DOCTOR OF PHILOSOPHY

Overheating investigation in UK social housing flats built to the Passivhaus standard

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Award date:
2019

Awarding institution:
Coventry University

Overheating Investigation in UK social housing flats built to the Passivhaus standard

By

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April 2018

A thesis submitted in partial fulfilment of the University's requirements

for the Degree of Doctor of Philosophy

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Acknowledgement

بِسْمِ ٱللَّهِ ٱلرَّحْمَٰنِ ٱلرَّحِيمِ

"In the name of Allah, his guidance and blessings, perfected goodness this work has been completed"

The completion of this doctoral thesis would not have been possible without the guidance and supports of the kind people around me. Above all, I would like to thank my family for their unconditional support over the past years.

This work would not have been possible without the help, invaluable criticism and advice of my supervisors, Dr Azadeh Montazami and Dr. Abdullahi Ahmad.

I am indeed grateful to Faculty of Engineering and Computing, Coventry University for offering me a Ph.D. Scholarship which provided me with the financial support.

Last, but by no means least, I would like to thank Prof Mark Gaterell for his great advice, and support which have been invaluable for completion of this project.

Abstract

Global environmental and energy concern have led to rapid growth in construction of more energy efficient buildings. For this reason, Passivhaus standard as one of the fast growing building energy efficiency standard has seen growing interest in the UK building industry particularly in the social housing sector. While considerable research has been undertaken regarding the effect of Passivhaus standard in reducing heating loads, less attention has been paid to its annual and whole-life performance characteristics. The aim of this study is to evaluate and mitigate the risk of overheating in social housing flats built to Passivhaus standard across the UK.

For the purpose of this study, the risk of overheating has been evaluated in existing social housing flats built to the Passivhaus standard. In addition, current and future risk of overheating has been investigated across four UK archetypical locations (London, Birmingham, Manchester and Edinburgh) using various design and occupant behaviour simulated models. Also, the influence of design and occupant behaviour parameters has been explored with relation to normal and vulnerable occupant types.

Results from the case study indicates that considerable number of flats overheated during the monitoring periods especially in the case of vulnerable occupants and the impact of occupant behaviour on temperature variation found to be significant.

Overheating risk in London is found to be the most significant and improving design or occupant behaviour in this location are shown to have no significant effect on avoiding this risk. Edinburgh and locations with a similar climate are the most suitable locations in the UK for developing Passivhaus flats, as current and future overheating risks are predicted to be negligible. Current overheating risk in other UK locations are shown to be low but considerable in the future specifically for vulnerable occupants.

Hence, to ensure delivery of thermally comfortable dwellings, there is a need for careful design and thermal modelling simulation at the design stage as well as increasing occupants' awareness and run Post Occupancy Evaluation in order to promote appropriate user actions to reduce this risk.

This study highlights that the control of solar gain through regulating glazing area, accurate external shading and appropriate glazing g-value have the most impact on reducing the overheating risk. However, it is notable that avoiding the occurrence of overheating through careful design or appropriate occupant behaviour is only achievable under certain summer condition within certain time scale and occupant types.

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List of Abberaviations

ASHREA	American Society of Heating, Refrigeration, and Air-Conditioning Engineers
BESTEST	Building Energy Simulation Test
BETWIXT	Built Environment Weather scenarios for investigation of Impacts and eXTremes
BPS	Building Performance Simulation
BRE	Building Research Establishment
BREAAM	Building Research Establishment Environmental Assessment Method
BSI	British Standard Institution
CEPHEUS	Cost Efficient Passive Houses as European Standards
CIBSE	Chartered Institute of Building Services Engineers
CRU	Climate Research Unit
CSH	Code for Sustainable Homes
CUI	Common User Interface
DBEIS	Department for Business, Energy and Industrial Strategy
DBRI	Danish Building Research Institute
DCLG	Department of Community and Local Government
DECC	Department of Energy and Climate Change
DEFRA	Department for Environment Food and Rural Affairs
DRT	Dry Resultant Temperature
DSA	Danish Standards Association
DSY	Design Summer Year
EER	Energy Efficiency Ratings
EHS	English Housing Survey
EPC	Energy Performance Certificates
EPDB	Energy Performance in Buildings Directive
EU	European Union
GHA	Good Homes Alliance
GHG	Green House Gas
GLA	Greater London Authority
HB	Housing Benefit
HHSRS	Housing Health and Safety Rating System
IAQ	Indoor Air Quality
IDM	Integrated Data Model
IEA	International Energy Agency
IES	Integrated Environmental Solutions
IES-VE	Integrated Environmental Solutions-Virtual Environment
IPCC	Intergovernmental Panel on Climate Change
LEEDS	Leadership in Energy and Environmental Design Standards
MVHR	Mechanical ventilation Heat Recovery
NHS	National Health System
NZEH	Net Zero Energy Home
OHE	Orbit Heart of England

ONS	Office for National Statistics
OT	Operative Temperature
PHI	Passivhaus Institute
PHPP	Passivhaus Planning Package
PMV	Predicted Mean Vote
POE	Post Occupancy Evaluation
PPD	Percentage People Dissatisfaction
PPM	Part Per Minion
ProClip	Probabilistic Climate Profile
PS	Parametric Study
RH	Relative Humidity
RoSPA	Royal Society for the Prevention of Accidents
RSL	Registered Social Landlords
SAP	Standard Assessment Procedure
SC	Shading Coefficient
SD	Scenario Development
SERG	Sustainable Energy Research Group
SET	Standard Effective Temperature
SNACC	Suburban Neighbourhood Adaptation for a Changing Climate
SWCDH	Static Weighted Cooling Degree Hour
TM	Technical Memorandum
TRY	Test Reference Year
UHI	Urban Heat Island
UKCP	UK Climate Projections
UKHPA	UK Health Protection Agency
UKHPA	UK Health Protection Agency
WHO	World Health Organisation
ZCH	Zero Carbon Hub
ZEB	Zero Energy Building

Chapter 1: Introduction

1.1 Background

Global environmental and energy concerns have led to a rapid growth in mandating the construction of more energy efficient dwellings in the UK. This legislation, and the voluntary use of energy efficiency standards such as Passivhaus, BREAAM and LEEDs etc., have resulted in significant changes in the design and construction of new dwellings (Mcleod et al., 2013). This is particularly true for the UK social housing sector which is partly founded by the government and it is expected to lead the way in building more energy efficient buildings (McManus et al., 2010). To address this issue, the Passivhaus approach has gained popularity in the UK in recent years and the standard is increasingly adopted by both private and social housing sectors. However, while considerable research has been undertaken regarding the effect of Passivhaus standard in reducing heating loads, less attention has been paid to its annual and whole-life performance characteristics (Mcleod et al., 2013). Hence, data describing actual thermal performance of dwellings built to such standards, particularly in the UK dense social housing flats, are scarce.

The Passivhaus standard was developed in Germany in 1990 as a way of reducing energy consumption and providing ultra-low energy and zero carbon dwellings (Hopfe and McLeod, 2015). Central to this approach is the reduction of space heating demand through minimising thermal transmission losses and optimising passive solar gain (ZCH, 2009; Feist et al., 2012).

The internal temperature of houses in the summer is of increasing concern, even in the mild summers experienced in the UK. High indoor temperatures can be life threatening (Lomas and Kane, 2013). The heat-wave of 2003 is estimated to have caused an additional 2,091 deaths amongst vulnerable groups in the UK (Johnson et al., 2005) with as many as 70,000 other deaths between June and September across Europe (WHO, 2008).

Whilst the summer of 2003 was very unusual, climate change projections indicate that, by the 2050s, similar extreme weather events will take place every two or three years and by the 2080s such temperatures would be considered unusually cool (Kershaw et al, 2010).

Indeed, the Zero Carbon Hub (ZCH) (ZCH, 2015) highlighted the risk of overheating and cautioned that "*There is some anxiety that homes we are building today may be at risk of overheating even in the current climate. Given the prospect of significant warming, well within the expected lifetime of homes this risk will increase with potentially serious consequences*".

1.2 Rationale for this research

While much attention has been focused on ways to mitigate the causes of climate change, mainly by minimising the use of fossil fuels to generate the energy used in buildings, there is a wide recognition that climate change is already happening. Consequently, there is a need to examine how the built environment can adapt to change and ensure that all buildings are capable of dealing with greater climate extremes (Nicol and Stevenson, 2013).

Any evaluation of the risk of overheating needs to reflect the occupants' perceptions of thermal comfort, particularly those vulnerable groups which are often tenants in social housing. There are two thermal comfort models available to evaluate the risk of overheating which can be characterised as the fixed and the adaptive. The fixed model considers a fixed comfort temperature as a base to evaluate overheating, while the adaptive model suggests a fixed maximum temperature is not appropriate to evaluate the risk of overheating as comfort temperature should reflect the outdoor climate at the time and the likely vulnerability of different groups to changing comfort conditions (Roaf et al., 2012; Montazami and Nicol, 2013).

This study investigates the risk of overheating in existing and new built social housing flats constructed based on Passivhaus principles. The implications of employing fixed and adaptive models to investigate the risk of overheating are demonstrated in detail. The influence of design, occupants and climate conditions on developing this risk in these flats that accommodate either Normal or Vulnerable are discussed. This study provides a list of recommendations in order to mitigate this risk across the UK in the light of climate change.

1.3 Research questions

The main question that is requited to be addressed to control the risk of overheating in Passivhaus social housing flats is whether we are using appropriate methods to understand the nature of this risk. The second important question is to identify the extent to which climate change may exacerbate overheating risk in these flats in different regions across the UK. The third question is to recognise the factors that contribute to develop this risk and how this risk can be reduced by regulating these factors in different regions for different types of occupants. Therefore, this thesis aims to answer the following questions.

- RQ1: What is the limit of Passivhaus overheating benchmark in identifying the overheating?
- RQ2: What is the level of overheating in social housing flats built to Passivhaus standard?
- RQ3: What is the impact of climate change on overheating risk for Passivhaus flats in the UK?
- RQ4: What are the main factors influencing the overheating risk in social housing flats built to Passivhaus standard?

1.4 Aims and Objectives

Empirical evidence is now beginning to emerge that indicates overheating has been experienced in a number of UK Passivhaus dwellings during the summer (Ridley, et al., 2013; Ridley et al., 2014). Scientific evidence demonstrates that even purpose built flats are at significantly greater risk of overheating (Gupta and Gregg, 2013). Considering the climate change scenarios, there are uncertainties associated with performance of the UK Passivhaus under projected future climate which are yet to be understood. Mcleod et al., (2013) suggest that future overheating risk in UK Passivhaus dwellings can be significant; however, available findings are only limited to one location (i.e. London) and one dwelling type (i.e. end terrace house) and also no data available to validate this finding.

In addition, although adaptive model can better reflect occupant thermal perception, the existing study used the fixed thermal model to assess the risk of overheating.

Hence, despite the growing interest in Passivhaus uptake in the UK Social housing sector, there is a lack of detailed understanding about the overheating risk in Passivhaus social housing flats. This cause a challenge to interpret the current and future of this risk for different types of occupant and in different regions of the UK.

Therefore, the aim of this research is as follow:

Investigation of overheating risk in UK social housing flats built to the Passivhaus standard under current and future climatic conditions

The specific objectives to achieve this research aim are:

1. To investigate the suitability of existing overheating benchmarks for assessing the risk of overheating in residential buildings.
2. To analyse the risk of overheating in existing social housing flats built to the Passivhaus standard.
3. To explore the current risk of overheating in new built Passivhaus social housing flats in different locations of the UK.
4. To investigate the impact of design and occupant behaviors parameters on the risk of overheating in social housing flats built to the Passivhaus standard.
5. To investigate the impact of climate change in developing the risk of overheating in UK social housing flats built to the Passivhaus Standard.

1.5 Brief methodology

The overheating analysis in this study relies on quantitative data relating to the indoor environmental condition of the building. The evaluation of overheating in buildings is complex due to the influence of various design and occupant behaviour parameters. True limits of discomfort (duration, severity and their relationship) are not yet known, especially in dwellings (CIBSE, 2013). Also the detailed investigation of design and occupant behaviour parameters creates significant complexity that requires pairwise models to ease the analysis and discovery of effective design and occupant behaviour factors that are difficult to establish in reality, and only simulation studies can provide pairwise models .Thermal comfort research tends to focus on field studies (de Dear et al., 2013) since the simulation process used to predict indoor temperature requires careful approach (Nicol et al., 2012). Therefore, this study adopts a balanced approach by performing overheating assessment using both case study and building modelling and simulation.

1.6 Overview of the Thesis Structure

This thesis comprises seven chapters:

- Chapters 1: Introduction. This chapter explains the reasons of conducting this research followed by research equations, aim, objectives, the outline of the methodology and the thesis structure.

- Chapter 2: Literature review. This chapter provides an overview of energy efficiency standards, explanation of Passivhaus model and its key requirements, description of thermal comfort and overheating benchmarks, overheating risk in the UK dwellings, an overview of the UK social housing sector and also the key issues related to thermal performance of energy efficient buildings. A detailed review of the published literature on the previous works on different aspects of Passivhaus and overheating risk is also presented.

- Chapter 3: Methodology. This chapter explains a theoretical approach to investigate the thermal performance of Passivhaus buildings under different geographical and climatic conditions within the UK.

- Chapter 4: Overheating investigation in the existing UK social housing flats built to the Passivhaus standard. This chapter presents a case study on overheating investigation in recently built Passivhaus flats in the UK social housing sector by analysing the data collected during three cooling seasons (2011-2013) in total of 25 flats located in Coventry, UK. This chapter also evaluate the suitability of using Passivhaus benchmarks in identifying the overheating risk in social housing flats built to Passivhaus standard.

- Chapter 5: Overheating investigation in new social housing flats built to Passivhaus standard across the UK under current and uncertain future climate. This chapter presents the results of the simulation modelling of building thermal performance of the UK social housing flats built to the Passivhaus standard. Integrated Environmental Solutions-Virtual Environment (IES-VE) Software is used for the purpose of dynamic building simulations. The simulations were carried out to measure the overheating risk in the UK flats built to the Passivhaus standard at four different geographical locations including London, Birmingham, Manchester and Edinburgh. Series of design and occupant behaviour scenarios are developed for overheating investigations in each location using current and future climate data. The data obtained from this chapter provides an improved understanding of Passivhaus overheating risk in the current and future UK climatic context.

- Chapter 6: Discussion. This chapter devotes to the overall discussions of the findings. In this chapter, the main findings and outcome of the work are explained.

- Chapter 7: Conclusion. This chapter presents the conclusion of this research as well as the recommendations and suggested future works.

Chapter 2: Literature review

2.1 Introduction

This chapter presents the key concepts and terms related to the sustainable construction, energy efficiency in buildings, Passivhaus, thermal comfort and overheating in buildings. A detailed review of the previous studies conducted on thermal comfort and overheating in dwellings is discussed with a specific focus towards overheating in flats built to the Passivhaus standards.

2.2 Sustainability and building sector

2.2.1 Introduction to the concept of sustainability

According to the Oxford English Dictionary, ‘sustainability’ is derived from the verb ‘sustain’ which means to support, maintain, keep, bear or endure.

The term ‘Sustainability’ can be described as the continuous capability of an interactive system (i.e., society, eco-system, etc.) to function without adversely affecting the environment and reducing key resources (Hopwood et al., 2005). The standard sustainability models are consisting of three separate but interconnected pillars of environment, economy and society, see Figure 2.1 (Giddings et al., 2002; Hopwood et al., 2005).

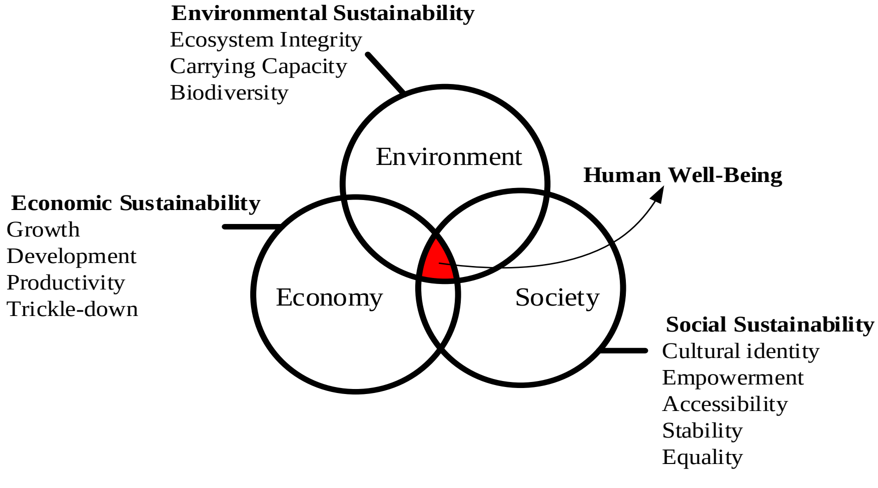


Figure 2.1 Common model of the various dimensions of sustainability (Giddings et al., 2002)

The term ‘Sustainable development’ is an ambiguous and complex concept to define (Carter, 2018). The most popular definition of sustainable development is given by the Brundtland Report published in 1987 (Brundtland, 1987):

‘‘*development that meets the needs of the present without comprising the ability of future generations to meet their own needs’’*.

In the recent decades, an increased awareness of the connections between environmental degradation and the socio-economic issues such as poverty, inequality and human health resulted in more attention towards the concept of sustainable development (Hopwood et al., 2005). The aim of sustainable development is to bring the three rings of sustainability (Figure 1.1) together in a well-adjusted and balanced way (Markandya and Halsnaes, 2002; Giddings et al., 2002).

2.2.2 UK Sustainable Development

The UK government was the first government to publish a national strategy for sustainable development in 1994 (UKSDS, 2005). The UK national strategy for sustainable development has identified a number of sectors of the economy as significant to sustainable development. Development and construction; energy; manufacturing and services; minerals extraction; transport and waste (Halliday, 2008) are amongst the sectors with major impact on sustainable development.

In 1999, the UK government published a document called ‘A Better Quality of Life – A Strategy for Sustainable Development in the UK’ (DETR, 1999). The new strategy set out the following principles to achieve sustainable development and higher quality of life (UKSDS, 2005):

• Living within environmental limits

• Achieving a sustainable economy

• Promoting good governance

• Ensuring a strong healthy and just society

• Using sound science responsibly – to ensure policies are developed and implemented based on scientific evidence and with taking into account the uncertainties associated with scientific findings and public values and perceptions.

The principals mentioned above define the approach that the UK government is taking to achieve sustainable development. Different sectors in the UK have used these principals as a framework to shape their own policies and action plans with the aim of achieving a better quality of life and securing a future in which economic prosperity is fairly shared, with more efficient use of natural resources and less pollution.

2.2.3 Sustainable Construction

Over the past decades, economic growth and rapid increases in population have accelerated the urbanisation process and together with industrialisation resulted in a reckless exploitation of natural resources and continuous degradation of environmental quality (Son et al., 2011). One of the consequences of urbanisation and industrialisation is an increased demand for construction and development, which made the environmental issues mentioned above become increasingly critical for the building professionals around the world (Sev, 2009). The construction industry, which is one of the industries dealing with improving quality of life (e.g. housing, workspace, utilities and transport infrastructure) is a critical sector in delivering sustainable development (Burgan and Sansom, 2006; HM Government, 2008). Both the existing built environment and the processes of adding to it have several environmental, social and economic impacts (Sev, 2009).

Worldwide review of construction industry shows that the construction industry is an energy intensive and material profligate sector. Around 40% of total energy production and 40% of all raw materials consumptions are by construction sector (Son et al., 2011). Around 35% of total CO_2 emissions and 16% of total water consumption in the world is related to construction activities (Son et al., 2011). These figures show the vital importance of adopting sustainable development strategy to minimize the tremendous environmental impact of construction around the world.

Sev (2009) argued that construction industry, compared to other industries, presents an unusual case in terms of long life span of the projects. Structures have an average life of 80-100 years, meaning that the design of a building will have long term impacts on its economic and environmental performance. Hence, incorporating principles of sustainability into the full life-cycle of a construction project is vital to achieve high performance buildings with low environmental impacts (Pearce, 2006; Son et al., 2011).

The traditional vision of design and construction activities pays attention to issues around cost, performance and quality (Latham, 1994; DETR, 1998), however, sustainable design and construction look-out also considers the minimisation of resource consumption, environmental degradation and the creation of a healthy and comfortable built environment (Sev, 2009). The sustainable construction principles outlined above have been widely adopted by the UK government in its policy papers, reports and strategies (Hall and Purchase, 2006).

Following the publication of ‘A Better Quality of Life - A Strategy for Sustainable Development in the UK’, the government has published ‘Building a better quality of life - a strategy for more sustainable construction’ in 2000 (DETR, 1999). The document indicated that a sustainable construction approach involves all of the following actions:

• Delivering buildings and structures that provide greater satisfaction, well-being and add value to customers and users;

• Enhancing and better protecting the natural environment;

• Minimising the construction impact on energy consumption (especially fossil fuels with carbon emission) and natural resources;

The ‘Review of Sustainable Construction’ document was published 2006 with aim to provide an effective basis for government policies related to construction (Hall and Purchase, 2006). In 2008, a strategy for sustainable construction was launched which is a joint government / industry initiative (HM Government, 2008) to identify collaborative actions and commitments by both the industry and the government to deliver sustainability in the construction sector.

The consequence of incorporating the above principles, planning policies and strategies in design of new buildings is lower operational and maintenance cost, lower energy consumption, lower pollution generation, healthier occupants, less material use and longer life-cycle for the building.

2.3 Energy efficiency

The climate change and the rise of global concern around CO_2 emission and energy demand have resulted in increased effort on reducing energy and carbon emission in construction sector.

Looking at climate change projections, it is clear that the disastrous consequences of climate change are biggest threats which can barricade sustainable development.

The scientific evidence shows that carbon dioxide emissions from fossil fuels burning are linked to climate change and are causing global warming (IPCC, 2015). The three main sectors which are in charge for majority of energy consumptions are the built environment, transportation and industry. The building sector is responsible for around 30% to 40% of the overall global energy consumption. Hence, the reduction of energy usage in buildings through the implementation of energy efficiency measures has become an increasingly important research topic in recent decades (IEA, 2013).

For the case of UK, 30% of overall energy usage and CO_2 emissions is related to homes, see Figure 2.2. The recent studies show that the construction sector is responsible for around 55% of the UK's carbon emissions, and the energy use in domestic buildings accounting for about 27% of the overall energy consumption. This figure includes the embodied carbon associated with the materials and products used. According to DBEIS (2016) report, the household CO_2 emissions are mainly related to electricity, followed by gas and oil. Given that building and construction sector is consuming more energy than any other sectors in the UK (Roaf et al., 2009), energy efficiency plans is of great importance for building sector in order to minimize emission and achieve sustainable development plans.

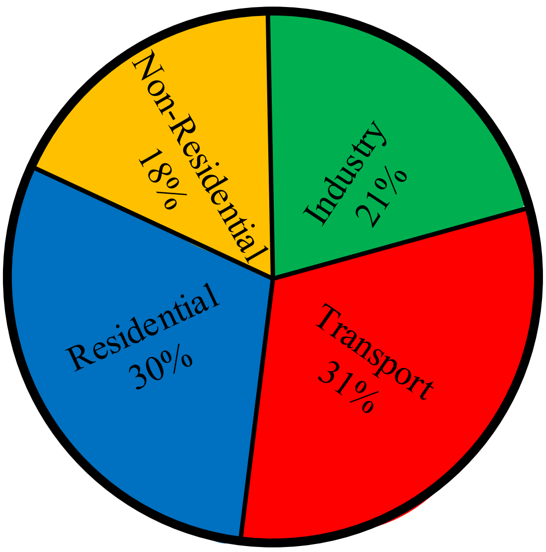


Figure 2.2 Proportions of total UK energy consumption in 2015 adopted from (DBEIS, 2016)

In recent years, UK policies target CO_2 emissions mitigations in order to achieve greenhouse gas (GHG) and energy reductions. One of the area of focus for the UK government policies is promoting the delivery of sustainable and energy efficient homes. In 2006, the UK government set out a very ambitious target of 80% emission reduction by 2050 and established a separate committee for climate change (Gething and Puckett, 2013) to tackle carbon emission problems and mitigate the climate change impact of the country.

Also, on the European scale, the EU Directorate-General for Climate Action has similarly set EU 2020 climate and energy targets, which include a 20% reduction in GHG emissions, a 20% improvement in energy efficiency and 20% of EU energy production through renewables sources (da Graça Carvalho, 2012).

Achieving such ambitious targets will heavily rely on improving the energy efficiency in buildings sector and moving towards renewable sources for electricity grid over time (CIBSE, 2018).

Well-designed and energy efficient homes have several benefits for both developers and households, including (CIBSE, 2018):

- helping to provide low energy bills and maintenance Costs
- providing healthy homes that are comfortable throughout the year, well-lit with good access to daylight, water efficient, and well ventilated to maintain good indoor air quality
- providing homes that are relatively simple to understand and operate
- offering reputational and marketing benefits to professionals involved in their design
- Helping to reduce greenhouse gas emissions and mitigate climate change.

2.3.1 Energy Efficiency in Building

Design and construction of energy-efficient buildings has become an increasingly important subject of interest to many architects and designers since the long term CO_2 mitigation is only achievable with investing in energy efficient buildings.

Energy efficiency is an effective climate change mitigation policy which moderates energy use, mitigates GHG emissions and ensures better indoor thermal comfort. According to a recent IEA energy outlook, one-third reduction in the global energy demand is achievable by implementing energy efficiency measures in the built environment by 2040 (IEA, 2013).

The Chartered Institution of Building Services Engineers (CIBSE) set out guidelines on Energy Efficiency in Buildings and states “An energy efficient building provides the required internal environment and services with minimum energy use in a cost effective and environmentally sensitive manner” (CIBSE, 2012). Many studies have investigated the effects of energy efficient measures on the built environment and its role on mitigating greenhouse emissions (Allouhi et al., 2015; Brown, 2015; Wada et al., 2012)

Governments, research groups and other NGOs have developed energy measurement and moderation codes and standards for the end-users. These regulating approaches are either mandatory building codes/regulations or voluntary standards or certifications (Allouhi et al., 2015; Bartlett, Halverson and Shankle, 2003; Casals, 2006).

In recent years, Technologies enabled us with better understanding of how to achieve energy efficiency in the built environment. Several researchers have investigated the methods of identifying the practices or techniques that led to achieving energy-efficient buildings (Ghaffarian Hoseini et al., 2013; Ionescu et al., 2015; Li et al., 2014; Li et al., 2013a). The results of recent studies indicated that energy efficiency techniques for building are versatile and their effectiveness are highly dependent on the climatic context and the construction methods and expertise in specific regions.

De Boeck et al. (2015) performed a comprehensive review and examined the improvement of energy efficient measures in the residential sector. De Boeck et al. (2015) study analysed 78 studies that targeted energy efficiency within domestic homes in 30 different countries located in Europe, Asia, Africa, north and south America and also Australia and concluded that the targets for improvement could be listed under five main categories:

- The building’s outer fabric, including the roof, floor/wall insulation thickness and material type.
- The building’s heating/cooling and ventilating systems, in addition to other systems such as solar systems, and other renewables.
- The building’s glazing and shading systems, with the focus on glazing type/size and external shading.
- The building’s other appliances and lighting.

- The whole building, which included the building shape, orientation, thermal mass and infiltration levels.

Harvey (2013), proposed similar solutions as the IEA report. He examined the energy and economic impacts of different technologies applied to the built environment around the globe. Harvey (2013), highlighted the basics of achieving a low energy consumption building, as follows:

- Optimising the building's form, orientation and thermal mass.
- Articulating a high-performance thermal envelope.
- Implementing passive techniques, such as passive cooling, passive heating and ventilation in addition to maximising daylighting.
- Implementing energy-efficient systems for the remaining loads, such as energy-efficient heating/cooling or ventilating and dehumidification systems.
- Utilising energy-efficient appliances and lighting.
- Finally, ensuring cost effective measures for the whole building and its systems.

2.3.2 Building Energy Efficiency in the UK

To achieve the energy efficiency targets set out by the government, the Building Regulations in England, Wales and Northern Ireland and Building Standards in Scotland set mandatory minimum requirements for the design and construction of new and existing buildings. These mandatory requirements include efficiency in energy and CO_2 emissions, ventilation, and water supply. In England and Wales, the Building Regulations are supported by Approved Documents (Pan and Garmston, 2012; Tricker and Alford, 2017) that provide official guidance on how to meet the functional requirements set out in the Regulations. In Northern Ireland there are Technical Booklets (Tricker and Alford, 2017) to provide guidance on the regulation implementation and in Scotland there is a Technical Handbook which sets out guidance on what is required to meet the overall Standards. In many instances other compliance routes are possible, as the Approved Documents are only guidance.

Also, relevant European Directives affecting the design of homes have been implemented through national legislation. The recast Energy Performance of Buildings Directive (EPBD) (EU, 2010) enforce home's Energy Performance Certificates (EPC) for construction, sale or rental, and has been fully implemented in the UK. In order to produce EPC, approved Document L in England, and its equivalents in Northern Ireland, Scotland and Wales, require the use of specified versions of the Standard Assessment Procedure (SAP) (BRE, 2009) to model energy use for the purposes of producing Energy Performance Certificates and to assess compliance with the requirements of Part L for new homes.

Due to Brexit, the EU Regulations have direct effect in the UK law until 1 April 2019. It is anticipated that the requirements of these regulations will be transferred into the UK law and will continue to apply beyond 1 April 2019 (CBSE, 2018).

In addition to the mandatory requirements of regulations, a range of voluntary standards have developed by third party organisations such as Passivhaus Institute, UK Building Research Establishment and Danish Building Research Institute, which help improve the sustainability and quality of homes. The main voluntary measures currently adopted in the UK are as follow (CBSE, 2018):

BRE's Home Quality Mark

The Home Quality Mark (BRE, 2015) provides a rating system for new homes, including an overall rating and indicators for the householder for running costs, environmental footprint health and wellbeing. The guideline addresses sustainable design in the area of energy use and costs, comfort, water efficiency, materials, ecological value, flood resilience, overheating, security, availability of various types of services, and measures to address potential performance gap issues. Compliance is assessed by qualified assessors.

BREEAM UK New Construction scheme

The BREEAM UK New Construction scheme (Scivyer, 2007) provides an environmental rating system for new mixed use buildings and multi-residential buildings such as student housing and care homes. Assessment categories include energy use, water efficiency, materials, pollution, health and wellbeing, waste, management and innovation. Compliance is assessed by qualified assessors.

The BREEAM UK Domestic Refurbishment scheme (Scivyer, 2007) provides an environmental rating system for existing homes that addresses similar issues to those of the New Construction scheme. Compliance is assessed by qualified assessors.

Passivhaus energy standard

The Passivhaus standard provides an energy performance standard which is primarily aimed at new developments. The standard focuses on improving the insulation, adoption of mechanical ventilation with heat recovery and making use of passive solar gain as well as internal sources of heat gains to reduce heating demand. Passivhaus standard sets a primary energy target for homes. Compliance is demonstrated through the use of the Passive House Planning Package tool (PHPP), and assessment by the Passive House Institute or accredited building certifiers (Hopfe and McLeod, 2015).

For refurbished homes, where it is not possible to meet the Passivhaus standard with ‘reasonable effort’, the EnerPHit standard (Hopfe and McLeod, 2015) offers a slightly relaxed set of certification criteria alongside a component-based compliance route. The certification process for such homes requires the implementation of the Passive House Planning Package tool and an accredited certifier.

EnergieSprong

EnergieSprong is developed in Netherland for fast refurbishment of the whole house. The guideline was introduced in the UK in 2015. Energiesprong involves the installation of an air or ground source heat pump heating system and efficient appliances to deliver a ‘near net zero energy home’, and the wrapping the house in pre-fabricated wall and roof panels (including integrated solar PV).

Developers and designers may adopt such voluntary standards for reasons such as client or funding requirements; environmental objectives and reduction in running costs for residents.

The Code for Sustainable Homes (DCLG, 2006) is the UK Government standard for new-build homes and was withdrawn in 2015. Code for Sustainable Homes may still remain a contractual requirement for legacy projects and in Wales (CIBSE, 2018).

2.4 Passivhaus standard for energy efficient buildings

Passivhaus (PH) method is one of the most successful energy efficient measures that is becoming increasingly popular in the Europe (Hopfe and McLeod, 2015; Ionescu et al., 2015).

The Passivhaus standard originated from collaboration between Professors Bo Adamson from Lund University, Sweden and Wolfgang Feist from the Institute for Housing and the Environment, Germany, in 1988 (Hopfe and McLeod, 2015). Passivhaus is a voluntary German standard for energy efficiency and comfort in buildings. The first Passivhaus home was built in Darmstadt in 1991 (Feist et al., 2005). The Passivhaus design focuses on minimising the requirement for space heating and cooling, and therefore reduction in overall energy consumption. Moreover, providing good indoor air quality and thermal comfort is one of the Passivhaus standard targets.

A number of Northern European countries have set their long-term goals to include Passivhaus certification as a voluntary or even mandatory requirement in the built environment (Mlecnik et al., 2008). In the United States, an independent research and certification on Passivhaus is being carried out under the Passive House institute in the US.

The official definition of the Passivhaus is “a building for which thermal comfort (EN ISO 7730) can be achieved solely by post-heating of the fresh air mass, which is required to achieve sufficient indoor air quality conditions – without the need for additional recirculation of air” (Hopfe and McLeod, 2015). There are other definitions for the Passivhaus in the literature. According to Lewis (2014), “A Passivhaus is a very well insulated and draught free building designed to provide the highest level of comfort”. Cotterell and Dadeby (2012) agreed in essence with the Lewis (2014) and stated that “A Passivhaus building is designed to be very comfortable and healthy, and to use vastly less energy than conventional buildings, irrespective of the climate”.

A number of researchers have also linked the zero energy building (ZEB) and Passivhaus buildings (PH). The justification for this link refers to the fact that a ZEB needs to be constructed in a highly energy-efficient manner, which is also the requirement for the PH standard (Carlucci et al., 2013; Hopfe and McLeod, 2015).

More than 50,000 buildings have been built around the world following Passivhaus standard, which a majority of them are located in Europe (Lewis, 2014). Currently, big proportion of the Passivhaus buildings are constructed in Germany and Austria (Müller and Berker, 2013). Additionally, number of projects have been launched in Europe since the beginning of the Passivhaus standard, such as the CEPHEUS project (1998-2001), the Passive On project (2005-2007), the Pass-Net project (2007-2010), the PEP project (Badescu et al., 2015) and the E-retrofit-kit. The aims of all these Passivhaus projects were to determine the feasibility of the Passivhaus concept in different geographical and climatic parts of Europe and to promote the standard to the European countries.

The CEPHEUS (Cost Efficient Passive Houses as European Standards) project consist of 221 Passivhaus homes across 11 projects in Sweden, Germany, France, Austria, and Switzerland. The CEPHEUS showed Passivhaus homes consume 80% less space heating and 50% less total energy usage compared to conventional new builds (Schnieders and Hermelink 2006). Comparison between the European standards and the Passivhaus standard shows that Passivhaus is very successful in achieving building energy saving and emission targets. Hence, Passivhaus is becoming increasingly popular choice across central and northern Europe. Passivhaus standard is already a legal requirement for all new buildings in vast areas of Germany and Austria. In 2010, Passivhaus Uptake is set to increase over the next eight years as European nations begin to respond to the legislative demands of all new buildings being 'nearly zero energy buildings' from 2020 onwards (EU, 2010). For example, from 2015 onwards all retrofits and new buildings in Brussels (Belgium) must be Passivhaus. Some European countries such as Norway (2017) and Finland (2015), have started to adopt equivalent standards, based on 'Passive House' definitions. Moreover, a failed European Parliament Resolution had proposed that all new EU buildings reach Passivhaus equivalent standards (EU, 2008). Passivhaus is thus set to be a key contributor to Europe's future housing stock and to reduce huge environmental footprint of construction and housing sector.

