here]		
B **Home data**					
Location risk category	**Moderate Risk**				
Shading provided?	**None**				
Cross ventilation?	**Yes**				
Total GIA of home (m^2)	**142.99**				
Largest glazed façade orientation	**North**				
C **Results**	**Value**	**Percentage**	**Target**	**Result**	**✓×**
Limiting solar gains:					
Total glazing area for home	19.28 m^2	13.48 %	18 %	< target	✓
Glazing area for most glazed room: **Kitchen/Dining**	8.37 m^2	34.29 %	37 %	< target	✓
Shading	None		Not required		✓
Removal of excess heat:					
Total equivalent area (% of floor area)	10.92 m^2	7.64 %	9 %	> target	×
Total equivalent area (% of glazed area)	10.92 m^2	56.65 %	55 %	> target	✓
Bedroom 1 equivalent area	0.49 m^2	3.33 %	4 %	> target	×
Bedroom 2 equivalent area	0.90 m^2	7.43 %	4 %	> target	✓
Bedroom 3 equivalent area	0.90 m^2	7.66 %	4 %	> target	✓
Bedroom 4 equivalent area	0.45 m^2	5.09 %	4 %	> target	✓
Bedroom 5 equivalent area	m^2	%	%		

Figure 39: FHH format of the Simplified Method Result of the Loughborough Home

The results in figure 39 show that the Loughborough home failed the simplified method overheating assessment method as can be seen with the red x marks in the result column. For limiting solar gains, the total glazing area 19.28m^2 is 13.48% and less than the maximum of 18%. The glazing area of the most glazed room (Kitchen/Dining at 8.37m^2), is 34.29% and just below the 37% upper limit as dictated by the north orientation of the largest glazed façade. For the criteria for removal of excess heat, this is where the criteria failed. The total equivalent area is 10.92m^2. This is 7.64% of the total floor area and 56.65% of the total glazed area. Therefore, it fails the 9%

lower limit, and barely passes the 55% lower limit of the equivalent area criteria. For the bedroom equivalent areas, bedroom 1 fails the 4% lower limit of equivalent area at 3.33%. This shows that the window in bedroom 1 does not provide as much equivalent area as it does its glazing area. All other 3 bedrooms exceed the 4% lower limit of equivalent area at 7.73%, 7.66%, and 5.09%. With the noise, pollution and security considerations shown in the workbook, the Loughborough home fails the simplified method for overheating assessment as per Approved Documents O (2021) for Overheating.

5.4.4.4 Birmingham Flat

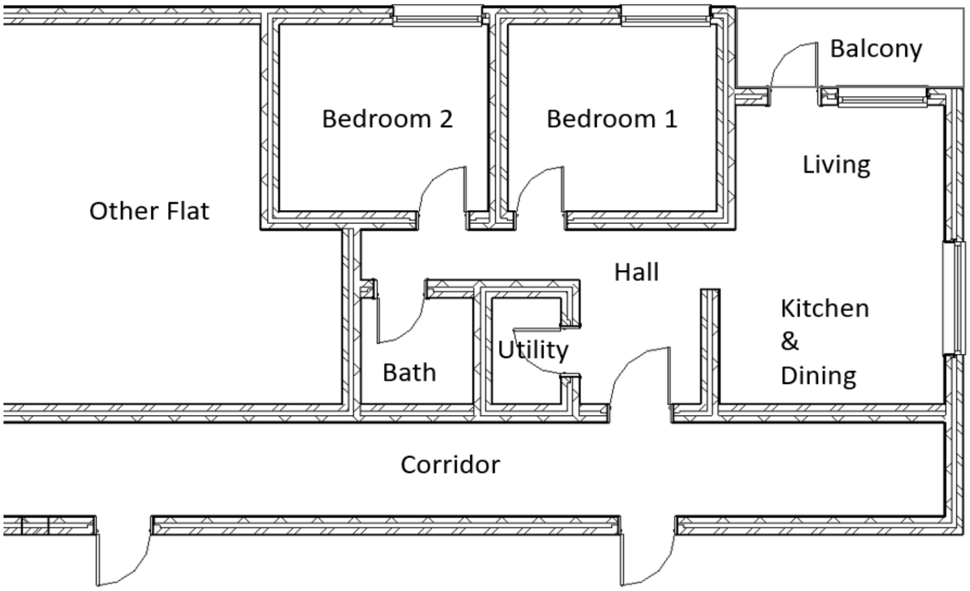
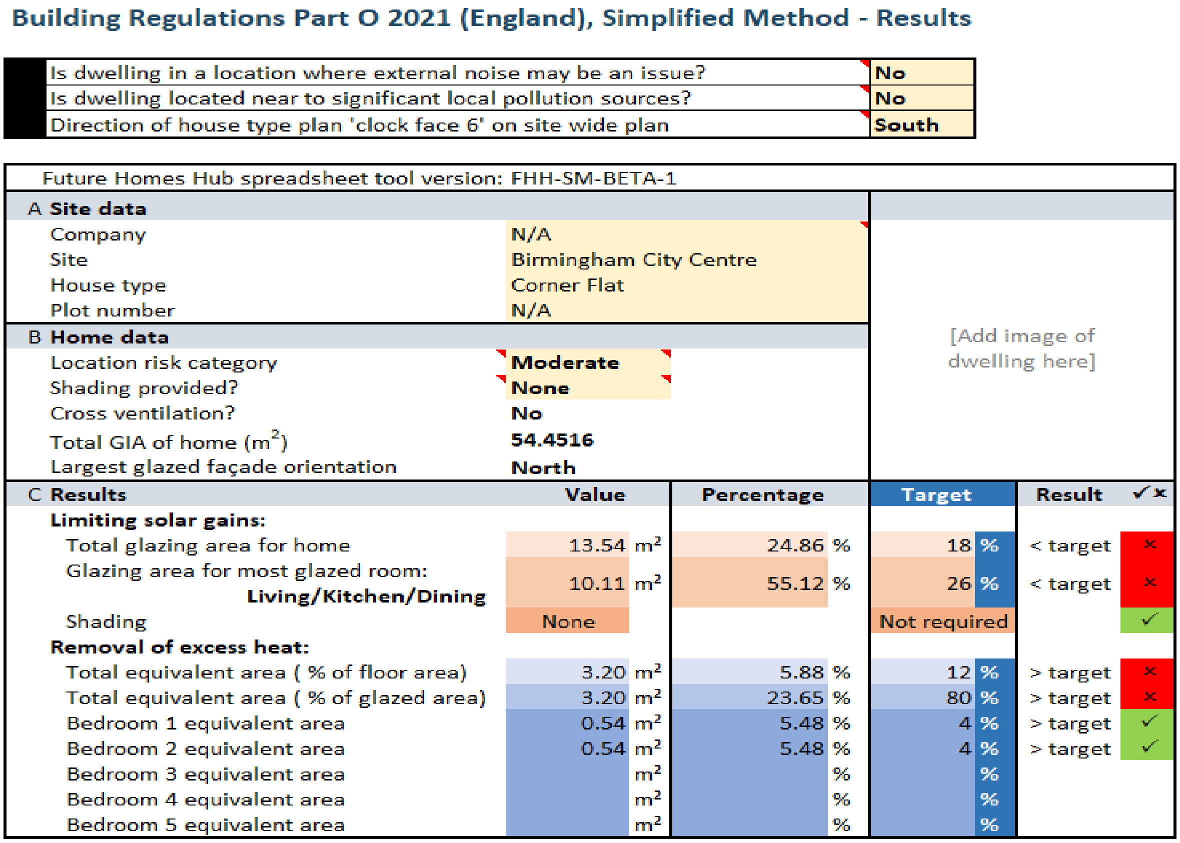


Figure 40: Floor Plan of Birmingham Flat

As can be seen in figure 40, the Birmingham flat does not meet the cross-ventilation criteria due to lack of openings on opposite facades; it is a corner flat. As it is in Birmingham, it is considered as a “moderate risk” location for Part O. The flat details including the gross internal area (GIA), window and door details, room floor areas, orientation, shading requirements, noise, and pollution considerations, were entered into the Future Home Hub’s (FHH) workbook to generate a simplified method overheating result as shown in figure 41. An extended excel spreadsheet capturing the window and door input data that was used to generate the results in figure 41 is attached in appendix 8 of this document.



Building Regulations Part O 2021 (England), Simplified Method - Results

Is dwelling in a location where external noise may be an issue?	No
Is dwelling located near to significant local pollution sources?	No
Direction of house type plan 'clock face 6' on site wide plan	South

Future Homes Hub spreadsheet tool version: FHH-SM-BETA-1

A Site data	
Company	N/A
Site	Birmingham City Centre
House type	Corner Flat
Plot number	N/A
B Home data	
Location risk category	**Moderate**
Shading provided?	**None**
Cross ventilation?	**No**
Total GIA of home (m^2)	**54.4516**
Largest glazed façade orientation	**North**

[Add image of dwelling here]

C **Results**	**Value**		**Percentage**		**Target**		**Result**	✓✗
Limiting solar gains:								
Total glazing area for home	13.54	m²	24.86	%	18	%	< target	✗
Glazing area for most glazed room: **Living/Kitchen/Dining**	10.11	m²	55.12	%	26	%	< target	✗
Shading	None				Not required			✓
Removal of excess heat:								
Total equivalent area (% of floor area)	3.20	m²	5.88	%	12	%	> target	✗
Total equivalent area (% of glazed area)	3.20	m²	23.65	%	80	%	> target	✗
Bedroom 1 equivalent area	0.54	m²	5.48	%	4	%	> target	✓
Bedroom 2 equivalent area	0.54	m²	5.48	%	4	%	> target	✓
Bedroom 3 equivalent area		m²		%		%		
Bedroom 4 equivalent area		m²		%		%		
Bedroom 5 equivalent area		m²		%		%		

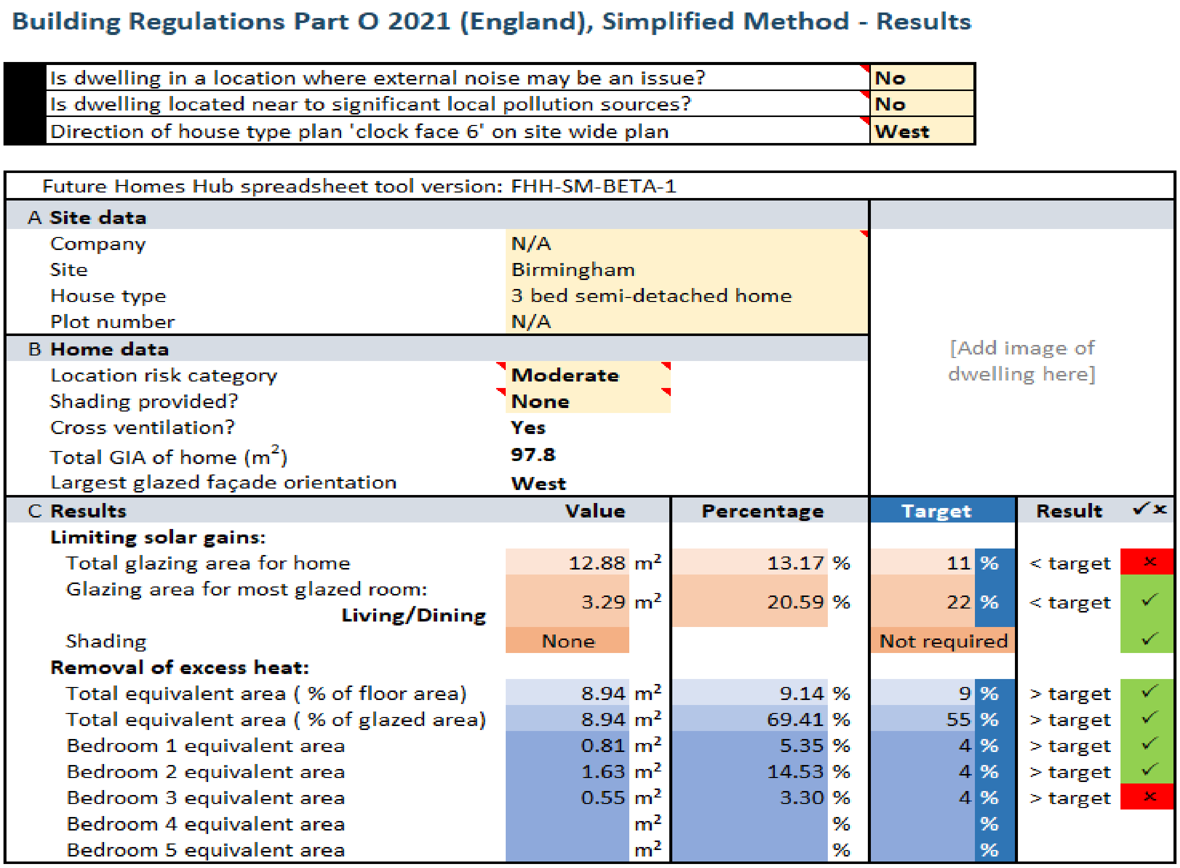
Figure 41: FHH format of the Simplified Method Result of the Birmingham Flat

The results in figure 41 show that the Birmingham flat failed the simplified method overheating assessment method as can be seen with the red x marks in the result column. For limiting solar gains, the total glazing area 13.54m^2 is 24.86%, more than the maximum of 18%. This is the highest percentage of glazing area for all five dwellings considered in this study. The glazing area of the most glazed room (Living/Kitchen/Dining at 10.11m^2), is 55.12% and way over the 26% upper limit as dictated by the north orientation of the largest glazed façade. Both aspects of limiting solar gain failed. For the criteria for removal of excess heat, the criteria also failed. The total equivalent area is just 3. 2m^2.The lowest of all dwellings considered in this research. This is 5.88% of the total floor area and 23.65% of the total glazed area. Therefore, it fails the 12% lower limit, as well as the 80% lower limit of the equivalent area criteria. For the bedroom equivalent areas, bedrooms 1 and 2 pass the 4% lower limit of equivalent area with both at 5.48%. With the noise, pollution and security considerations shown in the workbook, the Birmingham flat fails the simplified method for overheating assessment as per Approved Documents O (2021) for Overheating.

5.4.4.5 Birmingham Home

Figure 42: 4 Elevations for Birmingham Home (1st Property top left, 3rd property bottom right)

As shown in Figure 42, the Birmingham home meets the cross-ventilation criteria due to openings on opposite facades. As it is in Birmingham, it is considered as a "moderate risk" location for Part O. The home details including the gross internal area (GIA) – 97.8m^2, window and door details, room floor areas, orientation, shading requirements, noise, and pollution considerations, were entered into the Future Home Hub's (FHH) workbook to generate a simplified method overheating result as shown in figure 43. An extended excel spreadsheet capturing the window and door input data that was used to generate the results in figure 43 is attached in appendix 9 of this document.



Building Regulations Part O 2021 (England), Simplified Method - Results

Is dwelling in a location where external noise may be an issue?	**No**
Is dwelling located near to significant local pollution sources?	**No**
Direction of house type plan 'clock face 6' on site wide plan	**West**

Future Homes Hub spreadsheet tool version: FHH-SM-BETA-1

A **Site data**			[Add image of dwelling here]
Company	N/A		
Site	Birmingham		
House type	3 bed semi-detached home		
Plot number	N/A		
B **Home data**			
Location risk category	**Moderate**		
Shading provided?	**None**		
Cross ventilation?	**Yes**		
Total GIA of home (m^2)	**97.8**		
Largest glazed façade orientation	**West**		

C **Results**	**Value**		**Percentage**		**Target**		**Result**	**✓✗**
Limiting solar gains:								
Total glazing area for home	12.88	m^2	13.17	%	11	%	< target	✗
Glazing area for most glazed room: **Living/Dining**	3.29	m^2	20.59	%	22	%	< target	✓
Shading	None				Not required			✓
Removal of excess heat:								
Total equivalent area (% of floor area)	8.94	m^2	9.14	%	9	%	> target	✓
Total equivalent area (% of glazed area)	8.94	m^2	69.41	%	55	%	> target	✓
Bedroom 1 equivalent area	0.81	m^2	5.35	%	4	%	> target	✓
Bedroom 2 equivalent area	1.63	m^2	14.53	%	4	%	> target	✓
Bedroom 3 equivalent area	0.55	m^2	3.30	%	4	%	> target	✗
Bedroom 4 equivalent area		m^2		%		%		
Bedroom 5 equivalent area		m^2		%		%		

Figure 43: FHH format of the Simplified Method Result of the Birmingham Home

The results in figure 43 show that the Birmingham home failed the simplified method overheating assessment method as can be seen with the two red x marks in the result column. For limiting solar gains, the total glazing area 12.88m^2 is 13.17% and more than the maximum of 11%. Therefore, it fails this criterion. The glazing area of the most glazed room (Living/Dining at 3.29m^2), is 20.59% and just below the 22% upper limit as dictated by the west orientation of the largest glazed façade. For the criteria for removal of excess heat, the total equivalent area is 8.94m^2 and is 9.14% of the total floor area and 69.41% of the total glazed area. Therefore, it barely passes the 9% lower limit, and passes the 55% lower limit of the equivalent area criteria. For the bedroom equivalent areas, bedroom 3 fails the 4% lower limit of equivalent area at 3.30%. This shows that the window area in bedroom 3 does not provide as much equivalent area as it does its glazing area. The other 2 bedrooms exceed the 4% lower limit of equivalent area at 5.35%, and 14.53%. With the noise, pollution and security considerations shown in the workbook, the Birmingham home fails the simplified method for overheating assessment as per Approved Documents O (2021) for Overheating.

Table 24 contains a summary of the simplified method analysis of all home.

Table 24: Summary of Simplified Method Analysis of all homes

Home Location	Limiting Solar Gains	Pass/Fail	Removing excess eat	Pass/Fail
Cheshire	14.49% and 21.98%	Less than 18% and 37% **Pass**	8.65%	Less than 9% **Fail**
Birmingham Home	13.17% and 20.59%	More than 11% and less than 22% **Fail**	Bedroom 3 - 3.3%	Less than 4% **Fail**
Loughborough	13.48% and 34.29%	Less than 18% and 37% **Pass**	10.92% and bed 1 56.55%	Less than 9% and 55% **Fail**
Suffolk	14.28% and 21.24%	Less than 18% and 37% **Pass**	10.77% and 75.42%	More than 95 and 55% **Pass**
Birmingham Flat	22.86% and 55.12%	More than 18% and 26% **Fail**	5.88% and 23.65%	Less than 12% and 80% **Fail**

5.5 Implications of Overheating Analysis

Real time sensor monitoring results reveal that UK homes are at risk of experiencing higher summers temperatures. Monitoring revealed three significant heatwave periods during the summer of 2022, when temperatures above 30^0C were recorded. During the monitoring period, a maximum average temperature and a mean of 31.8^0C and 24.33^0C respectively were recorded for the five monitored homes. This was confirmed by home occupants revealing their perception of their thermal environments as hot – the extreme of the Linkert scale. This should be concerning given that more heatwaves of higher intensity and frequency are predicted for future summers.

Table 25 provides a comparison between the overheating analysis of the monitored homes using the two overheating methods: TM59 overheating analysis, and the Simplified Method. A retrospective TM59 overheating analysis that was done using monitored data revealed that only one of the five homes passed criterion 1, while all five homes failed criterion 2. A simplified Method analysis also revealed that only one of the five home designs would pass without requiring minor design changes when it comes to floor area, glazing areas, and equivalent areas.

Table 25: A Comparison of Overheating Analysis of Monitored Homes based on two methods.

Home	TM59 Analysis		Simplified Method	
	Criterion 1 **3%**	**Criterion 2** **33 hours**	**Limiting** **Solar gain**	**Removing excess heat**
Cheshire	Pass -2.31%	Fail -53 hrs.	Pass	Fail
Suffolk	Fail -19.2%	Fail -55 hrs.	Pass	Pass
Loughborough	Fail -5.43%	Fail -56 hrs.	Pass	Fail
Birmingham Flat	Fail -11.56%	Fail -260 hrs.	Fail	Fail
Birmingham Home	Fail -17.8%	Fail -139 hrs.	Fail	Fail

This comparison in table 25 shows that one house can pass one method and fail another. However, both overheating analyses show that most of the homes failed their respective criteria with only a few passing. This is not to be used as a basis for deciding which method to use. Approved Document Part O (2021) stipulates that the TM59 method, which is applied through Dynamic Simulation Modelling, applies to all residential buildings as it offers designers more flexibility in residential dwellings with: high levels of insulation and airtightness, specific site conditions that may not be represented by the two locations of the simplified method, and residential structures that are highly shaded with neighbouring properties, structures, and landscapes. According to the Approved Document Part O (2021), the Simplified method can be used for all residential buildings except buildings with more than one residential unit with a communal heating system or significant levels of hot water distribution pipework. This study therefore is not intended to critique the standards and their applications.

However, in this research, Table 25 provides perspective on the overheating performance of occupied monitored homes based on collected and/or measured data rather than simulated data, as is always the case with modelling. The overheating analysis in this chapter shows that recently built houses are failing to pass overheating assessment methods stipulated in current regulations based on real monitored data. For the TM59 method particularly (based on the dynamic simulation assessment method), the rooms and houses that fail do so with very high margins that are not usually obtained with simulated data. For Criterion 1 of TM59 that has a maximum exceedance-hours criteria of 3%, the Suffolk kitchen-dining fails by 19.2%, the Birmingham home kitchen-dining by 17.8% and the Birmingham flat kitchen-dining by 11.56%. These are significantly higher percentages that underscore not only the occurrence of overheating in homes, but more so the extent or “by how much” overheating occurs. Additionally, for bedrooms only in criterion 2 of TM59, the bedrooms of all five homes fail with high values. Against a maximum threshold of temperature exceedance over 26^0C capped at 33 hours annually, the homes fail by recording the following hours; 260 hours for the Birmingham flat, 139 hours for the Birmingham home, 53 hours for the Cheshire home, 56 hours for the Loughborough home and 55 hours for the Suffolk home. The first two show very high numbers of hours of exceedance beyond 33. Had there been more hours recorded for the last three homes, similar high figures could possibly have also been recorded. These results go beyond showing that overheating in UK homes exists, but that it occurs at a significantly high level that should require action.

These overheating analyses also suggest that overheating design methods are not sufficient to pick up the extent of overheating in homes. Design methods such as the Dynamic Simulation Method rely on synthetic occupant profiles and standard weather data for overheating analyses. However, the use of real time indoor temperature data and its collection in real occupied homes, has revealed that a higher level of overheating occurs, compared to using standard simulation data in design methods. This suggests that homes that comply with overheating assessment methods may be at risk of failing the same methods, if real time monitored data is collected a few years later. The dynamic simulation method requires the use of a minimum DSY 2020 50th percentile weather file for specific locations for the regulation to be passed. However, this real time monitoring analysis suggests the need to use more severe weather files like the 2050 or even the 2080 scenarios and more stringent occupancy profiles in design methods, to reflect climate trends that are more in line with reality. Though the real time indoor temperature data collected for this research was done in the 40^0C multi record-breaking hot and dry summer of 2022, the Met Office has warned that it will become typical in the UK in under 40 years (Sky News, 2023). Therefore, homes should be designed to survive for longer term periods while being resilient to future climates. Although these results are not meant to be definitive but rather indicative, they show that homes in the UK are at risk of experiencing higher temperatures than envisioned in design. It also has implications for policy requirements regarding overheating assessment design methods. Lastly, these overheating analyses justify the need for overheating mitigation measures to be introduced in home designs as a way of future proofing new housing stock against warming weather.

5.6 Chapter Summary

This chapter has presented the results of the sensor monitoring of occupied homes, in the quest of increasing the evidence base regarding the thermal performance of UK homes monitored during a very recent summer period. An analysis of both outdoor and indoor temperature is presented for each of the five homes and locations considered. The thermal performance of homes is affected by three heatwave periods in the summer of 2022. The monitored temperature trends for each home are presented with an analysis of mean, highest and degree hours of recorded temperatures and the significance of home characteristics, typologies, and location. This is further explained by analyzing the thermal perception and overheating experience of occupants during the monitoring period. The TM59 overheating analyses, though indicative, shows that all monitored homes failed. The Cheshire home passes criterion 1 but all bedrooms fail criterion 2, meaning all homes fail. For the Simplified method, only the Suffolk home passes, with other homes either failing the limiting solar gains or removing excess heat criteria. The results of this chapter confirm that overheating in UK homes is a genuine concern, that overheating design methods are not sufficient to pick up the extent of overheating in homes, and that mitigation measures should be applied. The next chapter presents the evaluation of overheating mitigation solutions.

Chapter 6: Evaluation of Overheating Mitigation Solutions

6.1 Introduction

The analysis of scalability from a development process perspective in Chapter 4 and a design method perspective in Chapter 5, provides a basis for targeted analysis of the effectiveness of individual mitigation solutions and their scalability based on the proposed scalability criteria described in section 4.4. This chapter presents and analyses data with the aim of evaluating overheating mitigation solutions. This is done in two steps. First is to assess the effectiveness of different overheating mitigation solutions applied to several UK housing typologies using dynamic simulation modelling. The second step presents an analysis of the scalability of overheating mitigation measures. This second step builds on the outcomes of previous chapters and combines them together to deliver on the common goal of proposing scalable solutions for overheating mitigation in UK homes. It combines the results of the home development process and overheating in homes presented in Chapter 4, Overheating Analysis presented in Chapter 5, and the first part of this chapter on evaluation of overheating mitigation solutions. This chapter is broken down into the following subsections: overview of DSM procedures, DSM results for modelled houses, analysis and discussion of results, scalability of overheating mitigation measures, evaluation workshop outcomes, and chapter summary.

6.2 Overview of Dynamic Simulation Modelling (DSM) Procedures

Scenario modelling was conducted in IES for five different overheating mitigation solutions. The modelling protocol followed the TM59 procedure outlined in Approved Document Part O for Overheating (2021). A London Weather File DSY 2020 50th Percentile was used. Each home was modelled in Model IT, assigned construction in Apache, ventilation designed in Macroflow, simulated in ApacheSim, and had results viewed in Vista Pro. A total of 120 simulations were conducted considering all four orientations. The range test results for hours above 26^0C for each home, each solution and each orientation were produced in Python and will form the subject of the data analysis in the next section. The scale of the x axis of the range test results varies from home to home based on the highest value for each home. Therefore, the x axis scale for each individual home should be considered separately when comparing it to the other homes.