A number of comparative studies were carried out on analysing the feasibility of Passivhaus in different parts of Europe by comparing the performance of Passivhaus buildings against other energy-efficient buildings method. Also, some researchers carried out investigations on the comparison between standard building and Passivhaus building followed the building codes adopted in various countries. In most cases, the results indicated that the Passivhaus approach provides a better performance in terms of thermal comfort, CO_2 emissions and significant reduction in energy use (Mahdavi and Doppelbauer, 2010; Badescu and Rotar, 2011; Rohdin et al., 2014).

Further studies have been carried out on risks that may be associated with implementing the Passivhaus standard. The risk of overheating for Passivhaus buildings was reported by some studies, although the Passivhaus Institute has acknowledged that with careful design and consideration the overheating issue could be resolved by just opening the windows or operating the ventilation system effectively to bypass heat recovery. In addition, with the aid of the Passivhaus, overheating risks can be dealt with during the design process by carefully designing the glazed surfaces and associated shadings (Junghans and Berker, 2014).

Bunsgaard et al. (2012a) analysed the Passivhaus building's thermal comfort from a number of studies which were carried out in different parts of Europe. The issues related to overheating were reported in a number of the examined studies mainly in Sweden and Denmark. Studies show that, a number of houses in Sweden built according to the Passivhaus criteria had suffered from variable temperature, cold floors and rooms, and overheating. The reports show that in general, for the Passivhaus buildings, the indoor environment during the winter is satisfactory. Brunsgaard et al. (2012a) also discussed the outcomes of Danish experience. The Comfort Houses project was one of the first Passivhaus projects carried out in Denmark, where nine different Passivhaus single-family houses were built and certified according to the German Passivhaus standard. Semi-structured interviews were used to evaluate the performance of the Passivhaus buildings, at the beginning and after 6-10 months of occupancy. Brunsgaard et al. (2012a) concluded that most occupants had experienced overheating and needed guidance on how to effectively operate the ventilation system and utilise natural ventilation.

A London post-occupancy study evaluated the first Passivhaus building in the city, known as the Camden Passivhaus (Ridley et al., 2013). The outcomes of this study were in line with the findings of the Danish study to some extent. One occupant was reported to find the heating controllers Confusing and difficult to use. Moreover, number of building simulation tools predicted that the house would be overheated in summer; however, the occupants claimed that they enjoyed the warmth of the summer. Furthermore, Ridley et al. (2013) reported a slight increase in primary energy demand in the house and argued that the issue could be resolved by amending the hot water system and solar heating.

Despite the increased primary energy load, the Camden house is one of the lowest-operating energy-efficient houses in the UK (Ridley et al., 2013).

The literature shows that, the Passivhaus standard has been mainly successful in Europe, by achieving up to almost 80% reduction in energy consumption. The design principles of the Passivhaus standard enable buildings to be heated with minimum energy, while ensuring comfortable winter conditions. Several post-occupancy surveys (mainly outside Germany) reported the overheating risk of Passivhaus buildings during summer (Khalfan, 2017).

2.4.1 Passivhaus standard: Criteria and requirements

The success of PH standard in reducing emissions and energy usage lies in effective heat recovery system and its highly articulated outer fabric. The existence of a clear and specified set of guidelines to follow has motivate the adoption of the PH standard in buildings around the world. According to the Passivhaus Institute (PHI), five main principles should be applied when constructing a Passivhaus building:

Thermal insulation: The main characteristic of a PH building is a continuous layer of insulation material covering the whole building envelope, including walls, roof and floors. According to the PH standard, the required minimum U-value for opaque surfaces is 0.15 W/m^2K for cool temperate climates (Hopfe and McLeod, 2015). The U-value is indicating thermal transmittance of the building elements, hence, the lower U-value, the better the building elements are in keeping heat in or out of the building. U-values are also used for glazed surfaces, to define the heat loss through the window frame, glazing and whole window, normally differentiated through the symbols U_f, U_g and U_w (Cotterell and Dadeby, 2012).

Passivhaus windows: PHI requirement is using high-definition glazing and well-insulated frames. Window U-values of 0.8 W/m^2K or less are required for cool temperate climates (Hopfe and McLeod 2015). Lewis (2014) stated that the design of a PH building should benefit from the full potential of windows by locating and sizing windows to benefit from heat gain in the winter and lessen overheating in the summer. In addition to using U-values to measure the heat loss from windows, total solar transmittances or g-values are used in the PHPP to measure the amount of solar heat entering the building through the window. To achieve heat gains in winter and avoid overheating in summer, windows should have low U-values, high g-values (typically around 50%) and there must be careful detailing around the windows (Lewis, 2014).

Ventilation heat recovery: a PH building must have an effective heat-recovery system with at least 75% of the heat extracted from the exhaust air and utilised to heat the fresh air through a heat exchanger (Hopfe and McLeod, 2015). The PH strategy is based on providing comfortable interiors and to do so, fresh air must be allowed to circulate through the building, either naturally by operating windows or mechanically through a ventilation system. A popular misconception is that occupants are not allowed to open windows in a PH. However, the PHI requires at least one openable window in each room (Cotterell and Dadeby, 2012). Also, when the outdoor conditions are pleasant, natural ventilation is recommended during the day and even in the night. The idea of using a mechanical ventilation system is on the basis that opening a window during cold weather is not practical. Hence, use of a ventilation system ensures continuous flow of fresh air into the building and maintaining indoor comfort.
Usually an MVHR system is used to supply the home's space heating all year round through the inclusion of a heating element within the unit, which is electric in majority of cases. To make this possible, the space heating demand must be reduced to 15 kilowatt hours per square metre of floor area per annum (kWh/m^2yr) or less. If an active cooling system is also included, then the additional energy demand must be less than 15 kWh/m^2yr. Also, mechanical ventilation and heat recovery (MVHR) systems incorporating fan coils fed by small gas boilers are entirely acceptable within the PH standard (Hopfe and McLeod, 2015).

Airtightness: there must be an airtight envelope that permits no more than 0.6 air changes per hour through the possible gaps within a building when an air pressure test is performed at 50 Pascals (Hopfe and McLeod, 2015). The airtightness in PH buildings reduces energy use and ensures a better indoor environment. An airtightness test is carried out by a blower door test and digital pressure devise, by placing a large calibrated fan in an airtight door or window panel. The test measures the air leakage levels by depressurising and pressurising of the indoor air, and determining the differences between the outdoor and indoor pressure (Cotterell and Dadeby, 2012).

Absence of thermal bridges: all corners, joints and connections must be handled with care to minimise any possible thermal bridges (Hopfe and McLeod, 2015). Thermal bridges normally occur when two building components are joined, or when different building fabrics come into contact. The difference between the conductivity of materials is the main reason for thermal bridges. Thermal bridge-free building is usually achieved by careful joint detailing and a continuous and uninterrupted insulation layer (Lewis, 2014).

In addition to the outer envelope and heat exchanger criteria, the PHI has also issued criteria to regulate the energy use and thermal comfort, see Table 2.1.

Table 2.1 Passivhaus requirements (Hopfe and McLeod, 2015)

Criteria	Passivhaus demand
Heating demand	$\leq$ 15 kWh/m^{2}yr
Primary energy demand	$\leq$ 120 kWh/m^2 for all domestic use, including heating, hot water and appliances
Thermal Comfort	Must be met in all living spaces during winter and summer, with no more that 10% of hours in a given year above 25 °C

For Passivhaus buildings, more detailed architectural drawing and better quality control during the construction phase is required in comparison to a standard building, see Figure 2.3. Also, a well-insulated thermal envelope and a sound selection of ventilating and heating equipment is essential for PH buildings. Hence, it can be concluded that, “Achieving Passivhaus is not about lots of ‘advanced’ technology; rather, it is about changing the way we build” (Cotterel and Dadeby, 2012).

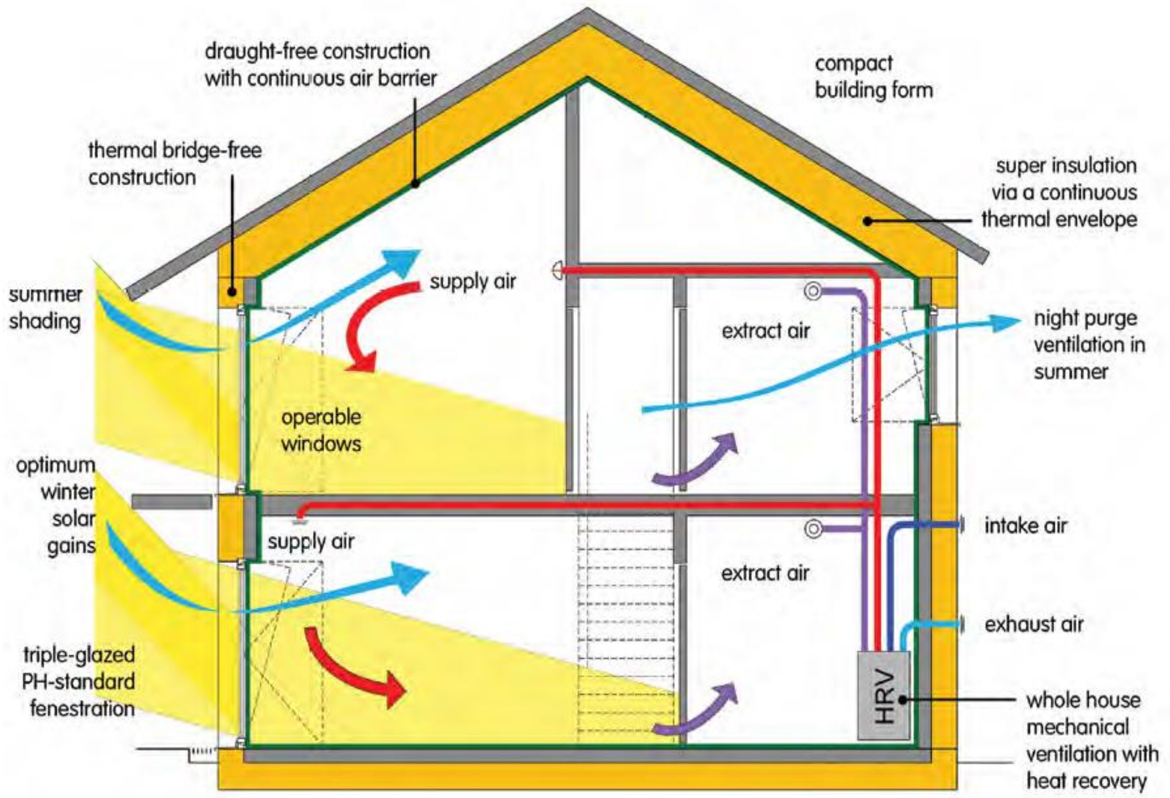


Figure 2.3 Passivhaus principles (adopted from Hopfe and Mcleod, 2015)

2.4.2 The Passivhaus Planning Package (PHPP)

The Passivhaus Planning Package (PHPP) is an energy calculation tool produced by the Passivhaus Institut in Germany, and first introduced in 1998. PHPPT is the only approved method for modelling and certifying the performance of a proposed Passivhaus building. The calculation tool has been verified and tested against a vast number of Passivhaus buildings and is said to provide highly accurate results (Müller and Berker, 2013). According to the Passivhaus Institute, the results obtained from the PHPP are highly reliable. This includes outcomes of cooling and heating loads, summer comfort percentages in passively cooled buildings, and the primary energy and renewable energy demands (Hopfe and McLeod, 2015).

PHPP is based around the same core energy calculation methods used throughout Europe (including SAP in the UK) but takes into account certain additional elements such as household appliances, and includes considerably more detail in some areas of the calculation (notably thermal bridging) (Khalfan, 2017).

2.4.3 Passivhaus and the UK building regulations energy efficiency targets

The UK has chosen to express building regulations requirements in terms of carbon dioxide emissions (in kilograms per square metre per year, kg/m^2yr). This focuses attention on the key greenhouse gas, and provides a common currency to compare the various carbon abatement policies designed to meet national reduction targets. Passivhaus, on the other hand, in line with most other European nations uses energy (in kilowatt hours per square metre per annum, kWh/m^2yr) as its measure of compliance. This avoids the issue of different carbon intensities of fuels, and the complication of changes in emissions over time as the national electricity generation mix evolves (Hopfe and McLeod, 2015).

It is difficult to compare directly the Passivhaus standard with UK building due to the different metrics and calculation procedures used. However, to a first approximation the space heating load in Passivhaus is around half that of UK building regulations (Hopfe and McLeod, 2015).

The UK's building regulations do not mandate a primary energy target – but by way of comparison, homes built to the UK standard will typically have a space heating demand twice that of a Passivhaus home, and will be 5 to 10 times less airtight. Table 2.2 shows the comparison between the Passivhaus guidelines and UK building regulations characteristics (Hopfe and McLeod, 2015).

Table 2.2 Comparison of additional Passivhaus guidelines with UK building regulation (Hopfe and McLeod, 2015)

Additional Passivhaus guidelines	UK building resulations characteristics
Insulation	
U-values of walls, floors and roofs =< 0.15 W/m^{2}K	U-values of walls, floors and roofs around 0.15 to 0.25 W/m^{2}K
Glazing	
Triple-pane windows with insulated frames U-values (including doors) =< 0.8 W/m^{2}K	Double-pane windows U-values (including doors) around 1.20 to 2.00 W/m^{2}K
Solar orientation	
Windows largely south-facing	No particular requirement for solar orientation
Thermal bridging	
Minial (ideally non-existent) Psi-(ψ)values =< 0.01 W/mK	Psi-(ψ)values typically 0.05 to 0.24 (or even 0.50 at steel lintels) W/mK
Ventilation	
High-efficiency MVHR system Heat recovery efficiency >=75%, specific fan power =<1.62 W/(l/s)	Background ventilation and intermittent extract fans
Appliances	
Low-energy lights and appliances throughout	Low-energy lights in 75% of internal fittings
Overheating	
Special care to avoid summertime overheating	Likelihood of summertime overheating must be calculated

2.5 Climate change and building sector

Climate change impact has already begun to change the built environment and the extent of these impacts is projected to increase in the future. Design of new homes should consider climate change mitigation factors (i.e., reduction and prevention of greenhouse gases emissions) as well as adaptation to the changes that have already started to happen. Hence, new and existing homes should be better able to deal with higher summer temperatures, warmer wetter winters, more extreme weather events and the rising sea levels (Gething, 2010; Gething and Puckett, 2013; Thompson et al., 2015).

The UK climatic records show that, between 1961 and 2006, maximum summer temperature across the south east had increased by an average of 2°C and in greater London by up to 2.7°C (Jenkins et al., 2009). The UK Climate Projections (UKCP09) study shows that even under a medium emissions scenario by 2080, the summer average temperature is estimated at 5.4°C higher than the 1961–1990 baseline in parts of southern England. Summer mean cover is also predicted to decrease over this period by up to 18% in parts of southern England and Wales. Such increase in the temperature will result in an extra +16 W/m^2 flux in downward shortwave radiation (Jenkins et al., 2010).

Also, the frequency of extreme weather events including heat waves is also predicted to increase. The UK Office of National Statistics data show that, during a ten-day heat wave period in August 2003 over 2000 excess mortalities occurred in England and Wales (Stedman, 2004). People over 75 years of age in London, were affected the most during heat wave period with an excess mortality rate of 59% than reference levels (Johnson et al., 2005). The UK Health Protection Agency have defined a heat wave as a period when daily temperatures on the current day, and at least the previous two days are above the 98th percentile of the whole year temperature distribution (Vardoulakis and Heaviside, 2012). According to this definition, a present day heat-wave in London would correspond to a daily mean temperature of 22.6°C or higher occurring for a minimum of three days.

During the 2003 heat wave, maximum daily Central England Temperature (CET) exceeded the baseline (1971 – 2000) reference values by 8°C. In London, a daily maximum of 37.9°C was reported with overnight lows of 26-27°C in some areas (Johnson et al., 2005). Wright et al. (2005) conducted a monitored study during 2003 heat wave and compared internal temperatures in four blocks of London flats and one semi-detached dwelling. Wright et al. (2005) results show that the average internal temperatures were above 27°C in every room in all of the dwellings throughout the 7days monitoring period. For one of the monitoring blocks, the mean internal temperature of flat was recorded as 29.9°C during the monitoring with a peak of 39.2°C.

The UK Met Office predictions suggests that by the 2080's and under a 'high' emissions scenario, daytime summer temperatures might exceed 42ºC in lowland England with a return period of 10 years (Wright et al., 2005). Hence, considering the changing climate, previous maximum temperature records will be more frequently exceeded (Rahmstorf and Coumou, 2011). According to the Met Office analysis (Jones et al., 2008), by 2040, the heat wave of 2003 could reflect an average summer conditions. By 2060 the current predictions shows that the heat wave of 2003 would represent a cooler than average summer under a medium-high emissions scenario Figure 2.4.

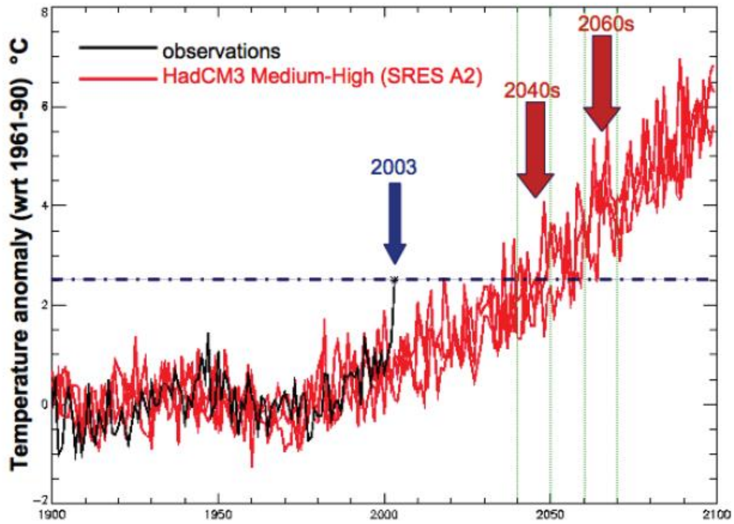


Figure 2.4 Temperature anomaly of 2003 heat wave in relation to a Medium-High emission trend (Met. Office, 2011)

Given that in the future there will be significantly warmer summer temperatures and an increase in extreme climatic events (Jenkins et al., 2010; Wilby, 2003), active cooling systems may become essential to maintain thermal comfort and to safeguard life in extreme events (Ostro et al., 2010). The use of domestic air conditioning in the UK is estimated to rise by 8% per year (Littlefair, 2005), which could result in an additional six million tonnes CO_2 emissions by 2020 (Rodrigues et al., 2013). The UK Health Protection Agency (UKHPA) have suggested that Passive cooling options implemented at the design stage of urban developments could be equally as effective as active cooling systems in reducing the health risks of heat (Vardoulakis & Heaviside, 2012).

The exact point that overheating occurs and therefore active cooling is required is important to the assessment of risk. Hence, the definition of thermal comfort and overheating risks will affect the outcome of any overheating investigation. Understanding the performance of the Passivhaus concept in delaying the onset of overheating and whether it is less vulnerable to heat related risks is highly important to adaptation planning and mitigation strategies. Given the increase in adoption of Passivhaus standard for the UK new developments, an aging population (ONS, 2012) and the global warming and climate change projections, it is becoming increasingly important to investigate the overheating risks of the UK homes built to the Passivhaus standard.

2.6 Thermal comfort

2.6.1 Thermal comfort and overheating assessment

Thermal comfort is defined as "the condition of mind that expresses satisfaction with the thermal environment" (Olesen and Parsons, 2002). Factors affecting thermal comfort are categorised as below in three groups (Szokolay, 2008):

(1) Environmental factors, which include air temperature, air movement, humidity and radiation;

(2) Personal factors, which include metabolic rate, clothing, state of health and acclimatisation;

(3) Other contributing factors, which include food and drink, body shape, subcutaneous fat, age and gender.

Given the various factors affecting the thermal comfort, it is not easy to define a universal thermal comfort index. A number of studies since the 1900s have been carried out to predict thermal satisfaction. Fanger's heat-balance thermal model is one of the most widely used measures which is based on the thermal sensation of individuals in a controlled climatic chamber. The Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD) are the two indices derived from the chamber experiments, and used to predict and measure thermal comfort. These two measures are frequently applied in BPS tools to determine thermal comfort in buildings (Attia and Carlucci, 2015; Rupp et al., 2015).

In Fanger's model, the environmental factors affecting thermal comfort, including air and mean radiant temperature, relative humidity and air movement, were maintained fixed at pre-assigned levels, while personal factors such as clothing and metabolic rates were varied. Based on the findings from the experiments, the PMV and the PPD models were developed. It is arguable that the PMV/PPD are only suited for measuring thermal comfort in steady-state conditions (buildings that are mechanically heated and/or cooled where occupants have no or very limited control of the indoor environment). A recent review on human thermal comfort in built environments indicated that the PMV model had also been used for non-air-conditioned buildings in warm climates (Rupp et al., 2015).

From the 1970s until the early 2000s, standards for indoor temperatures (EN ISO 7730, 2006) and ANSI/ASHRAE Standard 55 (ASHRAE, 2010)) were based on the PMV model or the Standard Effective Temperature (SET) based on the Pierce two-node model of thermal physiology (Gagge et al., 1971). The SET approach is not in use now a days and the PMV became the accepted model. EN ISO 7730 (2006) in specific, is based on the PMV approach.

The PMV is adopted to predict the thermal vote of occupants by using a thermal sensation scale. The thermal sensation of the occupants in a given space is defined based on a seven-point scale as follow: (-3.0) cold, (-2) cool, (-1) slightly cool, (0.0) neutral, (+1.0) slightly warm, (+2.0) warm and (+3.0) hot. The European Standard EN 15251 (2007), defines thermal comfort levels by categorising building types and assigning the relevant PMV according to Fanger's model, additional to acceptable indoor temperatures for mechanically cooled and naturally ventilated buildings.

Although both PMV and PPD indices are widely acceptable, the investigations show that the PMV method could result in under or overestimation of thermal sensation, especially in naturally ventilated buildings. Becker and Paciuk (2009) reported that in naturally ventilated buildings a discrepancy exists between the predicted PMV and the actual thermal sensation.

Investigations have shown that the PMV model is not appropriate method, especially in naturally ventilated buildings that are in free-running mode (neither heated nor cooled) (Dear and Brager, 2001; de Dear et al., 1997; Nicol et al., 1999 and Humphreys and Nicol, 2002). This has led to new formulations of various standards such as ANSI/ASHRAE Standard 55 in America (ASHRAE, 2010), and CEN standard EN 15251 (2007) in Europe, which include 'adaptive' temperature limits for naturally ventilated or free-running buildings.

The adaptive thermal comfort model was established to address the limitations of the steady state PMV model for naturally ventilated buildings. In order to develop the adaptive model, field studies and regression models were carried out in naturally ventilated and mixed mode buildings (ASHRAE, 2010).

Based on the adaptive thermal comfort model, occupants are interactive with the indoor environment and they can freely adapt to change their thermal sensation. Three aspects are included in the adaptive model including psychological comfort aspect, behavioural aspect and acclimatisation, which have not been fully considered in the steady-state model (Rupp et al., 2015).

Occupants' indoor satisfaction is a function of the outdoor conditions. Studies in hotter climates have reported that occupants show a higher level of thermal comfort satisfaction than expected, given the warm to hot outdoor conditions (Rupp et al., 2015). The distinctive factor in the adaptive model is that the occupants have more choice to operate windows, fans, blinds or even change their clothing level to achieve thermal comfort.

The ANSI/ASHRAE Standard 55 (ASHRAE, 2010) has also included a chart, see Figure 2.5 which shows an acceptable range of operative temperatures in naturally conditioned buildings related to the monthly mean of the outdoor temperature. Two acceptability ranges of 90% and 80% are shown on the chart. The ASHRAE standard define the adaptive comfort as:

$T_{comf} = 0.31\ T_{om} + 17.8$

where T_{comf} is the comfort temperature and T_{om} is the monthly mean outdoor temperature. It is notable that the adaptive thermal comfort model offers a wide range of acceptable operative temperatures ranging from around 17°C up to almost 32°C, depending on the mean outdoor temperatures as shown in Figure 2.5.

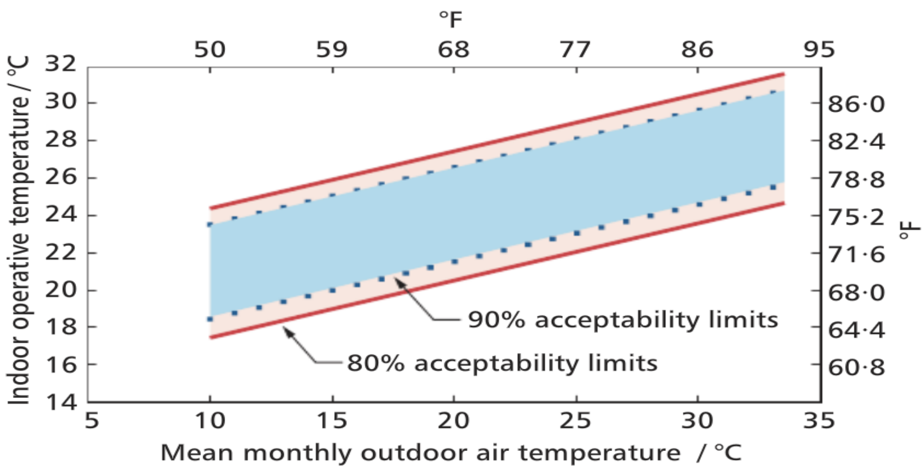


Figure 2.5 Acceptable operative temperature ranges for naturally conditioned spaces (ASHRAE, 2010).

The European standard EN 15251 (2007) is designed to underpin the Energy Performance of Buildings Directive (EPBD), and seeks to reduce energy use in the European building stock. EN 15251 (2007): Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. The standard defines indoor environments consistent with occupant satisfaction in order to ensure that energy efficiency is achieved without cost to the comfort, performance or wellbeing of building occupants.

The approach to naturally ventilated buildings in free running mode is also similar to that in ANSI/ASHRAE Standard 55 and the European standard EN 15251, as shown in Figure 2.5, however uses the exponentially weighted running mean of the daily mean outdoor air temperature as the measure of outdoor temperature (T_{rm}).

In the UK, CIBSE Guide A, 2006 edition (CIBSE, 2006a) states that (in warm summer conditions) 25°C is an acceptable operative temperature (OT) in the living area of dwellings and 23°C is acceptable for bedrooms. CIBSE Guide A (CIBSE, 2006a), defines 'overheating' when the OT exceeds 28°C for more than 1% of the annual occupied hours in the living areas of (free running) dwellings or when the bedroom OT exceeds 26°C for more than 1% of the annual occupied hours (unless ceiling fans are available). The CIBSE Guide A, 2006 edition (CIBSE, 2006a) assessment is based on a warmer than average summer, using a Design Summer year (DSY) dataset.

CIBSE overheating Task Force in 2013 (CIBSE, 2013) recommended that the existing advice on overheating in 2006 edition of CIBSE guide A (CIBSE, 2006a), is increasingly restrictive. Hence, the Task Force produced a more comprehensive guidance for the overheating assessment in the UK and published CIBSE TM52 (CIBSE, 2013) to inform designers and developers for defining the indoor environment in the building and also proposing a method of overheating assessment. The CIBSE Overheating task group approach is based on adaptive thermal comfort model which was outlined in European Standard EN 15251 (2007). Whist the approached outlined in this technical memorandum is primarily intended to be adopted in non-domestic building, the approach was also recommended to be relevant in dwelling overheating assessment (CIBSE, 2013). The methodology and benchmarking criteria for overheating assessment described based on CIBSEs guideline will be discussed in the methodology chapter (Chapter 3). The use of adaptive thermal comfort method for overheating assessment as outlined and recommend in TM52 (CIBSE, 2013), has been included in the latest edition of CIBSE Guide A (CIBSE, 2015) as a general methodology for overheating evaluation.

The overheating threshold used in the Passive House Planning Package (PHPP) (Feist et al., 2012) originated from the German DIN 1946-2 (1994) upper limit of 25°C. Rouvel and Kolmetz (1997) adopted this threshold and established the criterion for active space cooling as occurring when the 25°C limit was exceeded for more than 10% of the period of annual usage. For a Passivhaus dwelling and with the assumption of continual occupancy this criterion is interpreted as being 10% of the year (Feist et al., 2012). Voss et al. (2005) researched on energy efficient office buildings and post occupancy and suggested that the acceptable duration of overheating above 25°C should be reduced to 5% or less. However, DIN 4108-2 (2013), in contrast with Voss et al. (2005) findings, incorporated a more adaptive approach, defining a series of three limiting temperatures (25, 26 and 27°C) that cannot be exceeded for more than 10% of the occupied period depending on the monthly ambient temperature of the region (below 16.5°C, below 18°C and above 18°C respectively). Deutscher et al. (2000) argued that original overheating targets in Germany were too difficult to implement and therefore this resulted in slackening of overheating limits.

For the overheating assessment of buildings which are still in the design stage or have not long been occupied, the recommendations of EN 15251 (2007), together with evidence of the likely indoor temperatures in use, can be used. Overheating in such new buildings can only be predicted before occupation by using dynamic simulation. There may also be circumstances where the building is only recently occupied. In such conditions, survey of building occupants is not applicable, since occupants are not familiar with the building yet (EN 15251, 2007).

The criteria which currently define 'overheating' in dwellings have evolved from thermal comfort investigations on occupants in offices and commercial buildings and 'overheating' is defined as occurring at a point, or range, above which occupants experience discomfort. Dengel and Swainson (2012) argued that a counterproposal to this approach is needed, since the existing approach is based on thermal preference and not based on occupant health. Dengel and Swainson (2012) view is reflected in World Health Organisation (WHO) guidance for air temperatures in dwellings (WHO, 1985; WHO, 1990). The guidance, in particular, aims to protect health of those vulnerable to extreme temperature, and does not discuss the sensations of satisfaction with the ambient temperature (Ormandy and Ezratty, 2012). WHO research outcome advises that minimal risk to the health of sedentary people, including the elderly, in dwellings exist for the ambient temperature of 18°C to 24°C (WHO, 1990). Ezratty (2009) study provided the evidence that shows, the elderly may report feeling comfortable when the temperature is not healthy for them.

2.6.2 Thermal comfort and Human health

Housing Health and Safety Rating System (HHSRS) was established in 2005 to investigate and evaluate health and safety risks instigating from deficiencies in the UK dwellings (HHSRS, 2006). The health issues around 'excess heat' stated in HHSRS as "High temperatures can increase cardiovascular strain and trauma, and where the temperatures exceed 25°C, mortality increases and there is an increase in strokes. Dehydration is a problem primarily for the elderly and the very young" (HHSRS, 2006). Armstrong et al. (2011) developed a statistical model with a heat threshold of 93rd percentile of the all-year daily maximum ambient temperature distribution to investigate the mortality assessment within any given region of England and Wales. The UK Health Agency performed similar investigations and reported that the daily mean temperature can be used at the 93rd percentile as a threshold above which an elevated risk of heat related mortality occurs. For the case of London in the present day, this means an average ambient temperature of 19.6°C (Vardoulakis and Heaviside, 2012). Many studies have focused on regional ambient temperature thresholds for epidemiological predictions (Vardoulakis and Heaviside, 2012; Greenberg et al., 1983; Whitman, 1997; Wainwright et al., 1999), however, there is lack of comprehensive studies on building OT and Indoor Air Quality (IAQ) risk thresholds.

Basu and Samet (2002) reported that, the heat stress experienced across day and night determines the risk of heat related mortality. Hence, understanding of the relationship between OT thresholds and exposure periods is crucial for adaptive building design and assessing morbidity and mortality data as well as heat risk prevention strategies.

Despite CIBSE Guide A mentions that sleep impairment could happen for temperature above 24°C, there is lack of research on correlation between OT thresholds and morbidity rates in dwellings in the UK. Buysee et al. (2010) reported that increased sleep fragmentation is directly associated with poor health, reduced productivity and impairing the recoverability from daytime heat stress (Kovats and Hajat, 2008). Research show that skin temperature variations, as little as 1°C can impair sleep quality, especially in the elderly (Aries and Bluyssen, 2009; Raymann et al., 2008). Hence, the OT's of bedrooms plays an important role in the overheating risk assessment. Heat exposure is not the only parameter that cause heat related mortality. Johnson et al. (2005) data showed higher mortality occurred during the 2003 heat wave in England and Wales, in comparison to the 1976 heat wave (16% compared to 10%), although the temperatures were very similar. The higher mortality rate in 2003 could be attributed to an ageing UK population. There are clear scientific evidence which state the elderly (>=75 years of age) are more vulnerable to heat related mortality (Rooney et al., 1998; Cassadou et al., 2006; Na W et al., 2013).

2.7 Overheating in buildings

2.7.1 Current extent and evidence

As it was discussed, in recent decades there has been huge progress in terms of achieving energy efficiency and emission reductions in construction sector. The new regulations enforce strict energy efficiency standards for new homes and existing homes across the UK are now benefiting from energy efficient glazing, better insulated and efficient heating systems. As a result of this effort, the construction sector is taking steps forward in tackling the problem of cold homes and fuel poverty. However, as buildings are better built to prevent heat losses in the winter, the risk of overheating in warmer months is increased.

"Considering the climate change effects, construction sector will need to change to ensure buildings continue to fulfil their functions throughout their life-cycle." (Iannaccone et al., 2014). Several researchers have addressed the climate change impact on the built environment, with the specific focus on thermal comfort and energy use (Holmes and Hacker et al, 2008; Roetzel and Tsangrassoulis, 2012; Taseska et al,. 2012; Li et al., 2013a; Yau and Hasbi, 2013; Karimpour et al., 2015).

For the case of the UK dwellings, evidence shows that summertime overheating is becoming a significant problem under existing climatic conditions (Kershaw et al, 2010; Dengel and Swainson, 2012; Beizaee et al., 2013; Gupta et al., 2015; Gupta and Kapsali, 2016; Lomas and Kane, 2013; Pretlove and Kade, 2016; ZCH, 2015). The existing evidence advises that the overheating risk is not necessarily localised, however, it is widely accepted that it tends to be exaggerated in dense urban environments (Mavrogianni et al., 2009; Mavrogianni et al., 2011; Oikonomou et al., 2012; Sanchez et al., 2014).

In response to concerns regarding overheating in the UK dwellings, in 2014, the Zero Carbon Hub undertook a two-year investigation to improve the understanding of domestic overheating in England and Wales (ZCH, 2015). The project findings suggest that up to 20% of dwellings in England may already be overheating, even during cool summers (ZCH, 2015). These findings are primarily based upon two large-scale studies, which monitored around two hundred unheated properties during the summer months (Beizaee et al., 2013 & Lomas and Jane, 2013). Despite the studies being undertaken in different but relatively cool summers (the summers of 2007 and 2009 with an average external temperatures during monitoring lower than normal for the time of year, and with a short hot spell) and in different locations, a significant proportion of the bedrooms (~20%) were reported to have temperatures in excess of 24°C during their occupied hours, for both studies (Beizaee et al., 2013 & Lomas and Kane, 2013). Also, Lomas and Kane (2013) reported significant overheating in the living rooms of the monitored dwellings, with more than a quarter of them exceeding 28°C for more than 1% of occupied hours.

BRE has conducted Energy Follow-up Survey for 2616 households in 2010-2011 and found that 20% of the households interviewed in England had problems with keeping one or more rooms cool during the summer period (ZCH, 2016). A sub-sample of 823 homes were monitored and it was found that temperatures in those homes that reported overheating were 0.5°C to 1.5°C higher than those households who did not report overheating problem. The Energy Follow-up Survey investigated the time-length of overheating to understand the severity of the problem and reported that 22% of the households with overheating issues said that at least one room in their dwellings was difficult to keep cool ‘every day’ during the summer months (ZCH, 2016).

The Sustainable Homes's Overheating Survey investigated 75 Housing Provider organizations and reported that 70% of these organisations have experienced minimum of one instance of overheating in their housing stock during the last 5 years, 7% reported no overheating, and the remainder (23%) did not answer the question. The results are indicating that most of overheating reported was from organisations based in London, the South East and the South West of England.

The GHA studied the “extent of the overheating problem nationally” and conducted an online survey of Environmental Health Officers, local authorities, Housing Providers and GHA members. The survey identified 185 instances of overheating from 126 responses to the survey. The results show that 66 (73%) out of the 90 overheating instances were located in urban area and 19 (20%) in suburban locations. The survey concluded that “overheating can be a serious issue for people living in specific types of housing. The prediction of rising summer temperatures in the UK in future due to climate change, instances of overheating and associated problems are likely to increase”. The GHA survey information has the potential for selection bias and therefore should be used with caution. Although still more study need to be conducted to understand the national extent of the overheating problem, it is clear that overheating is an area if concern. The reported literature in this Chapter showed that overheating is already happening in summers with normal or below average temperatures and is not only limited to hot spells and heat-waves (ZCH, 2015).

2.7.2 Overheating risks in energy efficient and Passivhaus buildings

It is clear from the available evidence that in low energy dwellings and those dwellings constructed to Passivhaus Standards, the very low fabric transmission losses, high levels of airtightness and optimized passive solar design may make them particularly susceptible to overheating, particularly during the summer.

Although evidence indicates that overheating can occur in both new and existing dwellings, a recent study undertaken by Dengel and Swainson (2012) found that the number of instances in which overheating had occurred within existing dwellings was relatively low. Instead, the dwellings at most risk from overheating were new build and recently retrofitted small dwellings and flats that incorporated single-sided ventilation. Interestingly, Dengel and Swainson (2012) also found that although overheating occurred predominantly during the summer months, there were also instances where the dwellings experienced overheating throughout the rest of the year.

A number of studies have investigated overheating and the summer performance of Passivhaus buildings in a range of European climatic zones (Mlecnik et al., 2012; Wagner and Mauthner, 2008a; Schnieders et al., 2015; Feist et al., 2012). A majority of these studies confirm that the Passivhaus occupants often experienced better thermal comfort during winter than in summer period (Mlecnik et al., 2012; Wagner and Mauthner, 2008b). Also, Post Occupancy Evaluations (POEs) and monitoring studies carried out by the Passivhaus Institute, reported high occupant satisfaction under summer conditions (Schnieders et al., 2015; Feist et al., 2012).

CEPHEUS (Cost Efficient Passive Houses as European Standards) project monitored 221 dwellings across 5 European countries. The findings indicate that while mean indoor temperatures could be kept within a comfortable range in the summer, the comfort levels could be improved through appropriate occupant ventilation behaviour (Schnieders, 2003; Feist et al., 2005; Schnieders and Hermelink, 2006). In contrast, there have also been a number of published studies on Passivhaus certified dwellings which have reported summertime overheating in different European climates (Meulenaer et al., 2005; Larsen et al., 2012; McLeod et al., 2013; and Mlecnik et al., 2012;).

Further studies have focused on risks that may be associated with implementing the PH standard. Many studies found that overheating might be an issue for PH buildings, although the PHI has declared that with careful design and consideration the issue could be resolved by simply operating the ventilation system effectively to bypass heat recovery or even just by opening the windows. (Junghans and Berker, 2014).

Brunsgaard et al. (2012a) analysed a number of studies that were set out in different parts of Europe to assess the thermal comfort of Passivhaus buildings. Issues related to overheating were found to be raised in a number of the examined studies. This was cited mainly for projects carried out in Sweden and Denmark.

The northern European studies of overheating in Passivhaus dwellings have close climatic conditions to the UK and hence are more relevant for further investigations of overheating. Larsen and Jensen (2011) monitored 10 certified Passivhaus dwellings in Skibet, Denmark. The Skibet development is located at latitude slightly south of Glasgow in the UK. Larsen and Jensen (2011) recorded dry bulb temperature, relative humidity (RH) and CO_2 levels in multiple locations from 2008 to 2011. The data collected during this study was compared to the acceptable criteria of category B - DS/CEN/CR1752 (DSA, 2001), which is summertime dry bulb range from 23°C to 26°C. In 2009, the results for the month of July show that this criterion was exceeded for 40% of the time.

In 2010, the same criteria was exceeded 60% of the time, which means severe overheating have occurred (Larsen and Jensen, 2011). Occupant ventilation patterns and different weather patterns are the factors contributing to the difference in the duration of overheating over the two summer periods. It is notable that prolonged overheating risk reported by Larsen and Jensen (2011) was not predicted by the PHPP model of the certified dwellings, however, dynamic simulation programme, subsequently simulated the overheating (DBRI, 2013). Also, manual calculation in accordance with SBI instruction 202 could replicate the overheating (Andersen et al., 2002). Ruud and Lundin (2004) carried out similar investigations for a group of 20 terraced apartments built to the Passivhaus standard in Lindås, Sweden and showed that mean summer temperatures of 25.2°C with significant variation in the internal temperatures between apartments existed. Ruud and Lundin (2004) showed that some flats recordings are within acceptable conditions and others reaching internal temperatures of up to 30°C in summer. The Post Occupancy surveys carried out in the Glumslöv, Oxtorget and Frillesås districts in Sweden, reported overheating. Houses monitored in Glumslöv district were the worst case, with 56% of the Passivhaus residents reporting their indoor temperature as 'too warm' during the summer period (Samuelson and Luddeckens, 2009).

Empirical evidence is now beginning to emerge that indicates that overheating has been experienced in a number of UK Passivhaus dwellings during the summer. Specific examples include the Camden Passivhaus (Ridley, et al., 2013) and the Larch and Lime house (Ridley et al., 2014).

Recent study by Fletcher, et al. (2017) investigated the overheating risk of vulnerable occupants in a UK-based Passivhaus dwelling, using both static and adaptive thermal comfort assessment methods. Fletcher, et al. (2017) adopted 21 months of in-use monitored data to investigate the overheating risk and showed that substantial overheating occurs based on PHPP, CIBSE Guide A and CIBSE TM52 criteria.

2.7.3 Overheating: Future extent

The future extent and severity of overheating issue is a function of collective effects of a range of influential parameters and their future state (ZCH, 2016) these drivers include:

Increase in average temperatures and heatwaves incidence

More extreme weather events are predicted in the UK as the result of climate change. The data show that average summers are becoming hotter and generally drier. Longer and more frequent heatwaves and higher average peak temperatures are expected for the future. The scientific data suggests that by the 2040s a summer as hot as 2003 (when summer temperatures exceeded the 1961–90 mean by 2.3°C) will be very common in the UK (ZCH, 2016).

Demographic changes

Despite people living in hot regions are generally more adapted to higher temperatures, it is not clear how quickly people in the UK will adapt to the changing climate. In specific, there is increasing concern for those who are most vulnerable to the effects of excess heat, including the elderly population, who are at increased risk of heat-related illness. The elderly population have less ability to adapt to higher temperatures. According to data published by National Health Service (NHS), the proportion of the population who are overweight or suffer from cardiovascular diseases is also increasing, and these groups too, are more at risk of heat-related illness.

The UK population is growing and is projected to increase to over 73 million by 2037. The life expectancy has also increased in the UK. Hence, the population over 75 is predicted to nearly double in the next 30 years, to around 13% of the UK population in 2037 (ONS, 2012).

Working patterns

Direct heat exposure during the daytime for people who are working at home is likely to have an impact on their work capacity. Hence, the management of day and night time temperatures in homes is important.

Estimates show that around 14% of people in the UK are home workers. This percentage has increased by 2.8% since records began in 1998 (ONS, 2012) and it is likely to grow in the future.

Urbanisation

In 2011, nearly 82% of the population in England and Wales lived in urban areas with ~21% of the urban population aged 60 or over (DEFRA, 2012).

Many cities in the UK experience the UHI effect, where temperatures in the city centre can be much higher than in surrounding rural areas (difference of 9°C recorded in London and 8°C in Manchester). This condition predominantly happens at night (Levermore et al., 2012).
For the future, the prediction shows that a greater percentage of the population are expected to live in urban areas where building densities are usually high and the UHI is more pronounced.

Construction practices

High-density new developments usually have a central corridor with single-aspect apartments on either side to maximise the number of dwellings which can be built per unit area. However, studies show that such flats have a higher risk of overheating compared to other house types. This is due to the fact that it is harder to achieve adequate ventilation in a single-aspect apartment than in an apartment or house with opening windows on two or more sides.
In 2014, approximately 30% of the newly completed residential units in England were flats, compared to 20% in 2000 (ZCH, 2016).

Energy efficiency and air-tightness

In recent decades, minimising winter heating costs in homes by reduction of heat loss and adopting energy efficiency measures were very popular. Therefore, many dwellings have benefited from and increased levels of airtightness and insulation, and the heat loss through the building fabric have reduced to a minimum level. These energy efficiency measures are helping to keep homes warm during winter period, however, given the climate change, the designers and contractors need to actively consider summer thermal performance to ensure overheating issue will not happen.
Zero Carbon Hub (2016) stated overheating of buildings as an important risk for the future of the built environment sector. Currently, there are only very few projections relating directly to the potential future incidence of overheating in the UK dwellings.
Jenkins et al. (2014) studied the links between future climate and thermal discomfort in homes in London and the surrounding area. Jenkins et al. (2014) modelling results for

high emission scenario suggested that, by the 2030s, around 60-75% of residents living in flats in the Greater London area could be affected by thermal discomfort.

The Suburban Neighbourhood Adaptation for a Changing Climate (SNACC) (Williams et al., 2012) project investigated that how an existing suburban neighbourhoods in England be 'best' adapted to reduce further impacts of climate change and withstand ongoing changes. The SNACC team studies six suburban neighbourhoods in Oxford, Bristol and Stockport. Prior to modelling the adaptation options for the individual neighbourhoods, the overheating potential was assessed for each neighbourhood. For all the case study locations the overheating potential was assessed based on the current climate, and the 2030s and 2050s predictions using medium and high emissions scenarios (50% and 90% probabilities). Despite the variation in the results for the level of overheating potential, the results for all the neighbourhoods showed that a very large percentage of properties had a 'high likelihood' of being overheated in the 2030s and 2050s high emissions scenarios. The risk of overheating in Botley (Oxford in general) was the highest between all SNACC case study locations, which could be attributed to the existing warmer climate in southeast part of the country. The analysis of the results shows that risk in Cheadle (Stockport in general) was the lowest (Williams et al., 2012).

Number of other studies has predicted the impact of climate change on future domestic overheating in energy efficient dwellings in the UK (Porritt et al., 2012; Jenkins et al., 2013; Mcleod et al., 2013). The methodologies employed in these studies are all fundamentally very similar; DTS models are coupled with morphed simulation weather files to model a range of future scenarios. Results reported from these studies indicate that the naturally ventilated energy efficient buildings are likely to face excessive summertime overheating in the future based on their existing designs.

The impacts of future climate change in the performance of the UK Passivhaus dwellings could be investigated through examining the Passivhaus performance in those locations which already have warmer climate than the present day in the UK. However, few studies have investigated the performance of Passivhaus dwellings in a Southern European climatic context. Schnieders (2005) conducted the Passive-On project, and determined the optimal performance characteristics of a cost-efficient Passivhaus dwelling model located in Marseille. Schnieders (2005) adopted a DSP model (Dynbil) to simulate the performance of an end-terrace Passivhaus, based upon Hannover-Kronsberg development design (Fiest et al., 2005). Four Passivhaus were modelled to assess performance differences between the use of a well-insulated fabric U values (0.15 W/m^{2}K) with a less well insulated alternative U values (circa 0.25 W/m^{2}K). Schnieders (2005) used a typical weather year for Marseille to model the building's performance, both double (U value 1.19 W/m^{2}K, g value 0.64) and triple glazing (U value 0.71 W/m^{2}K, g value 0.5) options, with and without heat recovery ventilation (heat recovery of 0.75) are adopted in the modelling procedures (ASHRAE, 2001). Night purge ventilation and automated external blinds were considered for modelling of all dwellings. Schnieders (2005) used a weather file with maximum temperature of 34°C and a summer monthly average of ~25°C. The modelling results show that for all cases, PH overheating threshold (Feist et al., 2012) was exceeded despite the interventions and without active cooling, maximum temperature exceeding 27°C were recorded in bedrooms.

Schnieders (2009) conducted a larger study to examine the feasibility of the Passivhaus concept in twelve different reference locations across Southern Germany, Italy, Southern France and the Iberian Peninsula. He used different thermal specifications and cooling strategies in his investigations. Schnieders (2009) results indicate that for all studied locations, the Passivhaus concept is cable of providing comfortable indoor climate, in accordance with EN ISO 7730 (2006) exclusively by pre-conditioning (i.e. using active cooling) the supply airflow. Da Graça et al. (2012) studied two Net Zero Energy Home (NZEH) prototypes built to the Passivhaus standard in climatic context of Lisbon, Portugal and came to similar conclusions as Schnieders (2009).

2.7.4 Overheating, effective design factors and principal of overheating control

As discussed in this Many homes in the UK are already experiencing summertime overheating and the overheating risk will be increased in the future due to various reason described in section 2.7.3. Since the main aim of any building is to provide a comfortable and pleasing space for occupants and protect their occupants from the extremes of the external environment (ZCH, 2015), thermal comfort should always be a key consideration in the planning and design of homes (CIBSE, 2018).

The operative temperature will increase when the net heat gains exceed the losses in the dwelling. Such increase in operative temperature may results in uncomfortable temperatures for occupants, and at some elevated levels lead into potential health issues. Sources of heat can be inside or outside a building. The external (outside) sources of heat include (ZCH, 2016):

- Solar radiation
- Direct transfer of heat by conduction
- Air movement to inside when it is hotter outside.

The internal sources of heat include (ZCH, 2016):

- Occupants
- Electrical equipment including lighting and Cooking
- Hot water pipes and storage tanks

Limiting the heat gains could reduce unnecessary heat. This can be achieved through reducing the amount of:

- solar radiation
- Internal heat gains such as unnecessary use of electrical equipment or by limiting gains from other sources such as hot water distribution pipes
- Warmer outside air entering the building

When excess heat is inside a building, increasing the heat rejection and/or cooling of the space is essential to reduce the operative temperature. ZCH (2016) recommended that reduction in operative temperature can be attained by passive or active removal of heat through ventilation, passive or active cooling of the ventilation air or the structure of the building and using mechanical cooling.

CIBSE TM37 (CIBSE, 2006b) suggest controlling solar overheating by controlling the following factors:

Solar gain

Solar overheating can be controlled by selecting a suitable layout and orientation. Building spaces should be laid out in such a way that they allow the building to achieve a balance between the advantages and disadvantages of sunlight. For example, controlling solar gain by shading devices would be more efficient if the building spaces have windows faced to the north or south as opposed to the east or west. Solar overheating can be controlled by controlling the window area as well. Window area should be decreased in such a way as to control the solar heat gain, as the amount of solar heat gain is related (a function of) to the window area. However, reducing windows area can also limit daylight and restrict the view out. Reducing windows area will also result in the reduction of possible useful heat gain during the heating season. Therefore, its area should be minimized thoughtfully and an optimum area needs to be considered. Finally, solar overheating can be controlled by choosing suitable solar shading. Solar shading can be in the shape of external, internal, mid-pane shading or solar control glazing. According to CIBSE TM37 (2006b), the most effective way to control overheating is to prevent the sunlight from reaching the windows and external shading is particularly appropriate for this purpose.

Internal gain

Overheating can be controlled by internal gain. Internal gain depends on occupants, equipment and luminaries. In order to control internal gain, energy efficient equipment and luminaires should be utilised and they should be switched off when not required.

Thermal mass

Solar overheating can be controlled by utilising the exposed thermal mass in a building structure. The exposed thermal mass absorbs excessive heat and decreases the peak inside temperature of hot days. To maximise the benefit of thermal mass, night time ventilation is considered to be beneficial.

Ventilation

Solar overheating can be controlled by ventilation. Ventilation has two specific roles in a building: sustaining air quality and cooling effect. It should be noted that the ventilation rate which is required to remove excessive solar heat gain is higher than the ventilation which is required to maintain indoor air quality.

Mechanical cooling

Mechanical cooling and air-conditioning can be used to control indoor from overheating. National House Building Council (NHBC) report of "Understanding overheating where to start: an introduction for house builders and designers" illustrates some of factors that can contribute to overheating in homes, see Figure 2.6.

It is notable that other factors can also play rule in exacerbating the overheating.

Figure 2.6 Illustration of cumulative factors which can contribute to overheating in homes (NHBC, 2012)

In the most recent CIBSE publication, TM60 (CIBSE, 2018), the principal causes of overheating and possible mitigation measures are summarised as in Table 2.3.

Further detail information with regards to the different overheating solutions and their relative scales of cost and applicability in different situations are presented in Zero Carbon Hub report (ZCH, 2016).

Table 2.3 Examples of overheating causes and mitigation measures (CIBSE, 2018)

Design Issue	Principal Causes of overheating	Potential mitigation measures
Building location, orientation and construction type	• Single aspect dwellings that do not allow crossflow ventilation. • Noisy locations (e.g. near busy roads, stations or town centres) where opening windows to dissipate heat gains causes a noise or pollution nuisance for the occupants. • City developments where the urban heat island effect is likely to result in increased external temperatures particularly at night. • Lack of, or inappropriate use of thermal mass.	• Develop internal plans that can enable cross-flow ventilation. • Develop a ventilation strategy that minimises acoustic nuisance if windows are opened. • Position window openings and ventilation inlets away from external surfaces that are hot in the summer. • Utilise external landscaping and external water features to provide localised shade and transpirative cooling. • Reduce albedo on rooftops and facades exposed to significant solar gain. • Increase the thermal mass of the building in main living areas (but not bedrooms), and develop appropriate night cooling strategies. • Position bedrooms to avoid unwanted heat gains, i.e. on north side of building.
Glazing and orientation	• Rooms and circulation spaces with significant areas of unshaded glazing (large areas of south, east or west facing windows are a particular problem). • A high proportion of full height windows (including a proportion of low level glazing installed below the working plane). Low level glazing has no beneficial impact on daylight levels at the working plane but increases solar heat gain to the home).	• Reduce large areas of glazing that could significantly contribute to solar gains. • Reduce the g-values of glazing, optimising the reduction of excessive heat gains in summer against the loss of useful heat gains in winter • Provide shading to windows that will experience solar gain that is likely to cause overheating. • Install external shading devices (in preference to internal blinds). • Check that openable windows have sufficient free area to allow adequate background ventilation. • Provide feedback to the architect on the impacts of proposed glazing configurations on the contribution to overheating risk. • Specify horizontal rather than vertical windows to achieve daylight levels and avoid the specification of low level glazing below the working plane.
Occupancy densities	• Spaces with high occupancy. • Spaces with a lot of equipment or poorly controlled equipment which remains on during the day.	• If rooms will have high occupancy check that higher ventilation rates are achievable. • Specify controls that are easy to access and use.
Building engineering services	• Heat gains from pipes, cylinders and heat interface units (HIUs). • Heat gains from lighting and other electrical equipment. • MVHR systems without summer bypass.	• Pipes, cylinders and heat interface units should be well insulated. • Specify lighting with low heat output. • MVHR and (where applicable) air handling plant should have summer bypass option. • If the summer bypass is manual rather than automatic provide end users with information explaining how and when to use the bypass function.
Operational issues	• Poorly controlled communal heating systems (there is particular risk arising from continuous operation of heating systems at high flow temperatures). • Windows, and patio doors which: - do not offer occupant control over the ventilation area or do not have sufficient opening area - compromise security when opened or have restrictors and/or security constraints on opening - are heavy and so difficult for the elderly and/or infirm to operate. • All of which can result in lower ventilation rates than predicted. • Occupants not utilising blinds/ shading. • Occupants not using or understanding the summer bypass facility on MVHR systems.	Provide heating systems with controls that are simple to understand so that occupants and building managers can adjust programmes and set-points. • Blinds, where provided, should be simple to operate (guidance should be included in the Home User Guide). • Avoid conflicts that can occur between blinds and opening windows. • Ensure windows and patio doors are fit for purpose both in terms of ease of use and in provision of the required rate of ventilation.

2.7.5 Effective factors to avoid overheating risk in Passivhaus Dwellings

Schnieders (2009) investigated the feasibility of Passivhaus by using different thermal specifications, and cooling strategies across the south west Europe in twelve different locations including southern Germany and France and also Italy. Schnieders (2009) findings show that maintaining thermal comfort in summer is a function of solar control which could be achieved via external shading, reduction of solar load through opaque elements and minimising internal heat loads. Two parameters of night purge ventilation and to less extent ground coupling were shown to be critical factors in heat removal from the building. Da Graça et al. (2012) study showed that highly glazed Passivhaus in compare to moderately glazed Passivhaus will result in substantially higher risks of overheating, and also comparison of the building with and without external shading in this study showed that the externally shaded Passivhaus showed lower internal temperature variations and rarely exceeded the overheating threshold.

The literature reviewed within this chapter show the strong sensitivity of Passivhaus performance to design and operational parameters, and highlights the need to study these issues in the context. The overheating risks in Passivhaus dwellings are affected by user behaviour parameters including ventilation patterns, shading strategies and internal gains (Larsen and Jensen, 2011; Wagner and Mauthner, 2008a; Wagner and Mauthner, 2008b) as well as the building's thermal specifications of the dwelling (Schnieders, 2005; Schnieders, 2009).

Schnieders (2009) suggested that automated external shutters closing are very effective in overheating control. A number of investigations on on-residential buildings showed that the operation of blinds is mostly determined by visual comfort and not necessarily by indoor temperature (Raja et al, 2001; Hasselaar, 2008; Inkarojit, 2005; Voss et al., 2005). So far, full external shading devices have not been popular in the UK residential buildings. Result from a post occupancy survey of two Passivhaus building in Wales also indicates that the use of external shading devices is mainly driven by factors such as visual and psychological comfort and not rather thermal comfort

Number of other studies has done parametric investigation to find out the effective factor to control and reduce overheating risk in Passivhaus dwellings. Evidence obtained as part of the CEPHEUS project showed that mean indoor temperatures could be kept within a comfortable range in the summer and the levels of comfort attained could be improved through appropriate occupant ventilation behaviour (Schnieders, 2003; Schnieders and Hermelink, 2006; Feist et al., 2005).

McLeod et al. (2013) reported that excessive overheating can be avoided through the optimisation of the ratio of glazing on specific facades and external shading. Similar results were presented by Lavafpour & Sharples (2015), who found that future overheating could be significantly reduced by adopting a novel tilted facade on the south facade.

Number of research (Ridley et al., 2014; Figueiredo et al., 2016) found that the occupant behaviour including opening the windows and closing the solar shading system, could noticeably influence the thermal comfort and building energy performance. Yu et al. (2015) data showed that occupant number could heavily affect building thermal comfort. In a study of Passivhaus optimization for Portugal (Figueiredo et al., 2016), presence of external shading devices and building orientation found to heavily affect the thermal comfort.

2.8 The UK social housing and Passivhaus Standard

Social housing provides secure and decent homes for those who cannot afford open market prices in the UK.

The development of social housing in the UK started in the late 19th Century and reached its peak by the mid-20th Century. Social housing is one of the most important sectors in the UK, with 3.8 million households representing 17% of all UK homes (EHS, 2013). This stock belongs to local authorities and housing associations (Wheeler, 2011). In 2012, 53% (around 2.1 million) of social tenants rented their homes from a housing association and the rest (around 1.9 million) from local authorities (EHS, 2013).

Social housing also has the highest rate of overcrowding in the UK, at 7%, compared to an overall UK rate of 3% (EHS, 2013).With the increase in the UK population, social housing providers are under pressure to build more houses (McManus et al., 2010).

In 2017, the mayor of London announced that the pace of construction in London should increase from 29,000 homes a year to 66,000, adding that 65% of these homes needed to be affordable, far higher than the current rate of 38% (Booth, 2017).

The UK housing sector is also under pressure to move towards zero carbon houses to comply with UK regulations. This applies in particular to the social housing sector, since it benefits from public funds (McManus et al., 2010). For example, the government's Standard Assessment Procedure (SAP) is used in the UK to assess the energy and environmental performance of UK dwellings. The average SAP rating of UK homes increased from 45 to 57 (12 points) between 1996 and 2011, while in the same period the rating in the social housing sector rose by 14 points, from 49 to 63. In 2011-2012, the social housing sector also had the biggest proportion of dwellings earning A to C scores, the highest on the UK's Energy Efficiency Ratings (EER) scheme (EHS, 2013).

It has been estimated that in 2011 11% of UK households suffered from fuel poverty (when a household spends more than 10% of its total income on energy) (DECC, 2013). Average energy bills have also seen a sharp rise (24%) between August 2009 and August 2013, while the average household income increased by only 3% in this period (Peachey, 2014). Unless energy demand reduction techniques are integrated into social housing sector to improve the energy efficiency, there is further risk of more households going into fuel poverty. This risk is particularly relevant for social housing tenants since the social housing sector had the highest unemployment rate, around 10%, amongst occupants and almost two-thirds of social tenants were in receipt of Housing Benefit (HB) to help to pay their rent, approximately 40% more than private tenants (EHS, 2013). The ability of social tenants to pay their rent both now and in the future is essential for the long-term business of registered social landlords (RSLs).

Since tenants in the social rented sector also have a higher age profile – 45% aged 55 or over and 29% aged 65 or over (EHS, 2013) – it is important to consider the relative degrees of vulnerability of different tenants.

Given the specific sensitivities of the social housing sector outlined above, it is vital for social housing providers to adopt a standard of supplying energy efficient, comfortable and affordable dwellings now and in future climatic conditions, during both cooling and heating seasons.

2.8.1 Application of Passivhaus in social housing practice in the UK

Since the late 1980s, some 37,000 Passivhaus buildings have been constructed worldwide (Passivhaus Trust, nd). It is often referred to as a "comfort standard" as well as an energy efficiency standard, and the popularity of Passivhaus in Germany e including a 92% positivity rating by occupants has been largely due to a combination of social, political and financial circumstances which are specific to this nation (Dengel and Swainson, 2012).

Dwellings built to the Passivhaus Standards are a relatively new concept in the UK. The first certified Passivhaus dwelling, Y Foel a three bedrooms self-build house in Wales, was only completed in 2010 (Ridley et al., 2014). In the last few years, the number of UK Passivhaus certified buildings has grown rapidly, and as of January 2017, there were in excess of 500 certified buildings located throughout the UK, the majority of which were dwellings (Passivhaus Trust, n.d).

The adoption of the German Passivhaus standard in the UK as a template for providing low energy or zero carbon dwellings has increased significantly in recent years. Around 250 Passivhaus certified buildings were completed by 2013 and up to 1000 units are completed, on site, or in the planning phase (Bradshaw, 2013). According to the UK Passivhaus projects map (Passivhaus Trust, 2014), these projects are spread all over the UK and include some new social housing projects.

Wimbish and Sampson Close Passivhaus schemes are two examples of new social housing developments built to this standard (Passivhaus Trust, 2014). Touhy et al. (2011) investigated and monitored three dwellings, including the first Scottish Passivhaus, a Low Energy House (without MVHR), and a 1950s dwelling located in Dunoon, Scotland. Their results show that Passivhaus is a successful example of providing thermal comfort with a small amount of energy during the heating season. Bearing in mind that low income families and also vulnerable groups are the main occupants of social housing, the Passivhaus standard is likely to be able provide an affordable and comfortable building for them during the heating season. In addition to providing affordable comfort during the heating season it is also essential that dwellings constructed to the Passivhaus standards are able to deliver affordable comfort during the cooling season, given the particular vulnerability of many tenants.

2.8.2 Summer overheating risk in social housing dwellings built to Passivhaus standard

Questions regarding the performance in summer and the risk of overheating for some Passivhaus buildings located in different European climatic zones have been raised in a number of studies (McLeod et al., 2013; Mlecnik et al., 2012; Larsen et al., 2012; Derbez, 2014). In the UK, research studies focusing on summer temperatures and thermal comfort during the cooling season are fewer and more limited than those concerned with performance in the heating season (Lomas and Kane, 2013).

Although in recent years there has been an increase in the construction of Passivhaus in the UK, the first Passivhaus certified buildings were completed only in 2010. Consequently, post occupancy data for these dwellings are limited and minimal (McLeod et al., 2013).

A comprehensive review by Dengel and Swainson (2012) of the evidence of overheating in new UK homes indicates that there is a growing body of evidence that new energy efficient homes (i.e. well insulated, airtight dwellings) do suffer from overheating, and can in some cases result in adverse health effects for the occupants.

The important provisions which can help to avoid or reduce overheating are a proper layout which can minimise unnecessary solar gain, an adequate thermal mass, a good level of ventilation and reduced internal gains (CIBSE, 2006b). In order to identify the risk of overheating in dwellings built to the Passivhaus standard, the potential impact of such factors should be considered.

Roaf et al. (2009) argued that limited attention is paid to traditional means of reducing overheating, such as the inclusion of thermal mass and openable windows for natural ventilation in buildings constructed with the Passivhaus standard.

Urban areas and dense social housing, flats in particular, limit the opportunities for ventilating through windows (McLeod et al., 2013). In addition, in response to the arguments of the Royal Society for the Prevention of Accidents (RoSPA, 2002), the windows of new build social housing in the UK can open to an angle of only 10 degrees. This can limit opportunities for natural ventilation, notably in highly airtight dwellings.

The social housing sector not only has a higher proportion of dense, purpose-built flats, with more than two thirds of social renters having less than 70 m^2 usable floor space

(EHS, 2013) it also experiences high rates of overcrowding (EHS, 2013). Therefore, the impact of internal gains is likely to be higher than in other kinds of housing (McLeod et al., 2013). These risks are exacerbated when the implications of uncertain future climate conditions are considered (Jenkins et al., 2010).

2.9 Conclusion

This chapter has discussed key definitions, standards and guideline related to energy efficiency in buildings and in specific for the Passivhaus buildings. The studies related to energy efficient buildings have been reviewed and it was found out that overheating risk is a concern in such buildings and in particular for the Passivhaus. The thermal comfort concept and its effect of human's health was described in this Chapter. The effective factors in overheating risk was reviewed considering the Passivhaus concept for the UK. The importance of social housing in the UK and the demand for energy efficiency in this sector were discussed in details. Passivhaus is shown to be an increasingly popular building choice for the social housing market. However, there are some evidence that overheating risk may exist for such flats and this overheating risk increase in the future due to the effect of climate change. Overheating risk is also found to be more highlighted in this sector due to the higher proportion of vulnerable occupant. The literature review has shown lack of comprehensive investigation in evaluating the overheating risk for the UK social housing flats built to the Passivhaus standard. Therefore, the aim of this study is to investigate the risk of overheating in such flats across the UK under current and uncertain future climates. The next chapter will present the methodology for this research project.

Chapter 3: Methodology for overheating investigation

3.1 Introduction

This chapter presents the methodology for the research. The literature review on the Passivhaus standard shows the gap of knowledge in understanding the performance of Passivhaus flats in the UK climatic context and social housing sector, especially considering the uncertain future climate condition. Hence, this chapter sets out a robust methodology for evaluating the overheating risk in the UK social housing flats built to the Passivhaus standard under current and uncertain future climates. In the first stage, the underlying approaches and the overheating assessments benchmarks used in the evaluation of the overheating risk are explained. Secondly, the procedure for conducting the case study to explore the overheating risk in recently built Passivhaus flats in the UK social housing sector is explained. Finally, the procedure for generating Base Models for simulation purposes which represent such flats in different UK locations has been established. Various climate, design and occupant behaviour factors have been considered in this study to investigate the overheating risk by simulating ranges of modelling scenarios. Details of weather files, study locations and the factors and assumptions related to the modelling characteristics, as well as the method to explore the current and future overheating risks, are defined and described.

3.2 Overview of the methodology

Research is effectively a systematic process of collecting, analysing and interpreting information to support deeper understanding of a specific phenomenon of interest (Leedy and Ormrod, 2010). In the Built Environment, research is mainly carried out based on qualitative, quantitative or mixed methods (Amaratunga et al., 2002).

The overheating analysis in this study relies on quantitative data relating to the indoor environmental condition of the building, specifically indoor temperature. The evaluation of overheating in buildings is complex due to the influence of several design and occupant behaviour factors. True limits of discomfort (duration, severity and their relationship) are not yet known, especially in dwellings (CIBSE, 2013). Also the detailed investigation of design and occupant behaviour parameters creates significant complexity that requires pairwise models to ease the analysis and discovery of effective design and occupant behaviour factors that are difficult to establish in reality, and only simulation studies can provide pairwise models .Thermal comfort research tends to focus on field studies (de Dear et al., 2013) since the simulation process used to predict indoor temperature requires careful approach (Nicol et al., 2012). Therefore, this study adopts a balanced approach by performing overheating assessment using both case study and building modelling and simulation.

Case study

The case study approach can be justified for several reasons. Saunders et al. (2009) describes the case study as the main tool to comprehend, study and justify a subject under examination. Case studies help in ascertaining a clear understanding of the research context and the necessary processes to be explored in the current study (Saunders et al., 2009). Research based upon well-planned and executed case studies can lead to good quality results to challenge the existing literature and theories (Saunders et al., 2009).

This research utilises a case study approach to collect data relating to the performance of the existing flats. Using the case study approach for building performance analysis enables the researcher to use different data collection methods such as monitoring of indoor conditions, mapping of occupancy patterns, and the development of an accurate profile of building occupants and related information from the occupants.

Modelling and Simulation

Modelling is another form of empirical research. Modelling can be used in the process of constructing a model 'representing a designed or actual object, process or system as a representation of reality' (Fellows and Liu, 2015). The model should provide a good representation of the real object (in this case buildings) and the way the object is used.

There are a great many environmental factors that can directly affect internal thermal conditions within a dwelling; these can include the building geometry, the surrounding structures and orientation of the building, together with the building fabric, plus solar gains and radiation, air tightness and internal heat gains (CIBSE, 2006). In order to study the complex and multi-faceted factors affecting the performance of buildings, Building Performance Simulation (BPS) tools can aid with comprehensive and integrated appraisal of climate, design and occupant behaviour factors.

BPS aid designers, engineers and decision makers to understand the expected performance of the buildings in relation to factors such as energy consumption, carbon emission, and internal temperature (Maile et al., 2007). BPS tools also enable the evaluation of different design alternatives and predict their effects in a single project.

According to Crawley et al. (2008), BPS tools have been in use for over 50 years and they have become an essential and integral tool during the design of buildings in many developed countries (Nadarajan and Kirubakaran, 2016).

In order to carry out predictive analysis of building characteristics and systems, and the impact factors that these have on energy and environmental performance of buildings, there is an extensive range of building and system modelling software tools available for usage by both industry professionals and academics.

According to Attia et al. (2012a), around 400 BPS tools are available; however, only a limited number of them are industry standard software and independently validated. These programs contain features that are unique in terms of modelling resolutions and options, combined with solution algorithms, intended target audiences and variations in flexibility versus ease of use. BPS tools have been reviewed and compared in number of studies to understand the feasibility and appropriateness of them (Maile et al., 2007; Crawley et al., 2008; Weytjens et al., 2011; Attia and De Herde, 2011; Attia et al., 2012a; Attia et al., 2012b).

The Integrated Environmental Solution-Virtual Environment [IES-VE] (IES, 2016) software is adopted for the dynamic simulations in this study.

IES-VE software, which was developed in the early 1990s, offers a Common User Interface (CUI) plus a single Integrated Data Model (IDM) that are linked via an integrated suite of applications. This offers a consistent "look and feel" across all the applications, and compatibility of data input across all the applications. The software, which is specifically designed to analyse integrated building performance in multiple domains, and also incorporates a modular structure (i.e. thermal, airflow and daylight) (Attia et al., 2012b).

The IES-VE dynamic simulation software is now used widely, both in the UK and internationally. It has an extensive history of validation, being documented in the CIBSE Applications Manual AM 11 and the Appendix B protocol (CIBSE, 1998) by McLean in 2006 (IES, 2009). Furthermore, Crawley et al. (2008) have described the IES-VE software as having undergone rigorous validation studies in addition to other software, for example, EnergyPlus, ESP-r, ICE, and TRNSY, providing a robust and critical comparison of their features and capabilities. The software also performed well in an independent Building Energy Simulation Test (BESTEST) (Judkoff and Neymark, 1995) and has been subject to extensive empirical testing by Bloomfield (1994) and Gough and Rees (2004), as part of a benchmarking assessment that was carried out by BRE.