6.3 Dynamic Simulation Modelling (DSM) Results for Modelled Homes

This section presents the results of the simulations carried out. The results are presented in horizontal bar graphs with the length of each bar graph representing the number of hours above 26^0C from May to September for each solution. For each home and each solution, the results of all four orientations are considered. These results will be presented for each home.

6.3.1 Cheshire Home

Figure 44 shows the model IT view of the Cheshire home as modelled in IES. It is a three-bedroom detached house with most windows on the back and front and has a hip roof. Figure 44 also shows the modelled sun path analysis for a west-front facing scenario for the selected weather file at different times of the day. This is also accounted for in the simulation.

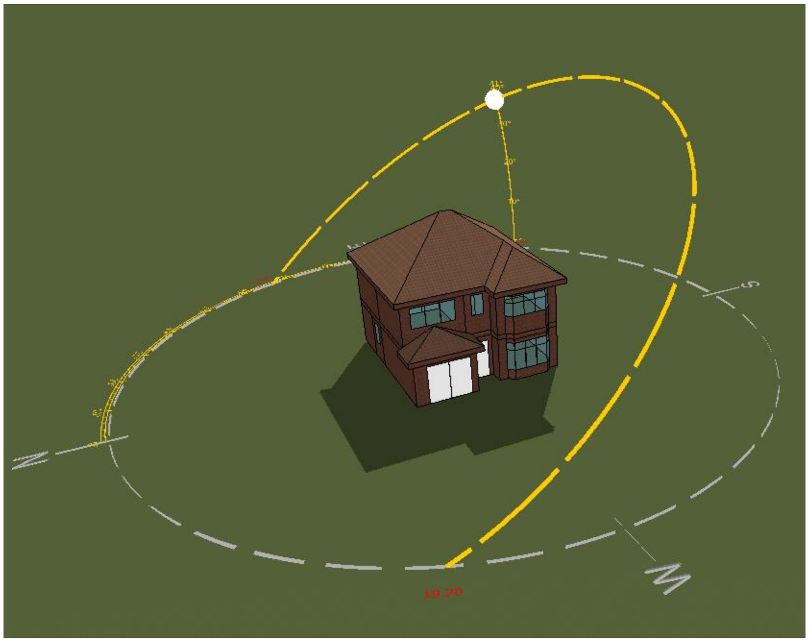


Figure 44: Cheshire Home as viewed in Model IT (IES)

Figure 45 shows the performance of different mitigation strategies for the main occupied areas such as the living space, kitchen/dining and the three bedrooms, with each corresponding to a different colour. All four orientations have been considered.

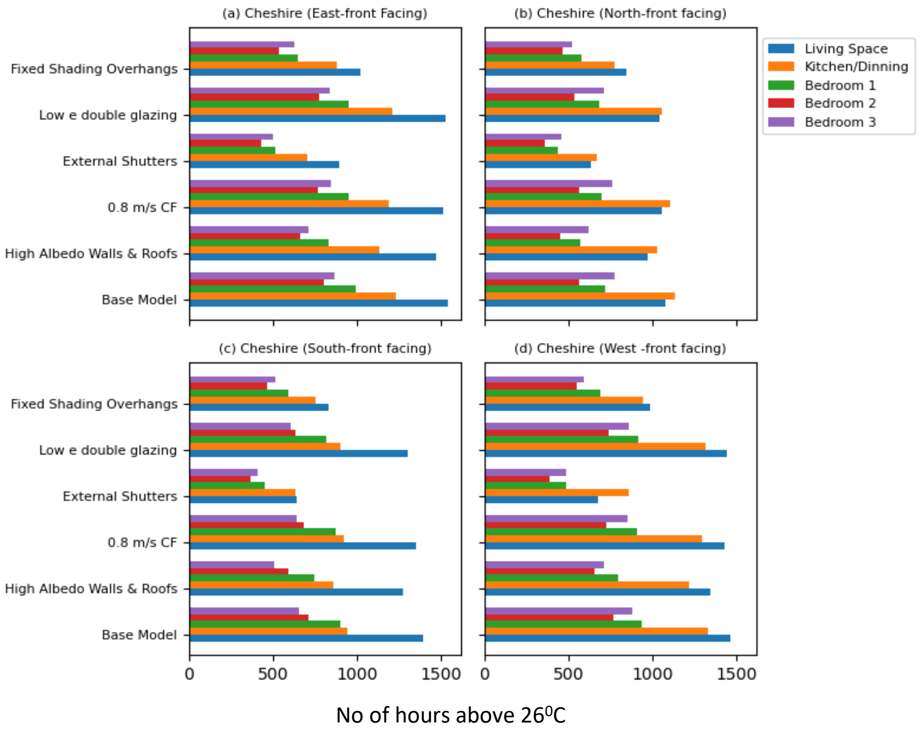


Figure 45: The Effectiveness of different Mitigation Solutions for Cheshire Home

From figure 45, the east and west-front facing scenarios produced the highest numbers of temperatures above 26^0C. For the east front facing scenario, the living space area recorded the highest number of hours above 26^0C at 1540 hours, followed by the west front facing scenario at 1463 hours. As can be seen in figure 45, the south-front facing scenario recorded the least overheating hours compared to the others. It is also clear that the living area for the Cheshire home recorded most hours above 26^0C for all four scenarios. This is followed by the kitchen/ dining area, then the bedrooms. Based on the base model, the five solutions reduced overheating hours (considering all orientations) by up to 2,517 hours for high albedo walls and roofs, 550 hours for 0.8m/s ceiling fans, 8,681 for external shutters, 815 hours for low e double glazing windows, and 5,856 hours for fixed shading overhangs.

6.3.2 Suffolk Home

Figure 46 shows the model IT view of the Suffolk home as modelled in IES. It is an L-shaped three-bedroom detached house with windows and doors evenly distributed on all facades and has a gable roof. Figure 46 also shows the modelled sun path analysis for an east-front facing scenario of the selected weather file at different times of the day. This is also accounted for in the simulation.

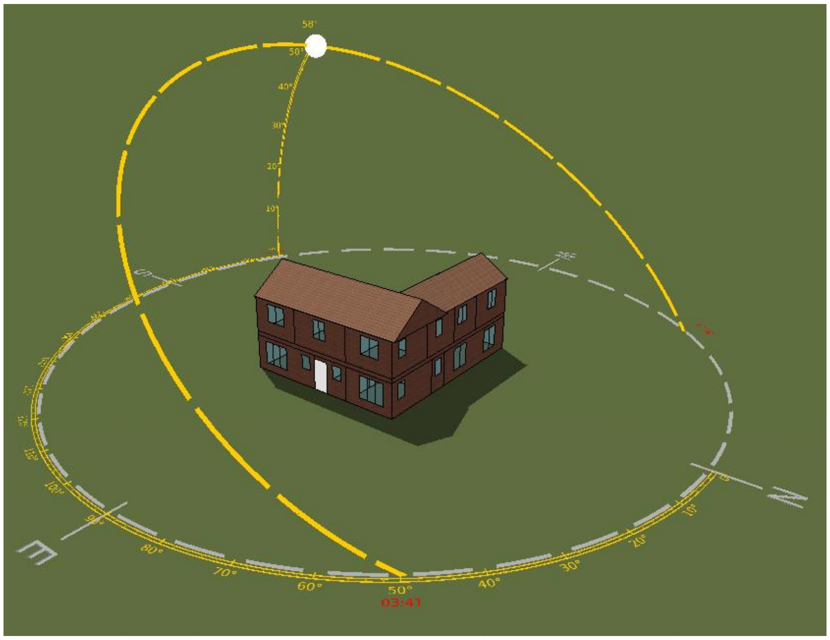


Figure 46: Suffolk Home as viewed in Model IT (IES)

Figure 47 shows the performance of different mitigation strategies for the main occupied areas namely the lounge, dining, kitchen/family and the three bedrooms, with each corresponding to a different colour. All four orientations have been considered.

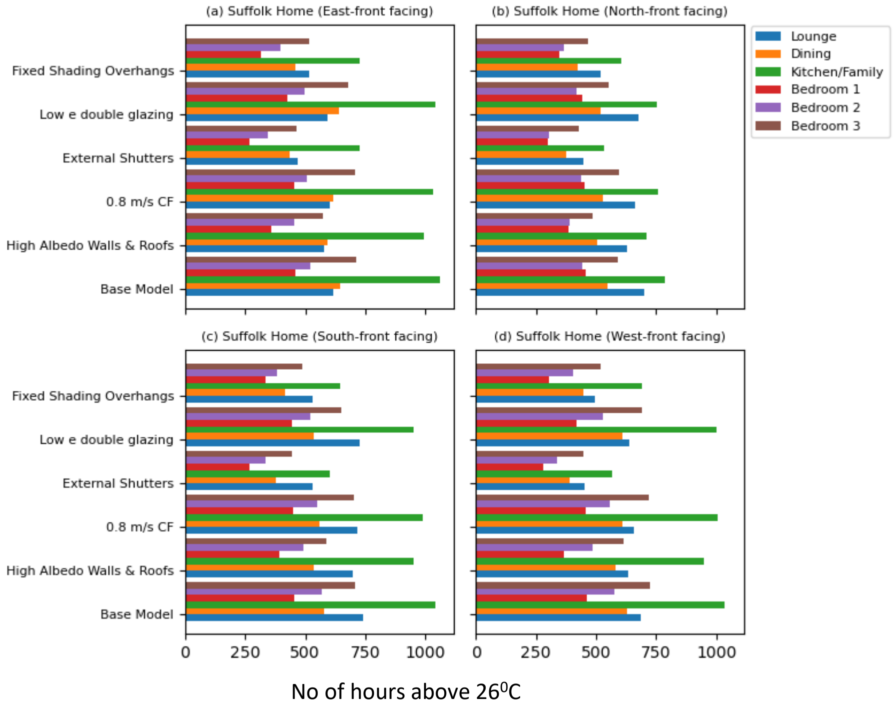


Figure 47: The Effectiveness of different Mitigation Solutions for the Suffolk Home

From figure 47, the degree-hours for all orientations seems rather similar. This could be due to the rather even distribution of windows and doors for all orientations and considering an L-shaped home design. However, the north orientation recorded the least hours of them all at 784 hours for the kitchen/family, compared to 1043 hours for the south orientation, 1062 hours for the east orientation and 1036 hours for the west orientation. It is also clear that the kitchen/family area of the Suffolk home (shown by the green bars) recorded most hours above 26^0C for all four scenarios. This is followed by the lounge area, bedroom 3, dining area, bedroom 2 and then bedroom 1. Based on the base model, the five solutions reduced overheating hours (considering all orientations) by up to 2,054 hours for high albedo walls and roofs, 459 hours for 0.8m/s ceiling fans, 6,382 for external shutters, 1,332 hours for low e double glazing windows, and 4,925 hours for fixed shading overhangs.

6.3.3 Loughborough Home

Figure 48 shows the model IT view of the Suffolk home as modelled in IES. It is a three-bedroom detached house with windows and doors mostly on the front and back orientations and has a hip roof. Figure 48 also shows the modelled sun path analysis for an east-front facing scenario of the selected weather file at different times of the day. This is also accounted for in the simulation.

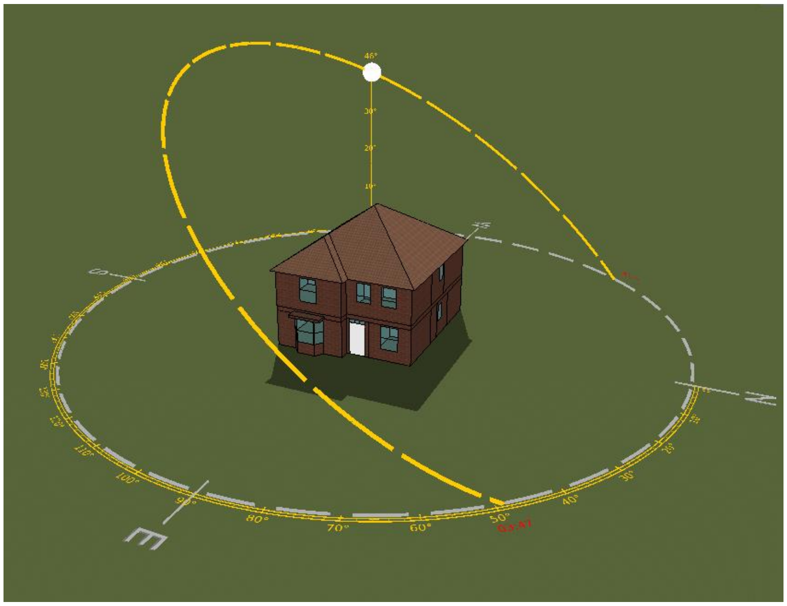


Figure 48: Loughborough Home as viewed in Model IT (IES)

Figure 49 shows the performance of different mitigation strategies for the main occupied areas namely the lounge, study, kitchen/dining and the three bedrooms, with each corresponding to a different colour. All four orientations have been considered.

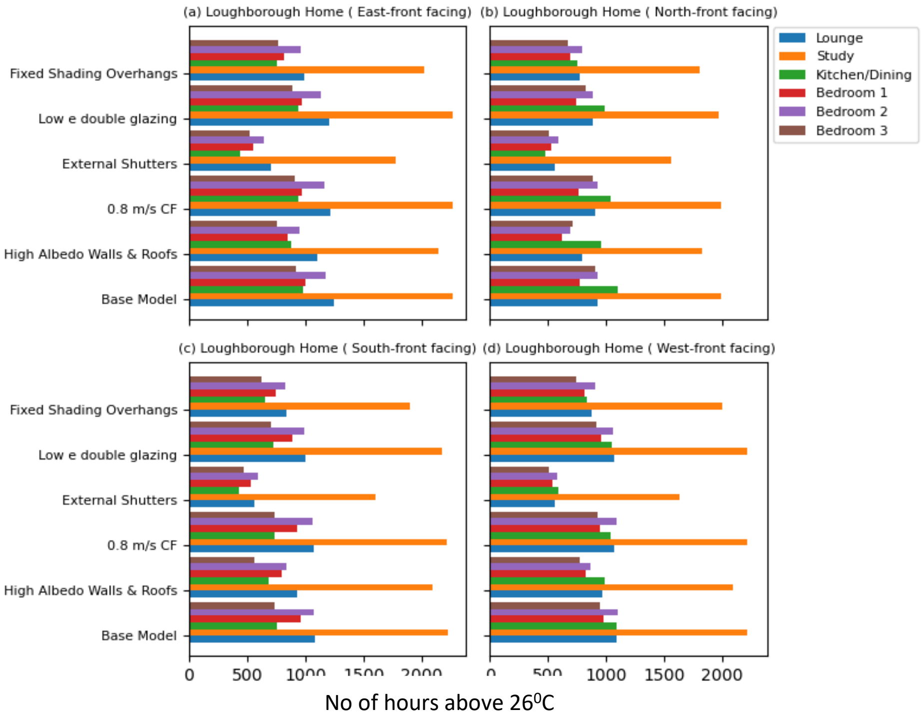


Figure 49: The Effectiveness of Different Mitigation Solutions for the Loughborough Home

From figure 49, the overheating hours for east and west facing orientations seem higher than the north and south orientations. This can be attributed to the sun rising and setting patterns in the east and west respectively, and the front-back window and door distribution. It is also clear that the study area of the Loughborough home (shown by the orange bars) recorded most hours above 26^0C for all four scenarios as compared to other rooms. The study room recorded 1.983 hours, 2,215 hours, 2,223 hours, and 2,269 hours for the north, west, south, and east orientations respectively. These high degree hours reflected in the simulation study of the Loughborough home, are consistent with more overheating hours that were recorded in the sensor monitoring of the actual Loughborough study room as shown in figure 28 in section 5.3.3 in chapter 5 (red line graph). The reason for this could be the lack of cross ventilation for a ground floor study room with a rather small window with only half the glazing area being openable. Also, due to window opening schedules in TM59, it does not allow for nighttime window opening for cooling due to security reasons. This is then distantly followed by the other rooms. Based on the base model, the five solutions reduced overheating hours (considering all orientations) by up to 4,621 hours for high albedo walls and roofs, 490 hours for 0.8m/s ceiling fans, 12,682 for external shutters, 1,159 hours for low e double glazing windows, and 5,668 hours for fixed shading overhangs. The most effective solution for reducing the number of hours above 26^0C in the study room is external shutters by up to about 480 hours (20 days) for the east-front facing scenario.

6.3.4 Birmingham Home

Figure 50 shows the model IT view of the Birmingham home as modelled in IES. It is a three-bedroom end of terrace house with windows and doors mostly on the front and back orientations and has a gable roof. Figure 50 also shows the modelled sun path analysis for a south front facing scenario of the selected weather file at different times of the day. This is also accounted for in the simulation.

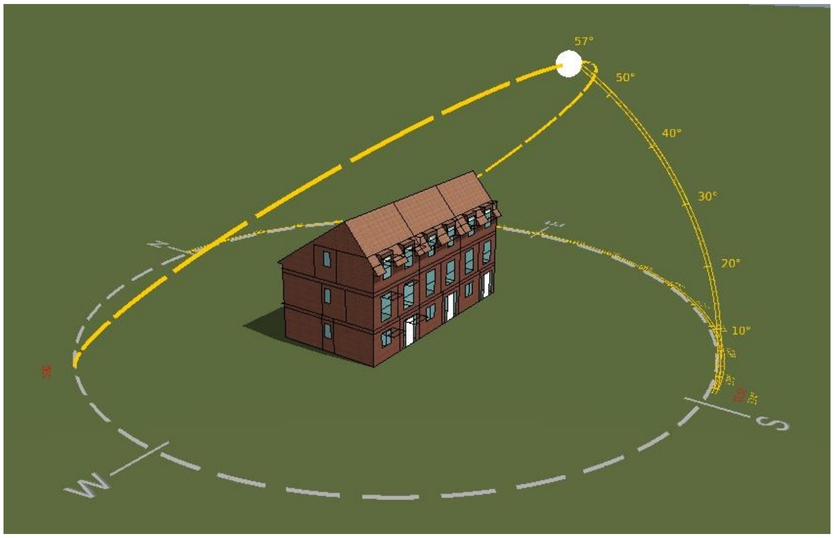


Figure 50: Birmingham Home as viewed in Model IT (IES)

Figure 51 shows the performance of different mitigation strategies for the main occupied areas namely the living/dining area, kitchen area and the three bedrooms, with each corresponding to a different colour. All four orientations have been considered.

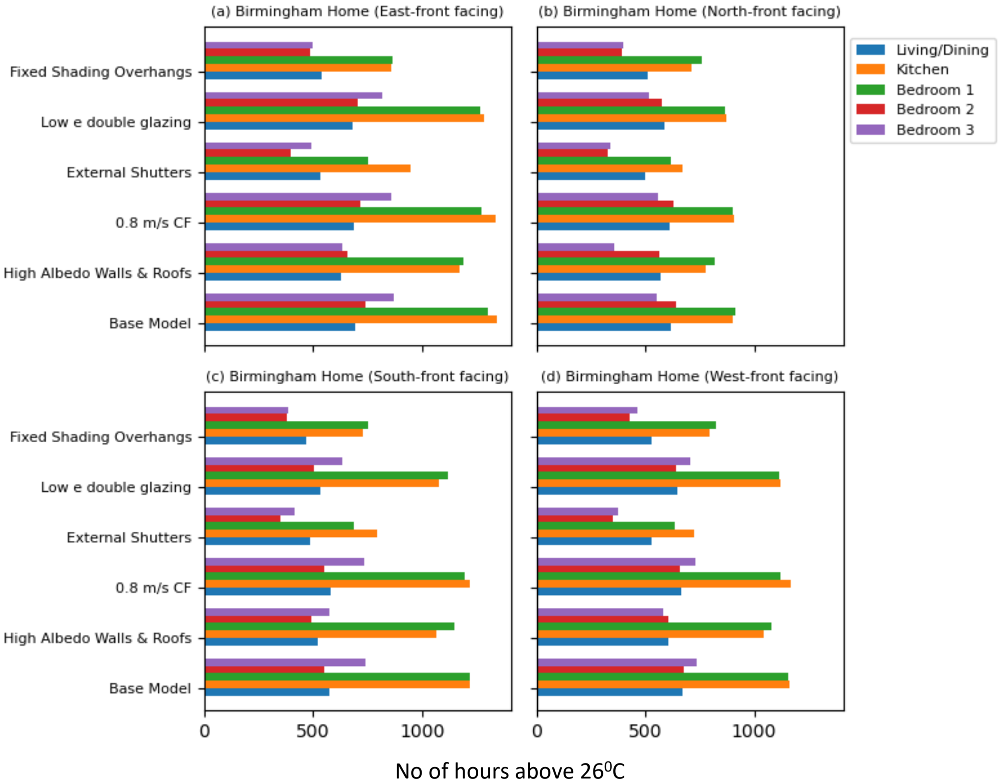


Figure 51: The Effectiveness of Different Mitigation Solutions for the Birmingham Home

From figure 51, the overheating hours for east, west and south facing orientations seem higher than the north orientation. This can be attributed to the sun's rising and setting patterns in the east and west respectively, the front-back window and door distribution of the end of terrace home and the size of the windows. For the kitchen area of all orientation scenarios, the number of hours above 26^0C was 1,342 hours and 1,163 hours for the east and west orientations and 1,220 hours and 904 hours for the south and north orientations. It is also clear that the kitchen area and Bedroom 1 of the Suffolk home (shown by the orange and green bars respectively) recorded most hours above 26^0C for all four scenarios. This could be due to the size and position of the kitchen window and bedroom 1 being in the attic area of the home and its proximity to the roof. Based on the base model, the five solutions reduced degree hours (considering all orientations) by up to 2,205 hours for high albedo walls and roofs, 946 hours for 0.8m/s ceiling fans, 6,379 for external shutters, 1,654 hours for low e double glazing windows, and 5,903 hours for fixed shading overhangs.

6.3.5 Birmingham Flat

Figure 52 shows the model IT view of the Birmingham flat as modelled in IES. It is a 17th floor two-bedroom corner flat with windows and doors mostly on one side of the building and unopenable glazing on one side. The surrounding buildings have been hidden to provide a clear view of the flat. Figure 52 also shows the modelled sun path analysis for a west front facing scenario of the selected weather file at different times of the day. This is also accounted for in the simulation.

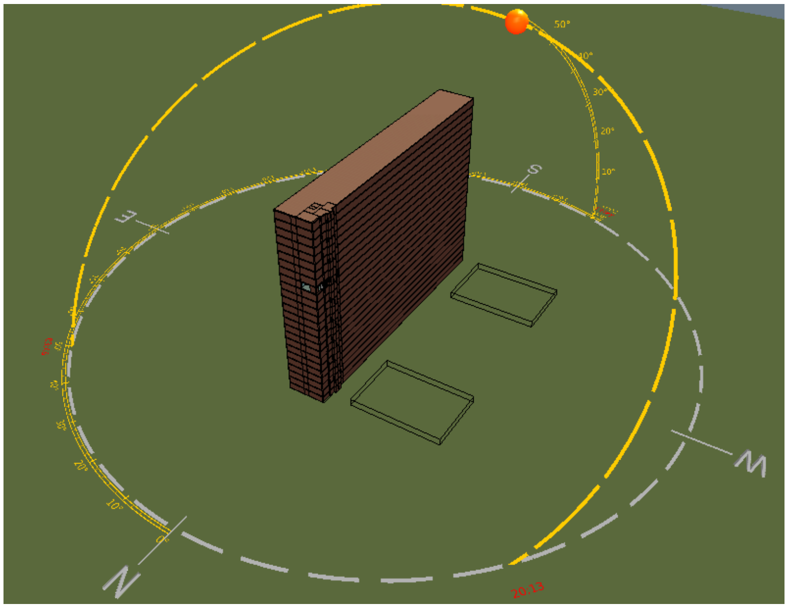


Figure 52: Birmingham Flat as viewed in Model IT (IES)

Figure 53 shows the performance of different mitigation strategies for the main occupied areas namely the living/dining/kitchen area, and the two bedrooms, with each corresponding to a different colour. All four orientations have been considered.