As a result, IES-VE has been categorized as one of the building simulation softwares with the most powerful modelling capabilities (Crawley et al., 2008). IES-VE also allows for maximum flexibility in terms of the ability to model unique building design and profiling of human behaviour factors within the simulation models.

3.3 Overheating assessment methodology

This section presents the applied methods used in this study to evaluate the risk of overheating. It also provides an overview of the fixed and adaptive models followed by describing benchmarks and their related compliances criteria which are developed based on the two fixed and adaptive models.

3.3.1 Adaptive VS Fixed thermal comfort model:

According to Nicol and Stevenson (2013), various factors should be considered in relation to comfort, however, thermal comfort and climate adaptation studies currently coincide in one key area: overheating. The Chartered Institution of Building Services Engineers states that it is vital to know the limits beyond which a building will overheat (CIBSE, 2006b). Generally, overheating is a very subjective topic, because the definitions of 'hot' and 'too hot' vary from person to person and depend upon a variety of factors. Whilst it is not possible to come up with a single solution to satisfy all occupants, there should be a standard that prevents the worst levels of overheating and enables designers to find cost effective options to limit overheating risks and also deliver all the other aspects of occupant comfort and requirements (e.g. daylight, insulation, view etc.) (CIBSE, 2013).

As discussed in Chapter Two, the adaptive thermal comfort approach, which was developed in response to the limitation of the steady state models implies, that a fixed maximum temperature (i.e. fixed thermal comfort benchmark) is not appropriate for all climates and that, to achieve thermal comfort, the target indoor temperature should reflect the outdoor temperature variations at the time (Nicol et al., 2012).

The adaptive thermal comfort approach is the main methodology for overheating assessment in the new edition of CIBSE Guide A (CIBSE, 2015), after the recommendation of this strategy was recommended in CIBSE TM52 (CIBSE, 2013). The adaptive approach stipulated in these guidelines is based on the criteria specified in the European Standard EN 15251 (2007). The comfort temperature (T_c) in summer within this approach is calculated from Equation 1:

$$T_c\ (^{\circ}C) = 0.33T_{rm} + 18.8 \qquad \textbf{(Equation 1)}$$

where T_{rm} is the running mean of the outdoor temperature which is calculated from Equation 2.

$$T_{rm}\ (^{\circ}C) = (T_{od\,-1} + 0.8\ T_{od\,-2} + 0.6\ T_{od\,-3} + 0.5\ T_{od\,-4} + 0.4\ T_{od\,-5} + 0.3\ T_{od\,-6} + 0.2\ T_{od\,-7})/3.8 \qquad \textbf{(Equation 2)}$$

where $T_{od\,-1}$ is the daily mean external temperature for the previous day and $T_{od\,-2}$ represents the daily mean external temperature for the day before and so on.

EN 15251 (2007) defines the risk of building overheating as relating to the comfort temperature as well as the type of building and occupants. Hence, the standard sets a maximum acceptable temperature (T_{max}) for each building category (Equation 3).

$$T_{max}\ (^{\circ}C) = T_c + \text{Acceptable range} \qquad \textbf{(Equation 3)}$$

Where the acceptable range is 2, 3 and 4K for building Category I, II and II, respectively.

Table 3.1 shows the building categories and applicability of the categories with their associated acceptable temperature range.

Table 3.1 Suggested applicability of the building categories and their associated acceptable temperature range for free-running building. Source (EN 15251, 2007)

Category	Explanation	Suggested acceptable range (K)
I	High level of expectation (only used for spaces occupied by very sensitive and fragile persons)	2
II	Normal expectation (for new buildings and renovations)	3
III	A moderate expectation (used for existing buildings)	4

3.3.2 Compliance criteria for overheating assessment

This section provides an overview of the benchmarks and their related compliances criteria for the overheating benchmarks that have been used in this study.

Passivhaus benchmark: The Passivhaus standard uses a fixed threshold temperature which remains the same irrespective of the external conditions and occupants' vulnerabilities to evaluate the risk of overheating. The Passivhaus standard states that it is not acceptable for living areas to exceed an operative temperature of 25°C for more than 10% of the total occupied hours (Fiest et al., 2012). However, given the climate change predictions, the BRE Passivhaus designer's guide (Mcleod et al, 2011) recommends achieving 5% overheating frequency or less under current conditions.

CIBSE TM52 Benchmark: CIBSE TM52 (CIBSE, 2013) provides a standardised approach for overheating assessments in European buildings. According to CIBSE TM52 (CIBSE, 2013), homes that are predominantly naturally ventilated, including homes that have mechanical ventilation with heat recovery (MVHR), and good opportunities for natural ventilation in the summer should assess overheating using the adaptive method proposed in CIBSE TM52 (CIBSE, 2013). Hence, an adaptive thermal comfort model is also used in this study to investigate the overheating risk in UK social housing flats built to the Passivhaus standard based on the fact that windows are the primary measure for occupant's control of thermal conditions. The bypass mode of the MVHR system, which may be used in Passivhaus buildings during the summer, provides unconditioned ventilation.

CIBSE TM 52 (CIBSE, 2013) suggests three Criteria for evaluating the overheating risk in European buildings. The criteria are all demonstrated in terms of ΔT, the difference between the actual operative temperature (T_{op}) in the room and the maximum acceptable temperature (T_{max}) in a free running mode. ΔT is calculated as:

$$\Delta T = T_{op} - T_{max} \qquad \text{(Equation 4)}$$

It is notable that ΔT is rounded to the nearest whole degree.

Criterion 1: Hours of exceedance (H_e)

The first criterion sets a 3% limit for the number of hours (H_e) that ΔT is 1°C or more during the occupied hours of a typical non-heating season (May to September).

According to CIBSE TM 52 (CIBSE, 2013), if data is not available for all of the cooling season (or if occupancy or monitoring applies only to part of the period) then 3% of the available hours should be used as a limit.

Criterion 2: Daily weighted exceedance (W_e)

The second criterion deals with the severity of overheating within any one day, which can be as important as its frequency. The severity of overheating that occurs in one day is a function of the sudden temperature rise and its duration. This criterion sets a daily limit of overheating which it states is acceptable during a single day.

The daily limit set for weighted exceedance (W_e) shall be less than or equal to 6 in any one day to allow for the severity of the overheating. The equation used to calculate weighted exceedance (W_e) is as follows:

$$W_e \text{ (Degree. Hour)} = (\sum h_e) \times W_F = (h_{e0} \times 0) + (h_{e1} \times 1) + (h_{e2} \times 2) + (h_{e3} \times 3) \qquad \text{(Equation 5)}$$

Where the weighting factor WF = 0 if ΔT <0, otherwise WF = ΔT, and h_{ey}, {y = 0, 1, 2,..., n} is the time (in hours) when WF = y.

Criterion 3: Upper limit temperature (T_{up})
The absolute maximum daily temperature for a room is set by the third criterion. Temperatures which exceed the absolute maximum temperature are deemed unacceptable. The absolute maximum value of indoor operative temperature is set as the value of ΔT should not exceed 4°C. In CIBSE TM 52 (CIBSE, 2013) standard, the absolute maximum temperature is the temperature for which adaptive actions are inadequate and cannot restore occupant comfort. Therefore, at no time during the assessment period should ΔT exceed 4°C.

According to CIBSE TM52 (CIBSE, 2013) guideline, a room is classified as an overheated space if it failed in any two of the three criteria.

CIBSE TM59 Benchmark: CIBSE TM59 (CIBSE, 2017) provides a standardised approach for overheating risk assessment in a residential building.
According to CIBSE TM59 method a flat will pass the overheating assessment if the following two criteria are met:

(a) 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 per cent of occupied hours. (CIBSE TM52 Criterion 1: Hours of exceedance).

(b) For bedrooms only: to guarantee comfort during the sleeping hours the operative temperature in the bedroom from 10 pm to 7 am shall not exceed 26 °C for more than 1% of annual hours.

In CIBSE TM59 (CIBSE, 2017) method Criteria 2 and 3 described for CIBSE TM52 benchmark may fail and still the flat could pass overheating assessment if both criteria (a) and (b) are passed for all relevant rooms.

Operative temperature calculations (used within CIBSE TM52 (CIBSE, 2013)) require assumptions on air speed. According to CIBSE TM59 (CIBSE, 2017), the modelled air speed in any space must be set at 0.1 m/s. The same consideration has been adopted for development of the simulation scenarios in this study.

The methodology derived by CIBSE TM 59 (CIBSE, 2017) suggests that for vulnerable occupant accommodation, which is predominantly naturally ventilated, criteria (a) and (b) above should be used with the assumption of building category I as described in Table 3.1. Therefore, for this study and considering the high level of vulnerable occupants living in Social housing flats in the UK, overheating investigations are carried out for both categories I and II. A summary of the compliances criteria is provided in Table 3.2.

Table 3.2 Overheating compliances criteria

Standard	Overheating compliances criteria
CIBSE Guide A and TM 52	Criterion 1-3 of adaptive thermal comfort method need to be assessed. A room is classified as overheated space if any two of the three criteria fail.
CIBSE TM 59	For all living areas criterion 1 of the adaptive thermal comfort method must be met. For bedrooms only, the operative temperature from 10 pm to 7 am shall not exceed 26 °C for more than 1% of annual hours.
Passivhaus standard	No more than 10% of the total occupied hours with temperature over 25^{0}C.

In this study, the overheating assessment for the monitored case study data uses compliance criteria in TM52 and Passivhaus as TM59 was not published at the time. However, TM59 used for further assessment of overheating in the simulation study in Chapter Five.

3.4 Overheating investigation in current UK social housing flats built to the Passivhaus standard

This section will present the methodology adopted to perform a case study on the overheating assessment in UK social housing flats built to the Passivhaus standard. The case study development is located in the Sampson Close, Coventry, West Midlands, UK.

This development comprises 23 social housing units built to Passivhaus standards. The development has 18 flats and 5 houses constructed by Orbit Heart of England Housing Association (OHE) Figure 3.1.

Figure 3.1 Sampson Close development by Orbit

3.4.1 Indoor temperature and occupancy pattern

Orbit Housing undertook a systematic monitoring programme of Sampson Close where four indoor environmental parameters (i.e. indoor temperature, humidity, CO_2, volatile organic compounds) were monitored in 23 dwellings. The analysis in this study is based on an evaluation of the flats' indoor air temperature. Given the thermally lightweight nature of these Passivhaus dwellings, the air temperature is likely to be a reasonable proxy for operative temperature. In some cases, there is a significant amount of missing data for various reasons, which makes the detailed overheating analysis of some flats impossible. Therefore, the flats included in this analysis were selected based on the availability and quality of monitored data. Table 3.3 shows the number of flats selected and monitoring period for each year between 2011 to 2013.

In this study, the analysis focuses on the overheating in the living rooms of these flats. The selection of living rooms for analysis is due to the daytime use of the space and the higher likelihood of overheating during the day when both temperature and solar radiation are at their peak. Living rooms also have the highest potential for internal gains during the day and the largest south facing aperture.

Table 3.3 Summary of the monitoring information

Monitoring period	Year	Period of monitoring	Number of monitored days	Number of monitored flats
A	2011	17 Aug – 30 Sep	45	11
B	2012	3 Jul – 5 Aug	34	9
C	2013	1 May – 30 Aug	122	5

The occupants of all selected flats were surveyed by OHE about their occupancy pattern. The responses from the occupants reveal the majority of the flats are occupied all day. Therefore, for the purpose of this study, due to the high likelihood of living rooms being occupied during the day and considering the occupancy pattern of livings rooms used in similar studies (Lomas and Kane, 2013; Gupta and Gregg, 2013), an occupancy pattern of 8.00-23.00 was used to evaluate the overheating risk in the selected living rooms. Hence, based on the assumed occupied hours and the number of monitoring days (Table 3.3), the total numbers of occupied hours monitored for each flat were 657, 510 and 1830 in 2011, 2012 and 2013 respectively.

3.4.2 Outdoor temperature and solar irradiation

Outdoor temperatures and solar irradiation information were taken from the local weather station (Coventry Coundon weather station which is about 3 miles away from the study site) (MetOffice, 2014).

3.4.3 Overheating assessment procedures

The data collected from case study flats were analysed for overheating assessment based on both the Passivhaus standard and adaptive thermal comfort (CIBSE TM52) benchmarks. The living room temperature recorded during each day of the data collection period was studied in accordance to the Passivhaus standard to understand the occurrence of indoor temperature exceeding a set temperature threshold of 25 degrees. The overall annual occurrence of overheating percentage based on the monitoring time is calculated and compared to the benchmark criteria.

The case study data were also analysed based on adaptive thermal comfort benchmarks in CIBSE TM52 (CIBSE, 2013). The outside temperature obtained from local weather station is adopted to calculate the daily T_{rm}, T_c and T_{max} (Eq. 1 – 3) for both building categories (I and II). Following determination of T_{max} and hourly indoor temperature, the three criteria of hours of exceedance (H_e), daily weighted exceedance (W_e) and the upper limit temperature (T_{up}) was determined for all monitored flats. The value determined for each criterion was assessed based on the limit stipulated within CIBSE TM52 (CIBSE, 2013) and if two of the assessed criteria failed, the flat was considered to be overheated.

Furthermore, to understand the effect of external environmental factors (outside temperature and solar irritation) on indoor temperature variations and overheating experienced, statistical analyses were carried out for each flat using the available internal and external recorded temperature and site solar irradiation. Also, other statistical analyses were conducted to explore the difference in significance of frequency and severity of overheating experienced by both occupant types.

3.5 Overheating investigation in the new social housing flats built to the Passivhaus standard

This section will describe the detailed method for overheating investigations of new social housing flats built to the Passivhaus standard with respect to the UK wide climate, design and occupant behaviour factors as well as uncertain future climate scenarios.

The literature review on the Passivhaus show the gap of knowledge in understanding the performance of such buildings in the UK climatic context and social housing characteristics, especially considering the future possible scenarios of global warming and climate change. Various climate, design and occupant factors have been considered in this study to investigate and assess the performance of UK social housing flats built to the Passivhaus standard through the use of scenario modelling and simulations.

To appraise the overheating risk associated with social housing flats built to the Passivhaus standard, Base Models have been modelled and simulated in typical archetypal locations. The overheating assessment is then carried out based on different level of occupant vulnerabilities and assessment benchmarks described in Section 3.3. The simulations also aim to investigate and explain the effective design and occupant behaviour factors on overheating risk in all studied locations.

3.5.1 Building simulation Process and generating reliable Base Models

Dynamic simulation using the IES-VE software is based on first principles of mathematical modelling of heat transfer processes in and around the building (Harish and Kumar, 2016). The input parameters required in IES-VE are:

1: Environmental conditions, including the location and climate data;

2: Building design factors (e.g. building geometry, building envelop properties, mechanical system and orientation);

3: Building operational factors (e.g. occupancy profile and internal gains).

The process of selecting the study locations and appropriate climate conditions are described in this section. All the parameters related to the building design factors, as well as mechanical systems, are selected and modelled based on the requirements and characteristics of the Passivhaus standard and UK social housing flats. The case study block used as the starting point for developing the appropriate Base Models and the necessary changes have been applied in order to present reliable samples of UK social housing flats built to the Passivhaus standard for the purpose of the overheating investigation in each study location. Operation parameters are then modelled based on CIBSE TM59 (CIBSE, 2017) as the standard methodology for overheating assessment in UK homes. Details of all the assumptions and standard values used for the modelling and simulations are described in Chapter Five.

To provide confidence in the modelling and simulation procedure, and the output of the computer modelling procedure used in this study, a block of social housing flats built to the Passivhaus standard in Coventry (used as case study for overheating assessment) were first modelled and the computed performance was compared and validated against collection of real data. The aim of the validation was specifically to make sure that the temperature predicted by the software was in-line with real life temperature recorded in the case study.

Error between the predicted and the recorded values over a set period of time is inevitable if actual weather data from the same period is not used in the simulation weather file. Birmingham's simulation weather file, as the closest match to the location of actual block, was therefore used as a baseline. Then, the weather file was modified manually using the recorded data for the duration of monitoring. Hence, an actual weather file based upon site data was adopted for the validation purpose.

The validation procedure was performed for all five flats which were monitored during the case study monitoring in Coventry in summer 2013, as the maximum monitoring data available for this cooling season. Chapter Five will discuss the validation procedure and simulation results in detail.

3.5.2 Climate condition for simulations

According to CIBSE guide A (CIBSE, 2015), the time scale for expected significant climate change is comparable with the life span of the new buildings in the UK. Therefore, it is generally accepted that future weather data should be used in building design as well as present day climate.

Dynamic building simulation tools are typically used with an associated weather data file for the specific location and period to study the building performance (Guan, 2009). Weather files specifically represent the climate of the selected location and normally include variables such as dry bulb and wet bulb air temperatures, relative humidity, solar radiation, wind speed, wind direction and cloud cover etc. for each hour of the year.

Present day weather files are readily available through the web from different sources, such as the US Department of Energy EEER website, or can be generated using weather generation tools such as Meteonorm (Jentsch et al., 2010). Future weather data, on the other hand, is not available normally for direct download from the web and has to be generated (Cox et al., 2015). According to Guan (2009), there are four different approaches to generating future weather data. These are known as the "extrapolating statistical method (degree-day method), the imposed offset method, the stochastic weather model and global climate models" (Guan, 2009). Many of the mentioned methods have been implemented in a number of studies to generate future weather files for specific contexts (Jentsch et al., 2008; Ebrahimpour and Maerefat, 2010; Haase et al., 2010; Zang et al., 2013; Cox et al., 2015).

Future weather files have been developed in the UK by a number of organisations and research groups. The Built Environment Weather scenarios for investigation of Impacts and eXTremes (BETWIXT) project undertaken by the Climate Research Unit (CRU) at the University of East Anglia in 2006 included the climate change impact on a number of weather parameters, such as temperature, precipitation and humidity, in addition to other parameters (CRU, 2006). As a result of this project, climate change weather file sets for a number of locations in the UK have been produced. The Sustainable Energy Research Group (SERG) at the University of Southampton has also produced future weather files for the UK by developing a Microsoft Excel-based weather generator tool. The weather generator operates by uploading standard current weather files approved by CIBSE to generate the future weather files through a morphing process. Additionally, a world weather generator was created by SERG which produces weather files for any location around the world, (Jentsch et al., 2008; SERG, 2015).

The simulation models in this study have been set up based on detailed climate condition for all locations and scenarios. In The UK, for the purpose of building simulation, standard CIBSE Weather files based on hourly weather data have been derived based on historic recorded weather for 14 locations across the UK. The geographical information and period of derived data about these locations are presented in Table 3.4.

Table 3.4 Station details for the UK 14 locations which the weather data is available for building simulation tools (CIBSE, 2015)

City	Met Station	Period	Alt. (m)	Lat. (^{0}N)	Long. (^{0}E)
Belfast	Aldergrove	1981–Sep 2012	63	54.66	-6.224
Birmingham	Elmdon	1981–1997	96	52.45	-1.741
	Coleshill	1998–Sep 2012	96	52.48	-1.689
Cardiff	Rhoose	1981–1997	65	51.40	-3.343
	St Athan	1998–Sep 2012	49	51.40	-3.445
Edinburgh	Turnhouse	1981–1998	35	55.95	-3.347
	Gogarbank	1999–Sep 2012	57	55.93	-3.343
Glasgow	Abbotsinch	1981–Apr 1999	5	55.87	-4.429
	Bishopton	May 1999–Sep 2012	59	55.91	-4.531
Leeds	Church Fenton	1986–Sep 2012	8	53.84	-1.197
London	Heathrow	1981–Sep 2012	25	51.48	-0.449
Manchester	Ringway	1981–2003	69	53.36	-2.279
	Woodford	2004–Apr 2012	88	53.34	-2.153
Newcastle	Newcastle WC	1983–Feb 2003	52	54.98	-1.597
	Albermarle	Mar 2003–Sep 2012	142	55.02	-1.880
Norwich	Marham	1981–Sep 2012	21	52.65	0.568
Nottingham	Watnall	1981–Sep 2012	117	53.00	-1.250
Plymouth	Mountbatten	1981–Sep 2012	50	50.35	-4.120
Southampton	Hurn	1981–Sep 2012	10	50.78	-1.835
Swindon	Brize Norton	1981–Sep 2012	82	51.76	-1.576

According to CIBSE Guide A (CIBSE, 2015), two types of weather file are recommended and available for climate input of building simulation software as follow:

i) **Test reference year (TRY)**

ii) **Design Summer year (DSY)**

Both of these two weather file types have been derived and available for all 14 locations described in table 3.4.

The Test Reference Year, known as TRY, comprises 12 separate months of data that incorporate data from the most average month. The use of the TRY weather file is considered to be the standardized approach for energy analysis, and in compliance with UK Building Regulations (Part L).

In addition, The Design Summer Year (DSY) is a standard weather file used in the assessment of overheating. These files represent a single continuous year as opposed to the composite option that is made up of data collated across average months

The DSYs weather files are slightly more complex. The return period of a hot event refers to the frequency of the event with an associated exceedance value. The DSY methodology originally considered the third hottest summer from a base period lasting 21 years. This gives rise to an assumption that implies there is no underlying trend within the current climate to suggest that any given future summer has a 1-in-7 chance of being equal or hotter than the selected design summer year (Jentsch et al. 2013) or that such a summer will repeat every 7 years.

An analysis of the baseline dataset for the historical years 1984 to 2013 allows for ranking by return periods and heat events per overheating metric. In accordance with CIBSE TM49 (CIBSE, 2014) and the probabilistic design summer years, it is possible to define overheating events that demonstrate three characteristics, and then used to select new candidate years.

The most recent DSY files form the basis of a new methodology, as follows:

Representing a moderate year, DSY 1 has a return period of 7 years (i.e., a 1-in-7-year chance of occurring) per the Static Weighted Cooling Degree Hour (SWCDH) metric ranking.

DSY 2 and DSY 3 represent warmer summer conditions, and were selected according to their dependence on the duration and intensity of the warm events within the selected year. DSY 2 represents a summer where the warmest event is the same duration as the year chosen for DSY 1, but more intense event.

DSY 3 represents a year where the duration of the warmest event is much longer in duration than both DSY 2 and DSY 3, but less intense than DSY 2 and more intense than DSY 3.

The compilation of these new DSY files aimed to improve the detailed description of hot events, together with their relative severity and expected frequency. To summarise, three DSYs are now available per location, which serve to represent summers with different hot event types:

- DSY1: Moderately warm summer
- DSY2: Short, intense warm spell
- DSY3: Long, less intense warm spell

Previous projections of the UK climate have been superseded by the UKCP09 climate projections which are based on the Met Office Hadley Centre HadCM3 model (CIBSE, 2015).

The key characteristic of the UKCP09 climate projections is their probabilistic approach to the calculation of changes in climate variables. Uncertainty in climate projections is due to natural variability, incomplete understanding of the climate system and its imperfect representation in models (Murphy et al., 2009).

Modelling uncertainty has been addressed in the UKCP09 projections by generating probability density functions (pdfs) of the key climate variables from a large ensemble of variants of the Met Office Hadley Centre global model, together with an ensemble of twelve international global models. Details of the methodology used in the production of the projections are available in the UKCP09 Science Report: Climate change projections (Murphy et al., 2009).

The probabilistic projections were produced on a 25 km grid for three of the Intergovernmental Panel on Climate Change (IPCC) emissions scenarios (high, medium and low) and are relative to the baseline period of 1961 – 1990. These scenarios represent different pathways for economic and social change and cannot be assigned relative probabilities. The robustness of the projections decreases towards both the high and low tails of the distribution, so it is recommended that values of change factors for the climate variables outside the probability range 10% (i.e. very unlikely to be less than) to 90% (i.e. very unlikely to be more than) be used only with caution.

The climate variables available directly from the UKCP09 projections are temperature, precipitation, humidity, cloud cover, net surface short and long wave flux, total downward short wave flux and mean sea level pressure and all changes refer to the baseline (control) period of 1961 – 1990.

A useful way of displaying the future scenario temperatures are as in Figure 3.2, which shows the probabilistic climate profile (ProCliP) graph for London.

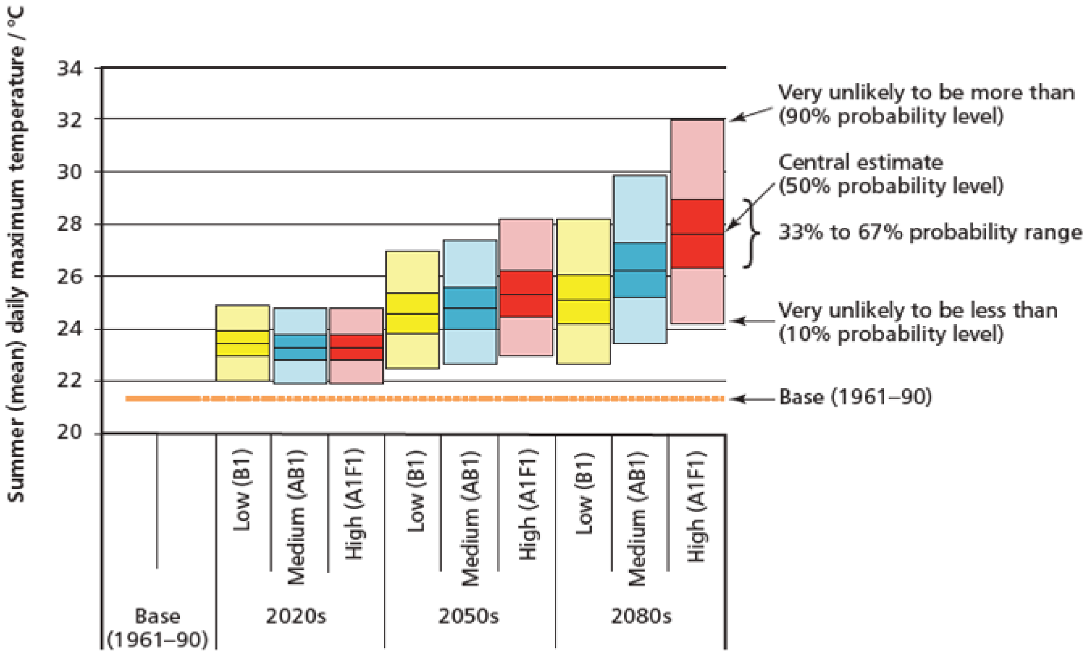


Figure 3.2 Probabilistic climate profile (ProCliP): London summer (Jun, Jul, Aug) mean daily maximum temperature Source (Shmash et al.,2012)

For each of the 14 locations in which TRY and DSYs file are available for building simulation, weather files are also available in three time periods by incorporating the UKCIP09 climate change scenarios (2020s (2011-2040), 2050s (2041-2070) and 2080s (2071-2100)). The available future weather files are as follows:

- 2020s – High emissions scenario – 10th, 50th, 90th percentile,
- 2050s – Medium – 10th, 50th, 90th,
- 2050s – High – 10th, 50th, 90th,
- 2080s – Low, 10th, 50th, 90th,
- 2080s – Medium – 10th, 50th, 90th,
- 2080s – High – 10th, 50th, 90th.

Probabilistic climate profiles (ProCliPs) is a user-friendly format as follows:

“Time period, Emission Scenario, Probability level”

According to CIBSE TM59 (CIBSE, 2017), for the purpose of overheating assessment, the latest CIBSE design summer year (DSY) weather files (for the nearest point to the building location) must be used for the moderately warm summer (DSY1) "*2020s, high emissions, 50% percentile*" scenario. Other weather files which cover more extreme scenarios (DSY2, DSY3) are recommended for further tests during the test design phase; however, CIBSE TM59 did not mandate this further assessment as a compulsory requirement.

In order to investigate the future performance of UK social housing flats built to the Passivhaus standard, the recommended weather file according to CIBSE TM59 (CIBSE, 2017) was used for overheating assessment of all scenarios (DSY1). Other weather files (DSY2 and DSY3) are also used for all Base Models to investigate the future overheating risk for both normal and vulnerable occupants.

3.5.3 Selection of archetypical location across the UK

Figure 3.3 shows the average temperature experienced across the UK during the summer months between 1981-2010. As it can be seen, comparison of the mean average temperature indicates up to 8 °C difference between various locations. Hence, any study with the focus of overheating risk in the UK built environment, should take into account the wide range of UK climate and summer temperature variations by considering representative locations which could present the different climates.

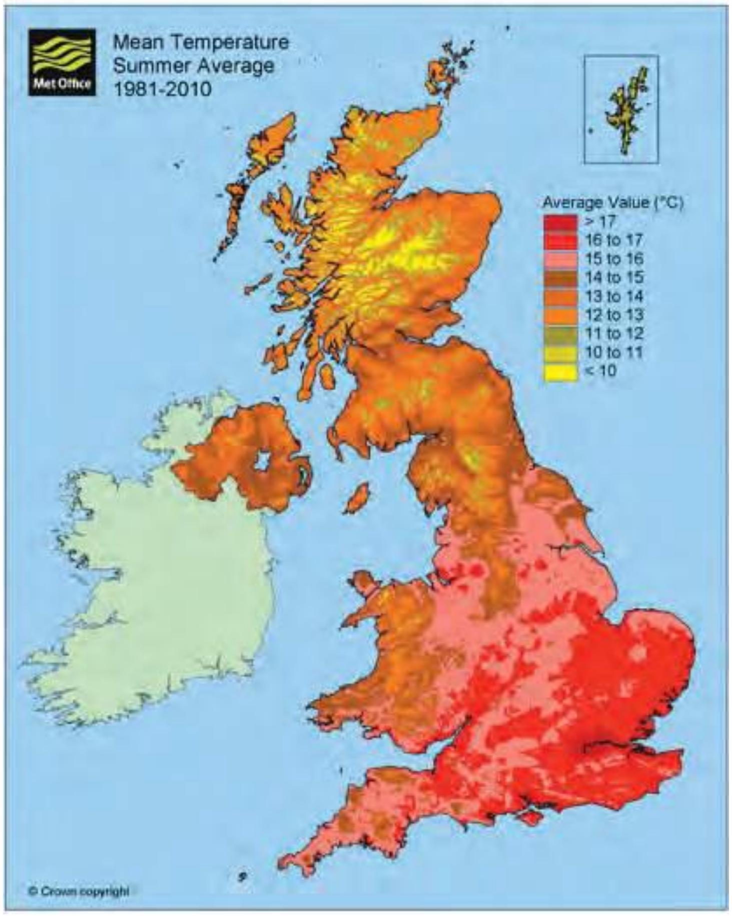


Figure 3.3 Average mean temperature in summer months between 1981-2010 (Met. Office, Crown copyright)

As mentioned in section 3.5.2, there are 14 separate geographical locations within the UK, where the weather climate condition files are available for building simulation. Therefore, the selected locations for this study should be among these sites. It has been also argued that various weather files are available for each location. However, since the specified weather file (*DSY1, 2020s, high emissions, 50% percentile*) is the recommended weather condition for overheating assessment by CIBSE TM59 (CIBSE, 2017), climate conditions within these 14 locations are compared using these specific weather files and by calculating the cumulative frequency of occurrence of external temperature.

Hence, based on the analysis of DSY1 weather files (details in chapter 5), and in order to consider a wide range of latitude as well as climate conditions within the UK, in this study four different site locations including London Heathrow, Birmingham, Manchester and Edinburgh have been selected for the simulation and further studies.

3.5.4 Overheating investigation

This section describes the approach that has been used in this study to explore the current and future risk of overheating in the selected location, as well as effective parameters.

3.5.4.1 Identifying the flat with higher risk of overheating

In the first stage, in order to identify the flat with a higher risk of overheating within the Base Model blocks, Base Models in selected locations are simulated and the internal predicted temperature of the living rooms are compared with each other. The flat with higher potential of developing the risk of overheating is then selected to investigate the risk of overheating under current and future conditions.

3.5.4.2 Parametric study to investigate the impact of design and occupant behaviour parameters in overheating risk

Various design and occupant behaviour parameters affect the thermal performance of dwellings. A number of studies have performed parametric investigations to measure the importance of various factors on the performance of buildings by testing the impact of the parametric variations within the built environment on a number of areas, such as energy use, thermal comfort, peak loads and economical payback (Fallahtafti and Mahdavinejad, 2015; Alaidroos and Krarti, 2015; Croitoru et al., 2016). Parametric study has also been used in number of studies focused on thermal performance of Passivhaus buildings which are described in Chapter Two.

For the purpose of this study and to investigate the affective factors on overheating risk in UK social housing flats built to the Passivhaus Standard, a parametric study has been carried out, using a Base Model and by changing one design or occupant behaviour factor at each time.

Following the analysis of recommended UK weather files for overheating assessment (available in 14 locations) described in section 3.5.2 (details in chapter 5), Birmingham as a location which offers a relatively average climatic condition amongst available UK locations, was selected for the site location in the parametric study

The parametric study was performed for both design and occupant behaviour factors. Six design parameters and five occupant behaviour factors were selected for the analysis. The selected parameters and the range for each of these selected parameters are discussed in detail in Chapter Five.

3.5.4.3 Scenario modelling and overheating investigation

The scenario modelling is developed based on the combination of the affective parameters on overheating of Passivhaus flats, found in the literature review and according to the parametric investigation performed in this study. The various scenarios modelling will provide a range of possible options in terms of design of social housing flats built to the Passivhaus standard. Also, a separate scenario modelling was conducted with regards to the range of occupant behaviour factors, to study the effect of various occupant behaviours on the overheating risks in Passivhaus flats.

In order to have a comprehensive overview of overheating assessment, all scenarios were developed and evaluated for all the locations investigated in this study. In total, 32 scenarios for design and 32 scenarios for occupant behaviour as well the base model were developed and assessed for each study location. The details of scenarios will be presented in Chapter Five.

According to Nicol et al., (2012), one of the main aspects which makes the evaluation of overheating and various parameters a complex issue, is the need to have pairwise models to study and discover affective factors, unlikely to be found in reality.

The scenarios modelling performed in this study not only provide a comprehensive overview of overheating risks considering various design options and occupant behaviour models in each location, but also provide a number of pairwise models for each selected parameter. In order to understand the relative importance of each factor in various UK locations, statistical analysis (T-test) was carried out among the risk of overheating (calculated based on both Passivhaus and adaptive criteria) for pairwise models attained from scenario modelling.

3.5.4.4 Future overheating investigation

To study the feasibility of Passivhaus standard for UK social housing flats in terms of the overheating risk, the future performance of these buildings needs to be investigated in order to have a realistic understanding of whole-life assessment. Understanding the future performance of Passivhaus is critical due to high risk of overheating in the future (discussed in Chapter Two). Also, UK statistics show that in social housing flats, a high percentage of occupants are classed as vulnerable people, which require careful assessment of overheating risk in such flats. Furthermore, as the majority of the houses which are built now will remain in use in the future decades, it is important to understand how the current development will perform in the future given the evidence of climate change and its impact on building performance as well as occupant health. The future overheating investigation in this study has been conducted in two stages as follow:

1: Future overheating investigation considering various predicted summer conditions

According to CIBSE TM59 (CIBSE, 2017), DSY1 weather file (Moderately warm summer) must be used as a minimum requirement to pass the stipulated compliances criteria for overheating assessment in a new residential building. However, simulations with other weather files (DSY2 and DSY3) with more extreme events are recommended where more in-depth overheating assessments are required due to particular concerns such as the presence of vulnerable occupants.

Considering the high percentage of vulnerable occupants in UK social housing flats, all base models used for locations studied in this thesis are simulated and evaluated by using all future weather files including DSY1, DSY2 and DSY3. The results obtained from the simulations provide a comprehensive understanding and assessment of the future overheating risk for UK social housing flats which are built to the Passivhaus standard under uncertain future climate and occurrence of different extreme events.