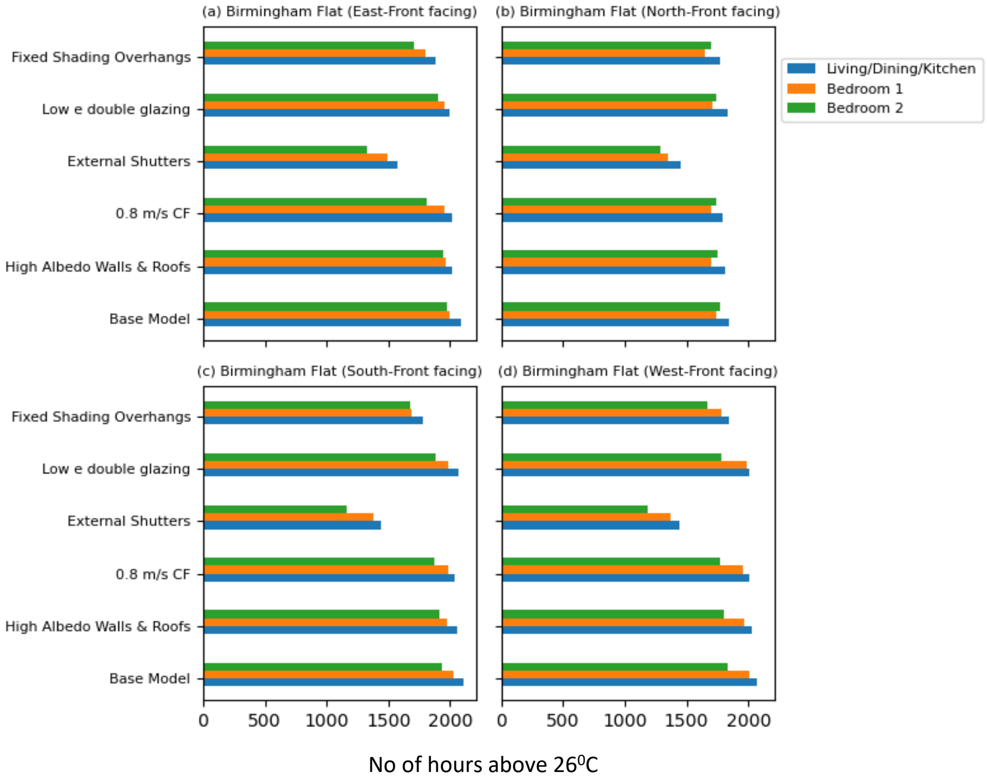


Figure 53: The Effectiveness of Different Mitigation Solutions for the Birmingham Flat

From figure 53, the overheating hours for all orientations seem rather the same, apart from the north front facing scenario, that recorded slightly lower numbers. This can be attributed mostly to the single-aspect nature of the flat design and its position as a corner flat. For all the solutions, all the three rooms seem to have a similarity in the number of hours above 26^0C. The base models recorded the following numbers 2,106 hours, 2,069 hours, 1838 hours, and 2084 hours for the south, west, north, and east orientations respectively. The base model of all solutions seems to have recorded a higher number of hours above 26^0C compared to the singular detached and end of terraced nature of the other four modelled homes. This can be attributed to flats being more prone to higher temperatures than singular detached homes. Based on the base model, the five solutions reduced overheating hours (considering all orientations) by up to 445 hours for high albedo walls and roofs, 735 hours for 0.8m/s ceiling fans, 6,907 for external shutters, 513 hours for low e double glazing windows, and 2,441 hours for fixed shading overhangs. Among all monitored homes, the solutions had the least effect of reducing hours above 26^0C in the Birmingham flat, compared to all other modelled homes. Considering all the solutions for the Birmingham flat, the one that seems to have made a significant difference is the use of external shutters which reduced hours above 260C by 506 hours (21 days) for the living/dining/kitchen area for the east front facing scenario.

The next section analyses the performance of each solution considered in the dynamic simulation modelling.

6.4 Analysis and discussion of Simulation results

Figure 54 shows the effectiveness of all five mitigation solutions for all houses and orientation scenarios combined. The x-axis represents the number of hours when temperature was above 26^0C for all 120 simulation scenarios.

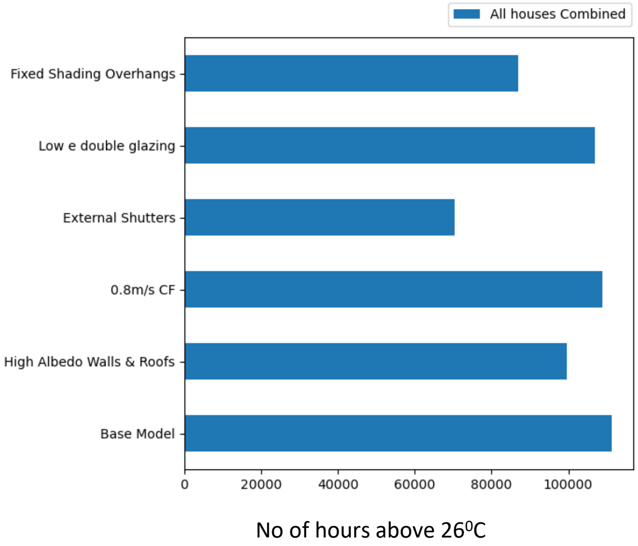


Figure 54: The Effectiveness of Mitigation Solutions for All Modelled Homes

Among all the five solutions considered, the most effective at reducing incidences of higher temperature is the use of external shutters. From figure 54, external shutters reduced the number of hours for temperatures above 26^0C by 37%. This is followed by fixed shading – overhangs by 22%, high albedo roofs and walls by 11%, low e double glazing by 4% and then ceiling fans by 3%. This can be converted to the number of days when these solutions reduced the occurrence of higher temperatures above 26^0C, between May and September. External shutters would reduce this occurrence by 56 days. 33 days for fixed shading - overhangs, 17 days for high albedo walls and roofs, 6 days for low e double glazing and 4.5 days for ceiling fans. The results suggest that the two most effective ways for reducing the occurrence of higher temperatures in homes are the use of external shutters and fixed shading – overhangs. Both methods are aimed at primarily blocking the ingress of unwanted solar gains into rooms (Sivasankar et al. 2016).

This agrees with several studies that point towards the same. In an Arup (2022) report, mitigation measures that reduce solar gain through windows were found to be the most effective. In this report, external shutters were found to be the most effective shading options, followed by internal blinds and internal shutters. In a study by Porritt et al., (2012) external shutters were found to reduce the number of degree hours by up to 39% and were also more effective compared to internal blinds and curtains. In the same study, fixed shading was also found to be effective at reducing degree hours by up to 28%. A study by Taylor et al., (2018), revealed that external shutters were found to be the most effective in reducing heat related mortality by 43%, 40%, and 37% for weather conditions representative of 2030s, 2050s and 2080s summers respectively. Likewise, a study by Hoof et al., (2014) found that exterior solar shading has a very large effect on the number of overheating hours and degree hours.

Overhang shading devices seem to be the most investigated type of shading devices in hot regions. Sghiouri et al., (2018) showed that optimized overhangs reduce cooling demands in a Mediterranean climate by 4.1% and overall improves thermal comfort. The use of overhang shading devices in a hot summer in Cyprus lowered demand on energy by 50% and improved thermal comfort levels by 20% (Ogbeba and Hoskara 2019). Dudzińska (2021) however states that although properly selected horizontal overhangs act as a passive cooling system by blocking solar energy in summer, it could limit heat gain from solar radiation in windows during winter due to the low angular height of the sun. Critical to the shading performance ratio of overhangs is the shading depth to window height, number, and angle of tilt (Alwetaishi et al., 2021)

High albedo walls and roofs are also quite effective in reducing degree hours and overheating hours. Porritt et al., (2012) confirms that coating walls with high performance reflective paint could reduce degree hours over 26^0C by 50 to 60%. Using the same coating on roof tiles was also found to be effective but not as much as on walls. In the Arup (2022) report, solar reflective paint applied to walls gave a moderate reduction in overheating. Solar reflective roofs were also found to be much less effective than the solar reflective walls. A study by Hoof et al., (2014) also found that increasing shortwave reflectivity results in less overheating hours and degree hours, to a varying extent depending on house type. Pisello and Cotanan (2014) agree that high albedo surfaces can reduce indoor operative temperatures by up to 4^0C. A study by Taylor et al., (2018) found that reduced façade absorbance reduced heat mortality by 12 to 15%. Sukanen et al., (2023) adds that high albedo surfaces can be effective at reducing overheating in dwellings with low levels of roof insulation. Also, its widespread adoption in urban dwellings can reduce the urban heat island (UHI) effect. However, Sukanen et al. (2023) cautions that it may not be as effective in well insulated homes, and it could increase heating requirements in winter.

This research also points out the moderate effect of low double e glazing on reducing hours when temperature exceeded 26^0C from May to September. Low e double glazing has a low g value (in this case 0.45), signifying a reduction in the total solar energy transmitted through the glazing. The lower the g value, the lower the solar transmittance. Low e double glazing also incorporates a near visible coating on the inner surface. The coating achieves the dual effect of allowing daylight in, while rejecting solar heat. The Arup (2022) report confirms that low g value glazing is moderately effective at reducing criterion 1 of TM59 and reasonable effective for Criterion 2. A study by Basok et al., (2016) also shows that the replacement of one of the panes of a double-glazed window to a low emissivity glass significantly increases the heat resistance of a glazing unit as it reduces heat flow by about 27%. Therefore, there is a significant reduction in solar transmittance through glass.

According to this research, ceiling fans reduce the degree hours by 3%. The Arup (2022) report confirms the effectiveness of ceiling fans for most home types. The fan-generating cooling effect produced through elevated air speeds can offset thermal discomfort in high temperature environments (Melikov and Dzhartov, 2009). In such situations, the energy used to increase air speed is much lower than the energy used to lower the temperature, while maintaining an equivalent thermal comfort condition (Hoyt et al., 2015). Additionally, the use of fans can reduce heat stress in heatwave periods as they considerably enhance the amount of sweat that evaporates from the skin (Tartarini et al., 2022). Compared to air conditioning, Jay et al., (2019) states that moving air instead of chilling it produces more sweating, however, it saves on electricity use.

Though this research focused on standalone mitigation measures, different exclusive combinations of mitigation measures could be more effective. Combinations of different mitigation options such as high albedo walls and external shading would create package options that would be more effective (Gupta et al., 2021). In Oikonomou's et al., (2020) research, the most effective passive overheating reduction measure was a combination of external window shading and increased ventilation through larger openable window areas. In the work done by Grussa (2019), external shading combined with nighttime ventilation were stated as the most effective passive mitigation solutions.

The effect of these mitigation solutions is also affected by orientation. For most home designs with most of their windows on the front and back, more overheating hours were recorded for west-front facing designs and east front facing designs. This is due to the sun's path. Pana (2013) mentions orientation as a significant modifying factor of overheating. In Porritt et al. (2012), building orientation was discovered to have a substantial impact on overheating exposure varying by almost 100% between different orientations. The greatest overheating was seen when windows face west as they are exposed to low angle solar radiation for most of the day. In Gupta and Gregg (2020), solar gain implications due to orientation were noted especially for west-facing facades which are also difficult to shade. For such cases, fixed vertical shading or external shutters would be the most effective interventions.

The next section goes into more detail in discussing the scalability aspects of these overheating mitigation solutions.

6.5 Scalability of overheating mitigation measures

For overheating mitigation measures to be effective and implementable, they need to be seen to be cost-effective and scalable by volume builders. Scalability is the ability of a system to accommodate an increasing number of elemental change while processing growing volumes of work without failing (Bondi, 2000). Scalable solutions are choices that when introduced, will still work without many disruptions. This is vital for volume builders who aim to increase the volume of their output year on year. This section analyses each of the five overheating mitigation solutions presented in the previous sections of this chapter, through the five aspects of the scalability criteria proposed in Chapter 4; cost implications, point in the development process when a decision needs to be made and who needs to be involved, the resilience to supply chain dynamics, and occupant involvement and perception.

To assess the scalability of overheating mitigation measures, the five aspects of the scalability criteria proposed in this research are applied to all five measures. Estimated quotes from RICS, Energy Saving Trust and Manufacturers websites were used to assess cost implications. Supply chain resilience was analyzed by considering aspects of material availability, delivery timelines, compatibility, skilled labour, and training needs. This is based on supply chain analysis from Chapter 4. Customer perception was analyzed by a literature review exploration of assumed customer expectations regarding visual appeal, ease of operation, effects on energy bills, health priorities among others. The home development stage criterion was used to reflect on when a decision needs to be made regarding a solution, and the last column looks at stakeholders that should be involved. These analyses were accompanied by examples of use in UK case studies and learnings from such.

The scalability analysis of the overheating mitigation measures presented in this research is summarized in table 26.

Table 26: Summary of Scalability Analysis of Overheating Mitigation Measures

	Cost Implications	**Occupant Perception**	**Supply Chain Resilience**	**Home Development Stage**	**Stakeholders Involved**
External Shutters	£3,100-5,600	Aesthetic concerns Restricts views, daylight, and airflow. Heritage values Incompatible for outward opening windows	Could cause a strain when mass production is required	Preplanning stage	Overheating Assessors, Ventilation Manufacturers and Suppliers
Fixed Shading Overhangs	£3500 - £21,000	Aesthetic concerns Restricts views and daylight. Potential damage from storms and debris build-up Fire resistance concerns	Could cause a strain when mass production and installation is required	Preplanning stage	Overheating Assessors, Shading manufacturer/supplier Wind analysis expert, Fire analysis expert

High Albedo walls and Roofs	£1,500-£9,500	Aesthetic concerns Increased heating requirements in winter	May be readily available for mass homes	Preplanning stage	Overheating Assessors, Solar reflective paint supplier
Low e double glazing	around £7,500.	Restricts daylight between 20%-80% Damage to indoor plants. Low scratch resistance for soft coated glass	May be readily available for mass homes	Preplanning stage	Overheating Assessor, Ventilation Consultant, Glazing Manufacturer/Supplier
Ceiling Fans	£500-£4,000	Aesthetic concerns Air con more preferred Implication on energy bills	May be readily available for mass homes	Ideally at the design stage but can be implemented later. Ceiling height should allow for it	Overheating Assessor, Ventilation Expert, Manufacturer/Supplier

The next section provides more information on the scalability analysis summary presented in Table 26 by analyzing each mitigation measure through these five criteria.

6.5.1 Cost Implications

Home development occurs in a free market largely governed by cost. For home developers, consideration of cost is a key element of evaluating change as margins are slim. In Farmer's (2016) review he states that *"low profitability is a long-standing problem for the industry".* As a result, developers are stuck in a cycle of maximizing profits, achieving compliance, and continuing with traditional construction methods (Mayouf et al., 2022). Therefore, a key element for assessing the scalability of overheating mitigation measures is cost.

The Arup (2022) report considered the cost implications of overheating mitigation measures by assessing their cost as applied to specific London home archetypes at a per sq/m Gross Floor Internal Area (GIFA) rate. Of the fifteen measures considered in the Arup (2022) report, the five measures considered in this research performed as follows; The most expensive was the replacement of windows with low g value glazing (£200 -£300 per m^2 GIFA), followed by external shutters (£100-£200 per m^2 GIFA), then fixed external shading (Around £100 per m^2 GIFA), the use of solar reflective walls and roofs (£50-£100 per m^2 GIFA), and lastly the cheapest was the use of ceiling fans (under £50 per m^2 GIFA). Another study by Nazarian et al., (2022) agrees that ceiling fans are the most affordable and market ready solutions for increasing air movement in indoor built environments. However, it is worth noting that the Arup report considered a refurbishment approach to determining these costs. Therefore, these costs included costs related to scaffolding, costs involving builders' work to make good, and even access equipment costs.

In a study to rank overheating interventions during heatwaves, Porritt et al., (2011) considered the cost implications of several interventions. He considered solar control measures, insulation, and ventilation measures on a whole dwelling basis. According to this study, external shutters would cost £3300 per dwelling, fixed shading would cost around £1300-£2200 per dwelling depending on orientation, high albedo walls and roofs would cost £1700-£2200 per dwelling depending on property type, and low e triple glazing would cost £5100 per dwelling. Not one single source was relied on to provide these costs. The cost for High albedo walls and roofs alongside fixed external shading were obtained from Langdon (2004). The Royal institution of Chartered Surveyors Building Information Cost Service (2009) was used to derive glazing costs. External shutter costs were obtained from commercial quotes. Additionally, these costs excluded tax and were obtained between 2009 and 2011.

The Arup (2022) report assessed the cost of overheating measures from a refurbishment perspective and included other associated costs such as scaffolding, costs related to making good and even equipment costs. The Study by Porritt et al., (2011) is based on quite outdated figures and it considers a refurbishment approach as well. This research, however, considers the up-to-date cost implications of overheating mitigation measures from a new build perspective. This therefore allows for the inclusion of savings that are associated with design decision making at the early stages of home development. Table 27 summarizes the cost implications of the five overheating measures investigated in this research and highlights their sources. This research acknowledges that Table 27 does not contain exact figures but rather speculative ranges of costs. This is considered adequate as the main aim was to use it as a stimulus to engage home developers in an evaluation of the proposed scalability criteria of overheating mitigation solutions.

Table 27: Cost Implications of Overheating Mitigation measures

Mitigation measure	Cost Implications	Source
Fixed shading Overhang	From £3,500 for overhangs including installation For a typical home requiring around 6 overhangs, Total cost per home is from **£3500 - £21,000**	Price from available commercial supplier Cb solar shading
Ceiling fan	Ceiling fan and installation cost @£100-£800 per unit For a 3-bed house with ceiling fans in main areas; kitchen, Livingroom, and bedrooms (5 rooms), Total cost per home is around **£500-£4,000**	Prices from available commercial suppliers e.g., Checkatrade, Costco, Creoven, Henley, Illumination
External Shutter	Exterior shutter and installation cost **@£310-£560** per m2 For a typical home requiring 10m2 of external shutter, Total cost per home is **£3,100-5,600**	Commercial suppliers e.g., Checkatrade, Enviroblinds
Low e double glazing	A set of A-rated windows for a semi-detached house will typically cost around **£7,500.** 6mm low emissivity glazing @ **£56.50m^2** per unit.	Energy Saving Trust BCIS 2022
High Albedo Roofs and Walls	Solar reflective paints @ **£50-£400** per 5L can 2.0 sqm per liter application area 90 m^2 wall area and 135m^2 roof are for typical single home. Paint Sprayer rate @ **£18.65** per hour.	Prices from available commercial suppliers e.g., Rawlins, Resincoat, Paintoutlet, Valsparpaint etc. Wall and roof areas estimated form averaging the sqm of monitored and modelled homes. Paint Sprayer rate from BCIS (2022)

	Assuming work for 8 hours by a gang of 2 Total cost per home is **£1,500-£9,500**	

From the average values shown in table 27, fixed overhang shading options are the costliest, at around £21,000 per home, external shutters cost between £3,100-£5,600 per home, low e double glazing at around £7,500 peer home, high albedo roofs and walls costing between £1,500-£9,500, and ceiling fans being the cheapest at around £500-£4,000. Though these are average figures not meant to be definitive, they provide perspective as to the indicative costs associated with overheating mitigation measures for new homes. Costs related to external shutters and low e double glazing could be lower when compared to conventional windows already in use. They exist as replacement items as other window designs already exist as part of new build costs. The other measures, however, are additional costs that are not normally incurred in the typical building process of new homes in the UK. Additionally, the costs of all interventions will vary significantly in practice due to differences in logistics, house typologies, material considerations. Volume builders are also likely to benefit from economies of scale due to the high volume of new builds and targeted discounted-rate supply chain contracts with manufacturers and suppliers.

6.5.2 Occupant Perception

The perceptions and concerns that occupants may have about overheating mitigation measures are key to scalability. For Home developers to implement changes, such as the ones described in this research, home occupants' concerns must be considered. Without this, sales/rents of their homes would go down, and so profitability. Putting aside the effectiveness of overheating mitigation measures, the role of occupants needs to be adequately recognized. When investigating occupants' motivation to climate-related overheating, Murtagh (2019) described occupants as "gatekeepers" of the domestic building stock. Therefore, in striving for resilience to a warming climate, the willingness of occupants to accept necessary changes to home design cannot be overlooked.

The overheating mitigation measures considered in this research are common in most countries with warmer climates and are already part of the fabric of their homes. However, in the UK, home design is adapted to suit the historically cooler climate. Therefore, it is expected that most overheating mitigation measures could encounter cultural challenges due to, perceived effectiveness, aesthetic concerns, practicality issues, heritage concerns, energy consumption, and occupant behaviour (Arup, 2022, Nazarian et al., 2022, Schünemann et al., 2020, Elsharkawy and Zahiri, 2020, Wise et al., 2021). For the five overheating mitigation measures described in this research, these are the barriers in relation to occupant perception.

The implementation of external shutter interventions and fixed shading overhangs could be perceived by occupants in different ways. Its use could lead to an undesirable aesthetic (Arup, 2022), loss of view and low daylight levels especially during winter (Porritt et al., 2011). A UK study done by Wise et al., (2021) on resident's views and values found that external shutters were viewed as unacceptable to many of the residents due to their effects on heritage values. External shutters are also not common in the UK because current construction practices means that most UK home window designs open outwards (Mylona, 2019). Its implementation would require the redesign of windows to open inside. Depending on design, fixed overhangs could collect debris like leaves and make it difficult to clean and maintain. There could also be a concern about possible damage due to stormy conditions and heavy snow loads in winter (Sukanen et al., 2023). Additionally, the fire performance of materials used for overhangs could cause concern.

High albedo walls and roofs would constitute of light-coloured walls and roofs that would change the colour of homes from the traditional red brick walls and dark colored roof tiles that many are used to. Additionally, as high albedo walls and roofs would reflect much of the solar heat from homes, there are concerns that it could lead to an increase in heating requirements in winter (Sukanen et al., 2023).

Ceiling fans are not common in most UK homes; therefore, their presence would be something that occupants could take time to get used to. There could be aesthetic concerns related to having an object panning in a space (Chappells & Shove, 2005). Also, ceiling fans consume energy and could therefore be of concern to occupants regarding energy bills. For vulnerable occupants who heavily rely on it, it could cost more.

As low e double-glazing high-performance windows do restrict the entry of excessive light and heat, they could lead to the dying of indoor plants for occupants who like to place them by the window. Depending on the specification, low e double glazing windows could reduce direct sunlight into a space by around 20% to 80% (Somasundaram et al., 2020). While this would be mostly fine, it could be an issue in winter when low daylight levels are experienced.

However, most of these overheating mitigation solutions have been used in other warmer climate countries for decades and are part of the architectural character of their buildings. This therefore suggests that the occupant perception of overheating mitigation solutions described in literature, is not only static, but could partially be a resistance to change. This is consistent with the adaptive thermal comfort theory that states that "*If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort". *(Nicol and Humphreys, 2002, p. 564). Therefore, occupant perception presented in literature could be actively changing based on prevailing thermal conditions. In this research, the occupants of monitored homes were engaged through thermal comfort questionnaires periodically through the monitoring duration. Four of the five home occupants recommended the need for external shading options for effective overheating mitigation. Low e glazing, blind control, and use of internal fans were also recommended.

6.5.3 Supply chain resilience

For overheating mitigation solutions to be scalable to a mass scale, dependable supply chains for both materials and labour are vital. Supply chains are the only way developers can obtain specific resources from external parts of their enterprises. However, supply chains are vulnerable to unpredictable market conditions, such as supply network disruptions that lead to longer lead times. The 2020 pandemic, geo-political issues, and the Suez Canal blockage are good examples of unpredictable market conditions that affected global construction supply chain networks. Such disruptions lead to increases in shipping, logistics and warehousing costs. As such, developers have to integrate, build and reconfigure internal and external competencies to address rapidly changing market environments (Kochan and Nowicki (2018). As management strategists have argued, supply chain resilience has become the ultimate competitive advantage (Pettit et al., 2010). How reliably available products or materials are, is a major factor in a firm's preferences when considering what to specify. (Brocklehurst et al.,2021). Therefore, the resilience of supply chain networks becomes critical when considering the scalability of overheating mitigation measures.

There are already several companies in the UK that specialize in the manufacture and supply of high specification glazing products, ceiling fans, and solar reflective paints. Since most of these companies are in the UK, developing resilient supply chain networks with such companies would be much easier than if they were located elsewhere. This could translate to shorter lead times, just-in-time deliveries, and fewer supply chain disruptions. Ceiling fans are also commercially available and are already in use as most UK households use portable fans as a means of keeping cool in hot weather periods. Therefore, there is already a market for fans and supply chains already exist. Similarly solar reflective paints are widely available in the UK market. The supply chain for these materials is well established because they are mostly used for commercial buildings, offices, and high-rise homes. However, external shutters and fixed shading overhangs may not be readily available if they are to be installed at a mass scale. These measures are not common in the UK mainstream residential brick and block housing market and therefore their demand is low. Although forms of external shading and fixed overhangs are already used in commercial buildings in the UK, they are not commonly used in individual brick and block home typologies.

Labour availability is also a critical aspect of supply chain resilience. The introduction of overheating mitigation measures in new builds in the UK will not be possible without a well-trained labour. A House Builders Survey by the Federation of Master Builders in 2021 showed that 53% of its small and medium-sized contractors had difficulty finding workers. A CITB (2023) industry report revealed that almost 225,000 new workers will be required to meet UK construction demand by 2027. A Guardian (2023) report shows that the cost of labour has increased by 30% since the 2016 referendum with an expected rise in build cost of 2.5%. Therefore, when considering which overheating measure to employ and how, labour-related ramifications such as labour availability, training costs, numbers needed, need to be considered.

6.5.4 Home Development Decision Making Stage and Stakeholders Involved

The stage in the home development process when a decision on a mitigation solution is made is key to the success of that solution. Fundamental design decisions taken at the earlier stages of design have far reaching environmental impacts later (Baba et al., 2013). Measures that are detrimental to the design of newly built homes should ideally be introduced at early stages of design, when planning approvals have not yet been obtained. Stevanovic (2022) argues that passive measures should be considered early on in a build process, prior to energy consuming strategies.

Baba et al., (2013) proposed a RIBA-referenced Decision Support Framework (Appendix 11) with sustainability and environmental design decision tasks, and the characteristics of simulation tools that fit the intrinsic was that architects make decisions at different stages of design. The framework deals with aspects of design such as appraisals of building orientation, topography, site usage, sun path, air exchange rate, building shape, insulation, and glazing, building shape, orientation, solar control, material selection and lighting strategy. Though this framework focuses only on the design stage, it provides a sequential analysis of when decision making steps that are vital to building performance are to be made.

The Technical Guidance of the new Part O Overheating (2021) by the Future Homes Hub also provides a timeline (appendix 10) of when key decisions need to be made regarding overheating considerations. It suggests several actions with the following steps: portfolio appraisal, site selection, early design (up to planning), design development, building control design submissions, construction, and building control as-built submissions.

Having analyzed these two timelines, and work from this research (chapter 4 on Home Development Process), this study underscores that “when” a decision is made in the development process is vital to building performance. The implementation of external shutters, fixed shading, low e double glazing, and high albedo walls and roofs, involve detrimental changes to the typical design and look of home typologies in the UK. Therefore, these measures need to be discussed at the early stages of development, preferably in preplanning. Making design-related changes after planning approvals can be costly and time consuming. According to government timelines, planning approvals should take between 8 -13 weeks, however, this could take longer for complex projects. The use of ceiling fans, however, can be considered at later stages of home development through non-material amendments (NMAs) if ceiling heights are high enough.

The implementation of these changes also requires that relevant stakeholders are involved at the appropriate stages of home development. It is vital that an overheating assessor/ modeler, consultant is engaged earlier on to provide analysis on building form (glazing, ventilations, window sizes, fabric) vis a vis site conditions (noise, shading, greenery,) to ensure building compliance. As this research has pointed out, it is vital to engage assessors, contractors, manufacturers, and suppliers early in design, so that they can provide input before planning approvals are obtained (Emiliani, 2000; Envirowise, 2001). Their capabilities can only be fully captured when there is still scope to influence design.

6.6 Evaluation Workshop Outcomes

This section presents the responses of evaluation workshops with industry collaborators on the scalability criteria summarized in Table 26 that was used as the stimulus for discussions. These evaluation responses are presented for each developer, followed by a combined SWOT analysis for each overheating mitigation solution that was considered.

6.6.1 Home Developer 1

External shutters were seen to be difficult as they would be *“such a radical change to the UK.”* Its impact on window opening direction was also noted as incompatibility with typical window openings in the UK. Fixed shading overhangs were also seen to be a new strategy to UK home designs; *“it would be again a big change.”* However, there was a mention that canopy designs that are movable and could be hidden above window heads are being considered over patio doors. These were noted to be expensive. The use of solar reflective paint on walls and roofs was also considered a new technique that is not popular with UK new build. Its effects on the façade were noted and possible implications with planning. Its regular maintenance was also considered to be demanding and costly in the long run. Low e double glazing was seen as a *“probably good”* option as supply chains could be reasonably certain. Another form of solar control glazing; triple glazing was mentioned as being used for new houses going forward. Ceiling fans were considered *“a good option to explore and then sell as it is a simple one.”* Ceiling heights were noted to be high enough for most developer home designs and the possibility of using *“fairly flush”* fans. In conclusion, the use of patio canopies, solar control glazing and ceiling fans were considered as options with a high potential in the UK market.

The costs presented were largely agreed, but it was noted that lower rates could be achieved with supply chain negotiations. Supply chain concerns were shared, and it was noted that diligent negotiations are needed. Occupant perception was noted to be the highest priority when deciding which options to go for. Options that would provide a tangible benefit to occupants were seen to be favoured. Solar control glazing was seen as a tangible option because it would be seen as a good selling point to help lower energy bills. Occupants were perceived to be nervous with external shutters as they are not used to them. As shutters would alter the window opening direction, it was considered unfavourable as people like putting pictures or flowers on their windowsills. Canopies over patio doors were considered beneficial to occupants as it offers other benefits such as BBQ place apart from typical shading. In the proposed scalability criteria, customer perception was considered first, then supply chain, then cost.

When considering the development process, it was mentioned that supply chain companies were now being involved through the whole process, to provide input on possible solutions, volume forecasting, risks, and contingencies. The design process was noted to be largely taking place at a group level. However, Part O Overheating (2021) analysis was noted to take place at a business unit level because there are different weather files for different parts of the country. So, overheating assessment, ventilation analysis and related technical works are considered in the design stage, alongside responsible stakeholders. In terms of skills availability, the mass implementation of ceiling fans and solar control glazing was presumed to be okay. However, for the other options, supply chain data is not clear, but "*it is on our radar.*"

In the future, air conditioning and Mechanical Ventilation with Heat Recovery (MVHR) were seen to be possible in certain situations. However, their negative impact on current SAP applications was noted. Fixed shading for certain elevations that are getting more solar gain could be a future possibility, subject to considerations.

6.6.2 Home Developer 2

Low e double glazing was considered to not be effective as their homes usually have large, glazed areas that are part of their unique selling product (USP). This means that even with a reduction of the g value of windows (up to 0.37), it still would not pass the Part O Overheating (2021) regulation. The benefit of brief summer cooling vis a vis the need for more solar gain in long winter periods in the UK, was seen as a detriment for Low e double glazing. It was considered as *"probably putting too much emphasis on overheating, they should really be concentrating on energy efficiency."* For external window solutions like shutters and overhangs, the general perception was that "*I think we'd struggle.*" However, the relevance for this was on large patio doors that are part of their Unique Selling Product (USP). It was noted that they like to keep a large open plan area at the back of the house with large, glazed areas with bifold doors. To keep that, external canopy solutions that are stylish will probably be investigated. However, this would only be pinpointed for certain elevations, certain glazed areas such as patio doors, and certain locations across the country. Based on their assessment, houses are not failing as a whole, they are failing with specific rooms in specific orientations. A combination of low e double glazed window units that come with shutters was suggested as an option that could potentially look good and go well. Its extra cost would mean that it would only be applied to certain places. Ceiling fans were thought to be great in terms of acceptability and flexibility. They were considered passive, and if customers were not happy with them, they would have the option of taking them off. High albedo surfaces were seen to not be ideal as it would not be consistent with their unique selling product that is predominantly brick. Mitigation measures that can be integrated into the building fabric than actually be added externally were preferred. They "*would rather do in the building than add on to the building."* More resistance is to be expected for things that go on the outside of houses than the ones inside. The overheating methodology was however noted to not allow less intrusive measures such as internal blinds as part of assessment.

Occupant perception for overheating mitigation was also considered to be important. However, it was noted that according to them, occupants are more concerned about keeping their houses warm than keeping them cool. "*Maybe there is something in it and houses are overheating, but to be perfectly honest, you're talking about three or four weeks out of the year where it it's getting uncomfortable."* Options that give customers better control were preferred. "*If the customer decides, they don't want them, they can take them out. I think there needs to be certain things in the building that ultimately the customer can take it upon themselves to change.* "Supply chain concerns were noted to not be critical unless everybody suddenly starts specifying a particular type of product and the market becomes completely saturated. The construction industry was noted to be quick at ramping up if something is needed. The cost implications of overheating solutions if implemented, were noted to be absorbed and not passed to the customer. This would apply to cases where they must implement certain measures for a few houses in a development, maybe based on orientation or something else. If it was something that would have to be done for many homes, that would be made to be one of the selling points of the homes.

Their overheating assessment follows a national type of approval scheme where are national design standard is assessed based on extreme scenarios and weather files with an aim to overengineer homes. It was found to be easier to have a standard product that is nationally accepted. Regarding the development process and overheating, it was noted that most overheating assessment occurs too late and that in many developments, they are having to retrospectively apply mitigation measures to an existing product. This was noted to have led to massive delays. It was noted that they are constantly having to change drawings to issue to site when they have already gone out to tender, and figures agreed. As a result, this was felt to be distracting from the main driver of building more homes amidst a massive shortage. The knowledge within the housebuilding sector about the Part O requirement is still growing. As a result, there was thought to be a skills gap within the homebuilding sector of people involved in overheating, hence the need to outsource.

6.6.3 Home Developer 3

External solutions such as fixed shading and external shutters were considered not ideal due to incompatibility issues with the standard design character of the developer product. Also, occupant perception concerns especially related to aesthetics were echoed.

The use of solar reflective paint for high albedo external surfaces was also not considered ideal as it was not considered to be what their customers would like. Also, implications on Fabric Energy Efficiency performance rates (FEEs) were mentioned, and the possibility of its effects on Standard Assessment Procedure (SAP) figures that are vital for compliance.

Low e double glazing was seen as an ideal option but was considered hindered by regulation (Part O Overheating, 2021) requirements on security and noise. It was noted that more research is needed to understand the impact of noise and security on occupant window opening behaviours and occupant acceptance levels. *"Will occupants actually not open their windows?"*

Ceiling fans were seen as the most ideal and immediate solution. However, their impact was considered little, and more research on comfort and temperature is still needed to better understand the impact of ceiling fans on *"feel"*/operative temperature using black bulb testing.

Internal shading was considered an ideal solution that was not included in the five solutions assessed. Its exemption from overheating regulation was questioned and it was noted as disappointing. More research and justification for its consideration was noted.

6.6.4 Housing Association

Fixed shading was considered an actual solution with a good chance of being effective. The aesthetic concerns of occupants regarding fixed shading were considered surmountable as nice-looking aesthetic designs could be created to overcome that. Adaptive shading options with sensors that automatically regulate the angle of tilt depending on the sun's position was considered to be a better futuristic option but with high-cost considerations. The use of solar reflective paint was thought to be tricky considering the maintenance requirements that would be needed. Considering this, a light-coloured rendered wall was preferred over solar reflective paint being applied on brickwork. It could reduce maintenance requirements and be a more feasible option. However, not all external solutions were considered ideal. External shutters were not seen as ideal because they would require end users to open and close them when needed; a responsibility that was perceived to be a challenge to most home occupants. Low e double glazing was considered a fairly good option. Occupant concerns about slightly lower daylighting levels from low e double glazing was considered minimal as occupants would get used to them when they enter a new build that has them. It would be different if they were retrofitted to replace standard double-glazed units. Also, ceiling fans were not considered ideal because of high ceiling height requirements and that the responsibility for their use and operation is based on home occupants. Maybe automated ones would be an option. Ceiling fans were also considered as a little unaesthetic and could cause damage to vulnerable occupants like children. Robust solutions were considered as the ones that do not require occupant involvement or not to be interfered with by occupants. In summary, fixed shading was considered the most cost effective if it is designed early-on to look aesthetically pleasing and it involves no occupant involvement. This would be followed by light-coloured rendered walls and then low e double glazing.

Regarding the developmental stage of decision making, most solutions; high albedo surfaces, external shutters, fixed shading, and low e double glazing, were preferred to be incorporated as early as possible into design. Cost was considered a major factor as financial consideration for solutions involves replicating the numbers into hundreds of plots and factoring in additional construction costs for accompanying works. Supply chain concerns were downplayed as it was considered that industry has learned a lot from supply chain disruptions that were synonymous with the 2020 pandemic and geopolitical issues. As most of the solutions involve fabricated metal, many UK companies were considered able to do that if the need arises.

Developmental processes were still thought to be largely unchanged, with overheating concerns *"still largely being an afterthought"*. The capacity for "*decent and competent*" overheating assessors in the industry was also highlighted as a challenge given the requirements of the new Part O for Overheating. Also, it was mentioned that much needed to be done to integrate overheating assessment into design, to involve the architect, ventilation manufacturers and overheating assessors. The involvement of manufacturers and suppliers in the development process was mentioned to still occur very late and there is potential impact. However, it was noted that only suppliers that can have an impact on building design and layout features that are needed for planning should be involved at earlier stages.

Internal blinds were considered a good option however, they were recognized as not considered under the new overheating regulation Part O Overheating (2021). Green walls were also proposed as a future solution as it could help reduce indoor temperatures and meet biodiversity requirements; tick two boxes at the same time. As the Future Home Standard (FHS) advocates for heat pumps rather than boilers, the ability to use heat pumps as air conditioners in future was proposed as a worthy future solution. Air to air heat pumps could be reversed in summer to act as air conditioners. The additional energy consumption was perceived to be offset by installation of Photovoltaics (PVs) to offset energy requirements.

6.6.5 Combined SWOT analysis of Evaluation Workshops

This section presents a SWOT (Strength, Weaknesses, Opportunity, and Strengths) for the five overheating solutions considered based on industry evaluation of the scalability criterion summarized in Table 26. Table 26 was used as a stimulus to allow for discussions in evaluation workshops with home developers. A combined SWOT analysis representing the views of all the developers is shown Table 28 and discussed in the next section. The developers' views are represented in different colours; the ones in black are for Home Developer 1, blue comments for Home Developer 2, orange comments for Home Developer 3 and red comments for the Housing Association.

Table 28: A Combined SWOT analysis of the Scalability Criteria

External Shutters	
Strength	**Weaknesses**
• Effectiveness in overheating mitigation noticed	• Incompatibility with typical window opening designs in the UK. • Could be expensive. • Occupants could be deprived of internal windowsills. • Would require occupants to operate
Opportunities	**Threats**
• Low costs could be achieved with early negotiations. • Have window units that come with shutters to applied to certain places. • Costs can be absorbed if selectively applied. • Other design options like tilt and turn would still preserve windowsills. • Inward opening windows would be easier to clean	• Such a radical change • Occupants could be nervous. • Labour and Skills concerns • Perceived resistance from occupants • Incompatible with Unique Selling Product (USP) • Occupant concerns with aesthetics
Fixed Shading Overhangs	
Strengths	**Weaknesses**
• Effectiveness in overheating mitigation noticed. • An actual solution with a good chance of being effective	• Could be expensive
Opportunities	**Threats**
• Use in canopy designs that can be movable and hidden above window heads over patio doors. • Low costs could be achieved with early negotiations. • Offered BBQ places for occupants. • Application for specific orientations only • Stylish external canopy solutions for certain elevations, certain glazed areas and certain locations across the country should be investigated. • Costs can be absorbed if selectively applied.	• Such a radical change • Possible labour and skills concerns • Perceived resistance from occupants • Incompatible with Unique Selling Product (USP) • Occupant concerns with aesthetics

• Aesthetic concerns are surmountable with well-designed options of overhangs. • Automatic shading options with sensors • Cost effective if designed earlier on	
High Albedo Walls and Roofs	
Strengths	**Weaknesses**
• Applicable to smaller bespoke developments	• Regular maintenance • Costly in the long run • Implications with Fabric Energy Efficiency Performance Rates (FEEs) and Standard Assessment Procedures (SAP). Tricky maintenance requirements
Opportunities	**Threats**
• A light-coloured rendered wall preferred over solar reflective paint being applied to brickwork – less maintenance and more feasible.	• Its implications on planning • Not consistent with Unique Selling Product (USP) Occupant concerns with aesthetics
Low e double glazing	
Strengths	**Weaknesses**
• Good supply chain networks • Ideal option	• Hindered by Part O regulations on noise and security grounds
Opportunities	**Threats**
• Good selling point to help lower energy bills. • Occupant concerns of low daylighting levels is considered minimal as occupants would adapt to them.	• Part of their Unique selling product (USP) is large, glazed areas
Ceiling Fans	
Strengths	**Weaknesses**
• Simple and easy to install. • Great acceptability and flexibility • Most Ideal and Immediate solution.	• High ceiling height requirements Would require occupants to use and operate them – could be risky with vulnerable occupants (sick and the elderly)
Opportunities	**Threats**
• Developers already have high ceilings in their homes. • Possibility of using fairly flush fans • Gives customers better control.	• Could cause injury to vulnerable occupants (kids)

More research on their impact on feel temperature is needed.	

There was a general agreement that a point has been reached where home designs might have to change in response to overheating. Of all the five options presented, internal solutions such as ceiling fans and forms of solar control glazing were seen to be more acceptable and easily adaptable to current development processes, even though their effectiveness at reducing overheating hours is moderately low. Though external solutions such as shading and shutters were seen to be effective at reducing overheating hours, they were considered radical changes to home design with limited acceptability mainly due to occupant perception and planning implications. However, the developers accept that selective applications of external solutions like external shutters being used in specific houses in a scheme based on orientation analysis, canopies over French doors in gardens, and solar control glazing to particular glazing areas based on orientation and size is justifiable. Additionally, some developers seemed to be more willing to accept cost effective solutions such as fixed external shutters, overhangs, and light render as they feel these require low maintenance and that occupants might accept them if they are properly designed.

The use of solar reflective paint was seen to be more applicable to smaller bespoke developments considering that brick is predominantly the main construction material and a key aspect of the character of volume developer homes.

Though cost was seen as a significant factor, it was considered surmountable through targeted application of overheating solutions and negotiated supply chain collaborations. Supply chain concerns were noted, especially regarding the skills and capacity needed to implement these measures. However, it was noted to be reduceable by early negotiations with supply chain networks. The developmental concerns regarding the point of decision making and stakeholders involved were noted. As Part O regulation for overheating was passed in 2021, there was a consensus thus developmental procedures are still actively developing to accommodate this. However, inconsistencies regarding tender implications, design changes, overheating assessor competencies and perceived omissions and commissions in regulation requirements were noted.

Other options such as air conditioning and MVHR were noted as being considered for future use in limited situations like urban locations and apartments where windows cannot be opened for noise reasons. A cost benefit analysis that includes percentage reduction of carbon for each of these solutions was proposed to provide a better perspective. Also obtaining the perceptions of overheating solutions from planners was proposed to provide a better understanding of the most scalable and achievable solutions.

Industry evaluation of scalable solutions can be summarized with the following points:

- Different aesthetic design variations of external shading solutions that fit the UK market need to be explored to establish new trends.
- Targeted application of overheating mitigation solutions based on orientation and location to reduce cost implications.
- Stylish designs of mitigation solutions that give occupants the right to control them i.e., deployed and retracted by occupants.
- More public engagement and home occupant education on the benefits of these solutions i.e., being able to clean inward opening windows that allow for external shading solutions easily, without hiring window cleaners.
- Early involvement of relevant stakeholders such as overheating assessors, supply chain manufacturers is needed to obtain their input in design and negotiate on solution possibilities, volume forecasting, risks, and contingencies.

Having considered the proposed scalability analysis of overheating mitigation solutions and an evaluation from home developers' industry feedback, the next chapter proposes a scalability framework for embedding cost effective and scalable overheating mitigation solutions into the home development process.

6.7 Chapter Summary

This chapter has presented an evaluation of overheating mitigation solutions. This was done in two phases with the first phase focusing on the effectiveness of overheating mitigation solutions at reducing overheating hours, using dynamic simulation modelling for five sensor monitored homes in IESVE. The effectiveness of five overheating mitigation solutions was presented and analyzed for the five homes, each in four orientation variations. The results have shown that strategies aimed at preventing unwanted solar ingress into rooms are most effective at reducing the number of hours when temperatures are above 26^0C. External shutters and fixed shading – overhangs were seen to be more effective. Other solutions with moderate effectiveness were high albedo walls and roofs, low e double glazing and ceiling fans in that order. Also, the considered strategies were influenced by orientation. More overheating hours were recorded for east and west front-facing orientations than for north and south orientations because of the typical sun path for the modelled location.

The second phase sought to investigate how to make overheating mitigation solutions scalable. A scalability criterion for the critical evaluation of solutions was presented. This was based on five factors, cost implications, occupant perception, supply chain resilience, home development decision making stage and stakeholders involved. The results of evaluation workshops with 4 main industry partners regarding the proposed criterion were presented and analyzed. Based on the evaluation, preference is given to internal solutions such as internal fans and solar control glazing over external options such as shutters, overhangs, and reflective surfaces. This is despite external options being more effective at reducing degree hours when compared with internal solutions. The next chapter harnesses the learnings from the three previous chapters to propose a framework for embedding scalable solutions into the home development process.

Chapter 7. Proposed Scalability Framework.

7.1 Introduction

This chapter is the culmination of the previous chapters discussed in this research. This chapter draws from the home development process discussed in Chapter 4, the overheating analysis conducted in chapter 5, and the evaluation of overheating mitigation solutions conducted in Chapter 6. In this chapter a framework to incorporate scalability into home development processes is presented and discussed. This chapter is broken down into the following sections, outcomes from previous chapters, proposed framework for embedding scalable overheating mitigation solutions into home development Processes, and chapter summary.

7.2 Outcomes from previous chapters

An investigation of the UK home development process in Chapter 4 revealed gaps in awareness of the implications of decisions throughout the home development process. These include: the inclusion or not of environmental concerns in planning, the handling of ventilation design, scheme orientation decisions, the point of introduction of critical MEP supply chain companies and consultants, logistical issues around construction materials and skilled labour, and cost driven tendencies. These decision-making gaps in UK home development processes revealed five aspects that are key for home developers to adapt changes that lead to scalable overheating solutions at a mass scale. These factors include cost implications, point in the development process when a decision needs to be made and who needs to be involved, the resilience to supply chain networks, and occupant perception. These five factors form the scalability criteria for overheating mitigation solutions in UK homes.

Real time sensor monitoring results and overheating analysis presented in Chapter 5 reveal that UK homes are at risk of experiencing higher summer temperatures. The monitoring that was carried out revealed three heatwave periods during the summer of 2022, when temperatures above 30^0C were recorded. During the monitoring period, a maximum average temperature and a meanvtemperature of 31.8^0C and 24.33^0C respectively were recorded for the five monitored homes. This should be concerning given that more heatwaves of higher intensity and frequency are predicted for future summers. A retrospective TM59 overheating analysis that was done using monitored data revealed that only one of the five homes passed criterion 1, while all five homes failed criterion 2. A simplified Method analysis also revealed that only one of the five home designs would pass without requiring minor design changes when it comes to floor area, glazing areas and equivalent areas. Although these results are not meant to be definitive but rather indicative, they show that homes in the UK are at risk of experiencing higher temperatures. The overheating analyses show that overheating occurred at significantly higher percentages thereby underscoring not only the occurrence of overheating in homes, but more so the extent or “by how much” overheating occurs. These analyses show that there is a need for mitigation solutions to be implemented.

These overheating analyses suggest that overheating design methods are not sufficient to pick up the extent of overheating in homes. The use of real time data as opposed to simulated data for analysis suggests the need to use more severe weather files and more stringent occupancy profiles in design methods, to reflect climate trends that are more in line with reality.

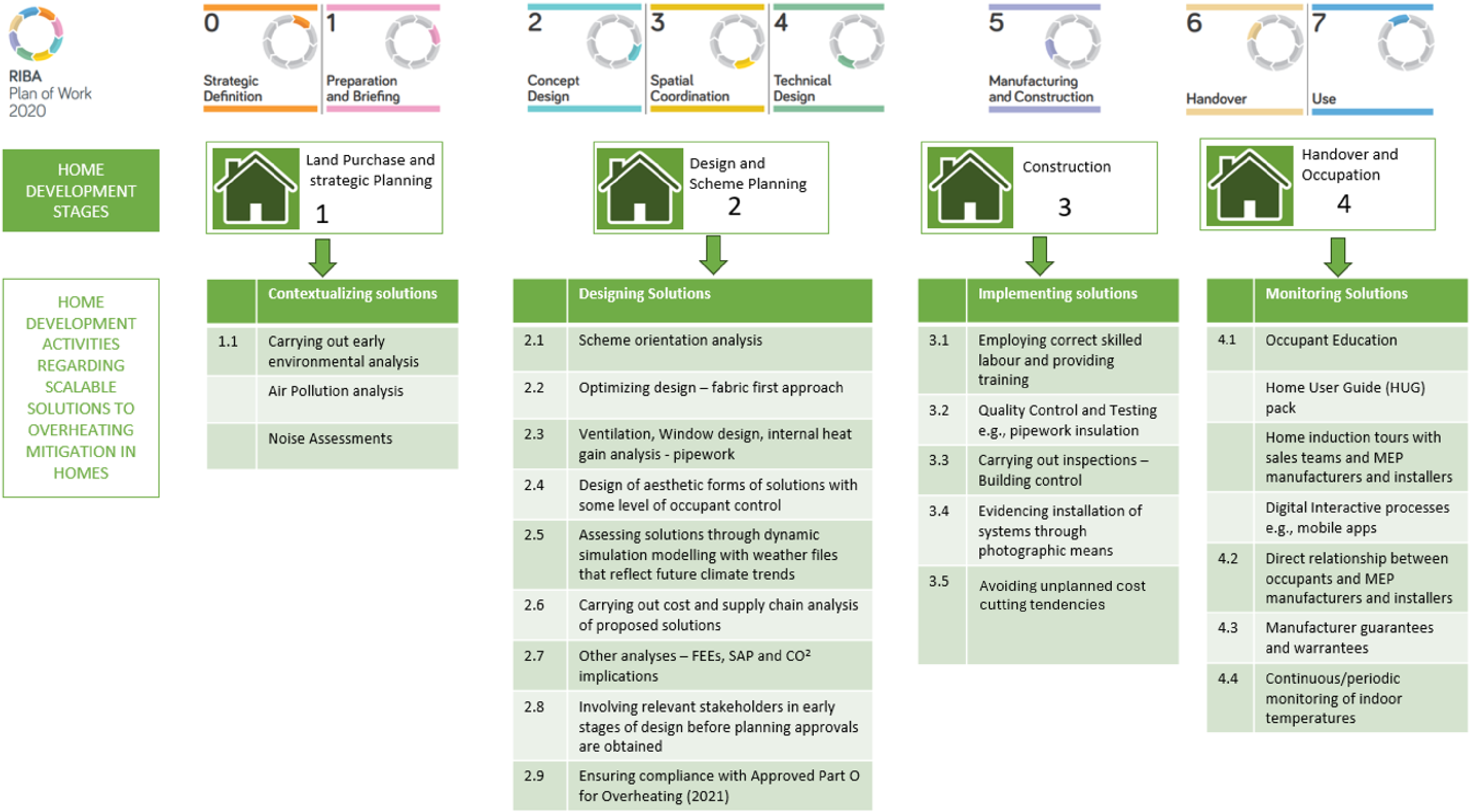
Chapter 6 presented the results of overheating mitigation evaluation through dynamic simulation modelling for the five monitored homes. Five overheating mitigation solutions were applied to simulated replicas of the five monitored homes to assess their effectiveness considering all orientations. Strategies such as external shutters and fixed shading – overhangs, aimed at preventing unwanted solar ingress into rooms, were seen to be more effective. High albedo roofs and walls, and low e double glazing solutions were seen to yield moderate results when it comes to reducing degree hours. Ceiling fans however yielded the least results among the five solutions considered. Additionally, the east and west front facing orientations recorded more degree hours than their north and south counterparts.

Chapter 6 also presented on the scalability analysis of overheating mitigation solutions. For overheating mitigation measures to be effective and implementable, they need to be seen to be cost-effective and scalable by volume builders. Scalability is the ability of a system to accommodate an increasing number of elemental change while processing growing volumes of work without failing (Bondi, 2000). Scalable solutions are choices that when introduced, will still work without many disruptions. This is vital for volume builders who aim to increase the volume of their output year on year. A proposed scalability criteria for scalable solutions is then presented and analysed based on cost implications, point in the development process when a decision needs to be made and who needs to be involved, the resilience to supply chain dynamics, and occupant perception. This is then followed by an evaluation with home developers.