2: Future overheating investigation considering various design and occupant behaviour scenarios with different risk of overheating

Assessing the future overheating risk for the flats with different levels of current overheating occurrences either due to the design or occupant behaviour provides a more comprehensive understanding of the future overheating risk in each location. This assessment also shows the importance and the requirement of careful design and occupants' awareness of the appropriate behaviour with regards to control the risk of overheating

Therefore, both design and occupant behaviour scenarios modelled in this study for each location, are sorted based on the annual percentage of occupied hours with temperature over 25°C as the Passivhaus overheating benchmark and acceptable indoor design operative temperature in summer by CIBSE (CIBSE, 2006a). Amongst the available scenarios, 4 design and 6 occupant behaviour models for each location with various overheating risks were selected for future overheating investigations using the standard weather scenario.

Given BRE recommendations for the annual percentage of occupied hours with temperature over 25°C to be 5% or less when using current weather data (Mcleod et al, 2011), the scenarios selected for future modelling are aimed to cover flats with an overheating range between 0 to 5% within available scenarios in design and occupant behaviour categories.

3.6 Conclusion

This chapter sets out the underlying methodology adopted for the case study and simulation modelling conducted for this study. The benchmark criteria are described based on Passivhaus standard and adaptive thermal comfort. The method for overheating analysis and assessment for the UK social housing flats built to the Passivhaus standard are described by considering current and future climate scenarios. The method adopted in this study for understanding the effective design and occupant behaviour factors were presented. The next chapters will present the case study conducted for this research and the simulation modelling. Figure 3.4 summarises the overall structure of this research and an overview of the research steps that carried out and presented in next chapters

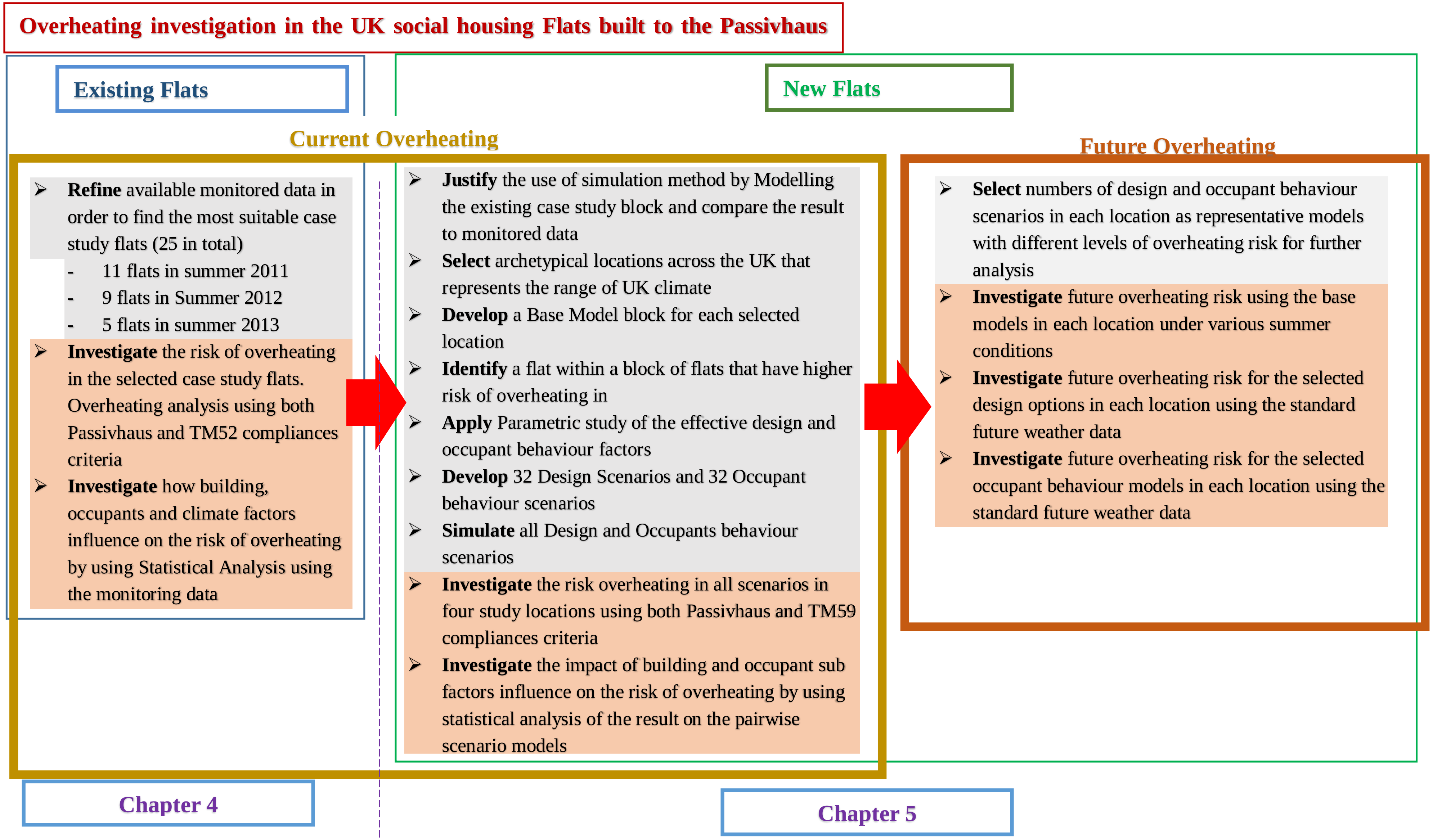


Figure 3.4 Overview of the research steps

Chapter 4: Overheating investigation in existing UK social housing flats built to the Passivhaus

4.1 Introduction

This chapter presents investigations into the overheating risk in newly constructed and occupied social housing flats built to the Passivhaus standard. The case study described in this chapter considers 25 flats over three cooling seasons in Coventry, UK. The following content outline how the case study is conducted, the results, the analysis of the data and discussion of the findings. Chapter 3 summarises the process of overheating analysis based on selected benchmarks. As evidenced in the literature review there is risk of overheating in existing homes with higher risk in energy efficient homes, however there is limited studies on the overheating risks in these types of flats in the UK and in particular social housing flats. This study is very important due to increasing use of Passivhaus standard in the UK residential building sector in response to demands for energy efficient homes. Vulnerable groups such as elderly are at higher risk and these groups constitutes a high proportion of social housing tenants. Hence the focus of this chapter is to investigate the overheating risk in existing social flats built to Passivhaus standard using Fixed and Adaptive thermal comfort benchmarks considering different level of vulnerabilities.

4.2 Description of case study

Detailed description of the case study and data collection has been presented in Section 3.4 of the methodology chapter. This sets out the building type, location as well as indoor and outdoor environmental data collection. The overheating analysis for the living rooms of the case study flats are based on indoor and outdoor environment data collected through the social housing landlord and the nearest Met Office weather station respectively. Other data sets used to establish occupancy pattern has been established from post-occupancy evaluation survey (POE) carried out by the social housing provider. These data sets have been the basis upon which the overheating analysis was carried out. The study has been carried out over three cooling seasons of 2011, 2012 and 2013 which named as monitoring periods of A, B and C respectively. Information about the duration of monitoring and also the number of case study flats for overheating assessment in each monitoring period is summarised in Table 3.3 in the methodology chapter.

This section presents an analysis of the local climatic condition around the case study building to establish the appropriateness of the data for the overheating analysis. Figure 4.1 shows the average mean and maximum outdoor temperatures during the selected monitoring periods since 2002. It indicates that the outdoor average mean temperature during monitoring periods in the summers of 2011 and 2013 are slightly higher (by 4% and 3% respectively) than the historic temperature of the same period. Whilst 2012 have slightly lower average mean temperature (2% decline). These results indicate that the temperatures experienced during the three monitoring periods are in line with those that would typically be expected in this location.

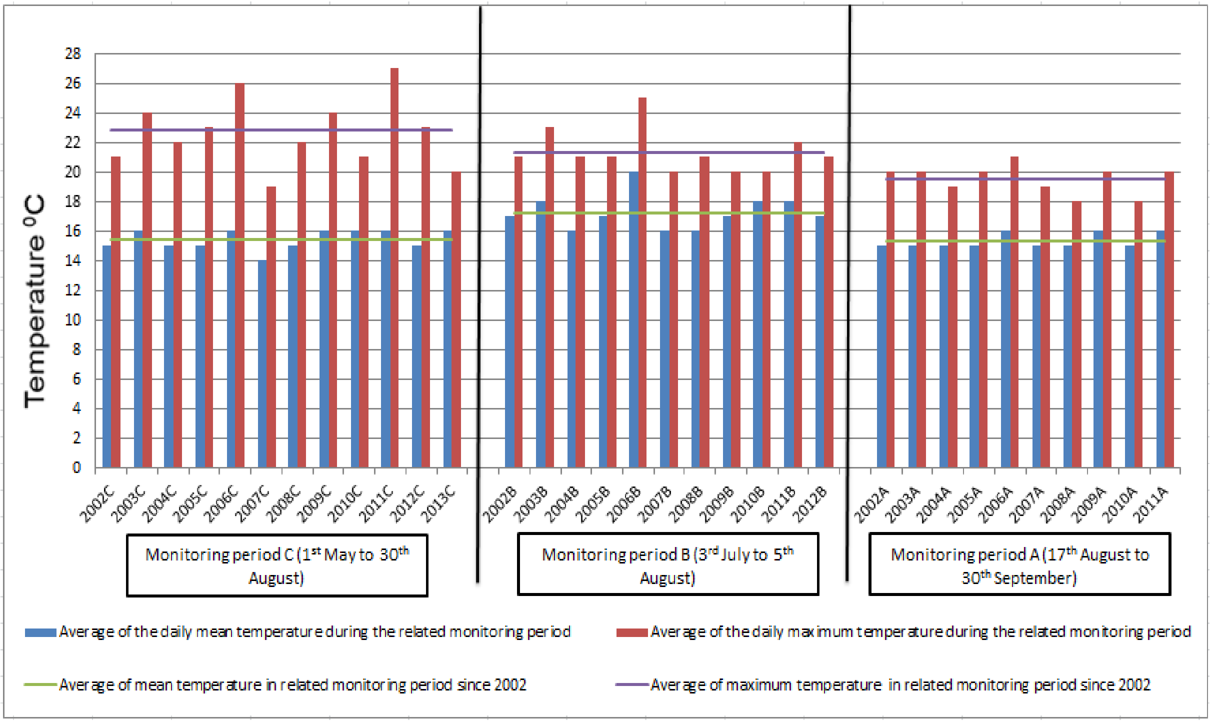


Figure 4.1 Coventry's average mean and max outdoor temperatures since 2002 in the selected monitoring periods

Further to this historical comparison of outdoor temperature, the environmental factors that affect indoor temperature and overheating (outdoor temperature and solar irradiation) for the three monitoring periods have been compared and presented in Figure 4.2.

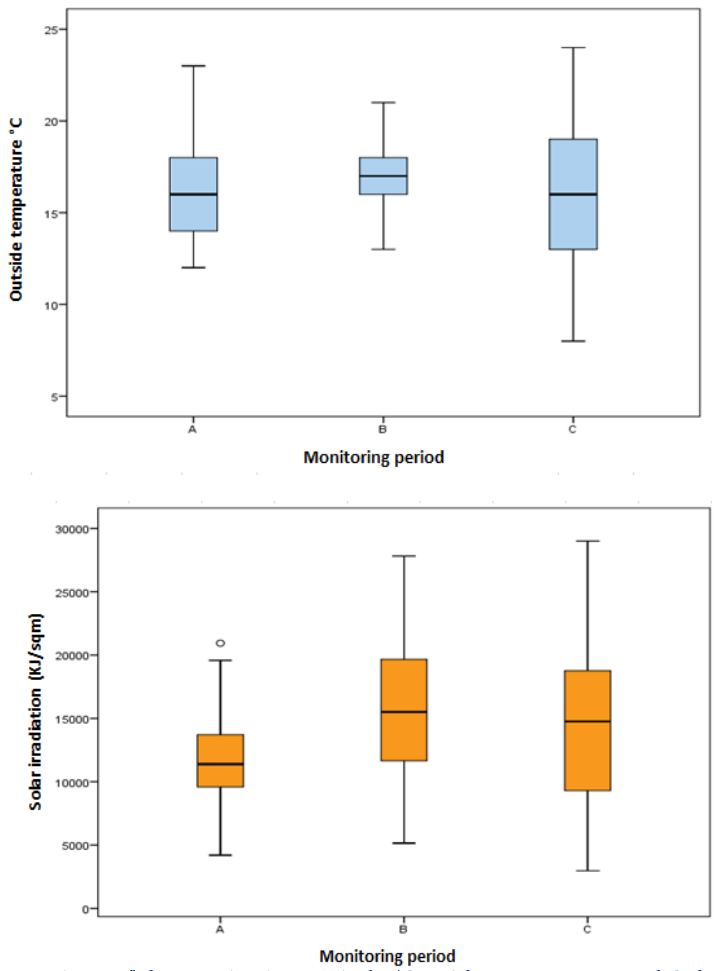
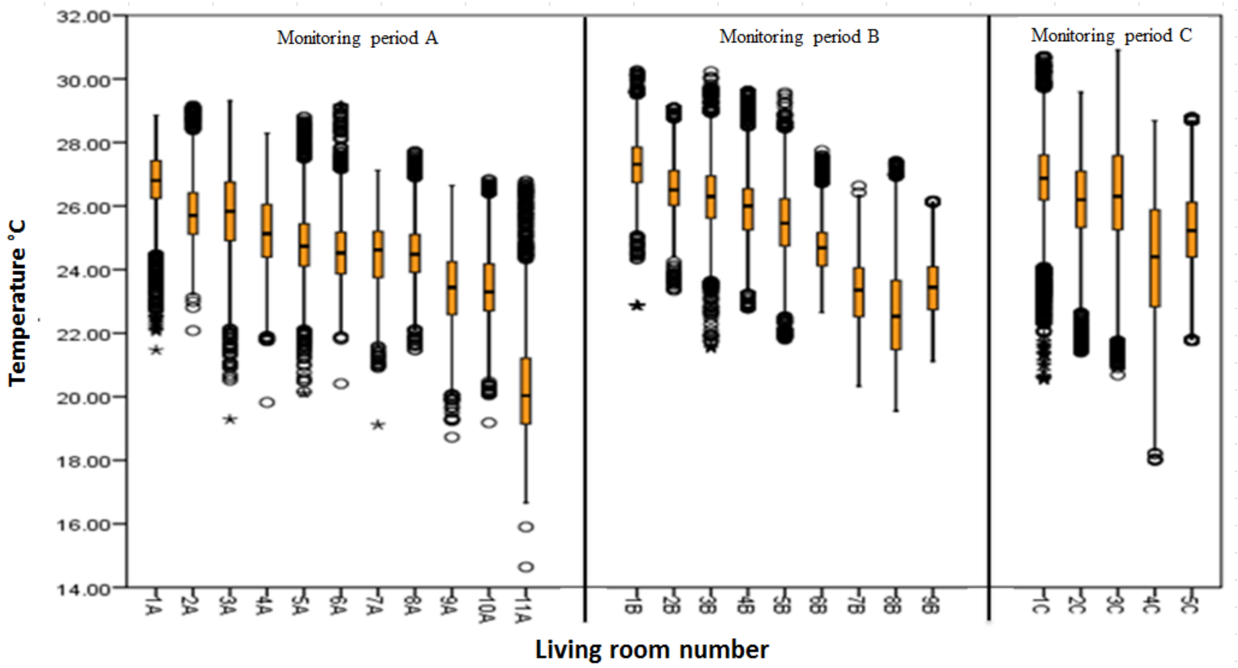


Figure 4.2 Comparison of the monitoring periods (Outside temperature and Solar irradiation)

The results showed that based on the number of monitored days, monitoring period C has the biggest range of outside temperature and solar irradiation. Comparing the three monitoring periods, monitoring period B and A have the smallest range of outdoor temperature and solar irradiation respectively and B has the maximum average outdoor temperature and solar irradiation.

4.3 Analysis the case study data and results

Recorded temperatures during occupied hours in all living rooms are summarised for all monitoring periods in Figure 4.3. This shows that the range of temperature variations is significant. However, judgment about the actual overheating requires in-depth analysis using the selected overheating benchmarks discussed in Section 3.3 of the methodology chapter and used for overheating analysis in section 4.3.1.



[1] Asterisks and circles in box plot graphs show the out range data

Figure 4.3 Recorded temperatures during occupied hours in all living rooms during all monitoring periods

4.3.1 Overheating evaluations based on the Passivhaus benchmark

Passivhaus overheating criteria has been used to analyses the risk of overheating in the flats. As noted in Section 3.3 of chapter 3, the criterion states that it is not acceptable for temperature in the living area to exceed 25°C for more than 10% of the total annual occupied hours. This has therefore been one of the key indicators of overheating risk in the flats. One limitation of the study is that it was conducted on a limited number of days during the three cooling seasons; therefore, it cannot show the actual risk of overheating based on the Passivhaus benchmark. The Passivhaus benchmark requires the overheating analysis to be carried out using annual indoor environmental conditions.

To calculate any rise in the annual elevated temperature above 25°C and indicate whether flats will overheat based on the Passivhaus criteria two percentages of overheating were calculated. To begin with, the annual overheating percentage was calculated, based on the actual number of hours with elevated temperature during the monitoring period. Second, assuming occupant behaviour to be consistent throughout the year, the likely number of occupied hours that each

[1] Asterisk (*) represents extreme outliers where a data point is more extreme than Q_1-2× Step or Q_3+2×Step.

Where Q_1= first quartile, Q_3= third quartile, IQR (Interquartile range) = Q_3-Q_1 and Step=1.5× IQR

Circle (O) represents mild outliers where a data point is more extreme than Q_1-Step or Q_3+Step, but are not extreme outliers.

flat would have had a temperature higher than 25°C in the rest of the cooling season was calculated based on the actual cooling degree hours recorded during the monitored and unmonitored periods of each cooling season. These anticipated hours were then used to calculate the annual overheating percentage in the unmonitored period of the cooling season. The sum of these two percentages was then used for comparison with the Passivhaus overheating limit.

Figure 4.4 represents the result which illustrates the significant risk of overheating in these flats, based on Passivhaus criteria.

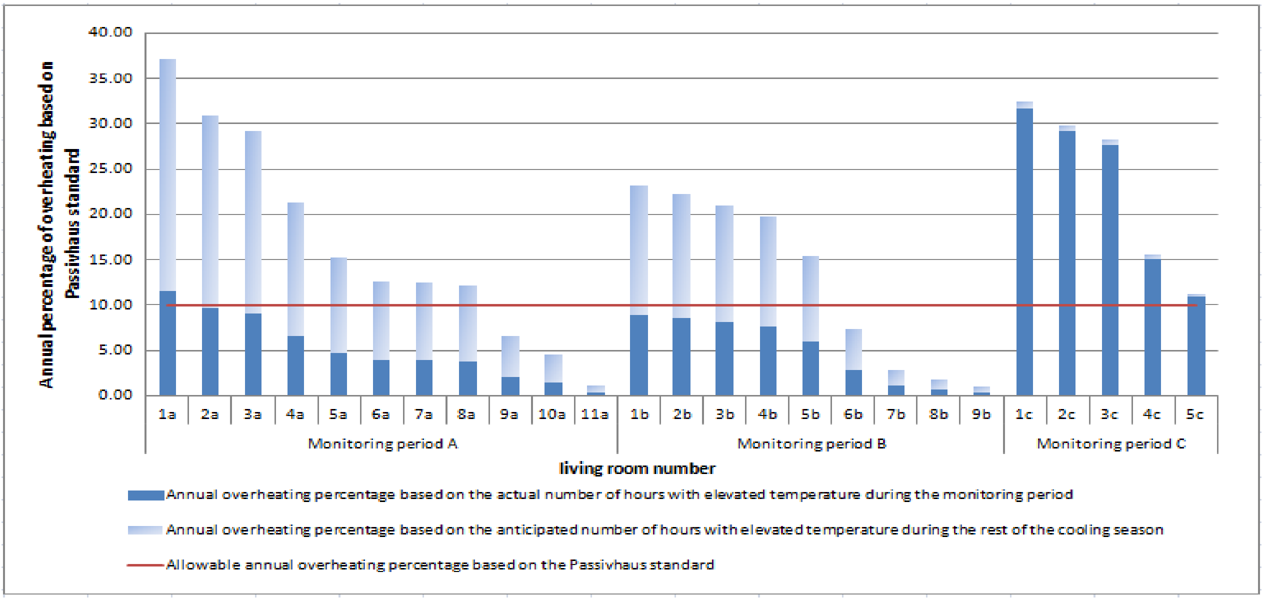


Figure 4.4 Overheating evaluation for all available living rooms and in all monitoring periods, based on Passivhaus Criteria

4.3.2 Overheating evaluations based on the adaptive benchmark

In order to assess the occurrence and severity of overheating, the adaptive comfort threshold temperature for each category was calculated, based on the daily outdoor temperature. The daily values of T_{rm} were calculated from the daily mean outdoor temperature (Equation 2 in Chapter Three) and then T_{max} for Categories I and II were calculated using Equations 3 described in Chapter Three.

Figure 4.5 shows the daily mean outdoor temperature (T_{out}) and the values of T_{max} for building Categories I and II during all monitoring periods.

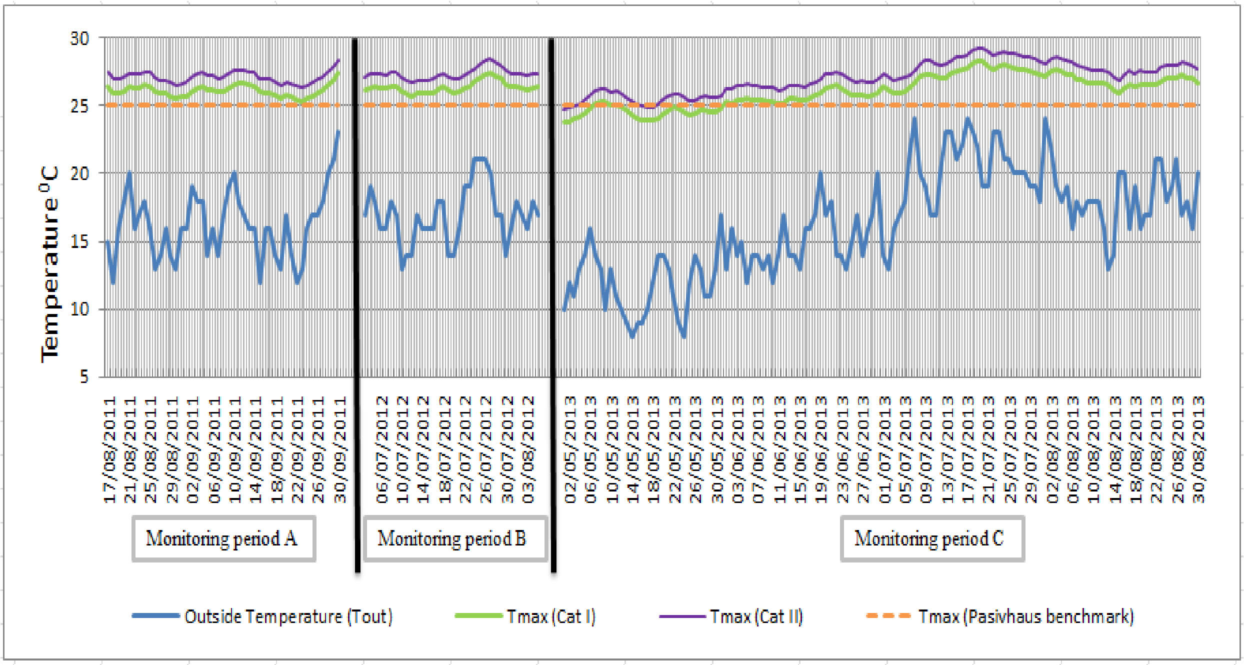


Figure 4.5 Daily mean outdoor temperature (Tout) and maximum adaptive thermal comfort temperature (Tmax) for building Categories I and II during all monitoring periods

Although the Passivhaus thermal comfort threshold (fixed) and the adaptive thermal comfort benchmark are not directly comparable due to the difference in their overheating evaluation criteria, Figure 4.5 clearly shows that the adaptive thermal comfort thresholds are significantly related to the outside temperature and vary according to it.

To evaluate overheating in the monitored living rooms, all three criteria were investigated separately and then the results were combined to determine the occurrence of overheating in each living room. In addition to Category II (this is the suggested category for new houses and for normal expectations), an analysis was also made of Category I buildings to examine the suitability of these flats for vulnerable occupants.

4.3.2.1 Criterion 1

As outlined above, Criterion 1 investigates the frequency of overheating in living spaces. The analysis of results based on this criterion is presented in Figure 4.6. In 2011, 3 living rooms failed Criterion 1 based on both building categories and 1 living room based on only Category I. In 2012, 5 living rooms out of the 9 did not meet the requirements of this criterion in both categories. In 2013, all living rooms failed Criterion 1 based on building Category I and three of them failed based on building Category II as well.

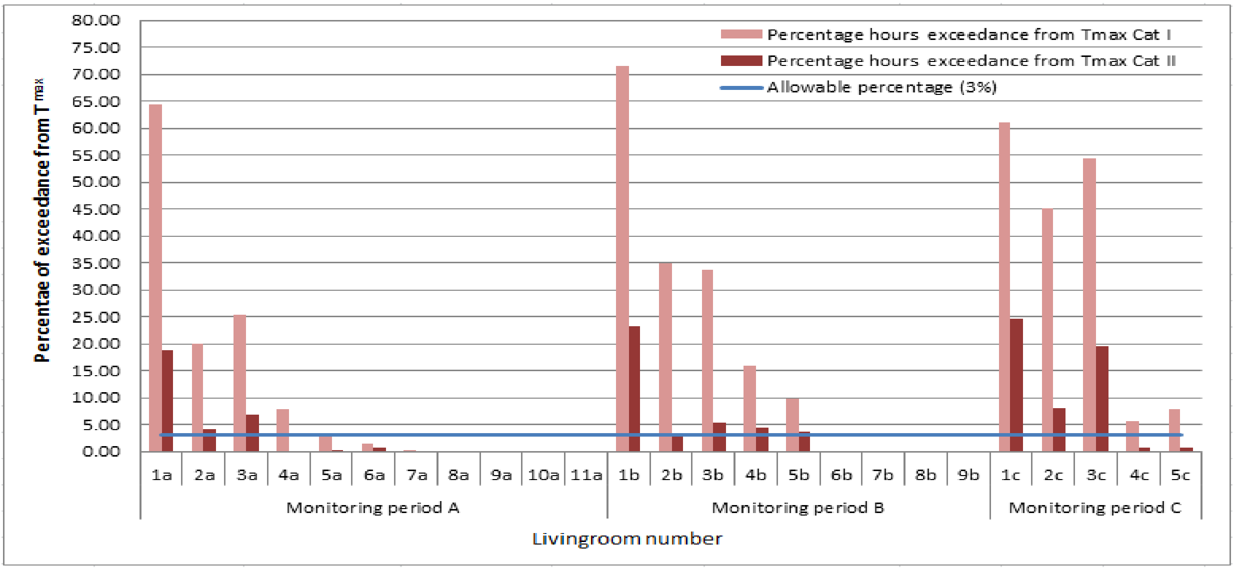


Figure 4.6 % hours of exceedance from Categories I and II threshold comfort temperature during the monitored occupied hours in all monitoring periods

4.3.2.2 Criterion 2

Criterion 2 considers the severity of overheating within any one day. During each day of monitoring, the weighted exceedance (W_e) was calculated for all monitored living rooms. Figure 4.7 reveals the total number of days that W_e was greater than 6 for each living room, on the basis of Categories I and II during all monitoring periods. The results indicate that nearly all the living rooms that failed Criterion 1 had at least one day (amounting to more considerable number of days in some cases) where W_e was higher than 6 and did not meet the requirement of Criterion 2.

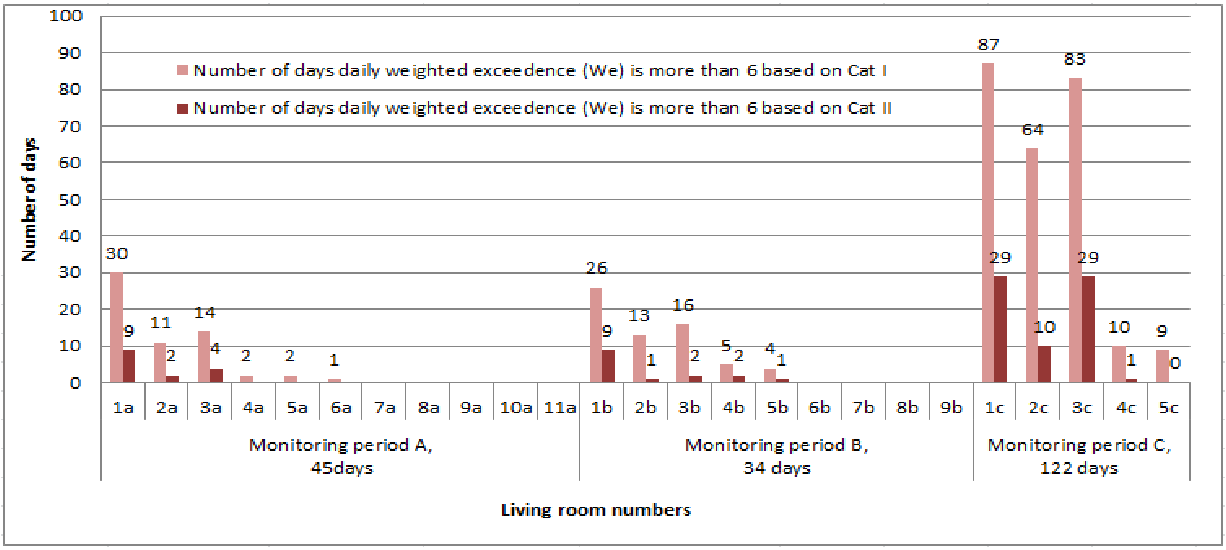


Figure 4.7 Number of days where the weighted exceedance was more than 6 from Categories I and II threshold comfort temperatures during all monitoring periods

4.3.2.3 Criterion 3

Criterion 3 establishes a maximum value for an indoor temperature. During all the monitoring periods, the ΔT values were calculated for all living rooms. The results show that in nearly all living rooms, ΔT was less than 4 °C. For only three days in 2013, two rooms failed this criterion based on building Category I (i.e. ΔT was greater than 4 ºC).

4.3.2.4 Summary of the results

Table 4.1 summarises the data analysis based on all three criteria for 2011, 2012 and 2013. According to CIBSE TM 52 (CIBSE, 2013), the room is classed as overheated when at least two of the three criteria have failed.

Table 4.1 Summary of the results for both adaptive and fixed benchmarks

Category	Monitoring period	A (17th Aug to 30th Sep 2011)											B (3rd Jul to 5th Aug 2012)									C (1st May to 30th Aug 2013)				
	Living room number	1a	2a	3a	4a	5a	6a	7a	8a	9a	10a	11a	1b	2b	3b	4b	5b	6b	7b	8b	9b	F1	F2	F3	F4	F5
I	Meets Criterion 1	x	x	x	x	√	√	√	√	√	√	√	x	x	x	x	x	√	√	√	√	x	x	x	x	x
	Meets Criterion 2	x	x	x	x	x	x	√	√	√	√	√	x	x	x	x	x	√	√	√	√	x	x	x	x	x
	Meets Criterion 3	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	x	√	x	√	√
	Overheated (at least two criterion failed)	Yes	Yes	Yes	Yes	No	No	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes	No	No	No	No	Yes	Yes	Yes	Yes	Yes
II	Meets Criterion 1	x	x	x	√	√	√	√	√	√	√	√	x	x	x	x	x	√	√	√	√	x	x	x	√	√
	Meets Criterion 2	x	x	x	√	√	√	√	√	√	√	√	x	x	x	x	x	√	√	√	√	x	x	x	x	√
	Meets Criterion 3	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
	Overheated (at least two criterion failed)	Yes	Yes	Yes	No	No	No	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes	No	No	No	No	Yes	Yes	Yes	No	No

4.4 Analysis of the results

4.4.1 Indoor temperature variation

The recorded indoor temperatures of all the flats are shown in Figure 4.8. To compare the indoor temperatures experienced in different living rooms, the Passivhaus discomfort temperature threshold is used (without any endorsement or judgment about the suitability of this threshold) to calculate and evaluate the elevated temperatures and their frequencies from this baseline. The percentage of hours in which the temperature exceeded 25˚C is shown in Figure 4.8 for the monitored living rooms for all monitoring periods.

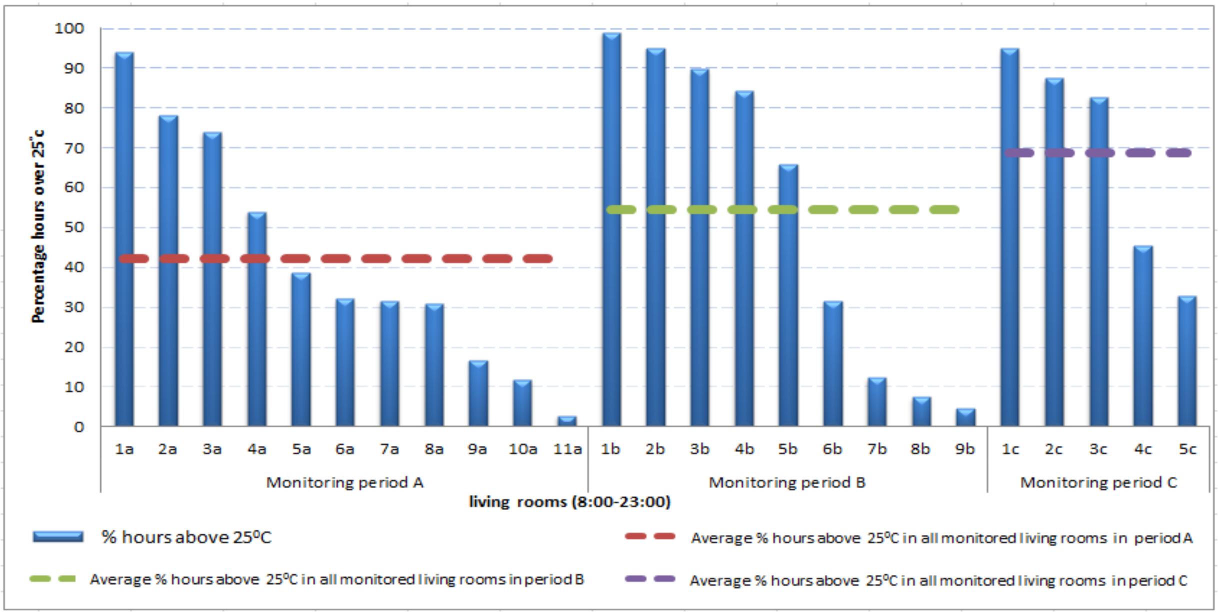


Figure 4.8 Percentage of occupied hours with measured temperatures over 25°C in all living rooms during all monitoring periods

The results reveal significant variations in the elevated temperature in different living rooms. The percentages vary from approximately 94% to 3% in 2011, from 99% to 5% in 2012 and from 94% to 33% in 2013. As discussed, different factors (outdoor temperature, solar gain, ventilation, thermal mass and internal gains) have significant effects on the indoor temperature range and overheating of a room. In general, the results suggest that in the monitoring period of 2013 monitored living rooms experienced more elevated temperatures, since the average percentage of hours above 25°C was 68% in 2013, 54% in 2012 and 42% in 2011. The daily averages of percentage hours with temperatures over 25 ºC in all flats for all monitoring periods are represented in Figure 4.9.