This evaluation revealed that home developmental processes prefer internal solutions such as internal fans and solar control glazing over external options such as shutters, overhangs, and reflective surfaces. This is despite external options being more effective at reducing degree hours when compared with internal solutions. There seems to be reluctancy in applying effective solutions due to assumed occupant perception and change to their unique selling product; so, resistance to change. However, the developers accept that selective applications of external solutions like external shutters being used in specific houses in a scheme based on orientation analysis, canopies over French doors in gardens, and solar control glazing to specific glazing areas based on orientation and size are justifiable. Additionally, some developers seemed to be more willing to accept cost effective solutions such as fixed external shutters, overhangs, and light render as they feel these require low maintenance and that occupants might accept them if they are properly designed.

This chapter combines all the work from these previous chapters, to propose a framework to industry, on how to incorporate critical aspects of scalable overheating mitigation solutions, into home development processes, aside from the effectiveness of solutions.

7.3 Proposed Framework for Scalable Overheating Mitigation Solutions in Home development Processes



HOME DEVELOPMENT STAGES

- Land Purchase and strategic Planning 1
- Design and Scheme Planning 2
- Construction 3
- Handover and Occupation 4

HOME DEVELOPMENT ACTIVITIES REGARDING SCALABLE SOLUTIONS TO OVERHEATING MITIGATION IN HOMES

	Contextualizing solutions
1.1	Carrying out early environmental analysis
	Air Pollution analysis
	Noise Assessments

	Designing Solutions
2.1	Scheme orientation analysis
2.2	Optimizing design – fabric first approach
2.3	Ventilation, Window design, internal heat gain analysis - pipework
2.4	Design of aesthetic forms of solutions with some level of occupant control
2.5	Assessing solutions through dynamic simulation modelling with weather files that reflect future climate trends
2.6	Carrying out cost and supply chain analysis of proposed solutions
2.7	Other analyses – FEEs, SAP and CO^2 implications
2.8	Involving relevant stakeholders in early stages of design before planning approvals are obtained
2.9	Ensuring compliance with Approved Part O for Overheating (2021)

	Implementing solutions
3.1	Employing correct skilled labour and providing training
3.2	Quality Control and Testing e.g., pipework insulation
3.3	Carrying out inspections – Building control
3.4	Evidencing installation of systems through photographic means
3.5	Avoiding unplanned cost cutting tendencies

	Monitoring Solutions
4.1	Occupant Education
	Home User Guide (HUG) pack
	Home induction tours with sales teams and MEP manufacturers and installers
	Digital Interactive processes e.g., mobile apps
4.2	Direct relationship between occupants and MEP manufacturers and installers
4.3	Manufacturer guarantees and warrantees
4.4	Continuous/periodic monitoring of indoor temperatures

Figure 55: A Proposed Scalability Framework for Cost Effective and Scalable Overheating Mitigation Solutions in Home Development Processes

Figure 55 proposes a framework for incorporating scalable solutions into the home development process. This follows on from the work in chapter 4 on understanding the gaps in the current home development process regarding decision making that affects overheating in homes. This also builds on work in chapter 5 on the overheating analysis of homes using real time data, the proposed scalability criteria of overheating mitigation solutions, and its evaluation with industry in chapter 6.

This framework breaks down the UK home development process into four general stages: land purchase and strategic planning (RIBS stages 0-1), design and scheme planning (RIBA stages 2-4), construction stage (RIBA stage 5), and handover and occupation stage (RIBA stage 6-7). Several scalability factors are attributed to each stage, representing what needs to be done at each stage in ensuring scalable and cost-effective overheating mitigation solutions are embedded into home development processes. The next sections are a discussion of these four stages and what is proposed in each.

7.3.1 Land Purchase and Strategic Planning

In this stage, site contextual matters that are pertinent to overheating need to be addressed by early environmental analysis. This analysis should include aspects of air pollution analysis such as being near busy highways or close to heavy smoke emission sites. Section 2 of Approved Document F states that *"Buildings located near to significant local pollution sources should be designed to minimize the intake of external air pollutants".* This can influence window opening behaviours and therefore the ability in homes to remove excess heat. Project teams should work with building control bodies (BCBs) and Environmental health Officers to agree on an approach to assess external air quality for air pollution problems. This analysis should also include noise.

Early noise assessments help to decide if a site is worth considering for a residential development. Noise issues are likely to affect all buildings located near main roads, rail lines and airports. An interview respondent in chapter 4 mentioned that "*there are sites that are too noisy to build homes on. It just isn't a good site for a home. That is too noisy, I don't think it's human to live in a place where you can't open the windows."* Otherwise, if external noise is an issue, local planning authorities may make certain requirements including the need for site noise measurements. Based on the data in the National Noise Incidence Survey 2000 (Skinner et al., 2005) and other correlation studies (Apex Acoustics, n.d), more than 30% of existing dwellings in England and mostly in city centers would not comply with the Approved Document Part O (2021) night-time limits with windows open. Noisy sites need to consider the likelihood that windows will be closed during sleeping hours (11pm to 7am). All this can be avoided if early noise assessments are done when considering locations of residential development. In unavoidable cases, early sound proofing options and alternative design features can begin to be considered.

7.3.2 Design and Scheme Planning

In the early stages of scheme design, scheme orientation analysis is vital to mitigating overheating in new homes. Scheme orientation determines the direct intake of sunlight into rooms, the positioning and sizing of ventilation infrastructure such as windows, doors, exhausts and the intake of pollution from adjacent sources among others. Orientation analysis should aim to achieve reasonable unit densities for large residential development projects. This analysis requires consultations with local planning authorities to ensure that planning guidelines are adhered to. To underscore this point, respondent 11, a design manager explained that to reduce potential overheating in a recent project, *"different orientations were considered but restricted by planning and unit density."*

Design optimization is another early strategy of overheating mitigation in homes. In this optimization process, passive mitigation options that are less energy and carbon intensive are first considered before other mechanical options; fabric first approach. This involves designing passive ventilation strategies such as stack and cross ventilation, as well as efficient window design that balances daylighting needs verses heat gain. In conducting this design optimization, where appropriate, the overheating mitigation solutions analyzed in this research (external shutters, overhangs, solar control glazing, light reflective external surfaces, and fans) can be considered. This is to be justified based on orientation, geographical location, and house type. Aesthetic design variations and some levels of occupant controls are recommended. These mitigation solutions need to be accompanied by an analysis of effectiveness through modeling. Dynamic simulation modelling needs to capture site contexts such as geographical location, house orientation, permanent shading, prevailing winds, and other specific design features.

Early cost and supply chain analysis of proposed overheating mitigation solutions needs to be conducted. An early cost-benefit analysis of overheating mitigation solutions is vital in assessing options especially from a mass builder perspective. This can be improved by a targeted application of overheating mitigation solutions to specific plots or orientations that are more prone to indoor overheating. An early cost analysis of overheating mitigation solutions will help to decide which costs to absorb and which ones to pass on to the end user. Supply chain networks of overheating mitigation solutions need to be included in this. Material availability, shipping, logistics and ware housing costs as well as labour costs need to be incorporated into this analysis (Brocklehurst et al.,2021). This translates to shorter lead times, just in time deliveries and fewer supply chain disruptions. In addition to cost and supply chain analysis of solutions, wider design implications on Fabric Energy Performance (FEEs), Standard Assessment Procedure (SAP) and even embodied and operational carbon require consideration to prevent unintended consequences.

In all aspects of scalability analysis discussed in this stage, the early involvement of all relevant stakeholders is vital. This includes but is not limited to designers and architects, overheating assessors, acoustic experts, energy assessors, contractors, manufacturers, and suppliers, not forgetting local planning authority and building control. Their involvement needs to be done early on to maximize their input and capabilities in design before final planning approvals are obtained.

Most importantly, compliance with Approved Document Part O Overheating (2021) needs to be ensured. Of the two compliance methods in the regulation, one should be chosen. Approved Document Part O (2021) stipulates that the Dynamic Simulation Method, applies to all residential buildings as it offers designers more flexibility in residential dwellings with: high levels of insulation and airtightness, specific site conditions that may not be represented by the two locations of the simplified method, and residential structures that are highly shaded with neighbouring properties, structures, and landscapes. Alternatively, the Approved Document Part O (2021), stipulates the Simplified method which can be used for all residential buildings, except buildings with more than one residential unit with a communal heating system or significant levels of hot water distribution pipework.

7.3.3 Construction

Designing and analyzing scalable overheating mitigation solutions is not complete without effective implementation on sites. As overheating mitigation solutions are not common in the UK, ensuring their implementation requires employing the correct skilled labour and possibly even training them. Quality control and testing should follow this to ensure that the performance gap between intended design and actual outcome is reduced. Building control should be involved to necessitate regulatory inspections are done for compliance purposes. In aiding this, evidencing construction process and installations can be done through digital photographic systems at different stages of construction; especially areas that can be less easily inspected. Respondent 15 in chapter 4 when asked about potential barriers to building performance explained that *"it's really cost concerns, you know, the nature of our industry is, it's all about value engineering or cost-cutting, and we can do calculations properly, we can provide the correct materials on the site, but if it's out of their budget, people take shortcuts, you know, that's the biggest barrier to providing real good performance on site."* Therefore, as the construction process progresses, necessary steps should be taken to prevent unplanned cost cutting tendencies during the construction phase. If necessary, it should be done through a structured process of reviewing existing products to reduce costs and increase functionality, thereby increasing the quality/value of the project, value engineering (Atabay and Galipogullari, 2013).

7.3.4 Handover and Occupation

As this research points out, scalable overheating mitigation not only involves actions in the development-cycle of homes that is more industry led, but also a reconciliation with the occupation-cycle of homes that is more practically led from home occupants' perspective. Murtagh (2019) describes home occupants as "gatekeepers" of the domestic building stock and as such, their role should not be neglected. In achieving this, the transition to the occupancy stage of home development should involve effective occupant education through the home user guide (HUG) that most developers use, induction tours from sales teams and representatives of Mechanical, Electrical and Plumbing (MEP) suppliers and manufacturers, and other interactive means such as digital apps. A direct relationship between home occupants and MEP suppliers, manufacturers, and installers means that more tailored support can be given to occupants in relation to the use of heating, ventilation, and cooling systems. Through this direct relationship, occupants can gain access to the full potential of the systems installed in their homes, as well as manufacturer guarantees and warranties. Additionally, continuous/periodic monitoring of indoor temperatures in occupied homes can provide more data for future learning and interventions.

7.4 Chapter Summary

A scalability framework for embedding cost effective and scalable overheating mitigation solutions in the home development process is proposed. This framework breaks down the UK home development process into four general stages and highlights several scalability factors that are attributed to each stage. These factors represent what needs to be done at each stage in ensuring scalable and cost-effective overheating mitigation solutions are embedded into home development processes. The scalability framework emphasizes that it is important to understand the performance of different houses in context, including the way they are planned, designed, built, and occupied. The next chapter is the last section that summarizes and concludes this research.

Chapter 8: Conclusions and Recommendations

8.1 Introduction

This research has investigated the overheating risk in new homes through a holistic analysis of the home development process with industry developers and their supply chain, real time sensor monitoring of occupied homes in the UK and dynamic simulation modelling of potential solutions. The main aim was to investigate the scalability of overheating mitigation measures in UK homes. The research has led to several findings which have been consolidated into developing a scalability framework for the embedding scalable overheating mitigation solutions in UK home development processes. This chapter presents a summary of the entire thesis, and presents the main conclusions, contribution to knowledge, and the limitations of the research. These are followed by some consideration of the potential industry implications of the research findings, particularly in relation to home developers, home occupants and government policy, as well as recommendations for future research. This chapter is subdivided into the following sections: Achievement of research objectives, conclusions of the research, research contributions, recommendations, dissemination, limitations for the study, areas for future research, reflecting on the research journey, and chapter summary.

8.2 Achievement of Research Aim and Objectives

The aim and objectives of this research are presented in section 1.3 of Chapter One. Five research objectives were framed to help achieve the aim of the study. All Five objectives have been achieved through undertaking the research methodology presented in Chapter Three. Table 29 summarizes the methods applied in achieving each research objective and the chapters containing the evidence of such achievements.

Table 29: Achievement of Research Aim and Objectives

Research Aim	Research Objective	Method of Achievement	Chapter Presented
The aim of this research is to investigate cost-effective scalable solutions to mitigate overheating and improve thermal comfort in new	To review the current trends (including policy and regulation) on overheating and thermal comfort in residential dwellings and understand	Reviewed literature	Chapter 2

build residential developments in the UK, from a home development process perspective.	their scale and depth in UK homes.		
	To examine the UK home development processes and the influence of decision-making on overheating in UK homes.	Reviewed Literature and carried out interviews with 15 respondents including housing developers, manufacturers, and building professionals	Chapter 2 and 4
	To conduct an overheating analysis of homes with real time indoor temperature data, using the dynamic simulation method and simplified method stipulated in Approved Document Part O Overheating (2021).	Sensor Monitoring of occupied homes and thermal comfort questionnaires for data collection, and overheating analysis using dynamic simulation method and simplified method.	Chapter 5
	To evaluate the performance of different mitigation strategies in new build residential developments in the UK using dynamic simulation modelling of monitored homes.	IESVE Dynamic Simulation Modelling Software	Chapter 6 (6.2-6.4)
	To develop a scalability criterion for evaluating overheating mitigation measures through evaluation workshops with developers.	Combining the results from dynamic simulation modelling with the scalability criteria developed from the analysis of the home development process. This was enhanced by evaluation workshops with home developers	Chapter 6 (6.5-6.6)
	To propose a scalability framework for incorporating overheating mitigation solutions in home development processes.	The outcomes of all the previous chapters are used to develop a framework for scalable overheating mitigation measures in home development processes	Chapter 7

8.3 Conclusions of the research

The following conclusions are made in relation to the research objectives of this research:

1. Current trends on overheating in UK homes

Overheating in houses in the UK is a growing concern because of increases in climate change-instigated heatwaves and as an unintended consequence of low energy requirements in homes. According to the UK trade body Zero Carbon Hub (ZCH) (2015), the issue of overheating will be one of the predominant issues over the next 5 to 10 years for the sector. Governance models and institutionalization of overheating assessment in homes is a recent phenomenon. In the UK, overheating has become part of building regulations with the introduction of the new Part O for Overheating (2021). However, its complex multidisciplinary nature means that many wider analyses of indoor overheating need to be done (DEFRA, 2018).

2. Home development processes and influence of decision making on overheating.

An investigation of the UK home development process has revealed challenges in the decision-making process, that should be addressed to mitigate potential overheating in homes. These include: the inclusion or not of environmental concerns in planning, the handling of ventilation design, the possibilities of making needed changes after obtaining planning requirements, decisions around material selection, the point of introduction of critical MEP supply chain companies and consultants, logistical issues around construction materials and skilled labour, and cost driven tendencies. These decision-making challenges in UK home development revealed five aspects that are key for home developers to adapt changes that lead to scalable overheating solutions at a mass scale. These factors include cost implications, point in the development process when a decision needs to be made and who needs to be involved, the resilience to supply chain dynamics, occupant perception. These five factors form the scalability criteria for the critical evaluation of overheating mitigation solutions in UK homes.

3. Overheating Analysis using Real time data.

Real time sensor monitoring presented revealed that UK homes are at risk of experiencing higher summer temperatures. Outdoor temperature trends revealed three heatwave periods during the summer of 2022, when temperatures above 30^0C were recorded. During the monitoring period, a maximum average temperature and a mean of 31.8^0C and 24.33^0C respectively were recorded for the five monitored homes. A retrospective TM59 overheating analysis that was done using monitored data revealed that only one of the five homes passed criterion 1, while all five homes failed criterion 2. A simplified Method analysis also revealed that only one of the five home designs would pass without requiring minor design changes when it comes to floor area, glazing areas, and equivalent areas. These overheating analyses suggest that overheating design methods are not sufficient to pick up the extent of overheating in homes. Design methods such as the Dynamic Simulation Method (TM59) rely on synthetic occupant profiles and standard weather data for overheating analyses. However, the use of real time indoor temperature data and its collection in real occupied homes, has revealed that a higher level of overheating occurs, compared to using standard simulation data in design methods. This suggests that homes that comply with overheating assessment methods may be at risk of failing the same methods, if real time monitored data is collected a few years later. This real time monitoring analysis suggests the need to use more severe weather files and more stringent occupancy profiles in design methods, to reflect climate trends that are more in line with reality. Although these results are not meant to be definitive but rather indicative, they show that homes in the UK are at risk of experiencing higher temperatures than envisioned in design.

4. The Performance of different Overheating Mitigation Strategies through simulation

Five overheating mitigation solutions were applied to simulated replicas of the five monitored homes to assess their effectiveness considering all orientations. Strategies such as external shutters and fixed shading – overhangs, aimed at preventing unwanted solar ingress into rooms, were seen to be more effective at reducing degree hours. High albedo roofs and walls and low e double glazing solutions were seen to yield moderate results when it comes to reducing degree hours. Ceiling fans however yielded the least results among the five solutions considered. Additionally, the east and west front facing orientations recorded more degree hours than their north and south counterparts. Air conditioning was not considered as it undermines climate change aspirations to reduce emissions while potentially putting more strain on the electric grid (MCHLGb, 2019).

5. A Proposed Scalability Criterion and a Scalability Framework for Overheating Mitigation Solutions

A scalability criterion for the critical evaluation of solutions based on home development process analysis is proposed. It is based on five factors: cost implications, occupant perception, supply chain resilience, home development decision making stage and stakeholders involved. Based on the scalability analysis of five mitigation solutions, a SWOT evaluation is done through interviews with home developers. This aligns with comments from occupants of monitored homes. Four of the five home occupants involved through thermal comfort questionnaires recommended the need for external shading options for effective overheating mitigation. This scalability analysis and evaluation led to the development of a scalability framework for incorporating cost-effective and scalable overheating mitigation measures into the Home Development Process. This framework emphasizes that it is important to understand the performance of different houses in context, including the way they are planned, designed, built, and occupied.

6. Main Conclusion.

This research has established that overheating in UK homes is a growing concern now and more so in the future. The research demonstrated that typical overheating design and assessment methods that rely on synthetic occupant profiles and standard weather data, may not be accurately predicting the true extent of overheating in UK homes. A selection of real houses lived by real people were monitored and different overheating assessment methods run, showing that houses were overheating and failing the assessments. The research identified that only cost-effective mitigating solutions would have the potential to be used by home builders and, therefore, being implemented across the home development sector. The research identified, simulated, and validated different cost-effective mitigating solutions. External overheating mitigating solutions were found more effective than internal solutions. However, their implementation in UK homes depends on addressing infrastructural, capacity, and developmental barriers related to cost, supply chain resilience, stakeholder involvement and occupant perception. Addressing these issues will ensure that scalability is integrated into home developmental processes, and that scalable solutions that are not just seen are removing causes to events but rather strategies for wide scale and long-term success, are implemented. This can be achieved through the implementation of a scalability framework that has been proposed in this research.

8.4 Research Contributions

Overheating in UK homes is a multifaceted, complex problem that cuts across many disciplines i.e., physics, physiology, phycology, culture, and climate. It entails subjective and objective aspects that have different standards and definitions based on different jurisdictions. It draws the attention of various stakeholders including government policymaking institutions, housing developers and their supply chain, sustainability experts, services engineers and building occupants. The complexity of overheating in homes fits Rittell and Webber's, (1973) definition of a wicked problem. A problem that is so complex, less understood and that any attempt to understand it is riddled with dispute and uncertainty. Understanding such a complex problem required the holistic analysis of the entire home development process from land acquisition to the in-use phase. It is the limited understanding of contextual issues that make home development procedures and processes prone to failure and unintended negative consequences such as overheating (Janda, 2011). Given the many different actors (both up-and down the supply chain) involved in creating, operating, and maintaining the built environment, it was imperative to adopt a wider developmental evaluation, considering the different decisions that are made in these stages, to understand how housebuilders address potential overheating.

Therefore, different from other research, this study followed a home developmental process approach to understanding overheating mitigation in UK homes. This holistic analysis examined the normal procedures and organizational chains of command in the development process to see how decisions affecting overheating are made and executed. This research found that the UK home development processes are not perfectly suited to prevent the occurrence of summertime indoor overheating in UK homes. The following issues affecting overheating in homes were identified: the inclusion or not of environmental concerns in planning, the handling of ventilation design, the possibilities of making needed changes after obtaining planning requirements, decisions around material selection, the point of introduction of critical MEP supply chain companies and consultants, logistical issues around construction materials and skilled labor, and cost driven tendencies.

This study has also contributed to the evidence base on the thermal performance of homes based on assessment standards of the new regulation for Overheating Part O Overheating (2021). The performance of a three-bedroom detached home, two -four-bedroom detached homes, a two-bed flat and a three-bed semi-detached home, all occupied and in different locations within the UK, is presented. This analysis is based on real time monitoring conducted in the summer of 2022 – the first year when temperatures above 40^0C were recorded in the UK. A TM59 overheating analysis is conducted (retrospectively using real time data), alongside a simplified method analysis as well as Dynamic Simulation Modelling. This provides perspective into the performance of new homes based on the overheating standards in the new regulation Part O Overheating (2021). These overheating analyses suggest that overheating design methods are not sufficient to pick up the extent of overheating in homes. The use of real time data as opposed to simulated data for analysis suggests the need to use more severe weather files and more stringent occupancy profiles in design methods, to reflect climate trends that are more in line with reality.

The exploration of decision making in UK home development and an analysis of overheating mitigation design methods provides great insight into developing scalable solutions to mitigate overheating in homes. Addressing the scalability of overheating mitigation solutions, required a much more holistic analysis of not just the technical design but the development process decisions and occupancy expectations. This was significant to enable a critical analysis of solutions as not just removing causes to events but enabling strategies for wider scale and longer-term success. A five - point scalability criterion for the critical evaluation of overheating mitigation solutions is proposed, and a critical evaluation of mitigation solutions is done is based on: cost implications, occupant perception, supply chain resilience, home development decision making stage and stakeholders involved. This is used to develop a scalability framework for incorporating overheating mitigation solutions into home development processes.

In conclusion, this research used a novel home developmental process analysis to investigate overheating in UK homes, proposed a scalability criterion for the critical evaluation of mitigation solutions and proposed a framework for incorporating scalable overheating mitigation solutions, based on overheating analysis using real time data, and simulation of potential solutions in a sample of occupied homes in the UK.

8.5 Recommendations

In achieving the aim of this research, which is to propose scalable solutions, considering the UK home development process, to mitigate overheating and improve thermal comfort in new build residential developments in the UK, this research proposes a scalability framework that outlines activities that should be undertaken at each stage of home development. These are summarized below:

1. Conducting early environmental analysis to include air pollution and noise assessments when land purchase and strategic planning decisions are being made.
2. In the design and scheme planning stage, solutions should be designed following a raft of analyses that include:
    - Scheme orientation analysis.
    - Design optimizations involving ventilation design, window design and internal heat gain analysis.
    - Assessing the effectiveness of solutions through dynamic simulation modelling that considers weather files that reflect future climate trends.
    - Conducting cost and supply chain analysis of proposed solutions
    - Early involvement of relevant stakeholders to obtain their input in design and negotiate on solution possibilities, volume forecasting, risks, and contingencies before planning approvals are obtained.
    - Ensuring compliance with the Approved Document Part O for Overheating (2021)
3. In the construction stage, designed solutions should be effectively implemented on site through:
    - Engaging the correct skilled labour and providing training needs
    - Ensuring quality control and testing
    - Evidencing installations through photographic means for easier inspections by Building Control
    - Avoiding unplanned cost cutting tendencies
4. In the last stage, handover and occupation, activities should involve occupants through:
    - Occupant induction into hew homes through home user guides, interactive home tours and digital means such as mobile apps.

- Keeping a direct relationship between home occupants and the MEP manufacturers and installers of heating, cooling, and ventilation systems in their homes
- Continuous or period monitoring of indoor temperatures to provide more data for future learnings.

8.6 Implications of research findings

To Home developers and Housing Associations, this study offers more perspective on the thermal performance of current homes based on recent data from a record breaking- temperature year. This research shows that homes designed and built to pass current regulations based on simulated data, could still fail when real time data is collected a few years later. Therefore, future proofing building stock against an ever-warming weather should involve considering more stringent weather files and synthetic occupancy profiles that reflect a more severe reality of a warming climate in current overheating design methods. Home developers and Housing Associations need to begin looking at scalable options for overheating mitigation, so that they can begin evaluating and adapting them to be part of their standard products. This will majorly have to involve an evaluation of cost implications, home occupant perspective and logistical issues. This research is also vital as it shows areas in the development process that require attention to improve the thermal performance of homes. As this research has shown, involving relevant stakeholders for early decision making is key to the thermal performance of homes.

To Home Occupants, this research highlights the increased risk of overheating in homes and the significance of their role as “guardians of the building stock”. Home occupants need to understand how their use of their homes influences their thermal environments and the measures they can take to ensure they do not strain their indoor thermal environments beyond what they were designed for. For overheating mitigation to be a reality, occupants need more education and awareness of the benefits of mitigation solutions to their health and well-being. As this research has picked out occupant perception as a significant barrier to scalable solutions, home occupants should be more adaptable and flexible to accepting new solutions that prove effective in other jurisdictions. Home occupants should begin holding housing providers to a higher level of responsibility as they have the power to influence the expectations of the housing market.

To the Government, this research offers more evidence of the overheating performance of current homes of different typologies. This research shows the critical role of regulation and policy in influencing the way homes are designed and built. This study shows that while building regulations mostly address fabric and equipment requirements in homes, attention also needs to be given to home development processes as their impact on overheating in homes is significant. This study also highlights the need for widespread consultations with industry to ensure their views are considered, when new policy is introduced, or amended. The impact on policy and regulation, as well as market dynamics (all of which are under the government has power) on home developmental procedures that are inadequate against overheating, has been highlighted. The government should begin offering incentives to promising industry initiatives that prove their effectiveness. Local Authorities and Councils should start considering the implications of external solutions to mitigate overheating and how to adapt to them. Consultations should begin on ways of making passive and effective mitigation solutions such as external shading standard and scalable across the housing stock. All this should be considered in the Future Homes Standard that is coming up in 2025, and the broader goals towards achieving Net Zero 2050.