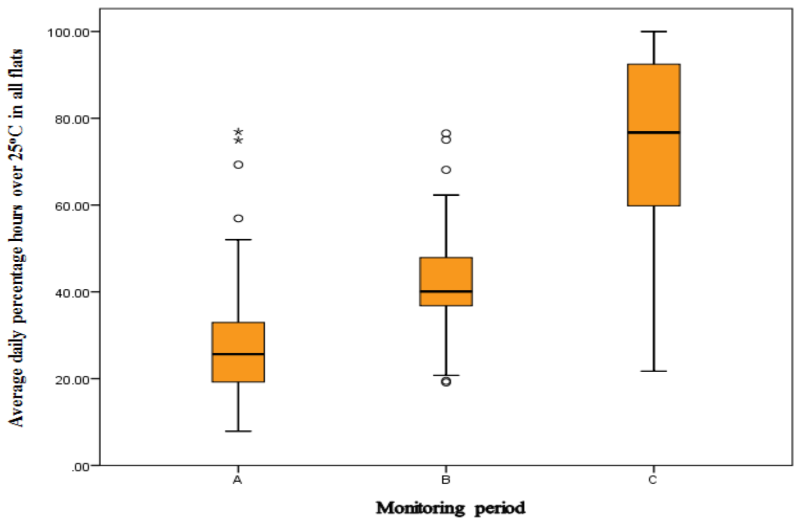


Figure 4.9 Daily comparison of average daily percentage hours with temperature over 25 °C in all flats during three monitoring periods

A comparison of external environmental factors and average daily percentage hours with temperature above 25°C in all flats (Figures 4.2 and 4.9), suggests no direct relationship between such factors and the overheating experienced in different flats. However, in order to understand the significance of the factors that did cause the variation, an in-depth analysis has been carried out. To assess the significance of the effective factors on temperature variations and overheating experienced, separate linear regression analyses has been carried out for each flat. Hourly outside temperature and solar irradiation were identified as the environmental factors that affect indoor temperature and were considered as the two input factors in each regression analysis.

It should be noted that solar gain on each vertical surface is affected by solar irradiance (direct and diffuse data) on the related orientation (Perez et al., 1990). Many meteorological stations in the world measure global irradiance on a horizontal surface; however, only limited number of them measure the solar component on vertical surfaces (Li et al., 2013b). Available solar data for this study is also global radiation on horizontal surface. Some methods to predict vertical global solar irradiation based on the horizontal value have been suggested by different researchers; however, most of them are complicated and their applications are debatable (Li et al., 2002; Li et al., 2013b). Therefore, as this study is concerned with the relative effect of solar irradiance, data for horizontal surfaces are used and are considered simply as being representative of the potential solar irradiation on vertical surfaces.

Occupant behavior, thermal mass, orientation and size of window aperture are the other factors that affect indoor temperature (CIBSE, 2006b). Occupant behavior in this study is defined as:

- Amount of natural ventilation and mechanical ventilation through MVHR bypass mode,
- Actual amount of solar gain affected by shading devices used by occupants,
- Actual internal gain.

Since the regression analysis was carried out separately for each flat, factors such as thermal mass, orientation and aperture which remained constant during the monitoring period will not affect the proposed regression model. Hence, the regression model in each flat can directly show the relative significance of the two input factors (environmental conditions) and also indirectly the significance of missing input factor (occupant behavior) (Table 4.2).

Table 4.2 Results from the regression analysis in each living room

Monitoring period	Flat Number	Environmental factors impact on inside temperature (R^2 value (%) of the regression model)	Occupants' behaviour impact on inside temperature ($100 - R^2$)
A	1a	5.0	95.0
	2a	33.7	66.3
	3a	15.6	84.4
	4a	21.5	78.5
	5a	21.2	78.8
	6a	22.3	77.7
	7a	14.6	85.4
	8a	28.9	71.1
	9a	10.8	89.2
	10a	42.4	57.6
	11a	62.8	37.2
	Average	25.3	74.7
B	1b	13.3	86.7
	2b	39.2	60.8
	3b	32.1	67.9
	4b	26.2	73.8
	5b	39.3	60.7
	6b	33.9	66.1
	7b	38.7	61.3
	8b	51.6	48.4
	9b	23.3	76.7
	Average	33.1	66.9
C	1c	30.8	69.2
	2c	45.0	55.0
	3c	60.8	39.2
	4c	55.6	44.4
	5c	32.8	67.2
	Average	48.1	52.0
Average		32.1	67.9

Table 4.2 shows the impact of environmental factors (R^2) and also the significance of occupant behavior ($100- R^2$). The result shows a range of R^2 values in different flats from 5% to 62.8%, in a majority of cases, the R^2 is less than 50% and in terms of the average of all monitoring periods, this value is 32.1%. This indicates that in most cases, less than 50% of the indoor temperature variations are explained by environmental factors (parameter in model) which means the impact of occupants' behavior as defined (missing factors in the model) on indoor temperature variations is greater.

The results from this investigation therefore show that occupant behavior has a significant impact on temperature variation and overheating. Also, comparison of the results in three monitoring periods (Table 4.2 and Figure 4.9) shows that where the average daily percentage hours with elevated temperature is lower, the average impact of occupants behavior on temperature variation is higher, which suggests that occupants have a considerable role in controlling overheating. Consequently, it is likely that occupant behavior can increase the risk of overheating even in cases where the environmental factors are not very severe, it also suggests that even in cases when the environmental factors are severe, effective occupant behavior can have a significant impact on reducing overheating risks in these flats.

4.4.2 Overheating assessment

4.4.2.1 Passivhaus benchmark

The results from the overheating evaluation show that in 2011, and for only 45 monitored days, two flats reached the overheating limits of the Passivhaus standard (10% of annual occupied hours) and two flats overheated more than 5% of occupied hours over the whole-year. In general, taking account of the anticipated overheating hours for the rest of the cooling season, 8 out of 11 monitored flats overheated based on the Passivhaus benchmark, this represents more than 72% of the case studies.

In 2012, during the 34 days of monitoring, overheating in three flats was more than 8% of the annual occupied hours and about 6% in two flats. After considering the anticipated overheating hours for the rest of the cooling season, 5 out of the 9 monitored flats overheated according to the Passivhaus benchmark, which represents more than 55% of all the case studies.

In 2013, flats were monitored during most of the cooling season and all of them exceeded the annual Passivhaus overheating limit. Some of the flats experienced overheating based on Passivhaus standard during most of the occupied hours monitored.

The average annual percentage of elevated temperatures in all monitored flats was 16.6%, 12.6% and 22.9% in 2011, 2012 and 2013 respectively and 72% of these flats (18 out of a total of 25 flats in 3 monitoring years) failed to meet their design criteria in terms of overheating. Therefore, according to the Passivhaus criteria, most of these flats face significant risks of overheating.

4.4.2.2 Adaptive benchmark

As discussed in Chapter Two, there is a consensus that the statistical benchmarks which define overheating, such as the Passivhaus benchmark, are increasingly restrictive. In contrast, adaptive thermal comfort benchmarks can provide better understanding and prediction of overheating. However, the results from this study indicate that the criteria for defining overheating based on adaptive thermal comfort benchmark as defined in CIBSE TM52

(CIBSE, 2013) can help identify overheated spaces in different categories, but they are relatively weak and limited in terms of determining the frequency, intensity and severity of overheating between categories I and II.

The results from this study indicate that nearly all the living rooms that overheated based on Category I evaluation were also deemed highly likely to overheat when evaluated based on Category II. However, on the basis of a detailed analysis of Criteria 1 and 2, it should be noted that the intensity and severity of overheating based on Category I were significantly higher than those based on Category II. In order to explore this in more detail and assess the significance of overheating in each category, a statistical analysis was conducted for both categories as summarised in Table 4.3. In this analysis, the daily average percentage hours exceedance from T_{max} (Criterion 1) and also the daily average weighted exceedance (W_e) (Criterion 2) for both categories, across all flats, are compared for all monitoring periods. This analysis indicates that on average, occurrence of overheating in terms of Category I is approximately 8.31, 14.01 and 26.27 percent higher than this occurrence in terms of Category II in the monitoring periods of A, B, and C and in each of these cases there are lower and upper limits based on 95% confidence interval as shown in Table 4.3. The statistical analysis shows that the results of each criteria based on each category are significantly different (Sig <0.05). Similarly, on average the daily average weighed exceedance was about 1.7, 2.81 and 5.85 percent higher in Category I than the occurrence based on Category II in the monitoring periods A, B, and C. Hence, both the frequency (comparison of Criterion 1) and the severity (comparison of Criterion 2) of overheating in terms of Category I are significantly higher than Category II.

Table 4.3 Statistical analysis of Criteria 1and 2 in all monitoring periods

Criterion	Comparing pair	Monitoring period	Paired Differences				Sig. (2-tailed)
			Mean	Std. Deviation	95% Confidence Interval of the Difference		
					Lower	Upper	
1	-Daily average percentage hours exceedance from Tmax Cat I in all living rooms during monitoring period -Daily average percentage hours exceedance from Tmax Cat II in all living rooms during monitoring period	A (2011)	8.31	4.90	6.84	9.78	0.000
		B (2012)	14.01	7.61	11.35	16.67	0.000
		C (2013)	26.27	14.80	23.61	28.92	0.000
2	-Daily average weighted exceedence (We) from Tmax Cat I in all living rooms during monitoring period -Daily average daily weighted exceedence (We) from Tmax Cat II in all living rooms during monitoring period	A (2011)	1.70	1.03	1.39	2.01	0.000
		B (2012)	2.81	1.73	2.21	3.42	0.000
		C (2013)	5.85	2.87	5.34	6.37	0.000

Apart from this general comparison, and in order to demonstrate these differences in all overheated living rooms, the same statistical analysis was undertaken for each overheated individual living room separately. A summary of the results can be found in Table 4.4 and Table 4.5.

Table 4.4 Statistical analysis of Criterion 1 for all overheated living rooms

Comparing pair	Monitoring period	Living room number	Paired Differences				Sig. (2-tailed)
			Mean	Std. Deviation	95% Confidence Interval of the Difference		
					Lower	Upper	
- Daily percentage hours exceedance from T_{max} Cat I during monitoring period - Daily percentage hours exceedance from T_{max} Cat II during monitoring period	A	1A	45.25	33.65	35.14	55.36	0.000
		2A	15.77	21.96	9.18	22.37	0.000
		3A	18.40	26.78	10.35	26.44	0.000
		4A	7.83	13.80	3.69	11.98	0.000
	B	1B	48.36	33.83	36.56	60.16	0.000
		2B	31.82	28.33	21.94	41.71	0.000
		3B	28.35	32.10	17.15	39.55	0.000
		4B	11.52	20.77	4.28	18.77	0.003
		5B	6.03	12.11	1.80	10.25	0.007
	C	1c	36.35	32.36	30.55	42.15	0.000
		2c	37.09	34.21	30.95	43.22	0.000
		3c	35.02	24.83	30.57	39.47	0.000
		4c	4.82	15.66	2.02	7.63	0.001
		5c	5.47	14.27	2.35	8.59	0.001

Table 4.5 Statistical analysis of Criterion 2 for all overheated living rooms

Comparing pair	Monitoring period	Living room number	Paired Differences				Sig. (2-tailed)
			Mean	Std. Deviation	95% Confidence Interval of the Difference		
					Lower	Upper	
- Daily weighted exceedence (We) from T_{max} Cat I during monitoring period - Daily weighted exceedence (We) from T_{max} Cat II during monitoring period	A	1A	9.83	6.67	7.82	11.83	0.000
		2A	3.06	4.32	1.76	4.36	0.000
		3A	3.87	5.57	2.19	5.54	0.000
		4A	1.19	2.10	0.56	1.83	0.000
	B	1B	10.92	5.74	8.91	12.92	0.000
		2B	5.32	4.75	3.66	6.97	0.000
		3B	5.15	5.66	3.17	7.12	0.000
		4B	2.43	4.43	0.88	3.97	0.003
		5B	1.50	3.50	0.28	2.72	0.018
	C	1c	9.33	5.78	8.29	10.36	0.000
		2c	6.90	6.17	5.79	8.00	0.000
		3c	8.31	4.96	7.42	9.20	0.000
		4c	0.87	2.81	0.37	1.37	0.001
		5c	0.94	2.48	0.40	1.48	0.001

These separate analyses also reinforce the results from general analysis of the average values. The statistical analysis shows that the results of each criteria based on each category for all overheated living rooms are significantly different (Sig <0.05). The range of the difference for daily percentage hours is from approximately 5 to 45 percentage (mean values) and this range for daily exceedance is about 1 to nearly 11 degree hours (mean values) in different flats.

4.4.2.3 Suggestions for revising Criterion 2 and comparison of the benchmarks

It is noted above that Criterion 2 used in the adaptive benchmark sets a daily limit for the severity of overheating (weighted exceedance). As discussed in Chapter Three, to meet the criterion, this daily limit, which is expressed as weighted exceedance (W_e), must be less than or equal to 6 in any given day. The number 6 is based on the assumption that similar occupancy patterns exist in all the spaces being investigated for overheating. In fact, this number in CIBSE TM52 (CIBSE, 2013) is considered with the assumption of having a room with 8 hours of occupancy. Obviously, in a room with higher hours of occupancy, this number can increase and a higher W_e can be acceptable. In order to investigate the effect of a higher acceptable W_e in overheating evaluation, Criterion 2 was tested over the W_e of 11 degree hours. The number 11 is based on adjusting W_e proportionally in line with the difference between the actual occupied hours of 15 and the standard, assumed, occupied hours of 8.

All the living rooms that failed against Criterion 2 were tested again using the new weighted exceedance of 11. The results of the initial and revised investigation of Criterion II are presented in Table 4.6. The results of the new overheating evaluation for all living rooms are also presented in Table 4.6.

The results show that according to this modified limit, in the monitoring period A, one flat based on Category I and one based on Category II are not classified as overheated. The difference in monitoring period B is more considerable: four flats based on Category II are no longer classified as overheating. It can be seen that in in monitoring period C one flat based on Category I is not classified as overheating according to the modified criterion. This clearly shows the importance of selecting an accurate weighted exceedance limit for the assessment of overheating. This study suggests that this number should be in accordance with the actual occupied hours rather than a fixed number.

4.4.3 Discussion, limitations and the need for further work

In all monitoring periods, 18 out of out of 25 living rooms, were classified as overheated based on the Passivhaus benchmark and the results from statistical analysis indicate that occupant behavior has a significant impact on temperature variation and overheating risk.

Interestingly, most of these living rooms are classified as overheated when assessed according to the adaptive benchmark of Category I (vulnerable occupants). However, when assessed according to Category II criteria (Normal occupants), significantly fewer of these spaces are identified as overheated.

Therefore, although considerable numbers of these flats failed against the Passivhaus criteria of overheating, when the adaptive thermal comfort model is applied, this risk is quite different and is based on occupant type. The results from this study show that the risk of overheating for vulnerable occupants is considerable, while this risk is not as significant for occupants with normal expectations.

As previously explained in detail in Chapter Two, the social housing sector has the most vulnerable occupants (both in terms of affordability and age profile) in the UK. Hence, the results from this study show a significant risk of overheating in Passivhaus social housing flats built in the UK under current climate condition.

Although the results from the case studies present a general overview of the overheating risk in UK social housing flats, it should be acknowledged that there are number of limitations regarding the case studies used in this study. The first limitation is related to the location as all case study flats have the same location and therefore this has limited the capability of this study to investigate the overheating risk in various UK climate conditions.

Furthermore, all selected dwellings have been selected from similar block of flats. Hence, all case study flats have similar building fabric characteristics such has thermal mass level, thermal transmittance and glazing type and also design parameters like orientation and glazing ratio. Also, although different number of flats have been selected for each monitoring period, some flats have been occupied by same tenants. Both these restrictions have limited overheating investigation to specific design and also not wide range of occupant behaviors.

In order to have a clear picture of the summer performance of social housing flats built to the Passivhaus standard, not only the current performance but also the future performance of these dwellings in an uncertain future climate should be investigated and assessed in different part of the UK. Also, determining the design and occupant behavior factors which have significant effects on overheating in these flats will help the social housing developers to design better houses and also to educate their tenants appropriately to reduce the risk of overheating occurrences.

Therefore, determining the effective factors on overheating and assessing the summer performance of the new Passivhaus social housing flats under current and future climate conditions in different parts of the UK are the focuses of the next chapter.

Table 4.6 Summary of all overheating assessment

Category	Monitoring period	**A** (17th Aug to 30th Sep 2011)											**B** (3rd Jul to 5th Aug 2012)									**C** (1st May to 30th Aug 2013)				
	Living room number	1a	2a	3a	4a	5a	6a	7a	8a	9a	10a	11a	1b	2b	3b	4b	5b	6b	7b	8b	9b	1c	2c	3c	4c	5c
Cat I	Criterion 1 (Percentage hours of exceedance)	64.44	25.36	20.07	7.83	2.95	1.49	0.22	0.00	0.00	0.00	0.00	71.60	34.86	33.75	15.91	9.84	0.00	0.00	0.00	0.00	61.15	45.23	54.49	5.70	7.77
	Meet the Criterion	x	x	x	x	√	√	√	√	√	√	√	x	x	x	x	x	√	√	√	√	x	x	x	x	x
	Criterion 2 (Number of days with daily weighted exceedance of more than 6)	30	14	11	2	2	1	0	0	0	0	0	26	13	16	5	4	0	0	0	0	87	64	83	10	9
	Meet the Criterion	x	x	x	x	x	x	√	√	√	√	√	x	x	x	x	x	√	√	√	√	x	x	x	x	x
	Revised Criterion 2 (Number of days with daily weighted exceedance of more than 11)	26	4	7	0	0	1	0	0	0	0	0	24	7	8	5	2	0	0	0	0	66	44	61	4	0
	Meet the Criterion	x	x	x	√	√	x	√	√	√	√	√	x	x	x	x	x	√	√	√	√	x	x	x	x	√
	Criterion 3 (Number of days with ΔT more than 4k)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	3	0	0
	Meet the Criterion	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	x	√	x	√	√
	Overheated	Yes	Yes	Yes	Yes	No	No	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes	No	No	No	No	Yes	Yes	Yes	Yes	Yes
	Overheated (Revised Criterion 2)	Yes	Yes	Yes	No	No	No	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes	No	No	No	No	Yes	Yes	Yes	Yes	No
Cat II	Criterion 1 (Percentage hours of exceedance)	18.83	6.96	4.30	0.77	0.11	0.00	0.00	0.00	0.00	0.00	0.00	23.24	5.40	4.39	3.81	3.04	0.00	0.00	0.00	0.00	24.81	8.14	19.47	0.87	0.89
	Meet the Criterion	x	x	x	√	√	√	√	√	√	√	√	x	x	x	x	x	√	√	√	√	x	x	x	√	√
	Criterion 2 (Number of days with daily weighted exceedance of more than 6)	9	2	4	0	0	0	0	0	0	0	0	9	1	2	2	1	0	0	0	0	29	10	29	1	0
	Meet the Criterion	x	x	x	√	√	√	√	√	√	√	√	x	x	x	x	x	√	√	√	√	x	x	x	x	√
	Revised Criterion 2 (Number of days with daily weighted exceedance of more than 11)	3	0	2	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	24	4	11	0	0
	Meet the Criterion	x	x	√	√	√	√	√	√	√	√	√	x	√	√	√	√	√	√	√	√	x	x	x	√	√
	Criterion 3 (Number of days with ΔT more than 4k)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Meet the Criterion	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
	Overheated	Yes	Yes	Yes	No	No	No	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes	No	No	No	No	Yes	Yes	Yes	No	No
	Overheated (Revised Criterion 2)	Yes	No	Yes	No	No	No	No	No	No	No	No	Yes	No	No	No	No	No	No	No	No	Yes	Yes	Yes	No	No
PH benchmark	Overheated based on PH ceriteria?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	Yes	Yes	Yes	Yes	Yes	No	No	No	No	Yes	Yes	Yes	Yes	Yes

4.5 Conclusion

This chapter presented case study of overheating assessment in Passivhaus flats built in the UK social housing sector using both fixed and adaptive benchmarks. The case study, data collection, results and analysis were presented. The result highlights a significant risk of overheating based on the Passivhaus benchmark, where 72 percent of all monitored flats failed the overheating criteria.

An alternative approach to evaluating overheating risk is the adaptive thermal comfort model, which takes into account occupant vulnerability and the variation of the outdoor temperature on the risk of overheating.

Use of the adaptive benchmark also suggests that a considerable risk of overheating exists in such flats. However, this overheating risk is shown to be more significant for vulnerable occupants in compare to the normal occupants. The result of the statistical analysis on the indoor temperature variations and the effective parameters indicates that occupant behavior is the most significant factor in increasing or decreasing the risk of overheating. This emphasizes the importance of occupant's awareness of the implication of their actions in the thermal performance of their homes and also developing targeted education packages.

The next chapter (Chapter Five) will presents simulation modelling approach to investigate the feasibility of the new UK social housing flats built to the Passivhaus standard with the use of scenario modelling and by considering various parameters including design, occupant behavior and wider range of the UK climate.

Chapter 5: Overheating investigation in new UK social housing flats built to the Passivhaus under current and uncertain future climate

5.1 Introduction

Scientific evidence has shown that the climate change is already having an impact on the built environment, and that current climate change projections also indicate that the extent of these impacts will increase in the future, as described in Chapter Two. New buildings designs based on the application of new energy efficiency standards such as Passivhaus should demonstrate ability to cope with current manifestations of climate change, as well as mitigating predicted future climate changes. As such, new and existing homes should be able to cope with more extreme weather events such as higher summer temperatures and warmer wetter winters which current predictions suggests are likely to occur under different climate change scenarios.

Dynamic simulation modelling (DSM) tools are the most rigorous method of assessing domestic energy demand and environmental factor. Such models have higher accuracy compared to steady state models. The DSM tools are better suited to more complex and novel designs, where non-linear behaviour needs to be represented (CIBSE, 2018). Despite this high accuracy of DSM tools, there is also evidence of performance gap which represents the difference between design and in-use performance of buildings. Zero Carbon Hub (2014) find many reasons for the gap such as user behaviour, poor quality of design information, poor communication and coordination of construction activities and lack of skills. This issue has been considered in this study through sensitivity analysis of range design and occupant behaviour factors. Also range of scenarios and locations have been investigated to ensure validity of DSM models.

Currently DSM tools are not widely adopted for energy demand assessment in the domestic building design sector. However, application of DSM tools could significantly improve the energy performance of domestic buildings and help the UK to achieve carbon emission reduction target by 2050. One of the most important applications of DSM tools is evaluation of overheating risks based on various occupant behaviour type, as well as design parameters. DSM is an excellent tool for understanding the energy performance and overheating risks for future climate scenarios which could help in shaping long term vision for dwellings which are currently being designed and constructed. Some local authorities, such as The Greater London Authority, have started to encourage developers on overheating risk assessment using dynamic modelling (GLA, 2014).

The assessment of current overheating standards in the UK reveals that both Standard Assessment Procedure (SAP) and the Building Regulatory compliance checks are not adequate for establishing the risk of overheating in homes. Hence, dynamic modelling is required to be undertaken to inform the design (CIBSE, 2018). Hence, CIBSE has developed a standardised design methodology for the assessment of overheating risk in homes (CIBSE, 2017) using dynamic thermal analysis.

Innovate UK (formerly called the Technology Strategy Board) has published three reports on climate change challenges and the potential design strategies to tackle these challenges (Gething, 2010; Gething and Puckett, 2013; Thompson et al., 2015). One of the areas highlighted by the Innovative UK reports are the parameters affecting thermal comfort, overheating and energy performance. According to the report, the impacts of climate change are a function of location; hence local conditions should be considered for scenario modelling. For example, higher temperatures during summer and the consequent overheating in homes are likely to be an issue for the Southern regions of the UK and in particular in urban centres due to the urban heat island effect (CIBSE, 2018).

Currently, the risk of overheating for social housing flats in the UK built based on the Passivhaus standard has not been comprehensively investigated. The majority of existing studies are limited to a case study with fixed location, design or occupant behaviour. These studies did not consider a wide range of locations, design parameters and occupant behaviours in the evaluation of the overheating risk. This Chapter presents the results of comprehensive DSM analysis of overheating risks in UK social housing flats built to the Passivhaus standards. The study is conducted based on a range of designs, occupant behaviour scenarios and considering the current and predicted future climate variations in different regions of the UK.

5.2 Model Development

This section presents the details of case study modelling and the validation process by using the recorded data presented in Chapter Four. The range of UK climate and archetypical locations considered in this study are presented in this section. Finally, the process of developing base models in each location based on characteristics of the UK social housing flats, Passivhaus standard requirements, BRE and CIBSE guidelines are discussed in detail. Base models will be used for parametric study and further scenario modelling and overheating investigation in this study.

5.2.1 Modelling the case study block

The case study building described in Chapter Four is modelled in Integrated Environmental Solution (IES) – Virtual Environment (VE) Dynamic simulation tool. The case study modelling is performed with the aim of validating the simulation processes based on the data recorded during the case study monitoring. The existing case study block consists of 18 flats in three stories. Figure 5.1 shows the geometry and layout of the case study block.

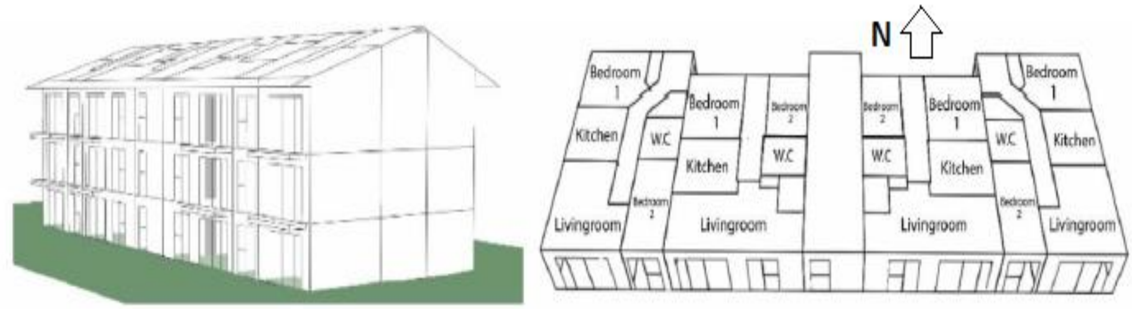


Figure 5.1 View of the case study block and the floor layout in IES

In order to provide consistency between the model and the case study building, the model was developed using similar design components, construction specifications and occupancy profiles. In this model, internal volume, glazing ratio, shading device and layout similar to the case study building has been used as the indicators of design components. The model also used timber frame, triple-glazed windows with glazing g-value of 0.6 and similar thermal characteristics to the case study buildings, see Table 5.1.

The infiltration rate of 0.035ac/h and thermal bridge free fabric were assumed in the model in accordance to the value calculated by Mcleod et al. (2013) in modelling of Passivhaus dwellings. The case study building MVHR system with 85% heat recovery efficiency has been modelled for each flat. Occupancy numbers and profiles are defined for each of the flats in the building block in accordance to the data recorded in the post occupancy survey.

Table 5.1 Case study construction specification

Parameter		Description
Construction Type		Timber Frame
U-value building fabric component [W/m^2 K]	External Wall	0.15
	Roof	0.12
	Ground Floor	0.10
U-value whole windows [W/m^2 K]		0.8
Glazing g-value		0.6
Total Heat capacity (KJ/m^{2}K)	External Wall	35.5
	Ground Floor	42.0
	Roof	36.0
	Internal Floor	24.0
	Internal wall	24.0
Infiltration [effective ac/h]		0.035
Mechanical supply air flow rate [l/s per person]		8
Efficiency of MVHR unit		85%

5.2.2 Modelling validation

The focus of this study is on overheating assessment in free-running mode, therefore the capability of the modelling techniques used in this chapter is determined by the accuracy of predicting indoor temperature recorded during the monitoring of the case study flats.

However, it was discussed in Chapter Two that occupant behaviour factors, are controlled or determined by the way occupants run their building or behave, and this will have significant impact on indoor temperature. Frequency and duration of natural and mechanical ventilation, (operation of window or MVHR bypass mode), actual amount of solar gain (which is affected by the operation of non-fixed shading devices), and actual internal gain are the main parameters related to the occupant behaviour. Results from the detailed analysis of the internal temperature and the effective factors presented in Chapter Four illustrates that occupant behaviour had a significant impact on the temperature experienced in the case study flats. This result agrees with the post occupancy survey of these flats which indicates that there was inconsistency between occupant behaviour in different flats. According to this report there is no consistency or trend for a single occupant in terms of actions such as windows opening, operating the MVHR bypass features, using internal blinds or heating systems.

According to Rijal et al., (2008, 2011, 2012), realistic algorithms for occupant behaviour with regards to the adaptive behaviour such as use of windows should be included in any simulation with the aim of studying the thermal behaviour of the building.
Therefore, for the purpose of this validation, discrete values of various occupant behaviour parameters were assumed and illustrated in Table 5.2. In this table, the equipment gains values and equipment use profiles are assumed based on the standard values and profiles in CIBSE TM59 (CIBSE, 2017) since no actual data with regards to the internal gain (equipment) was obtained in post occupancy survey. (For further information, refer to section 5.2.4.1)

Table 5.2 Occupant behaviour parameters input for modelling the case study flats

Parameter	Discrete values
Windows opening threshold	22°C, 25°C
MVHR bypass Mode	On, Off
Internal gains (excluding occupant gains)	Low- 50% of Values and profiles specified in CIBSE TM59
	High- Values and profiles specified in CIBSE TM59
Internal Shading device	Yes, No

To consider the effect of using more energy efficient appliances as recommended by the Passivhaus standard (Feist et al., 2012), new profiles with 50% of the stipulated gains in TM59 (CIBSE, 2017) standard has been developed and considered as ‘Low internal gain’ profile, while the actual internal equipment gains in CIBSE TM59 represents the ‘High internal gain’ in the scenario modelling. The combination of these parameters creates 16 occupant behaviour scenario models which will be used in the simulation for the validation purposes; these are shown in Table 5.3. Whilst these scenarios can cover a range of possible occupant behaviour and the combination of factors, it is acknowledged that each parameter is limited to only two, being the potential maximum and minimum values and therefore will not represent all the range of possible occupant behaviour factors. Therefore, these scenarios should be only viewed as limited possible behavioural scenarios which can result in a range of thermal behaviours of the building.

Table 5.3 Behavioural scenarios used for validation purposes

Scenario Number	Windows opening threshold(^{0}C)	MVHR Bypass mode	Internal gain	Internal Shading
1	22	On	Low	On
2	22	On	High	On
3	25	On	Low	On
4	25	On	High	On
5	22	Off	Low	On
6	22	On	Low	Off
7	22	On	High	Off
8	22	Off	High	On
9	25	On	Low	Off
10	25	On	High	Off
11	22	Off	Low	Off
12	25	Off	Low	On
13	22	Off	High	Off
14	25	Off	High	On
15	25	Off	Low	Off
16	25	Off	High	Off

The validation procedure was performed for all the living rooms of five flats, which were monitored during the summer of 2013. This is mainly due to the maximum monitoring data available for the 2013 cooling season. For the purpose of validation, the actual Coventry weather data collected from Met office for the monitoring period of 2013 has been assigned to the simulation model. The adequacy of modelling technique is appraised by comparing the recorded internal temperature and the simulated internal temperatures based on various occupant behaviour scenarios in the selected flats. This was achieved by plotting the measured and simulated internal temperatures during the monitoring period.