8.7 Dissemination

The findings from this research have been presented at an in-person conference of the UK Indoor Environments Group (UKIEG) on the 7th of September 2023 at Steamhouse Birmingham City university. The PowerPoint presentation elicited some very interesting debates about overheating solutions, and future trends, from a vast audience of experts specialised in indoor environmental quality and related fields. The findings have also been discussed in meetings with Industry stakeholders (Home Developers, Energy Assessors). The multidisciplinary nature of this thesis meant accessing a wide range of home development stakeholders. Furthermore, the findings from this research are to be published in more conference proceedings and peer reviewed journals in the near future.

8.8 Limitations of the study

The intent of this research was to collect indoor temperature data in occupied homes to investigate overheating in real homes. As the sensor monitoring data collection exercise involved occupied homes, it presented certain challenges that could have impacted the results of this research to some extent. This exercise therefore involved some compromise that from a building physics perspective, would require justification. Although the placement of sensors was designed to be placed on eye-level shelves, away from any sources of heat, draught, and direct sun exposure, there were situations where these locations were not workable for occupants and compromises had to be made. These decisions were made carefully to maintain the accuracy of the data collected. In one house, the fan noise generated by one of the sensors made the occupant uncomfortable, so they requested this to be located in another room. This therefore meant that there were some gaps in collected data. Even though around eighteen homes were initially monitored, only 5 homes were considered for detailed analysis since some sensors experienced data loss owing to unforeseen circumstances. Although the initial idea was to still monitor more houses and give more focus to a fraction of them, the failing of some air quality sensors constrained the process. Also, due to the impact of covid, access to homes was sometime limited when data download and troubleshooting was to be done. Based on these limitations imposed by collecting data in occupied homes, this research acknowledges the use of data and results obtained as “indicative”, rather than “definitive”. Therefore, the findings and conclusions drawn are based on this.

All the homes monitored in this research are in England and made predominantly of brick. Though this still represents a wider portion of new build homes, it still does not cover the other types of new build technologies like modular construction and timber frame. Additionally, the stakeholders involved in this research are predominantly practicing in England and mostly involved in volume building. Though this still represents most stakeholders involved in the new build process, other jurisdictions in the UK (Wales, Norther Ireland, and Scotland) were not well represented. Also, other industry stakeholders like local councils and owner-built home occupants were not involved. This therefore limits the empirical generalization of the results both jurisdictionally and respondent-wise.

The study of the home development process and decision making was largely carried out in 2021. However, the regulatory framework of overheating in homes has been actively developing with the consultation publication of part O regulation for overheating occurring shortly after. In line with the new regulation Part O, home development processes in industry companies are still actively restructuring to ensure they are best suited to deliver homes in line with this standard. Although the research has sought to reflect the accurate developmental procedures regarding overheating as they currently are, most recent changes in industry companies may not have been accurately represented due to active changes and the constrained timelines of this study. Also, the interviews were to be conducted after sensor monitoring was done to enable the research to obtain data on home development based on data from monitoring. However, the Covid crisis made it impossible to start the sensor monitoring of occupied homes during the lockdown periods. Therefore, interviews with home developers seemed to be the only data collection that was possible. This therefore meant that interviews with developers happened earlier than they should have been. To mitigate this, contact with the major home developers was maintained periodically through the duration of this research to enable a back-and-forth communication.

A more robust validation of the scalability criteria could have been conducted given more time and resources. Of the 11 research industry stakeholders interviewed regarding the home development process, only the four main home builders were involved in evaluation of the scalability framework. Though their response is believed to be sufficient, more in-depth results would have been obtained by involving more respondents. This could impact the generalizability of the results.

8.9 Areas for future research

The research limitations outlined in the preceding section provide an opportunity for future research in the following directions:

- Future research on overheating that is based on sensor monitoring should focus on even smaller samples of homes to minimize results' variability and increase accuracy of results. This would allow for more in-depth analysis of temperature data that this research could not achieve. Such focus should be based on home typologies that are prone to fail overheating assessments.
- A wider analysis of home development processes and overheating decision-making incorporating Industry stakeholders from all the four jurisdictions of the UK to establish

comparisons and differences. Also, the hierarchy of future research should involve sensor monitoring of homes, then interviews with industry developers in that order.

- A cost benefit analysis of overheating mitigation solutions to include percentage reduction of carbon for each proposed solution to provide better perspective.
- A wider validation of scalable overheating mitigation solutions to include a more diverse and jurisdictionally representative response from the UK home building industry.

8.10 Reflection of the Research Journey

The background and inclination of a researcher affects research through the areas of research chosen, the angle of investigation, data collection methods and analysis, and the conclusions obtained. In this section, I present the reflections of my research journey and how my background, beliefs, professional experiences, and pre-conceptions may have influenced the research process.

From the moment I saw the advertised post for this research studentship, my mind was engrossed in it. Having been raised in Kenya, I was no stranger to prolonged hot conditions. In some ways, I had already adapted to it, knowing what to wear, when to go out, the cool spots under trees in our compound and even simple things like taking cold baths. Buildings back home are usually made of high thermal mass blocks, large single pane windows and vents located in all rooms. Despite all this, I developed dry skin conditions and had to constantly use special creams during prolonged hot durations. Having just spent my first summer in the UK during my masters' studies, I couldn't help but note a few differences regarding how UK homes perform in hot summer conditions. The cavity insulation walls, double glazed windows and airtight feeling meant that during the peak of summer, being indoors felt like being inside a microwave. To add to this, coping with the high temperatures here in the UK was difficult because of the high humidity conditions that meant it was difficult to adapt easily through sweating. Therefore, I could not resist applying for this research opportunity, and I am grateful for being chosen to study for it.

My research journey started with meeting my supervisory team, alongside industry partners including four home developers with whom I would be collaborating with. I got to understand the main goals of the research and the potential that my academic-industry research has. A month into my research, the covid pandemic struck and everything went on a slowdown. As the pandemic had come earlier on in my research, its effects would be far reaching for my research.

Literature review was not affected as much, because I could still do it from a desk at home. I thought that I would not find many review papers on my topic. With more literature searchers, I found that there were an increasing number of studies that were pointing out the increasing risk of overheating in UK homes. Many of them included lessons that could be learnt from other hotter climates. Several of them focused on care home settings, synthetically occupied home typologies, and others focused on flats. For most of them, overheating risk analysis was done using indoor temperature data that was collected from previous years e.g., 2015 or even earlier. For most of these papers, overheating analysis was based on fixed temperature standards and early versions of CIBSEs TM52 and 59. From the "areas for future research" sections of these papers, there was still a lot of work to do, evidence to obtain, perspectives to consider and opportunities to explore.

During the lockdown period I began doing interviews with home developers to understand the home development process and how decision making directly or indirectly affects overheating in homes. Due to the pandemic, site visits were cancelled, and the interviews had to be done online. Although the initial goal was to interview only the four home developers, the prolonged lockdown meant that I could expand my interview list to include other members of their supply chain including manufacturers, contractors, ventilation experts, building physics experts and other relevant consultants. I came to understand that developers and their supply chain value their work as they understood the effects this would have on their companies' reputation.

A year into the research in mid-2021, the building regulations were changed to make overheating assessment mandatory for all new homes (Part 0 for Overheating 2021). This meant that my research had to include the new compliance methods as part of the overheating assessment. I had to learn a new compliance criterion (Simplified Method) and update my skills on dynamic simulation modelling. As an active topic in industry, I quickly learnt that I had to keep up with new material, publications, reports, and journals that were being published every day. My research still had to be relevant to its time and make a significant contribution to knowledge. Based on the interest from industry partners, it became obvious to me that my research was vital to industry as it explored a peculiar problem that was being introduced as part of regulation.

Due to the pandemic, sensor monitoring of indoor temperatures had to be postponed as it relied on accessing occupied homes. Later in 2022, after the purchase of sensor equipment and selection of occupied homes, sensor monitoring took place. In hindsight, though I had planned to conduct sensor monitoring in 2021, 2022 was the best year for sensor monitoring as it was the year when there were five summer heatwaves and temperatures above 40^0C were first recorded in the country's history. This probably meant some interesting data for overheating. However, its implication on data analysis was later felt due to constrained research timelines. Sensor monitoring was done in collaboration with another research on wider indoor air quality issues. This meant that the home selection for monitoring, monitoring duration and even location of sensors in rooms had to be discussed and agreed on for both projects. Even communication with home occupants had to be coordinated to prevent occupant fatigue. Several sensors occasionally dropped out due to network and connectivity issues. This meant frequent communication or visits to some monitored homes for troubleshooting purposes. The aftermath of the covid pandemic meant that I had a better engagement with occupants whose homes I was monitoring. People spent a lot more time in their homes and were now aware of the significance of their indoor environments to their health and wellbeing. However, getting access to some homes to address sensor issues was sometimes difficult due to occupants' daily routines and some research fatigue especially towards the end of the monitoring. Afterwards, dynamic simulation modelling took place.

Throughout my research period, I had to meet industry partners every three months and update them on progress. I came to learn of the high ethical standards that my research had to live up to. I had to stay objective and commercially sensitive at the same time. This meant having to meet them altogether sometimes, then having to meet them individually at other times as I could get more targeted information that way. Dealing with the objective aspects of my studies like sensor monitoring, was quite straightforward. However, when dealing with the subjective parts like engaging developers and their supply chain through interviews, as well as home occupants, I had to strive to maintain a good balance to reflect the multiple views. Despite this, I believe there must have been some level of subjectivity within the process.

8.11 Chapter Summary

This chapter started by revisiting the main aim and objectives of this research and discussed their achievement. A summary of the five main research conclusions has been presented and argued. Most importantly, this chapter has presented three main areas of novel research contributions and followed up by a set of recommendations. Implications of findings to different stakeholders have been presented. This is followed by limitations of the study, and consequently areas for future research. This chapter has been concluded by a personal reflection of the research journey and process. This research used a novel home developmental process analysis to investigate overheating in UK homes, proposed a scalability criterion for the critical evaluation of mitigation solutions, and proposed a framework for embedding scalable overheating mitigation in UK home developmental processes, based on overheating monitoring, assessment, and simulation, as well as evaluation with industry collaborators.

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Appendices

APPENDIX 1. Research Ethics Approval

Faculty of Computing, Engineering & the Built Environment Research Office Millennium Point, Curzon Street
Birmingham
B4 7XG

BCU_ethics@bcu.ac.uk

19/Jan/2021

Dr Monica Mateo Garcia
monica.mateogarcia@bcu.ac.uk

Dear Monica,

Re: Mateo Garcia /#7942 /sub3 /R(B) /2020 /Dec /CEBE FAEC - Indoor Air Quality and Overheating in new build residential

Thank you for your application and documentation regarding the above activity. I am pleased to take Chair's Action and approve this activity.

Provided that you are granted Permission of Access by relevant parties (meeting requirements as laid out by them), you may begin your activity.

I can also confirm that any person participating in the project is covered under the University's insurance arrangements.

Please note that ethics approval only covers your activity as it has been detailed in your ethics application. If you wish to make any changes to the activity, then you must submit an Amendment application for approval of the proposed changes.

Examples of changes include (but are not limited to) adding a new study site, a new method of participant recruitment, adding a new method of data collection and/or change of Project Lead.

Please also note that the Computing, Engineering, and the Built Environment Faculty Academic Ethics Committee should be notified of any serious adverse effects arising as a result of this activity.

If for any reason the Committee feels that the activity is no longer ethically sound, it reserves the right to withdraw its approval. In the unlikely event of issues arising which would lead to this, you will be consulted.

Keep a copy of this letter along with the corresponding application for your records as

evidence of approval.

If you have any queries, please contact BCU_ethics@bcu.ac.uk

I wish you every success with your activity.

Yours Sincerely,

Professor Sharon Cox

On behalf of the Computing, Engineering, and the Built Environment Faculty Academic Ethics Committee

APPENDIX 2. Home Occupant Information Leaflet

Indoor Air Quality and Thermal Comfort in new build residential developments in the UK

March 2022

The aim of the project is to propose cost effective scalable construction solutions and strategies that take account of human behaviours with the potential to improve the indoor environmental quality (IEQ) of new houses. The research will seek to analyze the factors that affect users' comfort and well-being in indoor environments so residential dwellings can be improved not just in terms of energy savings but also in providing healthy environments. Participants for this project will need to reside in the UK, and have their houses built to the 2013 Building regulations for their houses to fit the description intended for the research sample. Occupant's views on their experience relating to indoor air quality and thermal comfort in your home will be valuable to our research.

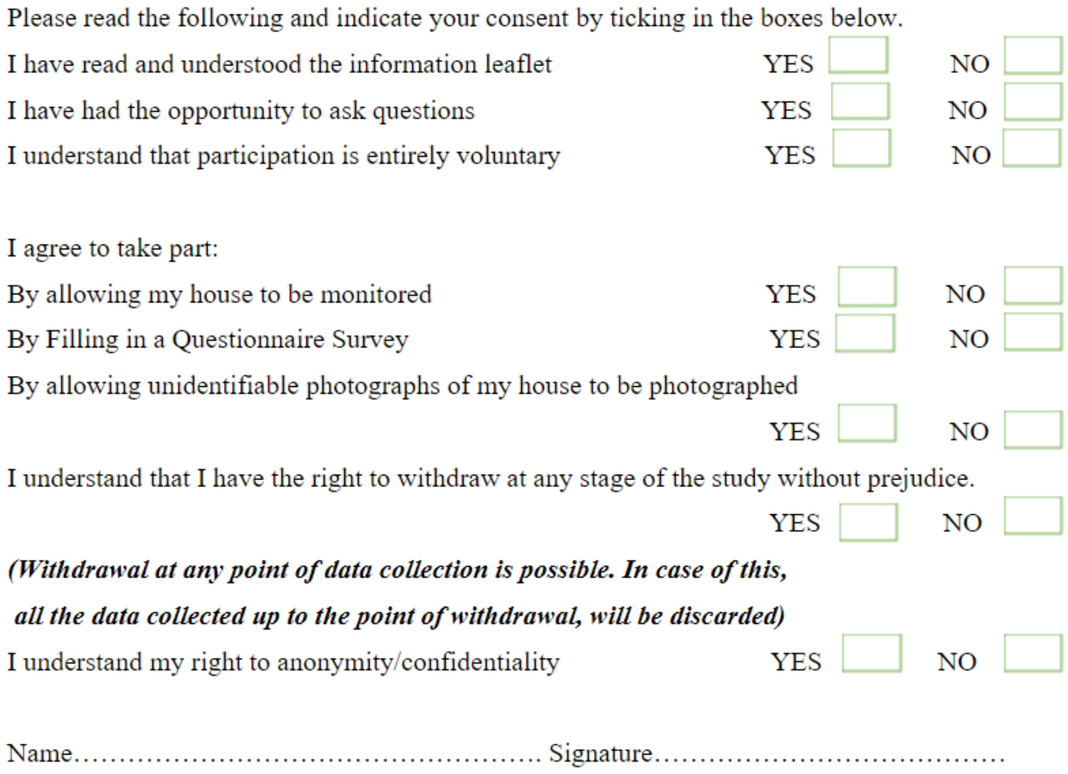
When consent is obtained, participants should expect to be engaged through part of 2022. This will involve monitoring of occupant houses for Indoor air quality parameters from February (As soon as practically possible) to end of September 2022 for Phase 2. Sensor installation should take around one hour or so to prep, position and set up the sensors. During the monitoring period, occupants should expect to be engaged through the following means:

1. A one-time home specification questionnaire at the onset (Usually done on the day of installing sensors)
2. A daily occupant diary for the first 12 weeks regarding home activities that affect Indoor Air Quality. This can be done remotely through email in two-week intervals.
3. A Thermal Comfort Questionnaire to be filled once a month from May to September. This will also be done remotely through email.

All this will be done in adherence to all health guidelines and at the convenience of participants' schedules without affecting their routines.

Engaging in this research will help to improve the indoor environmental quality of houses and as such, the health and wellbeing of housing occupants. This research will help to assess policies and standards that could bring about positive change in the field of Indoor Environmental Quality and hopefully lead the way to a confident Net Zero Carbon 2050 UK.

Private information such as names and addresses - house numbers, will not be needed. All the data collected will be anonymized and handled with strict levels of confidentiality. In case there is need to capture photographs or videos, these will be done in such a way that locations and individuals are unidentifiable. Any captured data will be in strict compliance to the Data Protection Act of 1998. All data will be stored in a secure university cloud-based storage for a maximum of 5 years with access granted to verified university researchers only. All participants have the right to informed consent, the right to withdraw from the study at any stage of data collection (without prejudice), the right to anonymity and data protection.



Please read the following and indicate your consent by ticking in the boxes below.

I have read and understood the information leaflet YES ☐ NO ☐

I have had the opportunity to ask questions YES ☐ NO ☐

I understand that participation is entirely voluntary YES ☐ NO ☐

I agree to take part:

By allowing my house to be monitored YES ☐ NO ☐

By Filling in a Questionnaire Survey YES ☐ NO ☐

By allowing unidentifiable photographs of my house to be photographed YES ☐ NO ☐

I understand that I have the right to withdraw at any stage of the study without prejudice. YES ☐ NO ☐

(Withdrawal at any point of data collection is possible. In case of this, all the data collected up to the point of withdrawal, will be discarded)

I understand my right to anonymity/confidentiality YES ☐ NO ☐

Name…………………………………………… Signature…………………………………

In case of any questions or concerns about the study, please contact:

Callistus Gero
PhD Researcher
Birmingham City University Callistus.Gero@mail.bcu.ac.uk

Mohamed Barre
PhD Researcher
Birmingham City University Mohamed.barre@bcu.ac.uk

Birmingham City University
Research Ethics Committee bcu_ethics@bcu.ac.uk

APPENDIX 3. Interview Guide for Housing Developers

Indoor Air Quality and Overheating Research

Home Development Process

Land Purchase

- What are your sources of information on potential land purchases? ·
- Briefly describe the site selection decision-making process. What would make you look at different strategies in relation to selecting sites? Have you tried doing things differently before? If yes, what was the result? And why do you think that your strategy produces a better value?
- Which site selection criteria do you follow? In terms of Location, area, Surroundings, green areas, and communities? How long does the whole process take? ·
- At what point do environmental concerns come in the land Purchase stage?
- How do you handle Greenfield/Brownfield sites?
- How difficult or easy is it to work with respective Planning authorities at this stage?

Planning and Design

- Can you briefly describe the Tender & Procurement process? ·
- What is your average planning time frame from instruction to approval?
- Do you implement the National Planning Policy framework? If so how?
- Which local authorities do you get involved with at this stage?
- Apart from NPPF, what other planning regulatory document do you use in the planning stage of your projects.
- Are you participating in the Planning White Paper consultation for 2020?
- For your developments in London, do you follow the London Plan to actively assess overheating risks and reduce reliance on air conditioning systems?
- What drives design decision-making? ·
- Can you describe how BFL12 points inform your design process?
- What is your building design approach in terms of the environment and occupant's quality of life?
- Do you have certification systems for sustainable design principles? ·
- Have you had some projects where design modifications have been done? What were the reasons behind the changes? ·
- How is the current Covid-19 situation affecting the design of your future houses?
- New changes to Part L and F regulations are due to be introduced, how will that be integrated into your projects? (Timeframes & Processes). ·
- Once a site has been identified and purchased for construction, how are decisions concerning scheme orientation made? Which parties are involved?
- What are your views on the current change in Planning processes recently introduced by the government?
- Briefly describe how you specify material and products such as complying with regulations, manufacturing guidance, low level of emissions, etc.? ·
- What is the source control strategy in relation to the selection of low emission building materials? · What are the best practice procedures? ·

Construction

- Can you briefly describe the on-site inspection process, with attention to monitoring the insulation installation stage?
- Do you have a pollutant source management plan during construction?
- In the case of overheating mitigation, what strategies does your company use? (Passive or Active measures) Any examples of this? Do these decisions affect the sale value of the house? Do you engage occupants when making these kinds of decisions? If so how?
- What are your construction standards in relation to sustainability and passive houses? ·
- Do you have enough capacity (in terms of skilled personnel) when implementing potential HVAC strategies? ·

- Do you employ a collaborative approach when tackling the quality control of indoor environments throughout the construction phase? ·
- What intervention procedures and proactive measures do you have in place throughout construction phase?
- What are the barriers faced when sourcing for building materials? ·
- How do you assess the quality of workmanship to achieve your company standard? ·
- Do you have metrics on previously completed projects? For instance, the overall project time frame. Also, at completion, how close were these metrics vs initial projections? What was the degree of variance?

Technical Department

- What future trends are your R & D division working towards? ·
- What role do your innovation and technology play in building future homes?
- What are the main barriers when implementing new technology or methods?
- Are your houses naturally ventilated, mechanically ventilated or mixed? (If a mixture, in what proportions?) and how are decisions regarding these systems made? ·
- Do you routinely evaluate the performance of newly occupied properties? If yes, what is included in the evaluations? ·
- Do you consider the use of more conventional heating and ventilation systems? What are the barriers to implement those techniques?
- Do you carry out overheating assessments and indoor air quality related tests (Modelling, SAP)? And at what point in the construction process are these carried out? ·
- Which instrument and/or software (Dynamic Simulation Models) or tools do you use, and why? ·
- For overheating purposes, what assessment criteria, if any, do you follow? (TM59, TM52, CIBSE guide A, PHPP, PHE, WHO, HQM) ·
- Which criteria do you use to select sample properties within a flat or a scheme for an assessment?

Marketing and Sales

- How do you handle your company public image throughout the entire process from land purchase through to after sale? ·
- What is your after-sale care process?
- Do you have customer satisfaction and complaints data in relation to the indoor environment?
- What are customer expectations and perceptions of a healthy home? ·
- Apart from economics, what other factors are customers looking for when buying a home, i.e., environment, green area, neighborhood, etc.?
- If some properties not sold according to your expected timeframe, what happens to the unsold properties?

Operation and Maintenance

- Do current building user’s guides help occupants understand and operate the building efficiently in line with the original design intent? ·
- What factors do you consider when installing HVAC systems (i.e. location of the outdoor air intake, any contaminant sources nearby, etc.) ·
- Do you have operating instructions, maintenance and calibration records for components of any mechanical ventilation used in your buildings? ·
- Are there any previous investigations regarding environmental issues or overheating complaints, and do you have their results? ·
- Is there any dedicated customer care following occupation of your houses?
- Will the new occupants receive training for the liability periods, and if there is a defect, who will they report to?
- Can you briefly describe the steps of soft-landing procedures?
- What post-occupancy evaluation procedures do you follow?
- Do you undertake commissioning for the systems you install in your houses?
- Do you have a list of locations where indoor quality complaints have been reported in the first year of occupancy?
- Have you faced situations where significant changes (micro or major) were made following complaints after houses were occupied? Addition of rooms, change of fabric elements etc.?

BIRMINGHAM CITY
University

APPENDIX 4. Thermal Comfort and Overheating Questionnaire

Please tick where appropriate

1. How would you characterize the thermal conditions of this month?

Hot	Warm	Slightly Warm	Neutral	Slightly Cool	Cool	Cold

2. Do you remember any periods/days where temperatures rose above average/normal to you?

Yes	No

3. If yes, do you remember the week and/or date/day?

	Week 1	Week 2	Week 3	Week 4
Tick where appropriate				
Date/ day				

4. Did the increase in temperature affect you in any way?
5. If yes, please tick the case that applies

Yes	No

Heat Stress	
Allergy trigger	
General Discomfort	
Any other?	

6. How did you respond to that increase in temperature?

Change in clothing	
Changing location in the house	
Opening windows and/or doors	
Taking a shower	
Using electric cooling i.e., fans	
Any other?	

7. Was your response effective?
8. Please explain

Yes	No

………

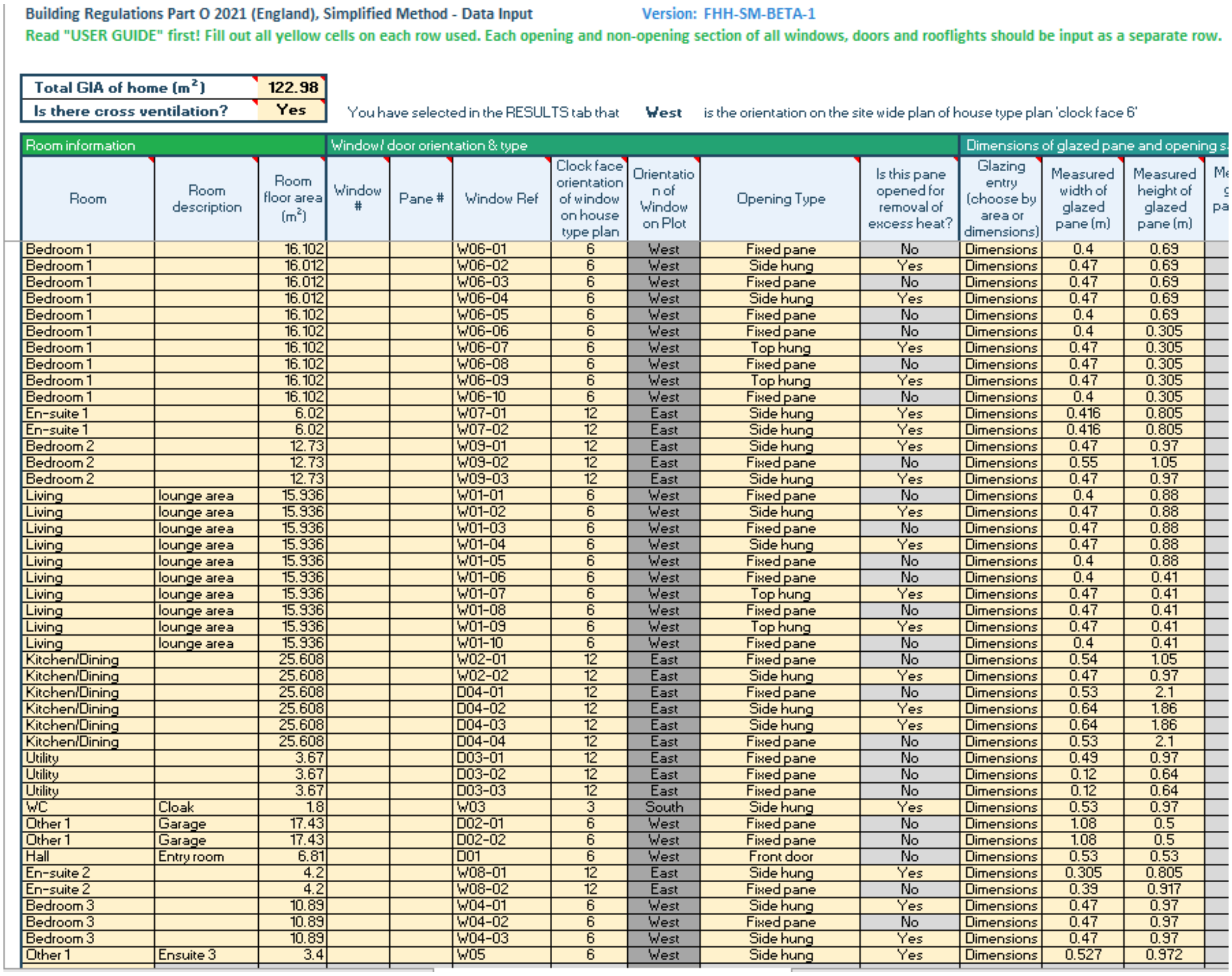
………

9. Any Recommendations you may have?

………

………

APPENDIX 5. Window and Door Input Data worksheet for Simplified Method Cheshire Home



Building Regulations Part O 2021 (England), Simplified Method - Data Input Version: FHH-SM-BETA-1

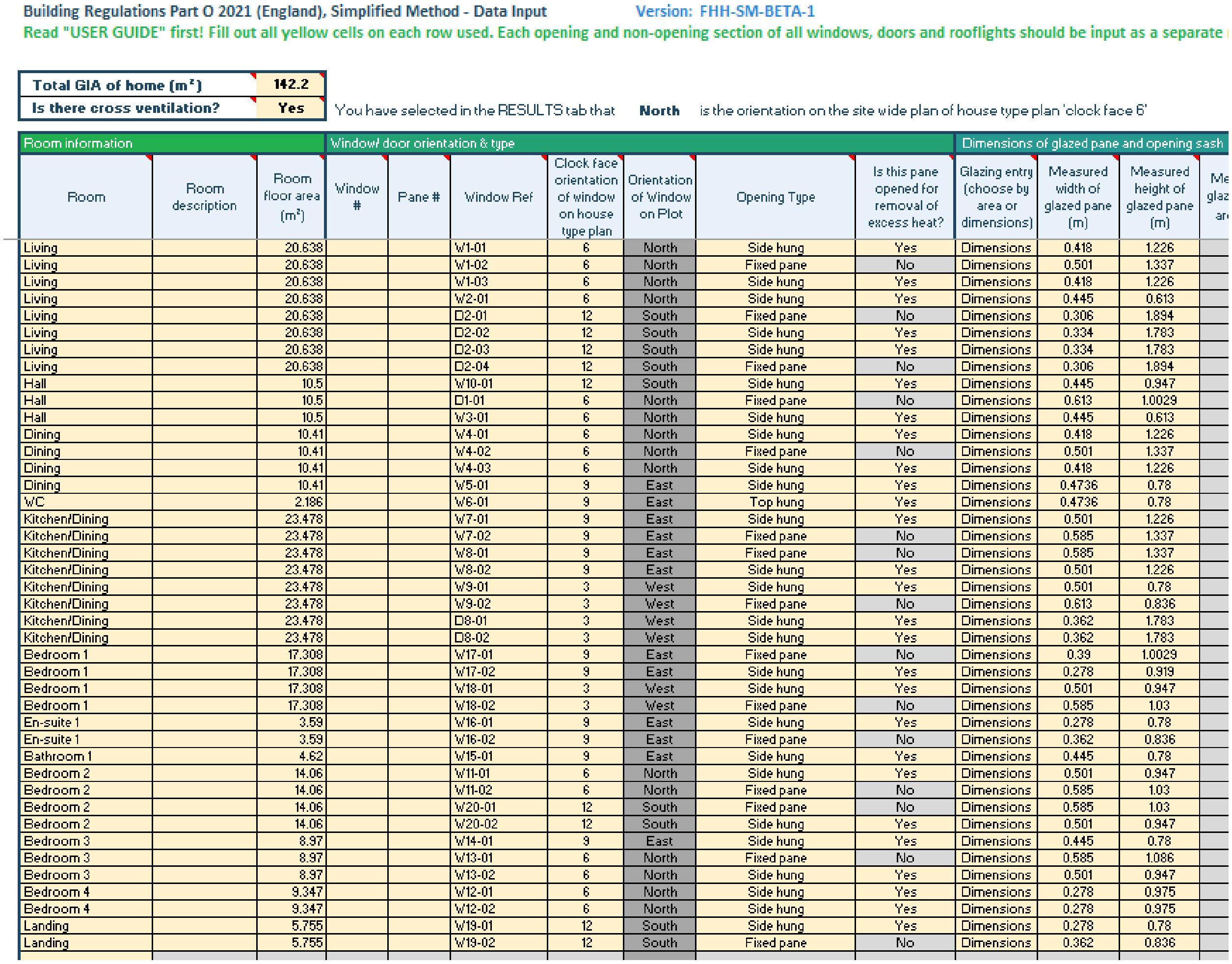
Read "USER GUIDE" first! Fill out all yellow cells on each row used. Each opening and non-opening section of all windows, doors and rooflights should be input as a separate row.

Total GIA of home (m^2)	**122.98**
Is there cross ventilation?	**Yes**

You have selected in the RESULTS tab that **West** is the orientation on the site wide plan of house type plan 'clock face 6'

Room information			Window/ door orientation & type							Dimensions of glazed pane and opening s		
Room	Room description	Room floor area (m^2)	Window #	Pane #	Window Ref	Clock face orientation of window on house type plan	Orientation of Window on Plot	Opening Type	Is this pane opened for removal of excess heat?	Glazing entry (choose by area or dimensions)	Measured width of glazed pane (m)	Measured height of glazed pane (m)
Bedroom 1		16.102			W06-01	6	West	Fixed pane	No	Dimensions	0.4	0.69
Bedroom 1		16.012			W06-02	6	West	Side hung	Yes	Dimensions	0.47	0.69
Bedroom 1		16.012			W06-03	6	West	Fixed pane	No	Dimensions	0.47	0.69
Bedroom 1		16.012			W06-04	6	West	Side hung	Yes	Dimensions	0.47	0.69
Bedroom 1		16.102			W06-05	6	West	Fixed pane	No	Dimensions	0.4	0.69
Bedroom 1		16.102			W06-06	6	West	Fixed pane	No	Dimensions	0.4	0.305
Bedroom 1		16.102			W06-07	6	West	Top hung	Yes	Dimensions	0.47	0.305
Bedroom 1		16.102			W06-08	6	West	Fixed pane	No	Dimensions	0.47	0.305
Bedroom 1		16.102			W06-09	6	West	Top hung	Yes	Dimensions	0.47	0.305
Bedroom 1		16.102			W06-10	6	West	Fixed pane	No	Dimensions	0.4	0.305
En-suite 1		6.02			W07-01	12	East	Side hung	Yes	Dimensions	0.416	0.805
En-suite 1		6.02			W07-02	12	East	Side hung	Yes	Dimensions	0.416	0.805
Bedroom 2		12.73			W09-01	12	East	Side hung	Yes	Dimensions	0.47	0.97
Bedroom 2		12.73			W09-02	12	East	Fixed pane	No	Dimensions	0.55	1.05
Bedroom 2		12.73			W09-03	12	East	Side hung	Yes	Dimensions	0.47	0.97
Living	lounge area	15.936			W01-01	6	West	Fixed pane	No	Dimensions	0.4	0.88
Living	lounge area	15.936			W01-02	6	West	Side hung	Yes	Dimensions	0.47	0.88
Living	lounge area	15.936			W01-03	6	West	Fixed pane	No	Dimensions	0.47	0.88
Living	lounge area	15.936			W01-04	6	West	Side hung	Yes	Dimensions	0.47	0.88
Living	lounge area	15.936			W01-05	6	West	Fixed pane	No	Dimensions	0.4	0.88
Living	lounge area	15.936			W01-06	6	West	Fixed pane	No	Dimensions	0.4	0.41
Living	lounge area	15.936			W01-07	6	West	Top hung	Yes	Dimensions	0.47	0.41
Living	lounge area	15.936			W01-08	6	West	Fixed pane	No	Dimensions	0.47	0.41
Living	lounge area	15.936			W01-09	6	West	Top hung	Yes	Dimensions	0.47	0.41
Living	lounge area	15.936			W01-10	6	West	Fixed pane	No	Dimensions	0.4	0.41
Kitchen/Dining		25.608			W02-01	12	East	Fixed pane	No	Dimensions	0.54	1.05
Kitchen/Dining		25.608			W02-02	12	East	Side hung	Yes	Dimensions	0.47	0.97
Kitchen/Dining		25.608			D04-01	12	East	Fixed pane	No	Dimensions	0.53	2.1
Kitchen/Dining		25.608			D04-02	12	East	Side hung	Yes	Dimensions	0.64	1.86
Kitchen/Dining		25.608			D04-03	12	East	Side hung	Yes	Dimensions	0.64	1.86
Kitchen/Dining		25.608			D04-04	12	East	Fixed pane	No	Dimensions	0.53	2.1
Utility		3.67			D03-01	12	East	Fixed pane	No	Dimensions	0.49	0.97
Utility		3.67			D03-02	12	East	Fixed pane	No	Dimensions	0.12	0.64
Utility		3.67			D03-03	12	East	Fixed pane	No	Dimensions	0.12	0.64
WC	Cloak	1.8			W03	3	South	Side hung	Yes	Dimensions	0.53	0.97
Other 1	Garage	17.43			D02-01	6	West	Fixed pane	No	Dimensions	1.08	0.5
Other 1	Garage	17.43			D02-02	6	West	Fixed pane	No	Dimensions	1.08	0.5
Hall	Entry room	6.81			D01	6	West	Front door	No	Dimensions	0.53	0.53
En-suite 2		4.2			W08-01	12	East	Side hung	Yes	Dimensions	0.305	0.805
En-suite 2		4.2			W08-02	12	East	Fixed pane	No	Dimensions	0.39	0.917
Bedroom 3		10.89			W04-01	6	West	Side hung	Yes	Dimensions	0.47	0.97
Bedroom 3		10.89			W04-02	6	West	Fixed pane	No	Dimensions	0.47	0.97
Bedroom 3		10.89			W04-03	6	West	Side hung	Yes	Dimensions	0.47	0.97
Other 1	Ensuite 3	3.4			W05	6	West	Side hung	Yes	Dimensions	0.527	0.972

APPENDIX 6. Window and Door Input Data worksheet for Simplified Method Suffolk Home



Building Regulations Part O 2021 (England), Simplified Method - Data Input Version: FHH-SM-BETA-1

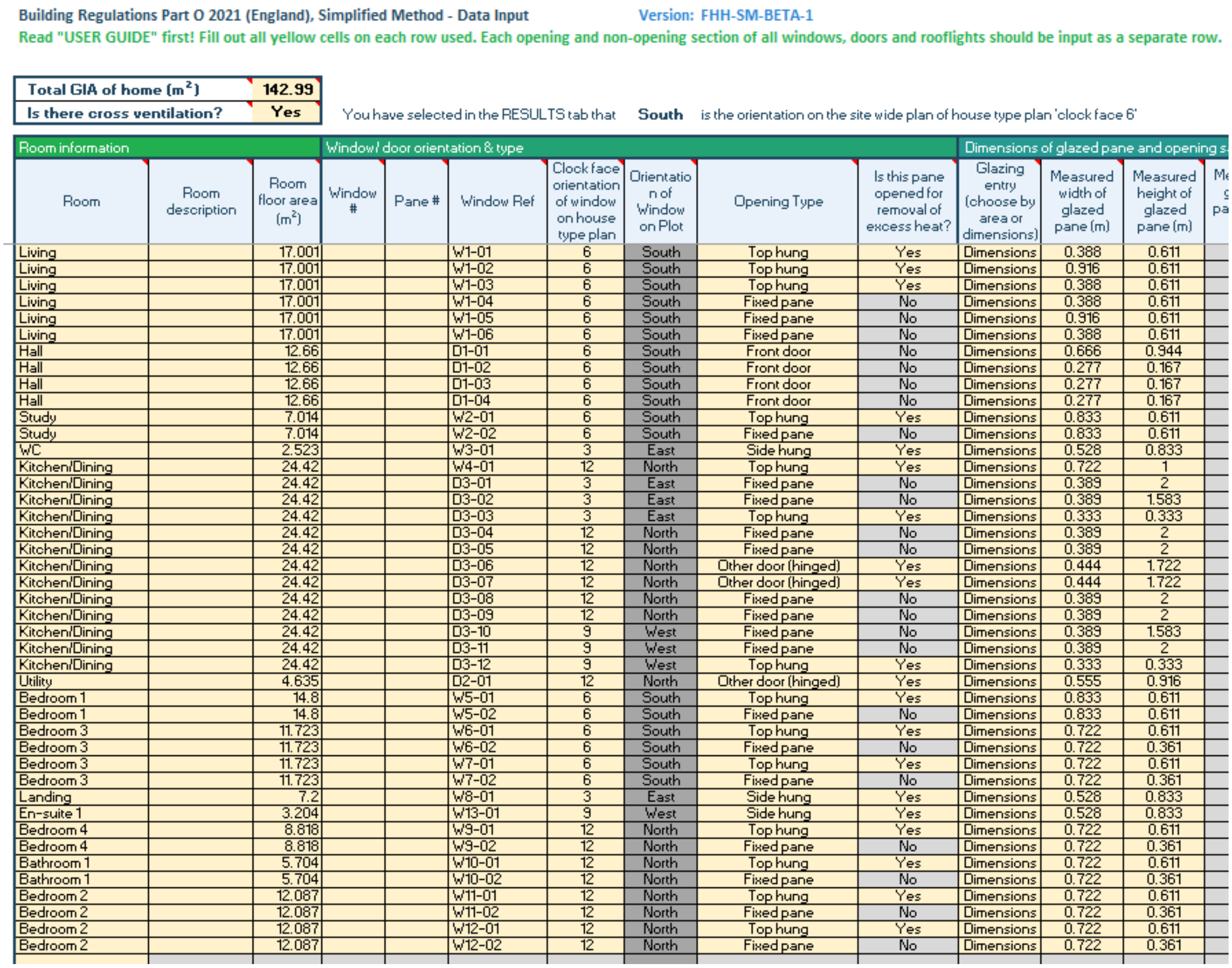
Read "USER GUIDE" first! Fill out all yellow cells on each row used. Each opening and non-opening section of all windows, doors and rooflights should be input as a separate

Total GIA of home (m²)	**142.2**
Is there cross ventilation?	**Yes**

You have selected in the RESULTS tab that **North** is the orientation on the site wide plan of house type plan 'clock face 6'

Room information			Window/ door orientation & type							Dimensions of glazed pane and opening sash			
Room	Room description	Room floor area (m²)	Window #	Pane #	Window Ref	Clock face orientation of window on house type plan	Orientation of Window on Plot	Opening Type	Is this pane opened for removal of excess heat?	Glazing entry (choose by area or dimensions)	Measured width of glazed pane (m)	Measured height of glazed pane (m)	Me glaz ar
Living		20.638			W1-01	6	North	Side hung	Yes	Dimensions	0.418	1.226	
Living		20.638			W1-02	6	North	Fixed pane	No	Dimensions	0.501	1.337	
Living		20.638			W1-03	6	North	Side hung	Yes	Dimensions	0.418	1.226	
Living		20.638			W2-01	6	North	Side hung	Yes	Dimensions	0.445	0.613	
Living		20.638			D2-01	12	South	Fixed pane	No	Dimensions	0.306	1.894	
Living		20.638			D2-02	12	South	Side hung	Yes	Dimensions	0.334	1.783	
Living		20.638			D2-03	12	South	Side hung	Yes	Dimensions	0.334	1.783	
Living		20.638			D2-04	12	South	Fixed pane	No	Dimensions	0.306	1.894	
Hall		10.5			W10-01	12	South	Side hung	Yes	Dimensions	0.445	0.947	
Hall		10.5			D1-01	6	North	Fixed pane	No	Dimensions	0.613	1.0029	
Hall		10.5			W3-01	6	North	Side hung	Yes	Dimensions	0.445	0.613	
Dining		10.41			W4-01	6	North	Side hung	Yes	Dimensions	0.418	1.226	
Dining		10.41			W4-02	6	North	Fixed pane	No	Dimensions	0.501	1.337	
Dining		10.41			W4-03	6	North	Side hung	Yes	Dimensions	0.418	1.226	
Dining		10.41			W5-01	9	East	Side hung	Yes	Dimensions	0.4736	0.78	
WC		2.186			W6-01	9	East	Top hung	Yes	Dimensions	0.4736	0.78	
Kitchen/Dining		23.478			W7-01	9	East	Side hung	Yes	Dimensions	0.501	1.226	
Kitchen/Dining		23.478			W7-02	9	East	Fixed pane	No	Dimensions	0.585	1.337	
Kitchen/Dining		23.478			W8-01	9	East	Fixed pane	No	Dimensions	0.585	1.337	
Kitchen/Dining		23.478			W8-02	9	East	Side hung	Yes	Dimensions	0.501	1.226	
Kitchen/Dining		23.478			W9-01	3	West	Side hung	Yes	Dimensions	0.501	0.78	
Kitchen/Dining		23.478			W9-02	3	West	Fixed pane	No	Dimensions	0.613	0.836	
Kitchen/Dining		23.478			D8-01	3	West	Side hung	Yes	Dimensions	0.362	1.783	
Kitchen/Dining		23.478			D8-02	3	West	Side hung	Yes	Dimensions	0.362	1.783	
Bedroom 1		17.308			W17-01	9	East	Fixed pane	No	Dimensions	0.39	1.0029	
Bedroom 1		17.308			W17-02	9	East	Side hung	Yes	Dimensions	0.278	0.919	
Bedroom 1		17.308			W18-01	3	West	Side hung	Yes	Dimensions	0.501	0.947	
Bedroom 1		17.308			W18-02	3	West	Fixed pane	No	Dimensions	0.585	1.03	
En-suite 1		3.59			W16-01	9	East	Side hung	Yes	Dimensions	0.278	0.78	
En-suite 1		3.59			W16-02	9	East	Fixed pane	No	Dimensions	0.362	0.836	
Bathroom 1		4.62			W15-01	9	East	Side hung	Yes	Dimensions	0.445	0.78	
Bedroom 2		14.06			W11-01	6	North	Side hung	Yes	Dimensions	0.501	0.947	
Bedroom 2		14.06			W11-02	6	North	Fixed pane	No	Dimensions	0.585	1.03	
Bedroom 2		14.06			W20-01	12	South	Fixed pane	No	Dimensions	0.585	1.03	
Bedroom 2		14.06			W20-02	12	South	Side hung	Yes	Dimensions	0.501	0.947	
Bedroom 3		8.97			W14-01	9	East	Side hung	Yes	Dimensions	0.445	0.78	
Bedroom 3		8.97			W13-01	6	North	Fixed pane	No	Dimensions	0.585	1.086	
Bedroom 3		8.97			W13-02	6	North	Side hung	Yes	Dimensions	0.501	0.947	
Bedroom 4		9.347			W12-01	6	North	Side hung	Yes	Dimensions	0.278	0.975	
Bedroom 4		9.347			W12-02	6	North	Side hung	Yes	Dimensions	0.278	0.975	
Landing		5.755			W19-01	12	South	Side hung	Yes	Dimensions	0.278	0.78	
Landing		5.755			W19-02	12	South	Fixed pane	No	Dimensions	0.362	0.836	

APPENDIX 7. Window and Door Input Data worksheet for Simplified Method Loughborough Home



Building Regulations Part O 2021 (England), Simplified Method - Data Input Version: FHH-SM-BETA-1

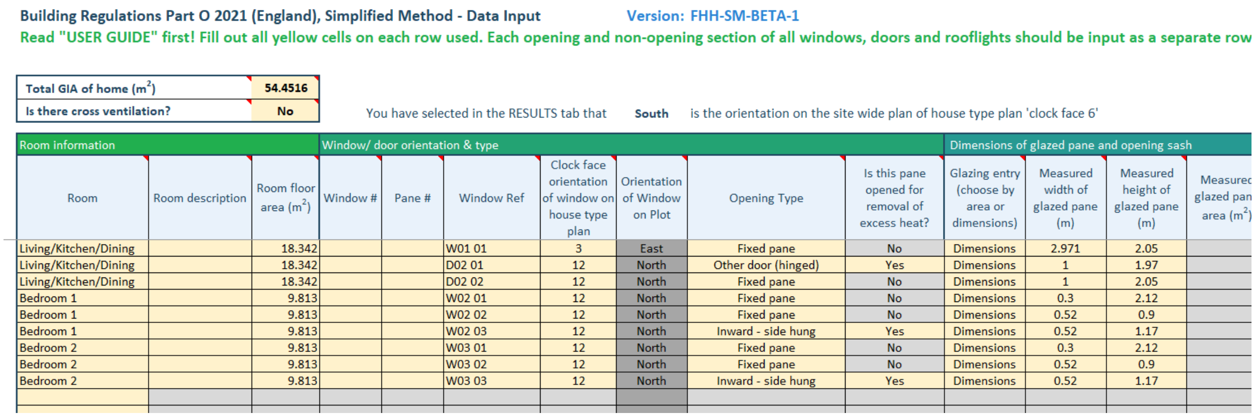
Read "USER GUIDE" first! Fill out all yellow cells on each row used. Each opening and non-opening section of all windows, doors and rooflights should be input as a separate row.

Total GIA of home (m²)	**142.99**
Is there cross ventilation?	**Yes**

You have selected in the RESULTS tab that **South** is the orientation on the site wide plan of house type plan 'clock face 6'

Room information			Window / door orientation & type							Dimensions of glazed pane and opening s		
Room	Room description	Room floor area (m²)	Window #	Pane #	Window Ref	Clock face orientation of window on house type plan	Orientation of Window on Plot	Opening Type	Is this pane opened for removal of excess heat?	Glazing entry (choose by area or dimensions)	Measured width of glazed pane (m)	Measured height of glazed pane (m)
Living		17.001			W1-01	6	South	Top hung	Yes	Dimensions	0.388	0.611
Living		17.001			W1-02	6	South	Top hung	Yes	Dimensions	0.916	0.611
Living		17.001			W1-03	6	South	Top hung	Yes	Dimensions	0.388	0.611
Living		17.001			W1-04	6	South	Fixed pane	No	Dimensions	0.388	0.611
Living		17.001			W1-05	6	South	Fixed pane	No	Dimensions	0.916	0.611
Living		17.001			W1-06	6	South	Fixed pane	No	Dimensions	0.388	0.611
Hall		12.66			D1-01	6	South	Front door	No	Dimensions	0.666	0.944
Hall		12.66			D1-02	6	South	Front door	No	Dimensions	0.277	0.167
Hall		12.66			D1-03	6	South	Front door	No	Dimensions	0.277	0.167
Hall		12.66			D1-04	6	South	Front door	No	Dimensions	0.277	0.167
Study		7.014			W2-01	6	South	Top hung	Yes	Dimensions	0.833	0.611
Study		7.014			W2-02	6	South	Fixed pane	No	Dimensions	0.833	0.611
WC		2.523			W3-01	3	East	Side hung	Yes	Dimensions	0.528	0.833
Kitchen/Dining		24.42			W4-01	12	North	Top hung	Yes	Dimensions	0.722	1
Kitchen/Dining		24.42			D3-01	3	East	Fixed pane	No	Dimensions	0.389	2
Kitchen/Dining		24.42			D3-02	3	East	Fixed pane	No	Dimensions	0.389	1.583
Kitchen/Dining		24.42			D3-03	3	East	Top hung	Yes	Dimensions	0.333	0.333
Kitchen/Dining		24.42			D3-04	12	North	Fixed pane	No	Dimensions	0.389	2
Kitchen/Dining		24.42			D3-05	12	North	Fixed pane	No	Dimensions	0.389	2
Kitchen/Dining		24.42			D3-06	12	North	Other door (hinged)	Yes	Dimensions	0.444	1.722
Kitchen/Dining		24.42			D3-07	12	North	Other door (hinged)	Yes	Dimensions	0.444	1.722
Kitchen/Dining		24.42			D3-08	12	North	Fixed pane	No	Dimensions	0.389	2
Kitchen/Dining		24.42			D3-09	12	North	Fixed pane	No	Dimensions	0.389	2
Kitchen/Dining		24.42			D3-10	9	West	Fixed pane	No	Dimensions	0.389	1.583
Kitchen/Dining		24.42			D3-11	9	West	Fixed pane	No	Dimensions	0.389	2
Kitchen/Dining		24.42			D3-12	9	West	Top hung	Yes	Dimensions	0.333	0.333
Utility		4.635			D2-01	12	North	Other door (hinged)	Yes	Dimensions	0.555	0.916
Bedroom 1		14.8			W5-01	6	South	Top hung	Yes	Dimensions	0.833	0.611
Bedroom 1		14.8			W5-02	6	South	Fixed pane	No	Dimensions	0.833	0.611
Bedroom 3		11.723			W6-01	6	South	Top hung	Yes	Dimensions	0.722	0.611
Bedroom 3		11.723			W6-02	6	South	Fixed pane	No	Dimensions	0.722	0.361
Bedroom 3		11.723			W7-01	6	South	Top hung	Yes	Dimensions	0.722	0.611
Bedroom 3		11.723			W7-02	6	South	Fixed pane	No	Dimensions	0.722	0.361
Landing		7.2			W8-01	3	East	Side hung	Yes	Dimensions	0.528	0.833
En-suite 1		3.204			W13-01	9	West	Side hung	Yes	Dimensions	0.528	0.833
Bedroom 4		8.818			W9-01	12	North	Top hung	Yes	Dimensions	0.722	0.611
Bedroom 4		8.818			W9-02	12	North	Fixed pane	No	Dimensions	0.722	0.361
Bathroom 1		5.704			W10-01	12	North	Top hung	Yes	Dimensions	0.722	0.611
Bathroom 1		5.704			W10-02	12	North	Fixed pane	No	Dimensions	0.722	0.361
Bedroom 2		12.087			W11-01	12	North	Top hung	Yes	Dimensions	0.722	0.611
Bedroom 2		12.087			W11-02	12	North	Fixed pane	No	Dimensions	0.722	0.361
Bedroom 2		12.087			W12-01	12	North	Top hung	Yes	Dimensions	0.722	0.611
Bedroom 2		12.087			W12-02	12	North	Fixed pane	No	Dimensions	0.722	0.361