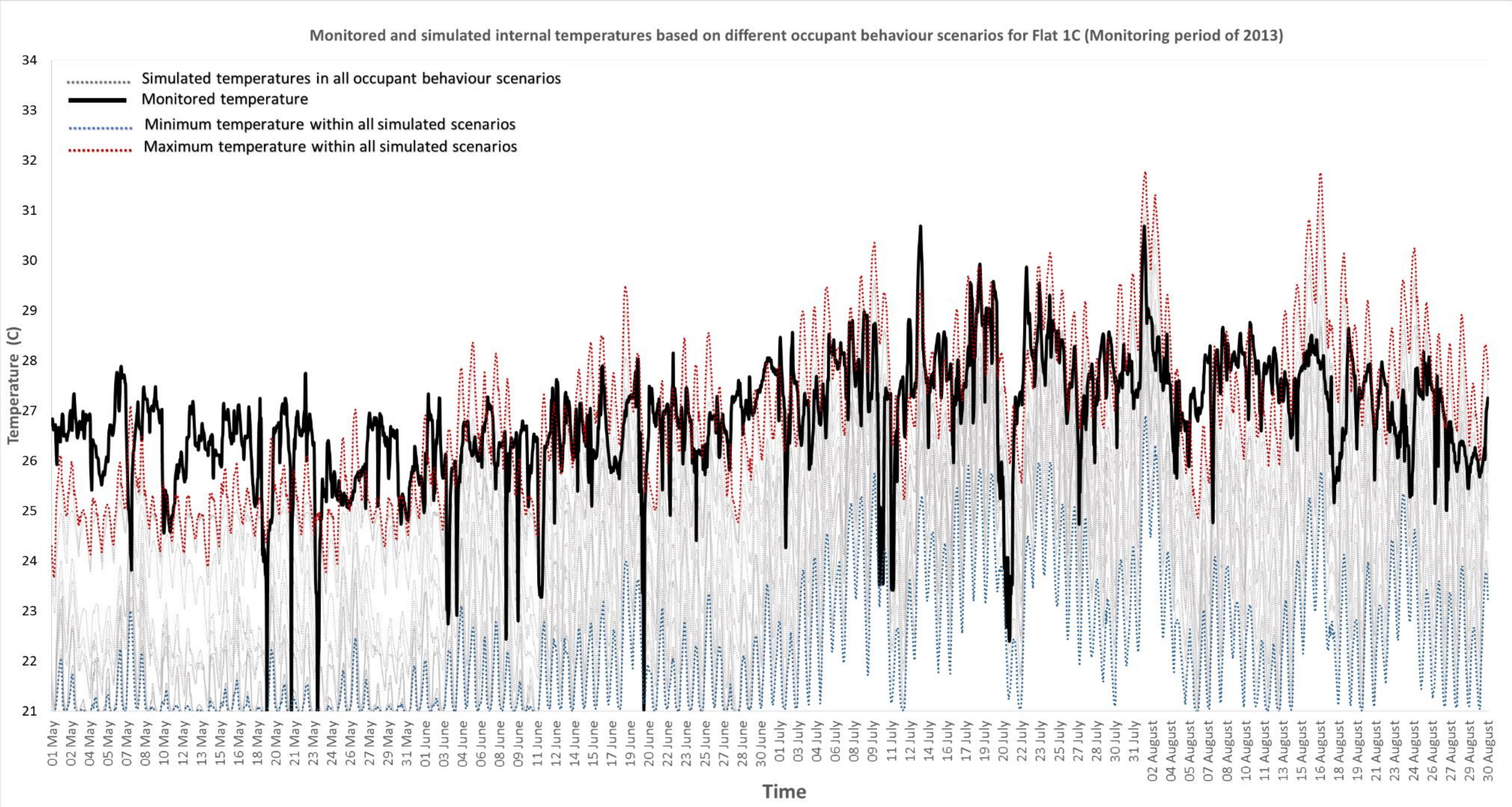


Figure 5.2 Comparison between the measured and simulated internal temperatures based on 16 different occupant behaviour scenarios for the Living room flat 1C (Monitoring period of 2013)

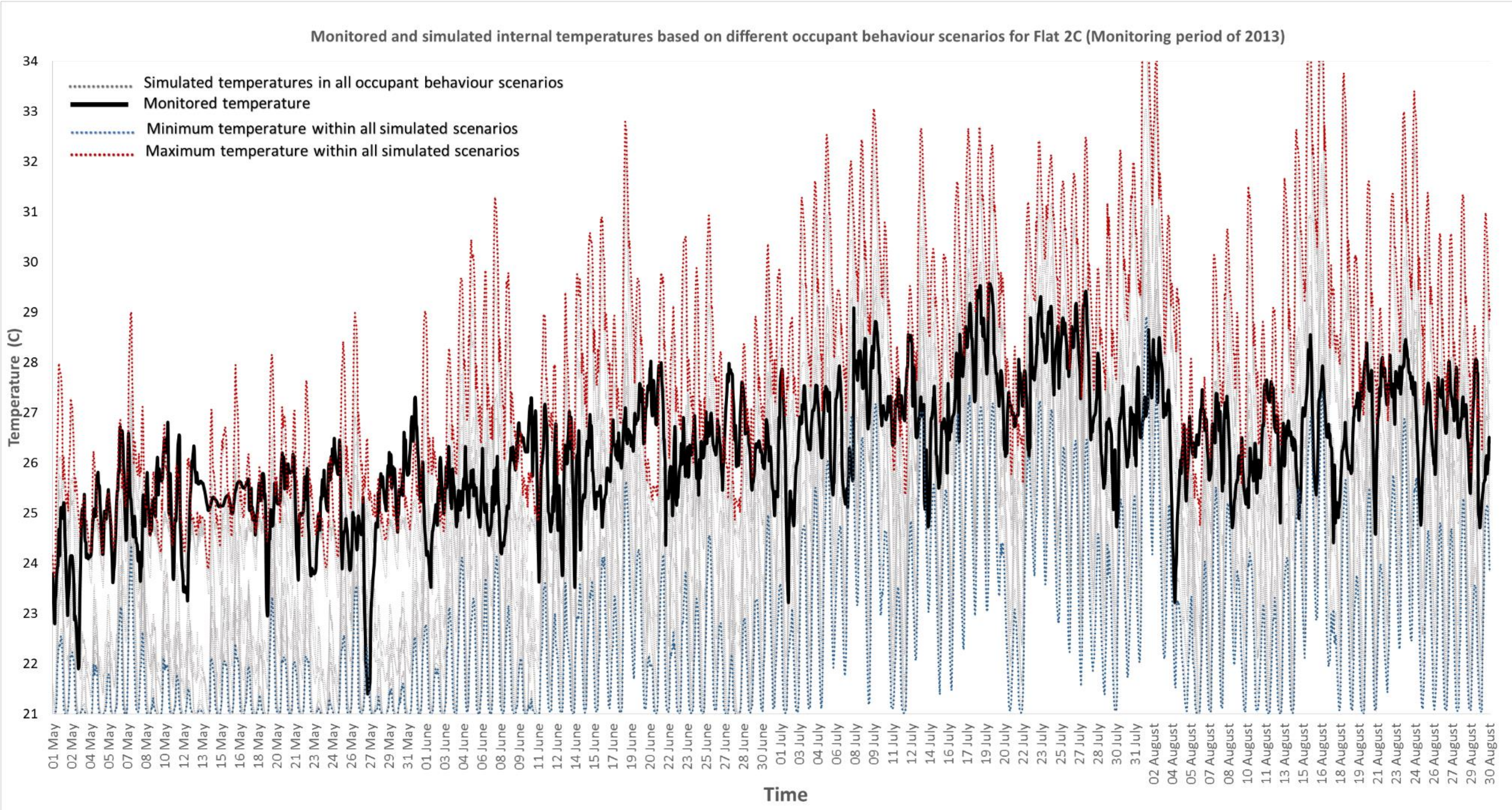


Figure 5.3 Comparison between the measured and simulated internal temperatures based on different occupant behaviour scenarios for the Living room of flat 2C (Monitoring period of 2013)

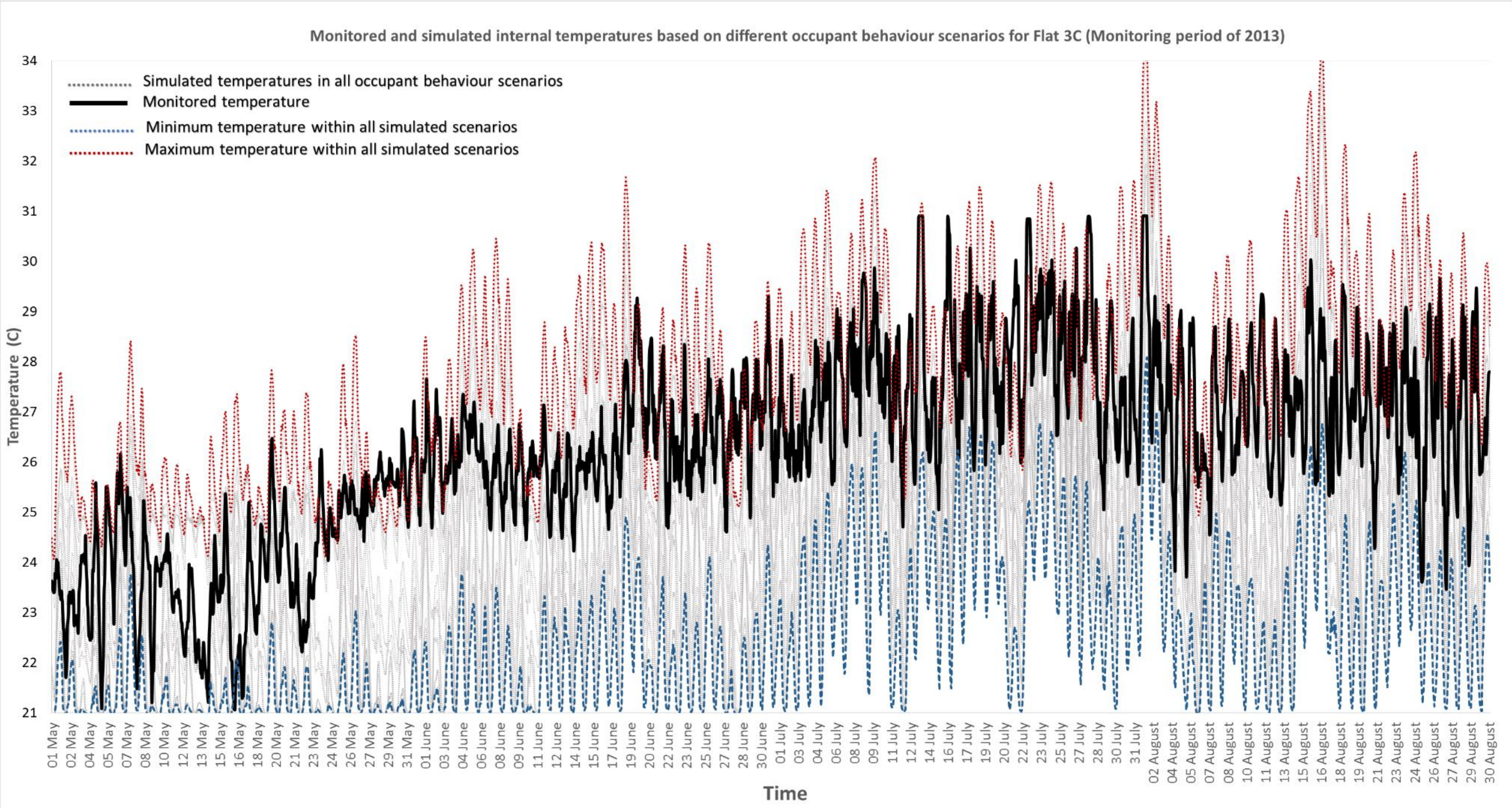


Figure 5.4 Comparison between the measured and simulated internal temperatures based on different occupant behaviour scenarios for the Living room of flat 3C monitoring period of 2013

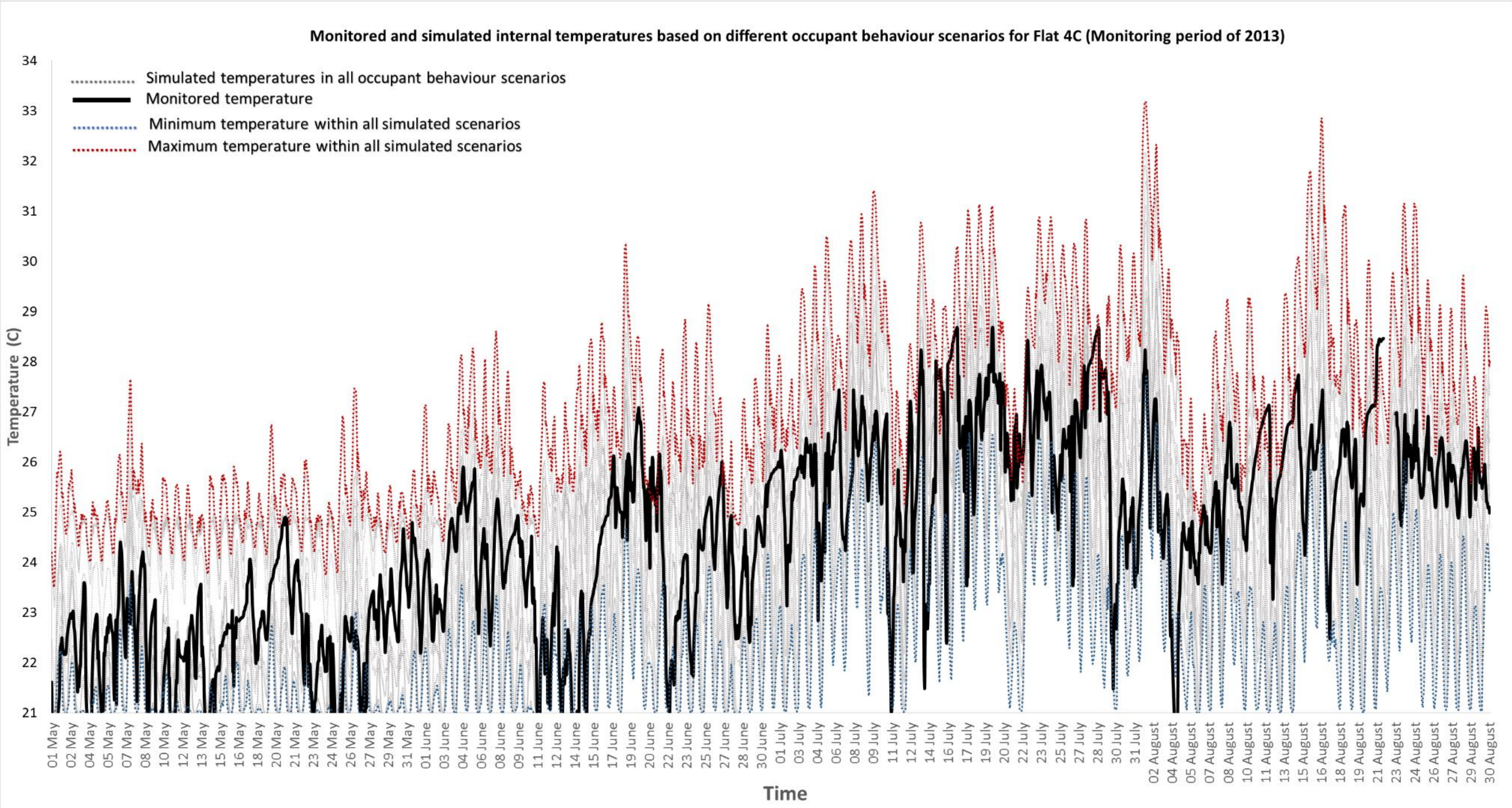


Figure 5.5 Comparison between the measured and simulated internal temperatures based on different occupant behaviour scenarios for the Living room of flat 4C monitoring period of 2013

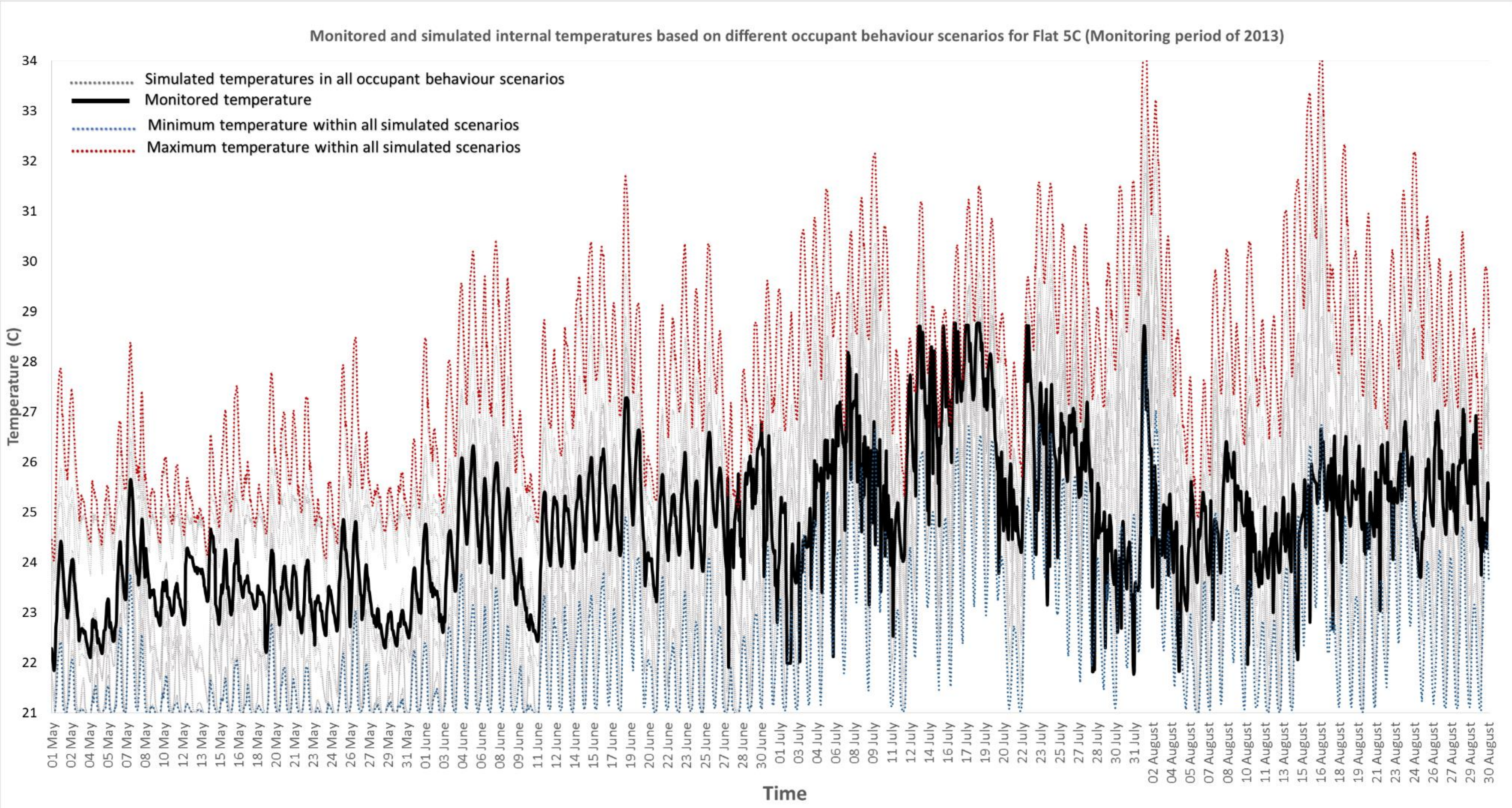


Figure 5.6 Comparison between the measured and simulated internal temperatures based on different occupant behaviour scenarios for the living room of flat 5C monitoring period of 2013

Figure 5.2-6 show the comparison between the measured internal temperature and the values obtained from the simulations for the case study flats during the monitoring period in 2013. The simulations are developed considering 16 different operational scenarios defined in Table 5.3. The comparison between the model output and the measured internal temperature shows good agreement in terms of the pattern of indoor temperatures. However, due to the complexity and randomness of occupant behaviour, while the simulation follows the trend of measured data, it is evident that a single scenario with constant assumption could not exactly model the recorded indoor temperature. Figure 5.2 compares the scenario simulation results with measured internal temperature of the living room of the flat 1C of the case study (Chapter Four), which indicates that simulations could predict the measured temperature in 50% of the time. Figure 5.3, compares the same parameters for flat 2C and it is evident that for 80% of the time, simulations are accurately predicting the measured data; these figures are 84% for flat 3C (Fig. 5.4), 88% for flat 4C (Fig. 5.5) and 89% for flat 5C (Fig. 5.6).

Given the number of uncertainties, simplifications and assumptions in the process, these have been interpreted as a reasonable guarantee for the validity of using IES-VE software for this simulation. This validation procedure proves the potential influence of the occupant's behaviour on indoor temperature. Therefore, in this study the influence of various occupants' behaviour on overheating risk under current and future climate scenarios will be tested in the following sections of this chapter.

5.2.3 Selection of archetypical UK locations for overheating study

The main aim of this chapter is to investigate the feasibility of adopting the Passivhaus standard in developing the new UK social housing flats with respect to their thermal performances. To achieve this aim, it is vital to study the performance of the flats built to this standard within various regions of the UK with different climate conditions. Therefore, archetypical locations across the UK must be selected to represent the climate variations across the country.

For building simulation purposes, standard CIBSE Weather files based on hourly weather data have been derived from historic recorded weather for 14 locations across the UK

(CIBSE, 2015). The geographical information and period of derived data about these locations are presented in Table 3.4 Chapter Three. The average Monthly dry bulb temperature for all these 14 locations is summarised in Table 5.4.

Table 5.4 Average monthly temperature based upon hourly dry-bulb temperature for 1981-2011 at the 14 UK locations for which weather files are provided (CIBSE, 2015)

Location	Average monthly dry-bulb temperature (°C) For stated month (1982-2011)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Belfast	4.5	4.7	6.0	8.0	10.7	13.2	15.0	14.6	12.7	10.0	1.0	5.0	9.3
Birmingham	4.3	4.4	6.4	8.4	11.5	14.5	16.6	16.2	13.7	10.4	6.9	4.7	9.9
Cardiff	5.3	5.2	6.8	8.7	11.8	14.4	16.4	16.3	14.3	11.5	8.3	6.0	10.5
Edinburgh	1.0	4.3	5.7	7.7	10.2	12.9	14.8	14.7	12.5	9.7	6.5	4.2	9.0
Glasgow	4.0	4.3	5.7	7.8	10.5	13.1	15.0	14.5	12.3	9.4	6.4	4.2	9.0
Leeds	5.0	5.3	6.8	8.7	11.8	14.6	16.7	16.5	14.0	10.7	7.3	4.6	10.2
London	5.4	5.4	7.4	9.8	13.1	16.2	18.4	18.0	15.3	11.9	8.2	5.9	11.3
Manchester	4.4	4.6	6.3	8.5	11.6	14.2	16.2	15.8	13.5	10.5	7.0	4.7	9.8
Newcastle	4.3	4.5	5.9	7.6	10.3	13.1	15.3	15.1	12.9	10.1	6.8	4.6	9.2
Norwich	4.0	4.1	6.2	8.6	11.7	14.6	16.9	16.7	14.1	10.7	6.8	4.4	9.9
Nottingham	4.0	4.1	6.0	8.2	11.2	14.2	16.4	16.0	13.5	10.2	6.7	4.5	9.6
Plymouth	6.6	6.3	7.5	9.2	11.9	14.5	16.3	16.3	14.6	12.1	9.2	7.3	11.0
Southampton	5.3	5.2	6.7	8.7	12.1	14.9	16.9	16.7	14.2	11.3	7.9	5.7	10.5
Swindon	4.5	4.5	6.5	8.7	11.9	14.9	17.1	16.7	14.1	10.8	7.1	4.9	10.2

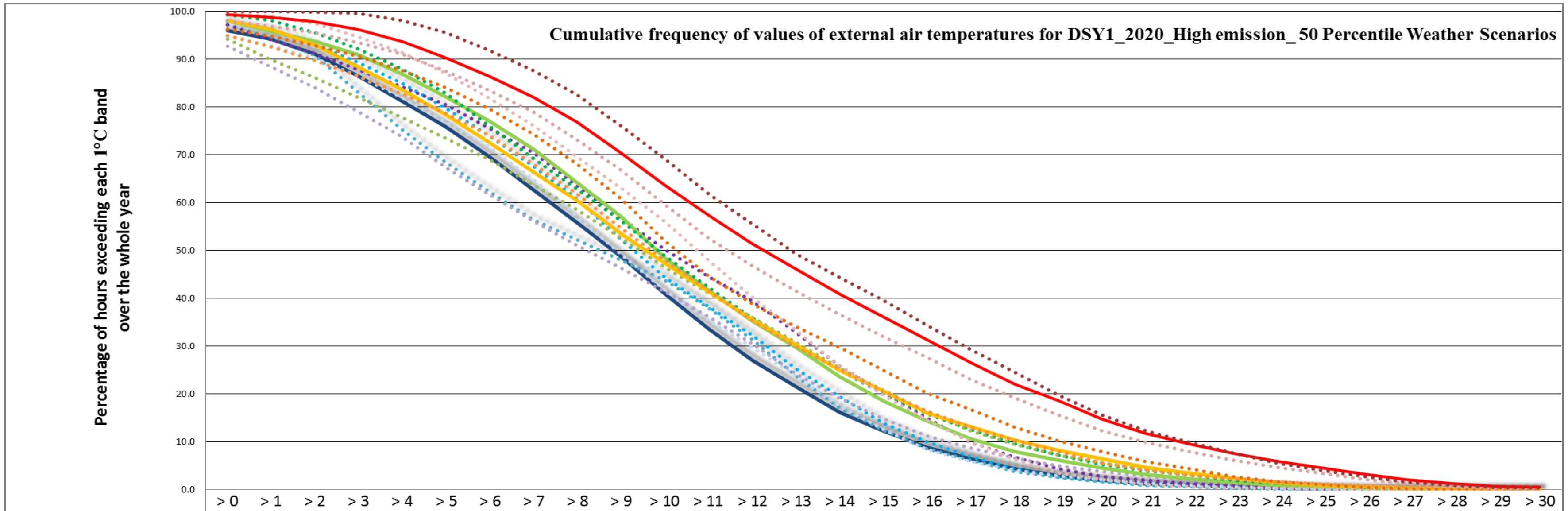
According to CIBSE guide A (CIBSE, 2015), the time scale for expected significant climate change is comparable to the life span of the new buildings in the UK. Therefore, the potential consequences of climate change such as reduced thermal comfort, heating load and increases in cooling load in building should be considered in the design of new buildings by using current and future weather data in evaluating building performance.

As discussed in Chapter Three, for all these 14 locations in which standard weather files are available for building simulation, weather files are also available for three time periods by incorporating the UKCIP09 climate change scenarios (2020s (2011-2040), 2050s (2041-2070) and 2080s (2071-2100)) and considering 10, 33, 50, 66 and 90% probability levels.

According to CIBSE guide A (CIBSE, 2015), for London, weather files are available for three locations (London Weather Centre, London Heathrow and London Gatwick). Therefore, weather files are available for 16 separate locations across the UK for the purpose of building simulation. Also, among all available weather files scenarios and types of weather files for each location, CIBSE TM59 (CIBSE, 2017) specifies the

“DSY1, 2020s, high emissions, 50% percentile” to be used for the purpose of overheating assessment in the new residential building. Hence, these specific 16 weather files represent the various climate condition available for overheating evaluation across the UK.

In order to investigate the various climates available for overheating assessment and compare the likely temperature variations across the UK, the cumulative frequencies of external temperature values for all available locations have been determined by use of the related “DSY1, 2020s, high emissions, 50% percentile” weather files. Figure 5.7 summarised all the values and presents a comparison between all locations with regards to the values of external temperature.



	> 0	> 1	> 2	> 3	> 4	> 5	> 6	> 7	> 8	> 9	> 10	> 11	> 12	> 13	> 14	> 15	> 16	> 17	> 18	> 19	> 20	> 21	> 22	> 23	> 24	> 25	> 26	> 27	> 28	> 29	> 30
Edinburgh	96.0	94.2	91.1	86.5	81.2	75.8	69.5	62.7	55.9	48.7	40.9	33.6	27.0	21.5	16.1	12.2	8.9	6.4	4.4	2.9	1.9	1.3	0.9	0.6	0.3	0.2	0.1	0.0	0.0	0.0	0.0
Belfast	97.9	96.0	93.0	89.3	85.0	79.7	73.9	67.6	60.7	52.3	44.4	38.3	32.2	25.3	19.4	13.9	10.0	6.9	4.4	2.6	1.7	0.9	0.6	0.3	0.2	0.1	0.0	0.0	0.0	0.0	0.0
Newcastle	97.1	94.5	90.8	83.0	75.3	68.4	62.2	56.5	52.2	47.9	43.7	37.9	31.3	23.8	17.0	12.4	8.6	6.1	3.8	2.5	1.7	1.0	0.7	0.5	0.3	0.2	0.1	0.1	0.0	0.0	0.0
Glasgow	94.8	92.8	90.1	86.4	82.0	76.8	71.6	64.8	57.2	49.1	41.6	35.4	29.7	23.7	17.5	12.5	8.4	5.9	4.1	2.9	2.1	1.4	1.0	0.6	0.4	0.3	0.1	0.1	0.0	0.0	0.0
Cardiff	97.2	94.0	91.2	87.8	84.2	80.4	75.5	70.5	63.6	56.8	50.1	44.5	39.4	32.8	25.9	20.1	14.9	9.9	6.7	4.3	2.7	1.9	1.3	0.9	0.6	0.3	0.2	0.0	0.0	0.0	0.0
Nottingham	92.7	88.3	84.0	78.9	73.7	67.4	61.6	56.2	51.1	46.3	41.4	36.1	30.4	24.2	19.1	14.8	11.2	8.7	6.6	5.0	3.8	2.8	2.0	1.4	1.0	0.7	0.4	0.4	0.3	0.2	0.1
Manchester	98.0	95.8	93.8	90.9	86.8	82.1	77.0	71.2	64.2	57.0	48.4	41.6	35.2	29.7	23.6	18.5	14.3	10.7	8.0	6.1	4.5	3.2	2.3	1.6	1.0	0.7	0.4	0.2	0.0	0.0	0.0
Leeds	99.2	98.0	95.6	92.1	87.9	82.9	76.0	69.2	62.8	56.1	48.8	42.2	35.8	30.2	25.0	20.0	15.9	12.6	9.6	7.2	5.3	3.9	3.0	2.0	1.4	1.0	0.5	0.2	0.0	0.0	0.0
Swindon	94.2	89.9	86.1	82.0	77.8	73.4	68.9	63.7	58.5	52.5	46.4	41.1	36.0	30.8	25.4	20.7	16.3	12.3	9.4	7.2	5.5	4.2	3.2	2.2	1.5	1.1	0.7	0.4	0.2	0.1	0.0
Birmingham	98.0	96.3	93.0	88.3	83.6	78.4	72.6	66.5	60.5	53.4	47.4	41.4	35.5	30.3	24.9	20.6	16.0	13.1	10.4	8.2	6.4	4.7	3.4	2.4	1.6	1.0	0.6	0.4	0.2	0.1	0.0
Plymouth	99.7	98.9	97.4	94.6	91.4	87.0	81.8	76.1	69.6	63.0	56.0	47.9	40.2	33.3	25.8	19.8	14.5	10.1	6.3	3.5	2.1	1.1	0.7	0.4	0.3	0.2	0.1	0.0	0.0	0.0	0.0
Norwich	95.0	92.6	89.7	86.4	82.7	78.6	74.0	68.0	61.8	54.7	48.0	41.6	35.2	29.9	25.2	20.5	16.5	13.0	10.3	7.9	5.6	4.0	3.0	2.2	1.7	1.3	1.0	0.7	0.3	0.1	0.0
Southampton	96.2	94.8	92.9	90.6	87.6	84.1	79.6	74.3	68.0	60.7	52.0	44.7	38.9	34.1	29.8	24.9	20.2	16.8	13.0	10.2	7.9	5.8	4.3	2.7	1.7	1.1	0.5	0.2	0.1	0.0	0.0
London Gatwick	98.0	96.9	95.5	93.5	91.0	87.4	83.4	78.9	73.2	66.7	59.5	52.6	46.7	41.5	36.6	31.9	27.6	23.0	19.2	15.5	12.3	9.9	8.0	6.2	4.6	3.4	2.1	1.3	0.7	0.4	0.2
London Heathrow	99.3	98.7	97.9	96.2	93.6	90.3	86.3	82.0	76.8	70.4	63.6	57.4	51.4	46.0	40.9	36.1	31.3	26.5	22.1	18.6	14.8	11.8	9.5	7.5	5.9	4.6	3.2	2.1	1.3	0.7	0.5
London City	100.0	100.0	99.9	99.5	98.1	95.5	91.8	87.6	82.5	76.0	69.1	61.8	55.5	49.3	44.4	39.5	34.3	29.3	24.5	19.8	15.5	12.3	9.9	7.6	5.6	4.1	2.7	1.6	0.9	0.5	0.3

Figure 5.7 Cumulative Frequency of values of external air temperature for “*DSY1_2020_High50*” Weather files in all locations with weather file for building simulation

In general, the London Weather Centre weather file appears to be the warmest external temperature across the sample year, while the London Heathrow weather file shows a more extreme temperature during the summer months, with more than 3% of the annual hours with temperature over 26°C. On the other hand, Edinburgh, Belfast and Newcastle appear to represent the coldest climate condition compared to the other locations. Birmingham and Manchester also seem to present more average external temperatures within the available sites. The latitude of each location is also effective in various climates by determining the angle of solar radiation and the length of days and nights. The UK is located in the northern hemisphere with the range of latitudes from 50° to over 58° north.

In this study, based on the analysis of DSY1 weather files, and in order to consider a wide range of latitude as well as climate conditions within the UK, four different site locations including London Heathrow (51.470 N), Birmingham (52.490 N), Manchester (53.480 N) and Edinburgh (55.950 N) have been selected for the simulation and further studies as they offer the range of conditions from coldest, average and warmest locations across the UK.

5.2.4 Development of base models for the selected locations

In order to study the feasibility and thermal performance of UK social housing flats built to the Passivhaus standard and achieve a reliable outcome, base models which can truly represent the characteristics of these flats must be used. Hence, the base models are developed in this study in accordance with the characteristics of UK social housing flats, Passivhaus and also in line with the available case study and also CIBSE guidelines. In this part of the study, four allocated base models have been developed for the cities of Birmingham, London, Manchester, and Edinburgh.

Base Model for London= BM_{Lnd}
Base Model for Birmingham= BM_{Bham}
Base Model for Manchester= BM_{Man}
Base Model for Edinburgh= BM_{Edin}

In the following sections, the details and rationales for all the values and assumptions which are used for design, together with occupants' behaviours parameters in order to develop the allocated Base Models, are discussed. These base models are then used for parametric study and scenario modelling in this study in order to investigate how the design parameters, occupant behaviour and also weather condition influence the risk of overheating.

5.2.4.1 Design parameters for the development of base model (BM)

The building geometry and the floor plan in designing the Base Model blocks have been developed based on the case study block. Each flat has the floor area of 66 m^2 and two bedrooms which is representative of the average floor area and average number of bedrooms per household in the UK social housing sector (EHS, 2013). However, in order to study the influence of various factors on the risk of overheating and to minimise the duration of simulation and the size of the simulation file, the existing case study block of flats were modified. In this modification, in order to create the condition for all the flats to have similar volume to be heated up or cooled down, and also investigate the influence of heat exchange through exposed surfaces:

1) Only one floor layout was adopted for all the flats and the roof of the building block has been altered from a pitch roof to a flat roof.
2) The building was designed as three storeys (ground, middle and top floor) and with three flats in each storey (east, west and middle). Therefore, the building block has flats with all possible exposed surfaces which influence on the amount of heating exchange.

Furthermore, the following considerations have been applied with relation to design parameter and occupant behaviours.

A: Solar gain in BM: This factor as one of the influential design parameters on the risk of overheating and heating demand is discussed under orientation, window size and also shading device.

A1: Orientations: Porritt et al. (2012) showed that dwelling orientation plays a decisive role in determining the magnitude of overheating risks. However, according to BRE Passivhaus designer's guide (Mcleod et al, 2011), it is argued that where possible, a Passivhaus building should be orientated along an east/west principle axis so that the building faces within 30 degrees of due south (in the Northern hemisphere). This allows the building to derive maximum benefit from useful solar gains, which are predominantly available to south facing facades during the winter months (Feist et al., 2012). Therefore, in this study the dwellings were orientated to the south side, as this is consistent with optimal Passivhaus design in the Northern hemisphere. The dwellings were assumed to be positioned on a horizontal plane without topographical shading. Whilst this arrangement is considered to be optimal from a passive solar design perspective, it is acknowledged that a large number of site specific constraints (including shading obstructions, density requirements and access issues) are likely to have some influence on the performance of dwellings built in an urban location. For these reasons, the findings of this study should be viewed as a comparative analysis of a series of theoretical scenarios rather than a context specific deterministic study.

A2: Glazing area: According to BRE Passivhaus designer's guide (Mcleod et al, 2011), to benefit from the useful solar gains, a Passivhaus requires the glazing to be optimised on the south façade with reduced glazing on the North façade. Historically, Passivhaus buildings in continental Europe had very large areas of south facing glazing often in excess of 50% of the façade area. With good design and modern glazing systems it is possible to reduce the glazed area of the South façade to approximately 25-35%, thus allowing more conventional glazing ratios to be adopted where this is a planning requirement. The south facing glazing area for the case study flats is about 50% of the façade area. Therefore, for the purpose of this study and in order to have the glazing ratio in line with BRE recommendations and allow for a more conventional ratio, 30% glazing ratio is considered for the south façade in all base models.

A3: Shading device: Sunlight in general is welcome in buildings and considered as one of the main principles of Passive design. Solar gain is also a significant design factor and the source of free heat gains during the heating season in Passivhaus buildings (Hopfe and McLeod, 2015). However, excessive solar gain can lead to overheating in summer. Shading is a much more energy efficient and cost efficient way to avoid and control overheating in comparison to mechanical cooling (CIBSE, 2006b; CIBSE, 2015). The UK Building Regulation Part L (ODPM, 2013), sets a requirement to limit the negative effect of solar gain during the cooling season. According to CIBSE TM 37 (CIBSE, 2006b), Design for improve solar shading control, solar shading as a part of passive strategy is particularly effective to avoid risk of overheating. Shading devices can be divided into two types; fixed and adjustable. A number of studies have argued that the operation of the shading devices, such as a blind, is predominantly determined by occupant visual comfort requirement and not indoor temperature (Raja et al., 2001; Nicol, 2001; Inkarojit, 2005; Voss et al., 2005). However, it should be noted that the focus of all these studies were on non-residential buildings. A post occupancy evaluation of the Passivhaus dwellings in the UK also supports the idea that adjustable external shading devices are controlled based on psychological and visual comfort, and not indoor temperature (Architects, 2012). According to McLeod et al., (2013), full external shading devices such as an adjustable external shutter, have rarely been utilised in UK dwellings. CIBSE TM 37 (CIBSE, 2006b) indicates that the most influential way to control overheating is to stop the sunlight reaching the glazing area when it is not required and in particular, simple overhang can be significantly effective for south facing glazing which can block the high angle summer sunlight. Also, overhangs do not hinder the valuable low angle winter sunlight, window opening and a full view.

Therefore, for the purpose of this study, overhangs as a means of providing effective shading is considered for the windows facing to the south in the base models. The performance of the overhang and the extent of solar protection depends on various factors, including the window height, the span between the window and overhang, projection of the overhang, orientation of the windows and the latitude of the site while the maximum solar shading can be provided in mid-summer and minimum over the mid-winter time (CIBSE, 2006b; IES user guide, 2016). In this study, optimum overhangs which are capable of providing 100% shading during summer for the glazing areas are modelled for each base model located in selected locations. This has been achieved by providing the overhangs with the same width as windows and projecting from the top of the windows with adequate depths considering the latitude of each location. In this study, the depth of the overhangs is the only factor which varies based on the locations' altitude which is the good indicator of the sun altitude. Optimum overhang length is calculated by Suncast analysis. The extent of shading protection by the designed overhang can be seen in Figures A1-4 appendix A for the selected locations and different time of the year. In summary, overhang depths for the Base Models of London, Birmingham, Manchester and Edinburgh are calculated as 65, 67, 70 and 75cm respectively. The geometry and layout of the base model blocks are depicted in Figure 5.8.