APPENDIX 8. Window and Door Input Data worksheet for Simplified Method Birmingham Flat



Building Regulations Part O 2021 (England), Simplified Method - Data Input Version: FHH-SM-BETA-1

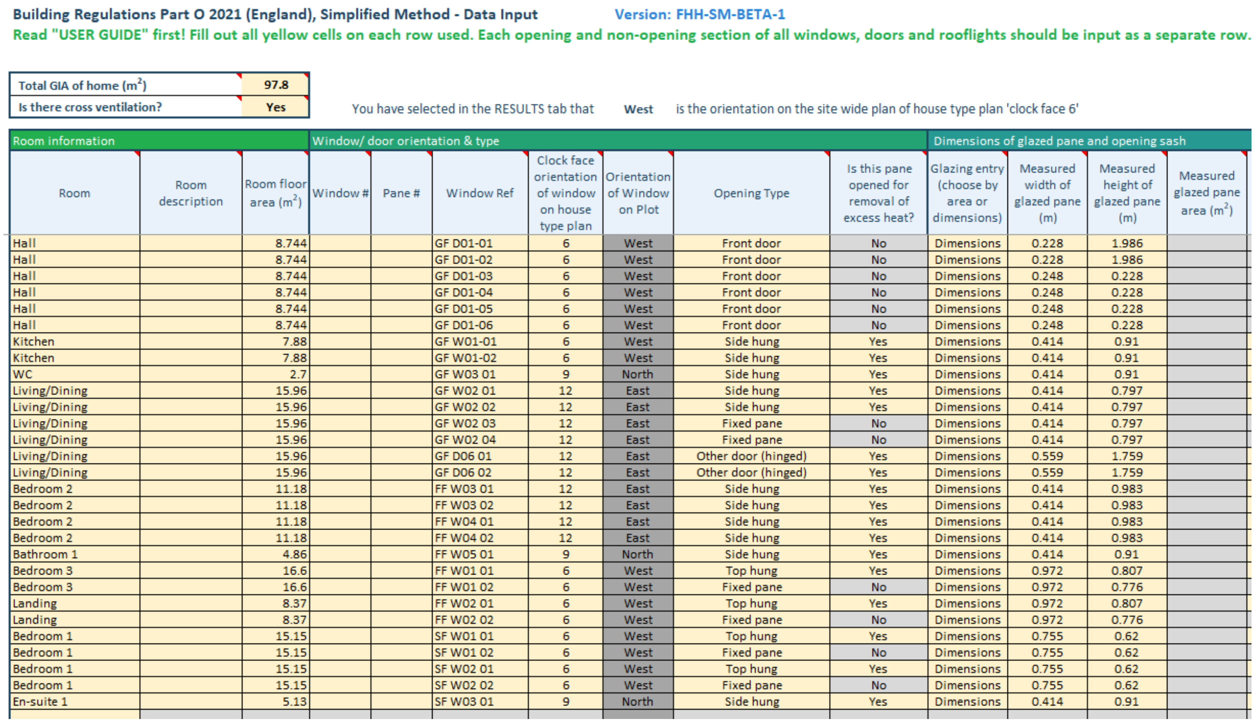
Read "USER GUIDE" first! Fill out all yellow cells on each row used. Each opening and non-opening section of all windows, doors and rooflights should be input as a separate row

Total GIA of home (m^2)	54.4516
Is there cross ventilation?	No

You have selected in the RESULTS tab that **South** is the orientation on the site wide plan of house type plan 'clock face 6'

Room information			Window/ door orientation & type							Dimensions of glazed pane and opening sash			
Room	Room description	Room floor area (m^2)	Window #	Pane #	Window Ref	Clock face orientation of window on house type plan	Orientation of Window on Plot	Opening Type	Is this pane opened for removal of excess heat?	Glazing entry (choose by area or dimensions)	Measured width of glazed pane (m)	Measured height of glazed pane (m)	Measured glazed pan area (m^2)
Living/Kitchen/Dining		18.342			W01 01	3	East	Fixed pane	No	Dimensions	2.971	2.05	
Living/Kitchen/Dining		18.342			D02 01	12	North	Other door (hinged)	Yes	Dimensions	1	1.97	
Living/Kitchen/Dining		18.342			D02 02	12	North	Fixed pane	No	Dimensions	1	2.05	
Bedroom 1		9.813			W02 01	12	North	Fixed pane	No	Dimensions	0.3	2.12	
Bedroom 1		9.813			W02 02	12	North	Fixed pane	No	Dimensions	0.52	0.9	
Bedroom 1		9.813			W02 03	12	North	Inward - side hung	Yes	Dimensions	0.52	1.17	
Bedroom 2		9.813			W03 01	12	North	Fixed pane	No	Dimensions	0.3	2.12	
Bedroom 2		9.813			W03 02	12	North	Fixed pane	No	Dimensions	0.52	0.9	
Bedroom 2		9.813			W03 03	12	North	Inward - side hung	Yes	Dimensions	0.52	1.17	

APPENDIX 9. Window and Door Input Data worksheet for Simplified Method Birmingham Home



Building Regulations Part O 2021 (England), Simplified Method - Data Input Version: FHH-SM-BETA-1

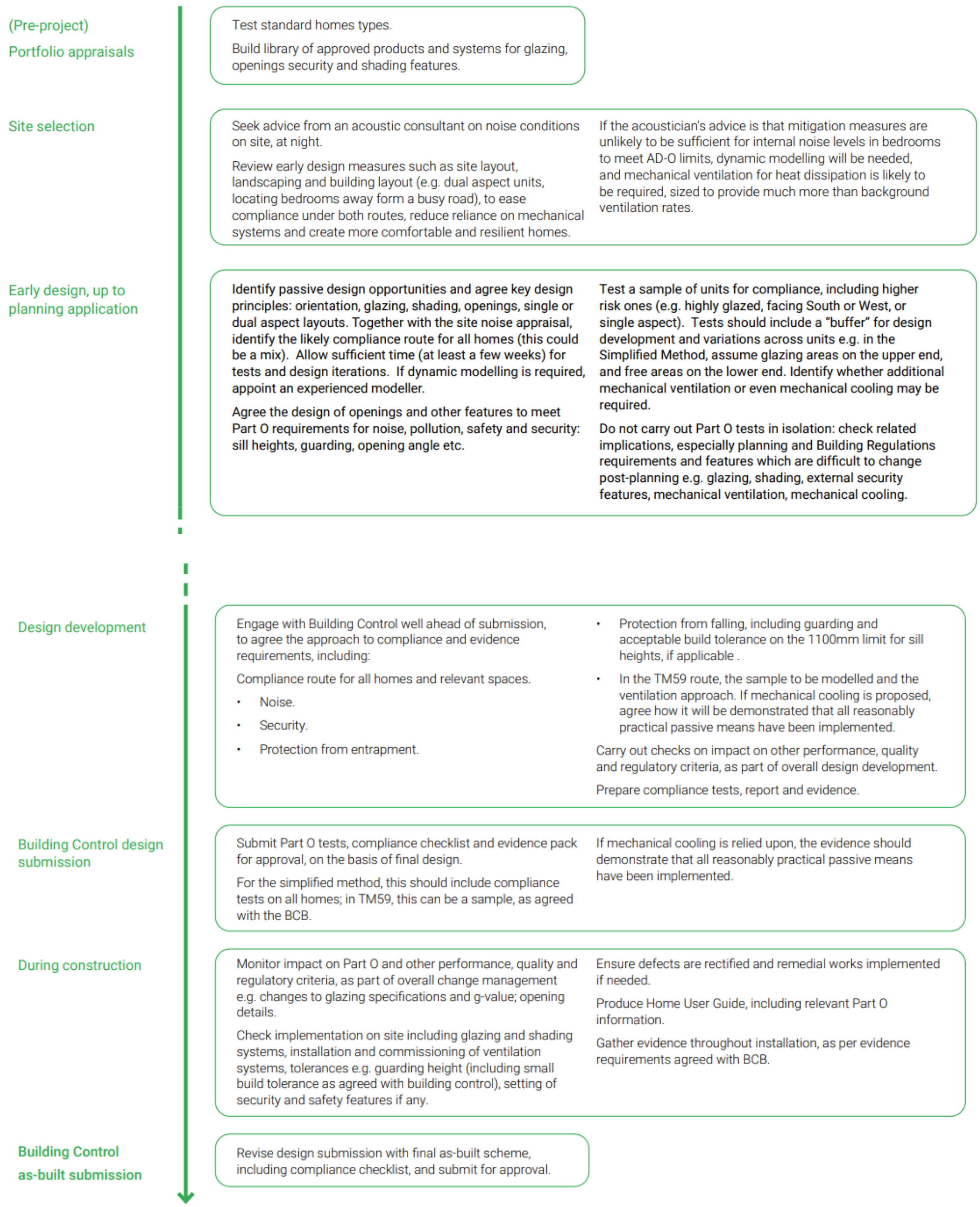
Read "USER GUIDE" first! Fill out all yellow cells on each row used. Each opening and non-opening section of all windows, doors and rooflights should be input as a separate row.

Total GIA of home (m^2)	97.8
Is there cross ventilation?	Yes

You have selected in the RESULTS tab that **West** is the orientation on the site wide plan of house type plan 'clock face 6'

Room information			Window/ door orientation & type							Dimensions of glazed pane and opening sash			
Room	Room description	Room floor area (m^2)	Window #	Pane #	Window Ref	Clock face orientation of window on house type plan	Orientation of Window on Plot	Opening Type	Is this pane opened for removal of excess heat?	Glazing entry (choose by area or dimensions)	Measured width of glazed pane (m)	Measured height of glazed pane (m)	Measured glazed pane area (m^2)
Hall		8.744			GF D01-01	6	West	Front door	No	Dimensions	0.228	1.986	
Hall		8.744			GF D01-02	6	West	Front door	No	Dimensions	0.228	1.986	
Hall		8.744			GF D01-03	6	West	Front door	No	Dimensions	0.248	0.228	
Hall		8.744			GF D01-04	6	West	Front door	No	Dimensions	0.248	0.228	
Hall		8.744			GF D01-05	6	West	Front door	No	Dimensions	0.248	0.228	
Hall		8.744			GF D01-06	6	West	Front door	No	Dimensions	0.248	0.228	
Kitchen		7.88			GF W01-01	6	West	Side hung	Yes	Dimensions	0.414	0.91	
Kitchen		7.88			GF W01-02	6	West	Side hung	Yes	Dimensions	0.414	0.91	
WC		2.7			GF W03 01	9	North	Side hung	Yes	Dimensions	0.414	0.91	
Living/Dining		15.96			GF W02 01	12	East	Side hung	Yes	Dimensions	0.414	0.797	
Living/Dining		15.96			GF W02 02	12	East	Side hung	Yes	Dimensions	0.414	0.797	
Living/Dining		15.96			GF W02 03	12	East	Fixed pane	No	Dimensions	0.414	0.797	
Living/Dining		15.96			GF W02 04	12	East	Fixed pane	No	Dimensions	0.414	0.797	
Living/Dining		15.96			GF D06 01	12	East	Other door (hinged)	Yes	Dimensions	0.559	1.759	
Living/Dining		15.96			GF D06 02	12	East	Other door (hinged)	Yes	Dimensions	0.559	1.759	
Bedroom 2		11.18			FF W03 01	12	East	Side hung	Yes	Dimensions	0.414	0.983	
Bedroom 2		11.18			FF W03 02	12	East	Side hung	Yes	Dimensions	0.414	0.983	
Bedroom 2		11.18			FF W04 01	12	East	Side hung	Yes	Dimensions	0.414	0.983	
Bedroom 2		11.18			FF W04 02	12	East	Side hung	Yes	Dimensions	0.414	0.983	
Bathroom 1		4.86			FF W05 01	9	North	Side hung	Yes	Dimensions	0.414	0.91	
Bedroom 3		16.6			FF W01 01	6	West	Top hung	Yes	Dimensions	0.972	0.807	
Bedroom 3		16.6			FF W01 02	6	West	Fixed pane	No	Dimensions	0.972	0.776	
Landing		8.37			FF W02 01	6	West	Top hung	Yes	Dimensions	0.972	0.807	
Landing		8.37			FF W02 02	6	West	Fixed pane	No	Dimensions	0.972	0.776	
Bedroom 1		15.15			SF W01 01	6	West	Top hung	Yes	Dimensions	0.755	0.62	
Bedroom 1		15.15			SF W01 02	6	West	Fixed pane	No	Dimensions	0.755	0.62	
Bedroom 1		15.15			SF W02 01	6	West	Top hung	Yes	Dimensions	0.755	0.62	
Bedroom 1		15.15			SF W02 02	6	West	Fixed pane	No	Dimensions	0.755	0.62	
En-suite 1		5.13			SF W03 01	9	North	Side hung	Yes	Dimensions	0.414	0.91	

APPENDIX 10. Timeline Future Homes Hub | Part O 2021 Technical Guidance



(Pre-project)
Portfolio appraisals

Test standard homes types.

Build library of approved products and systems for glazing, openings security and shading features.

Site selection

Seek advice from an acoustic consultant on noise conditions on site, at night.

Review early design measures such as site layout, landscaping and building layout (e.g. dual aspect units, locating bedrooms away form a busy road), to ease compliance under both routes, reduce reliance on mechanical systems and create more comfortable and resilient homes.

If the acoustician's advice is that mitigation measures are unlikely to be sufficient for internal noise levels in bedrooms to meet AD-O limits, dynamic modelling will be needed, and mechanical ventilation for heat dissipation is likely to be required, sized to provide much more than background ventilation rates.

Early design, up to planning application

Identify passive design opportunities and agree key design principles: orientation, glazing, shading, openings, single or dual aspect layouts. Together with the site noise appraisal, identify the likely compliance route for all homes (this could be a mix). Allow sufficient time (at least a few weeks) for tests and design iterations. If dynamic modelling is required, appoint an experienced modeller.

Agree the design of openings and other features to meet Part O requirements for noise, pollution, safety and security: sill heights, guarding, opening angle etc.

Test a sample of units for compliance, including higher risk ones (e.g. highly glazed, facing South or West, or single aspect). Tests should include a “buffer” for design development and variations across units e.g. in the Simplified Method, assume glazing areas on the upper end, and free areas on the lower end. Identify whether additional mechanical ventilation or even mechanical cooling may be required.

Do not carry out Part O tests in isolation: check related implications, especially planning and Building Regulations requirements and features which are difficult to change post-planning e.g. glazing, shading, external security features, mechanical ventilation, mechanical cooling.

Design development

Engage with Building Control well ahead of submission, to agree the approach to compliance and evidence requirements, including:

Compliance route for all homes and relevant spaces.

- Noise.
- Security.
- Protection from entrapment.
- Protection from falling, including guarding and acceptable build tolerance on the 1100mm limit for sill heights, if applicable .
- In the TM59 route, the sample to be modelled and the ventilation approach. If mechanical cooling is proposed, agree how it will be demonstrated that all reasonably practical passive means have been implemented.

Carry out checks on impact on other performance, quality and regulatory criteria, as part of overall design development.

Prepare compliance tests, report and evidence.

Building Control design submission

Submit Part O tests, compliance checklist and evidence pack for approval, on the basis of final design.

For the simplified method, this should include compliance tests on all homes; in TM59, this can be a sample, as agreed with the BCB.

If mechanical cooling is relied upon, the evidence should demonstrate that all reasonably practical passive means have been implemented.

During construction

Monitor impact on Part O and other performance, quality and regulatory criteria, as part of overall change management e.g. changes to glazing specifications and g-value; opening details.

Check implementation on site including glazing and shading systems, installation and commissioning of ventilation systems, tolerances e.g. guarding height (including small build tolerance as agreed with building control), setting of security and safety features if any.

Ensure defects are rectified and remedial works implemented if needed.

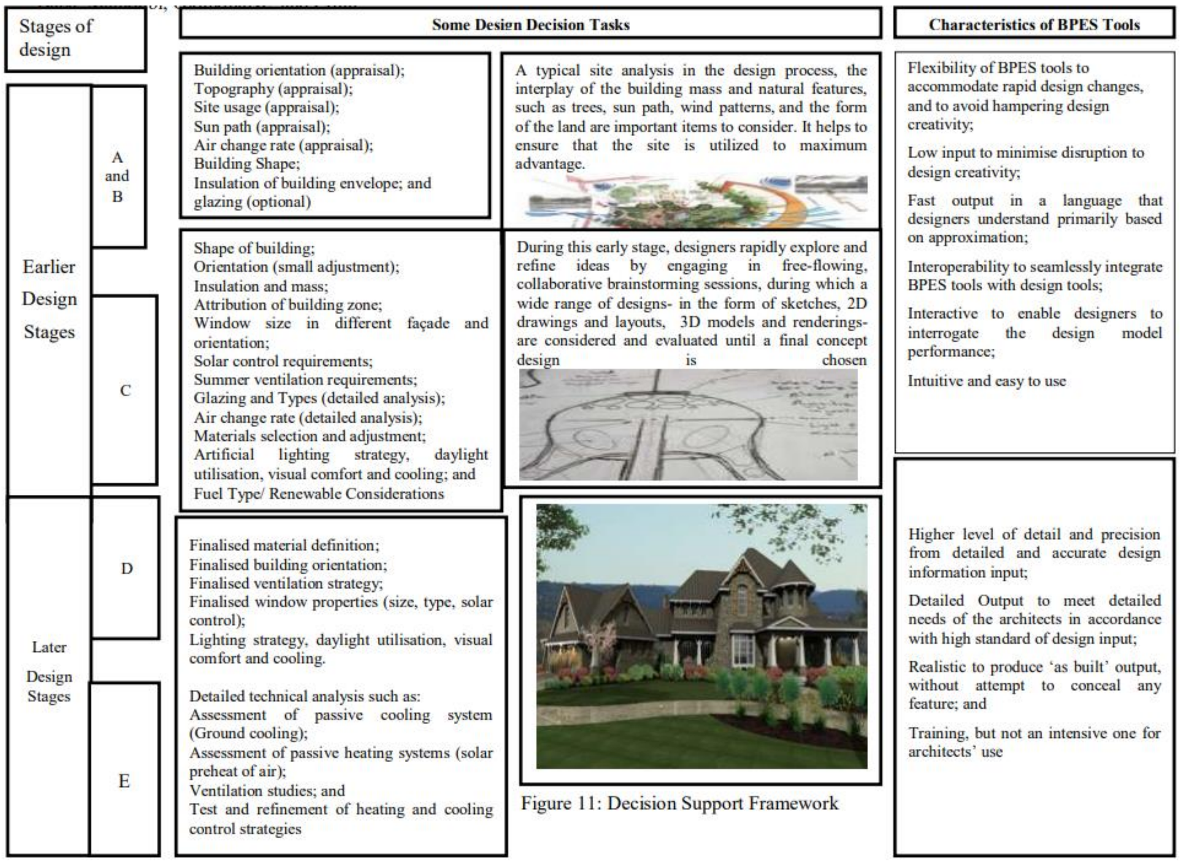
Produce Home User Guide, including relevant Part O information.

Gather evidence throughout installation, as per evidence requirements agreed with BCB.

Building Control as-built submission

Revise design submission with final as-built scheme, including compliance checklist, and submit for approval.

APPENDIX 11. Design Support Framework (Baba et al., 2013)



Stages of design		Some Design Decision Tasks		Characteristics of BPES Tools
Earlier Design Stages	A and B	Building orientation (appraisal); Topography (appraisal); Site usage (appraisal); Sun path (appraisal); Air change rate (appraisal); Building Shape; Insulation of building envelope; and glazing (optional)	A typical site analysis in the design process, the interplay of the building mass and natural features, such as trees, sun path, wind patterns, and the form of the land are important items to consider. It helps to ensure that the site is utilized to maximum advantage.	Flexibility of BPES tools to accommodate rapid design changes, and to avoid hampering design creativity; Low input to minimise disruption to design creativity; Fast output in a language that designers understand primarily based on approximation; Interoperability to seamlessly integrate BPES tools with design tools; Interactive to enable designers to interrogate the design model performance; Intuitive and easy to use
	C	Shape of building; Orientation (small adjustment); Insulation and mass; Attribution of building zone; Window size in different façade and orientation; Solar control requirements; Summer ventilation requirements; Glazing and Types (detailed analysis); Air change rate (detailed analysis); Materials selection and adjustment; Artificial lighting strategy, daylight utilisation, visual comfort and cooling; and Fuel Type/ Renewable Considerations	During this early stage, designers rapidly explore and refine ideas by engaging in free-flowing, collaborative brainstorming sessions, during which a wide range of designs- in the form of sketches, 2D drawings and layouts, 3D models and renderings- are considered and evaluated until a final concept design is chosen	
Later Design Stages	D	Finalised material definition; Finalised building orientation; Finalised ventilation strategy; Finalised window properties (size, type, solar control); Lighting strategy, daylight utilisation, visual comfort and cooling.		Higher level of detail and precision from detailed and accurate design information input; Detailed Output to meet detailed needs of the architects in accordance with high standard of design input; Realistic to produce 'as built' output, without attempt to conceal any feature; and Training, but not an intensive one for architects' use
	E	Detailed technical analysis such as: Assessment of passive cooling system (Ground cooling); Assessment of passive heating systems (solar preheat of air); Ventilation studies; and Test and refinement of heating and cooling control strategies		

Figure 11: Decision Support Framework

APPENDIX 12. List of Codes Developed from NVivo 12

i.e. the themes in brown colour are the major factors based on home development processes.

Main factors and Themes	**Files**	**Codes**	**Created On**	**Created By**	**Modified On**
Market Dynamics and Business Environment	0	0	08/05/2023 20:15	CG	08/05/2023 20:15
Supply chain issues	2	2	10/05/2023 14:03	CG	10/05/2023 14:18
Sample sizes for overheating assessments	2	3	08/05/2023 20:19	CG	08/05/2023 20:43
Housing Market trends	2	2	08/05/2023 20:48	CG	10/05/2023 14:14
cost implications	6	11	08/05/2023 19:52	CG	10/05/2023 14:15
Land Purchase and Strategic planning	1	1	08/05/2023 19:57	CG	10/05/2023 13:38
Noise assessment	2	2	08/05/2023 19:53	CG	10/05/2023 13:06
Environmental considerations	3	3	10/05/2023 14:02	CG	10/05/2023 14:43
Handover and Occupation	0	0	08/05/2023 20:14	CG	08/05/2023 20:14
Occupant engagement	8	8	08/05/2023 21:03	CG	10/05/2023 14:35
Occupant control of systems	2	2	10/05/2023 11:54	CG	10/05/2023 14:50
Lack of access to MEV installers	1	1	10/05/2023 12:22	CG	10/05/2023 12:22
Handover	4	4	08/05/2023 19:55	CG	10/05/2023 14:45
Government Policy and Regulation	3	3	08/05/2023 20:15	CG	10/05/2023 14:35
Simplified Method	1	2	08/05/2023 20:55	CG	08/05/2023 20:56
SAP	5	6	08/05/2023 19:42	CG	10/05/2023 14:49
Part O overheating 2021	3	3	08/05/2023 19:52	CG	10/05/2023 14:37
Part L and F	6	7	08/05/2023 20:57	CG	10/05/2023 14:36
Dynamic Simulation Method	1	1	08/05/2023 20:56	CG	08/05/2023 20:56
Design and Scheme Planning	0	0	08/05/2023 20:14	CG	08/05/2023 20:14
Ventilation decisions	2	6	10/05/2023 11:49	CG	10/05/2023 14:19
Timeline of overheating assessment	2	5	08/05/2023 19:40	CG	08/05/2023 20:58
Scheme orientation decisions	7	10	10/05/2023 11:57	CG	10/05/2023 14:44
Sample sizes for overheating assessments	1	2	08/05/2023 19:50	CG	08/05/2023 19:54
Point of engagement	9	13	08/05/2023 19:41	CG	10/05/2023 14:48

Planning	4	5	10/05/2023 13:08	CG	10/05/2023 14:53
Overheating assessment tools	2	2	08/05/2023 19:43	CG	10/05/2023 14:07
Overheating assessment procedure	5	9	08/05/2023 19:49	CG	10/05/2023 14:37
Software	1	1	10/05/2023 13:28	CG	10/05/2023 13:28
Sample sizes	1	1	10/05/2023 13:25	CG	10/05/2023 13:25
Potential strategies	6	6	10/05/2023 13:32	CG	10/05/2023 14:39
Material specification	1	1	08/05/2023 19:50	CG	08/05/2023 19:50
isolated ventilation decisions	1	3	10/05/2023 11:44	CG	10/05/2023 11:58
Collaborative design and assessment	2	3	08/05/2023 20:59	CG	10/05/2023 13:19
Change in material specification	1	1	08/05/2023 19:48	CG	08/05/2023 19:48
Construction	0	0	08/05/2023 20:14	CG	08/05/2023 20:14
SAP performance Gaps	2	4	08/05/2023 19:47	CG	08/05/2023 20:42
Quality assessment	3	3	08/05/2023 19:54	CG	10/05/2023 12:11
workmanship of trades	1	1	10/05/2023 12:07	CG	10/05/2023 12:07
Inspections	2	2	10/05/2023 14:05	CG	10/05/2023 14:37
Performance Gaps	3	3	10/05/2023 12:09	CG	10/05/2023 14:49
Gaps in skilled labour	5	6	10/05/2023 12:13	CG	10/05/2023 14:38