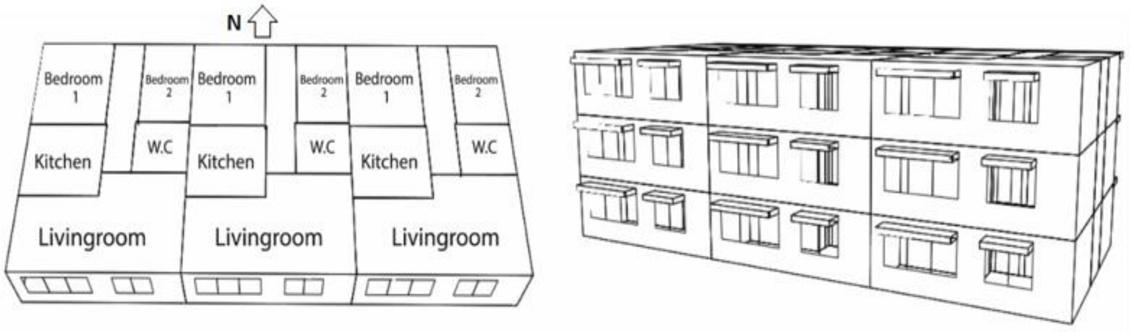


Figure 5.8 View of the Base Model and floor layout in IES

B: Thermal properties in BM: Building fabric specifications such as U-values, glazing g-values and fabric thermal properties and infiltration are modelled in accordance with the case study (summarised in table 5.1). It should be noted that all these values are consistent with Passivhaus specifications describe in Chapter Two. The building is also assumed to be thermally bridge free in line with the Passivhaus criteria (Feist et al., 2012). BRE guidelines for Passivhaus designers (Mcleod et al, 2011) argued that in some situations, U-values must be improved to meet the compliance criteria which is dependent on various factors such as location. A comparison between the maximum U-values for dwellings in the England and Scotland shows an improvement of about 25-40% for different building component U-values in Scotland (ODPM, 2013). Therefore, the improved U-values (0.11 W/m²K) has been considered for BM_{Edin}.

C: Ventilation in BM: This factor, as one of the inflectional design parameters on the risk overheating and heating demand, is discussed as follows:

CO_2 concentration is usually used as an indicator of Indoor Air Quality (IAQ) in building (Taylor and Morgan, 2011). The IAQ standard of any occupied space is classified into four categories as low, moderate, medium and high with default ventilation rates of 5, 8, 12.5 and 20 l/s per person respectively. The Minimum ventilation requirement depends on the nature of the building and occupant type, however, in the UK, this minimum requirement is largely defined within the medium and moderate category for residential buildings (CIBSE, 2015).
CO_2 concentration of 800-1000 ppm, which can be achieved by a fresh air ventilation rate of approximately 8 l/s per person, is commonly used as an indication that the ventilation rate in a dwelling is sufficient (CIBSE. 2015).

According to the BRE Passivhaus designer's guide (Mcleod et al, 2011), in all but the coldest temperatures a Passivhaus building will be capable of maintaining an internal temperature of 20°C solely by relying on the heat given off by appliances, occupants and solar gain and an operating MVHR unit. However, during the very coldest weeks of the year a small amount of supplementary heating may be required, and this can be provided in the form of a post-air heating unit in the MVHR ventilation system and/or small towel radiators or under floor heating in the bathrooms.
Therefore, in order to provide acceptable IAQ (maintaining the CO_2 concentration level below 1000 ppm) and also to maintaining the room temperature at 20°C during the heating season, a Mechanical Ventilation Heat recovery (MVHR) system with heat recovery efficiency of 85%, summer bypass mode and capability of providing 8 l/s per person is included in the model along with low temperature heating water boiler (to be used only when it is necessary). Maximum window opening angles were limited to 10° in all flats in keeping with the use of window restrictors. Such devices are a standard safety feature in new build social housing in the UK in accordance with guidance from the Royal Society for the Prevention of Accidents (RoSPA, 2002).
In summary, south facing glazing ratio, external shading device and roof type are the modified parameters for generating the base models in comparison to the case study block.

5.2.4.2 Occupant behaviour parameters for the development base model (BM)

A: Internal gains in BM: The amount of internal gain is affected by occupancy, lighting and equipment gain which are explained as follow:

A1: Occupancy: CIBSE TM59 (CIBSE, 2017) define occupancy and equipment gain profiles for domestic buildings and highly recommends the use of these profiles for the purpose of overheating investigation in any dwelling. Therefore, daily occupancy profiles were developed based on sub-hourly activity data recommended in this guideline of Table 5.5 with occupant gains data according to activity from CIBSE Guide A (CIBSE, 2015).

Table 5.5 List of occupancy profiles developed and used for this study based on CIBSE TM59 methodology

Room Type	Occupancy profile
Living room	9 am to 10 pm: 2 people at 75% gains Rest of the day: unoccupied
kitchen	9 am to 10 pm: 2 people at 25% gains Rest of the day: unoccupied
Double bedroom	8 am to 9 am and 10 pm to 11 pm: 2 people at full gains 9 am to 10 pm: 1 person at full gain 11 pm to 8 am: 2 people at 70% gain
Single bedroom	8 am to 11 pm: 1 person at full gain 11 pm to 8 am: 1 person at 70% gain

It is notable that the following values and assumptions are considered in development of the above Table 5.5 occupancy profile based on recommended profiles by CIBSE TM59 (CIBSE, 2017):

- Based on CIBSE Guide A (CIBSE, 2015), a maximum sensible heat gain of 75 W/person and a maximum latent heat gain of 55 W/person are assumed in living spaces. An allowance for 30% reduced gain during sleeping time is also included based on ANSI/ASHRAE Standard 55-2010 (ASHRAE, 2013).

- Bedrooms are set with a 24-hour occupancy profile, which means that one person is always considered in each bedroom during the daytime to assess robustly, and two people in each double bedroom at night. This means that one excess person (a visitor) to the assumed total number of occupants will be considered in the flat during the daily hours.
- Kitchens/living rooms are unoccupied during the sleeping hours and occupied during the rest of the day. This is the worst-case scenario since the room will be modelled as occupied only during the hottest hours of the day.

It can be seen that there are no differences between weekdays and weekend with relation to the occupancy pattern. Moreover, the Base Models will be modelled with the 24 hours occupancy profile, since the purpose of the assessment is to test the ability of the representative flat to mitigate the risk of overheating. This approach also helps to address the likelihood of the overheating risks for the vulnerable people (i.e. elderly people, disabled people and babies) who tend to be at home most of the day and whose health will be affected by the rise of temperature and experience of overheating. According to the English Housing Survey (EHS, 2013), the UK social housing sector has the highest unemployment rate and higher age profile (29% aged over 65), therefore, it is important to consider relative occupancy patterns in this study in order to represent a true picture of UK social housing flats.

It is also acknowledged in CIBSE TM59 (CIBSE, 2017) that methodology introduced in CIBSE TM52 (CIBSE, 2013) in order to assess the overheating is very sensitive to occupied hours (as only occupied hours are assessed). In the case of bedrooms, assessing the overheating only during the night-time considers the cooler, no solar gains periods which makes it relatively easy to pass and does not take into account more critical situations (e.g. bedroom used during the daytime by children or people who might use the bedroom as a study/ home office).

A2: Lighting: CIBSE TM 59 (CIBSE, 2017) indicates that for the purposes of the overheating assessment, lighting energy is assumed to be proportional to floor area, and lighting loads are measured in W/m². From 6 pm to 11 pm, 2 W/m² should be assumed as the default for an efficient new-build home. This assumes that good daylight levels are available (also noting that only May to September is assessed within the CIBSE TM52 (CIBSE, 2013) overheating methodology).

In accordance with this assumption and recommendation, an annual lighting gain profile with 2 W/m² between 6-11pm during the cooling season, and between 2-11pm for the rest of the year, was developed and considered in the model.

A3: Equipment gain: According to CIBSE TM59 (CIBSE, 2017), it is assumed that apartments with the same number of occupants and bedrooms are usually provided with the same appliances, therefore the heat loads given out by them should be assumed to be independent of floor area for the purpose of overheating risk assessment. Therefore, the equipment loads are defined in watts (not W/m²).

Table 5.6 shows a summary of the equipment loads recommended in this standard and used in this study. The profile and the associated loads are based on DECC's Household Electricity Survey and Electrical appliances at home: tuning in to energy saving (CIBSE, 2017).

Table 5.6 Details of the equipment loads used in this study based on CIBSE TM59

Room Type	Occupancy profile
Living room	9am to 6pm and 10pm to 12pm: 60W 6pm to 10pm: Peak load of 150W Rest of the day: base load of 35W
kitchen	6pm to 8pm: Peak load of 300W Rest of the day: base load of 50W
Double bedroom	8am to 11pm: Peak load of 80W Rest of the day: base load of 10W
Single bedroom	8am to 11pm: Peak load of 80W Rest of the day: base load of 10W

B: Ventilation factor affected by Occupant in BM: Window opening and use of MVHR bypass mode are the two means of ventilation and heat dissipation available for the occupant during the cooling season.

According to CIBSE TM59 (CIBSE, 2017), windows should be controlled independently in each room and modelled to be opened during the occupied hours of the room and when the internal temperature is above 22°C. The internal doors in the model can be left open during the daytime but must be closed during the occupants' sleeping time. In this study, all windows and doors are modelled as specified above in order to comply with CIBSE TM59 (CIBSE, 2017) guideline. In addition, MVHR bypass mode with capability of providing 8l/s per person was allowed in the model during cooling season.

Table 5.7 Principal characteristic of the base models

Category	Parameter	Description	Reference
Design & Planning Parameters	Floor Plan	Case study	UK social housing characteristic
	Orientation	South-facing	Passivhaus Recommendation/Optimal design from Passive solar perspective
	Topographical Shading	No shading	Passivhaus Recommendation/Optimal design from Passive solar perspective/Worst case from overheating perspective
	Building component U-value (W/m²K)	BM_{Lnd}, BM_{Bham}, BM_{Man}: Walls: 0.15, Roof: 0.12, Gr Floor: 0.12, Windows: 0.85 BM_{Edin}: Walls: 0.11, Roof: 0.11, Gr Floor: 0.11, Windows: 0.85	Passivhaus Requirement (Walls, floors and roofs ≤ 0.15 W/m²K & Complete window installation ≤ 0.85 W/m²K)
	Thermal bridge	Thermal bridge free	Passivhaus Requirement
	Glazing g-values	0.5	Passivhaus Requirement (g-values ≥ 0.5)
	Infiltration rate	0.035ACH	Passivhaus Requirement
	Thermal Mass	Light weight timber frame	Case study
	Glazing ratio	30% of south facing façade	Assumed based on recommended values by BRE (25%-35%)
	Windows opening restriction	10 degree	Social Housing Requirement
	External Shading (Overhang)	Optimal overhang size for south facing glazing designed based on the location latitude	Optimal design from Passive solar perspective
	MVHR flow rate	8L/S/P	Recommended value by CIBSE and literature
	MVHR heat recovery	85%	Passivhaus Requirement/ Common Practice
Occupant Behaviour Parameters	Internal shading	No shading device	Optimal design from Passive solar perspective/Worst case from overheating perspective
	MVHR summer bypass mode	On	Passivhaus recommendation
	Windows opening threshold	22°C	Specified in TM59
	Cross ventilation (Internal door opening)	Open	Recommended by BRE and allowed in TM59
	Internal gain (equipment)	As defined in TM59	Specified in TM59
	Occupancy number	As defined in TM59	Specified in TM59
	Occupancy profile	As defined in TM59	Specified in TM59

5.3 Identifying the flat with greater risk of overheating

According to McLeod et al., (2013), compact dwellings with reduced external heat exchange areas are at greater risk of summer overheating. Also, results from the study by Gupta and Gregg (2013) shows that the future overheating risk in flats and mid-terraced houses will be significantly higher in comparison to less dense dwellings.

For the purpose of this study, there is need to identify which flat within a low-rise social housing block built to the Passivhaus standard is at greater risk of experiencing overheating. For this reason, the percentage of the occurrence of occupied hours with temperature over 22°C in various flats within a sample block are compared using the developed Base Models for the selected locations. All the flats have similar design and occupants' behaviour. The threshold of 22°C is selected for this comparison as this is the recommended temperature for window opening by occupants in CIBSE TM59 (CIBSE, 2017), and it can be assumed as a threshold at which occupants may start feeling warm.

Figure 5.9 shows a comparison between the flats in different positions with regards to the percentage of occupied hours with temperature over 22°C.

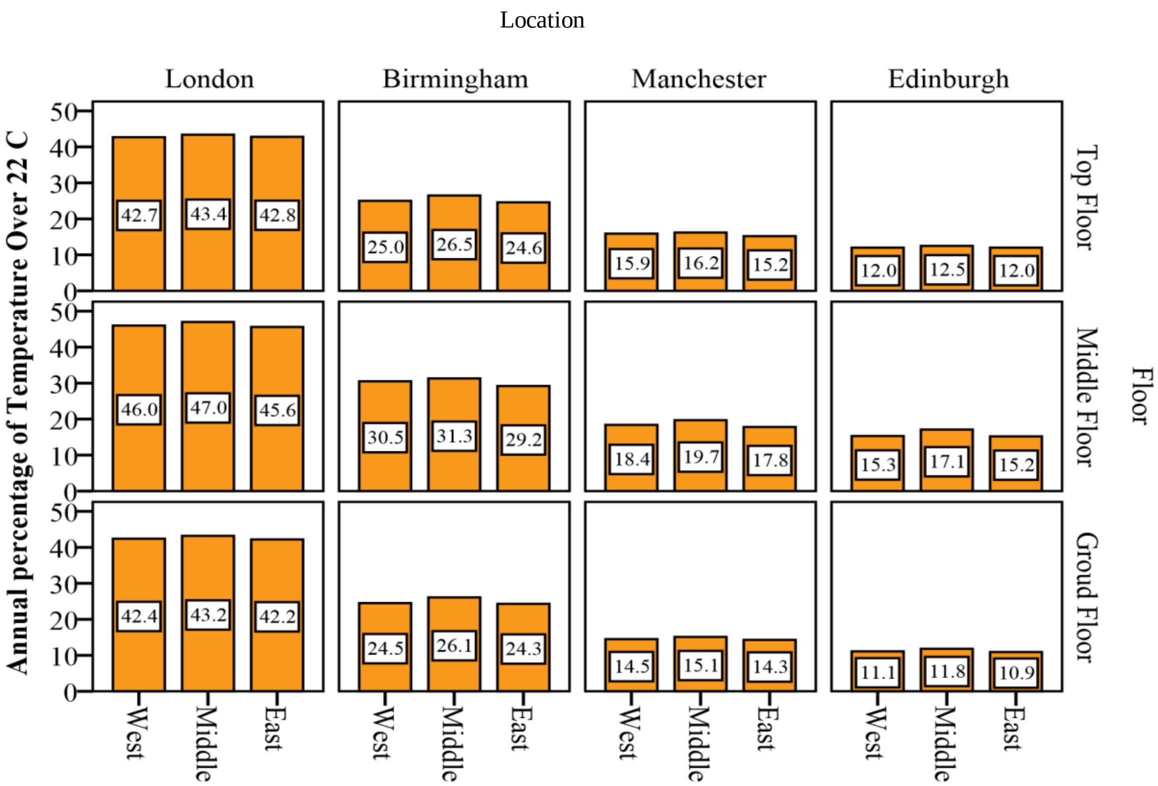


Figure 5.9 Comparison of the flats overheating risk base on flat location in case study blocks

The result shows that in all of these low-rise blocks which are modelled in different locations, flats located in the middle floors have higher elevated temperature in comparison to the flats on ground and top floors. In the London base model block, the average percentage of annual occupied hours with temperature over 22°C is 46.2% for middle floor flats whereas this percentage is 42.6% and 43% for the same flats located on ground and top floors correspondingly. Also, the average annual percentage of occupied hours with temperature over 22°C in middle floor flats indicate a 4.1, 3.4 and 4.1 percentage increase in comparison to ground and top floors flats in Birmingham, Manchester and Edinburgh respectively.
Amongst all middle floor flats located in different geographical locations, middle flats show approximately 1.7 percentage higher risk of experiencing temperature over 22°C in comparison to the east and west side flats.

In accordance with the finding from this comparison and given the importance and focus of overheating in this study, the flat located in the middle of the residential block which has shown to be in greater risk overheating, was considered for the detailed analysis of overheating, parametric study, scenario modelling and future overheating investigation.

5.4 Parametric study and scenario development

This section presents the details of parametric study and also scenario development for both design and occupant behaviour categories. Firstly, parametric study will be carried out based on the selected range of the factors that influence on occupant behaviour and design in order to identify the most influential ones on the risk of overheating. Secondly, two series of scenarios based on the result from parametric study will be developed upon the combination of the effective factors that influence on design and occupant behaviour. Thirdly, the risk of overheating will be tested in for the above detailed scenarios in all selected locations

5.4.1 Parametric study

According to CIBSE TM 37 (CIBSE, 2006b), the main factors that need to be controlled in order to reduce the risk of overheating are ventilation, solar gain, internal gain, thermal properties of the buildings and also design and layout. Each of these factors are influenced by series of sub factors. Parametric study allows the designers to discover which sub factors have the greater influence on the selected output and the use of this technique has been widely recognised in relation to the building simulation (Burhenne et al., 2010; Hopfe and Hensen, 2011; Struck 2012; Sanchez et al., 2014, Alaidroos and Krarti, 2015; Croitoru et al., 2016).

The process of selecting a value or profile for each parameter in developing the base models has been discussed in previous sections. It is also argued that parameters are modelled in line with the values and assumptions stipulated in the Passivhaus standard, CIBSE and BRE design and assessment guidelines, where necessary, and in accordance with the UK social housing characteristics and the existing case study in order to represent reliable base models for this study. However, it should also be acknowledged that these parameters either must be in compliance with the deterministic values or a range of possible values exist which in practice, there is a flexibility in design or occupant behaviour has influence on the value. Therefore, in reality, a wider range of options are available in terms of design and planning which are usually determined by various factors such as site obstructions and limitations, planning policies, cost implication, stockholder or architect preferences etc. Also, when it comes to the occupant behaviour factors, it is down to the occupant as to how they use and run their building and these parameters are in practice determined by them.

The fundamental question which needs to be resolved, is the influence and importance of these parameters on the overheating risk.

The importance of various design and occupant behaviour parameters on the Passivhaus building performance, and particularly with regards to the overheating, were discussed in previous chapters. In summary, parameters such as fabric thermal properties, suitable layout to reduce unnecessary solar gain, glazing area and properties, shading devices, sufficient ventilation and openable windows for natural ventilation, use of MVHR bypass mode and internal gain are mainly identified to have significant effect on overheating (Schnieders, 2005; Wagner and Mauther, 2008a; Wagner and Mauther, 2008b; Schnieders, 2009; larsen and Jensen, 2011; Brunsgaard et al, 2012b; Carrilho da garca et al, 2012; McLeod et al., 2013; Junghans and Berker, 2014; ZCH, 2015; Lavafpour & Sharples, 2015).

Whilst a number of previous studies have investigated the impact of various factors on overheating risk in Passivhaus dwellings, there are a limited number of studies available in context of the UK and also none of these studies have examined the influence of the above parameters particularly in the UK social housing flats built to the Passivhaus standard.
In order to identify the effective parameters and the significance of their influence on the risk of overheating, a parametric study has been carried out, using the Birmingham base model which represents the most moderate/average climate within the UK. For this reason, the parametric study is then divided into two sections including design and planning parameters and occupant behaviour parameters. In this parametric study, the risk of overheating is calculated by changing one factors of design or behaviour at each time.
In order to investigate the relative influence of each parameter on the risk of overheating, the compliances criteria of Passivhaus benchmark together with adaptive thermal comfort based on the specified criteria described in CIBSE TM59 (CIBSE, 2017) for normal occupants' use and the overheating risk in the flat's living room is tested against them. The living room is selected as it is offers a greater risk of overheating with more prolonged occupancy profile during the hours with higher external temperature as well as the existence solar gain.

5.4.1.1 Design parameters in the parametric study (PS)

The design factors which are selected for this parametric study can be classified into three types, including building fabric parameters influencing thermal performance of the dwellings, parameters affecting the solar gain and finally the design factor related to the capability of the building fabric in providing the natural ventilation. The details of each factors are explained as follows:

A: Building fabric parameters in PS:

A1: Thermal mass: Thermal mass has been identified as one of the most important building fabric parameters which influence the thermal performance and consequently the risk of overheating, particularly in highly insulated and airtight buildings (CIBSE, 2006b).

According to IES (2016), weight (Thermal mass) is categorised as follow:

- Very light weight – Total heat capacity less than 95 $KJ/M^2.K$
- Light weight – Total heat capacity less than 137.5 $KJ/M^2.K$
- Medium weight – Total heat capacity less than 212.5 $KJ/M^2.K$
- Heavy weight – Total heat capacity less than 315 $KJ/M^2.K$
- Very heavy weight – Total heat capacity greater than 315 $KJ/M^2.K$

Considering the above limits for categorising the thermal mass, construction materials used in the case study and the all based models (table 5.1) are classified as light weight material.

In order to evaluate the role thermal mass plays in Passivhaus dwellings performance and overheating risk, different construction types, classified as medium and heavy weights, were also developed and modelled, see full details in Table 5.8. Hence, the available construction types can be categorised into three groups of light, medium and heavy weight which are represented in the various possible construction materials. It should be noted that lightweight construction is based on timber frames and internal insulation while the medium and heavy weight construction rely on internal blocks of different thermal properties and external insulation. Also, different construction types are designed and modelled to have the same U-values. The greater weight of the construction is achieved by using higher density blocks and use of wet plaster rather than plasterboard on dabs.

Table 5.8 Building fabric specification used in the parametric study

Parameter	Construction Type/Components	Light Weight	Medium Weight	Heavy Weight
Total Heat capacity (KJ/m^{2}K)	External wall	36	138	238
	Internal wall	24	68	144
	Internal floor	24	109	187
	Roof	36	129	220
	Ground floor	42	120	230
Thickness (mm)	External wall	386	410	410
	Internal wall	150	271	272
	Internal floor	176	211	290
	Roof	290	330	360
	Ground floor	486	486	486
U value (W/m^{2}K)	External wall	0.15	0.15	0.15
	Internal wall	0.30	0.32	0.32
	Internal floor	0.27	0.27	0.27
	Roof	0.12	0.12	0.12
	Ground floor	0.12	0.12	0.12

A2: Thermal conductivity: With regards to the other building fabric characteristics, glazing g-value and fabric u-values are also selected for the parametric study as the factors which can affect the thermal performance of the dwellings. According to the Passivhaus standard (Feist et al., 2012), recommended values for building component U-values (=<0.15W/M^{2}K) and glazing g- value (>=0.5) must be regarded as maximum and minimum acceptable limits respectively. This guideline also argued that in some situations, these values must be improved to meet the compliance criteria and it depends on various factors such as location. Therefore, to investigate the effects of these parameters on the overheating risk, a range of values with discrete figures, described in Table 5.10, has been assumed for these two parameters.

B: Solar gain in PS:

A south facing glazing area and fixed solar shading devices are selected as the effective parameters on the flat solar gain.

B1: South facing glazing area: As discussed in Section 5.2.4.1, a south facing glazing area was considered as 30% of the façade in all base models and this value has been selected as the average of recommended value by the BRE Passivhaus designer's guide (Mcleod et al, 2011). For the purpose of the parametric study, and to investigate the impact of this important factor on overheating, a 20% range with minimum and maximum values of 20% and 40% has been selected to cover the recommended range as well as 5% offset.

B2: Shading device: Following the discussion presented in this chapter with regards to controlling the excessive solar gain and solar shading devices, optimum overhang, with the capability of providing the maximum shading during the summer months, has been selected as a preferable shading device and designed for all base models. It was also argued that based on CIBSE TM 37 (CIBSE, 2006b), preventing the sunlight reaching the glazing is the most effective means of overheating control. Hence, the performance of the overhang, in providing the different extended shading, has been selected as the next factor for the parametric study to investigate the effect of solar shading in overheating risk within the UK Social housing flats built to the Passivhaus standard. This has been carried out by changing the overhang depth to achieve a shading extends of 0 -100% with 10% interval during the summer months.

C: Ventilation in PS:

The capability of the building components in order to provide natural ventilation has been selected for the parametric study. A suitable level of ventilation is required in building for maintaining the indoor air quality at the acceptable level. It was discussed that in Passivhaus buildings, this ventilation rate is provided through the MVHR system. According to CIBSE TM37 (CIBSE, 2006b), the ability to achieve higher air change rate is one of the most effective ways to control overheating. Higher ventilation rates can be achieved by window opening during the summer months in Passivhaus dwellings. Providing a free area through the openable glazing in each building is one of the most effective factor in the amount of natural ventilation and the total free area depends on various factors including number of openable windows, type of the window (i.e. side-hung or top-hung), proportion of the width and height, openable area and maximum angle of opening (IES, 2016).

The maximum angle of window opening in the UK social housing flats is limited to 10^o in accordance with the limit stipulated by Royal Society for the Prevention of Accidents (RoSPA, 2002). However, this is only limited to the factors influencing the free area of the openable glazing, and changing the other effective factors mentioned above can result in having a different available free area for ventilation.

This study investigates the effect of windows opening area and the availability of ventilation rate on the risk of overheating in the UK Passivhaus flats for the first time. Although the window operation in the dwellings is considered as one of the occupant behaviour factors that has an effect on ventilation rate, once the occupant has opened the windows to the maximum angle, the ventilation rate will be determined by the environmental factors (e.g. wind speed) as well as the window opening area.

For purpose of the parametric study in this research project, the range of openable area is considered from $0.21m^2$ to $1.71m^2$ which is achieved and modelled by changing the number of openable windows and also using two main window opening types of side and top-hung with restricted opening angle of 10^o.

5.4.1.2 Occupant behaviour parameters in parametric study (PS)

The influence of occupant behaviour on the variation of internal temperature during the summer months in the UK social housing flats built to the Passivhaus standard has been shown in the case study section in Chapter Four. Results from statistical analysis presented in Chapter Four showed that in majority of the case study flats, less than 50% of the temperature variation can be explained by environmental factors and the temperature variation in each flat is mainly dependent on its occupant behaviour. Occupant behaviour scenario modelling which was developed in section 5.2.1 has also shown that summer internal temperature in a flat could be considerably different and depended on the factors determined by the occupants.

This part of study investigates the influence of occupant behaviour on ventilation, solar shading and internal gain by the use of parametric study.

A: Ventilation factors affected by the Occupant in PS: According to CIBSE TM37 (CIBSE, 2006b), the ability to achieve a higher air change rate is one of the most effective factors in avoiding and controlling overheating. In the Passivhaus dwellings during the summer, natural ventilation can be achieved by opening the windows and mechanical ventilation through MVHR bypass mode.

An internal room temperature of 22°C is the recommended threshold for window opening in accordance with the CIBSE TM59 (CIBSE, 2017), however there is a possibility that occupants open the windows at a higher temperature. Therefore, in order to investigate the implication of window opening threshold on indoor temperature, a range of window opening thresholds from 22°C to 28°C with 1°C interval has been considered in the parametric study.

Ventilation through the MVHR bypass mode during the summer is also modelled in the base model in line with the Passivhaus standard recommendation. However, to explore the influence of the operation of MVHR bypass mode on reducing the risk of overheating, the base model is simulated with and without the inclusion of this supplementary ventilation for the purpose of the parametric study.

In addition to these two effective parameters, possible cross flow ventilation can also increase the air change rate in the dwellings. Based upon the flat geometry illustrated in Figure 5.8, cross flow ventilation in the base models can be possible when the bedrooms' door are open. In accordance to the recommendation of CIBSE TM59 (CIBSE, 2017) with regard to the internal door opening, all internal doors are left open in the base model during the day time but modelled to be closed during the sleeping time. Therefore, allowing the bedroom door to be opened provides an opportunity for the creation of cross ventilation during the daytime in this study, to investigate the effect of single and cross ventilation to reduce the risk of overheating, two values of open and close during the day time are assumed for the internal door in the parametric study.

B: Internal Gain in PS: With regards to the internal gain, the specified profiles presented in Tables 5.5 and 5.6 should be used for the overheating assessment (CIBSE, 2017). As was discussed in section 5.2.4.2, recommended profiles in this CIBSE document are based on the UK household electricity survey and electrical appliances at home (CIBSE, 2017) with the assumption that same appliances are provided for the dwellings with the same number of bedrooms. However, highly energy efficient appliances and equipment must be specified and used in Passivhaus dwellings in order to meet the primary energy target (BRE, 2015).

Some studies (Hopfe and Hensen, 2011; Hu and Augenbroe, 2012; Kim and Augenbroe, 2013) argued that internals gains are a priori scenario dependant and therefore, they cannot be treated the same as other factors and should not be included in the parametric study. However, the non-occupant element of the internal heat gains is considered in this parametric study since this component of the internal gain is affected by the appliances and services specification. Thus, to investigate the effect of internal gain (related to the equipment and not occupant gain) and also use energy efficient appliances and equipment on the risk of overheating, a range of reduced gains, with reference to the specified profiles within CIBSE TM59 (CIBSE, 2017) with 10% interval and up to 50% reduction, has been developed and used for the parametric study.

C: Shading factor affected by the occupant in PS: Effective shading can avoid summer overheating and improve the indoor thermal environment, however, internal shading is less effective in comparison with external shading devices as it can re-radiant or conduct solar radiation into the room (CIBSE, 2006b).

The influence of external shading devices has been considered in this study by parametric study of the shading provided by overhang. However, the occupants also have the choice of using internal shading devices, such as blind or curtain, in their dwellings which can provide them with solar shading. Therefore, the use of internal shading by the occupants and its influence on overheating has been also selected as the other occupant behaviour factor for parametric study in this section.

The internal shading devices can be classified based on the proportion of the incoming solar radiation that passes through them, which is presented by Shading Coefficient (SC). According to CIBSE TM37 (CIBSE, 2006b), SC can be calculated as follow:

$$SC = \frac{Solar\ gain\ through\ subject\ glass\ and\ blind\ at\ direct\ normal\ incident}{Solar\ gain\ through\ reference\ glass\ at\ direct\ normal\ incident}$$

Where the solar gain through the reference glass at normal incident is 0.87

Hence, the shading coefficient specifies the extent to which the shading device decreases the solar gain that passes through the windows, where the value of 1 indicates no shading and 0 means perfect shading. SC for internal shading devices are depend on numerous factors such as type of the shading, colour, material, etc. Undoubtedly, various internal shading devices with different SCs are available for the occupant to use. However, for the purpose of this study and in order to explore the influence of internal shading, which is operated by the occupants, 4 main shading devices that cover a range of shading coefficients, have been selected for the parametric study. The SCs for these devices are summarised in Table 5.9. Values are obtained from the IES (IES, 2016) which are based on the BRE data (BRE, 2002).

Table 5.9 Internal shading devices used in parametric study

Shading Type	Shading Coefficient
No Shading	1
Net Curtain	0.76
Venetian blind	0.61
White cotton curtain	0.54
Mid-pane Venetian blind	0.44

Table 5.10 present a summary of all selected parameters used in parametric study as well as each parameter variation range.

Table 5. 10 Selected design and occupant behaviour factors for parametric study

Parameter Type	Parameter Description	Min- Max (Discrete Values)
Design and Planning Parameters	Thermal Mass	Light, Medium, Heavy
	Building component U-value	0.1 – 0.15 W/m²K (with 0.01 interval)
	Windows G values	0.5- 0.6 (with 0.01 interval)
	South Facing Glazing ratio	20 - 40 % with 1% interval
	External Shading (Overhang)	0 – 100 % shading provided on peak summer day by various overhang length. (with 5% interval)
	Total windows opening area	0.21 to 1.71 m² (interval varies based on selected windows type and number)
Occupant Behaviour Parameters	Windows opening threshold	22- 28°C (with 1°C interval)
	MVHR Summer bypass mode	On – Off
	Cross flow ventilation (Bedrooms' door opening during the day)	Close – Open
	Internal gain (Equipment)	50 -100% of the values specified in TM59
	Internal shading	Tested for four main shading device with associated shading coefficient (0.44, 0.54, 0.61, 0.76)

5.4.2 Scenario development based on results from the parametric study:

The process of selecting design and occupant behaviour factors and their associated ranges for the parametric study has been discussed in the previous section. It has also mentioned that to benefit a more moderate climate, Birmingham's base model has been used for the parametric study and the overheating risks were evaluated in the living room using both Passivhaus and CIBSE compliances, since living rooms are in greater risk of overheating.

Figure 5.10 and Figure 5.11 illustrate the results of this parametric study for the selected factors. It is important to note that these figures are only showing the potential of each parameter to affect the overheating risk when other parameters are fixed using the Birmingham Base Model. The severity of variations in the overheating risk associated with each factor can be different in other locations and the real influence of each parameter is subject to change by the variations and changes in other factors.

Feasibility of Passivhaus standard with regards to the overheating risk in development of the new social housing flats in the UK is the main aim of this study. To date, the studies have been carried out with this regard are either reliant on one base model (fixed design and occupant assumptions) or one location. This study for the first time considers and explains the overheating risk in UK social housing flats built to the Passivhaus standard by considering the implication of various design and occupant behaviour scenarios and in different locations across the UK.

According to CIBSE TM60 (CIBSE, 2018), good practice can be achieved by integrated design where the designers and clients coordinate their inputs in developing the design from the planning through the design, delivery and post occupancy. For this reason and in order to present a comprehensive overheating investigation, a number of scenarios are developed based on various design and occupant behaviour factors that contribute to the risk of overheating and evaluated in all of the selected archetypical locations. In order to develop these scenarios, firstly there is a need to illustrate the effectiveness of design and the effect of occupant factors on the risk of overheating and secondly to select the values for each design and occupants behaviour parameters for the purpose of scenario development. Obviously, the more values selected for each parameter, the greater number of scenarios need to be developed. For this reason, two discrete values (i.e. maximum and minimum) which cover the possible range of values are selected for each parameter for the purpose of scenario development. This will also result in the creation of pairwise models for each selected parameter and in each different location. These pairwise models will be also used in this chapter to investigate the pronounced influence of each parameter on overheating risk in different locations using statistical analysis.

Effective parameters and the associated values to be included in scenario development are selected based on the results from parametric study. As discussed previously, scenario modelling in this study is divided into two categories of design and occupant behaviour.

5.4.2.1 Design parameters in Scenario development (SD)

Figure 5.10a-f shows the results for one factor variable parametric study of the design factors. The variation of the risk of overheating in living room are shown in each figure based on both Passivhaus and CIBSE overheating compliances. Both compliances show the elevated temperature from their related threshold, it is clear that the variation of the overheating risk is higher when this risk is calculated based on Passivhaus criteria compare to CIBSE criteria. The two criteria are not comparable as they use different compliances; however, the wider variation in Passivhaus criteria is mainly due to the two reasons. Firstly, the percentage of the elevated temperature from the related threshold for the Passivhaus criteria is caudated over the whole year whereas the CIBSE criteria is only evaluated during the cooling season. Secondly, the threshold for Passivhaus criteria is generally lower than the adaptive thermal comfort threshold (an example for comparison these thresholds can be seen in Figure 4.5, Chapter Four. Figure 5.10 (a-f) shows the variation of g value, glazing ratio and overhang shading percentage (which have influence on solar gain), window-opening area (that have influence on ventilation) and thermal mass have an impact on the variation in the overheating risk, however, the variation of U-values with the range of 0.1 to 0.15 W/m^2K doesn't have any influence on the variation of the risk of overheating. This finding complies with the factors that need to be considered in order to reduce the risk of overheating in CIBSE TM 37 (CIBSE, 2006b). Therefore, in developing the design scenarios, all the above parameters except U-Value are considered. The values that are considered for each of these parameters in development of design scenarios are explained as follows.

A: External shading in SD: As it can be seen from Figure 5.10 (d), existence of an optimum overhang, which can provide shading during the peak summer time, can reduce the annual frequency of internal temperature over 25°C by 2%. Therefore, to include the effect of external shading, two options to represent the models with optimum overhang and models without any external shading have been included in the scenario modelling.

B: Ventilation in SD: Increasing windows openable area, by adding a greater number of openable windows and also selecting window type with higher openable area (with the restricted angle of 10°), have an influence on reducing the overheating risk. However, although the increase in openable area continues to show the positive effect on Passivhaus criteria, no changes in the adaptive thermal comfort criteria can be observed after achieving a certain value in the available free area. Two values of $0.45m^2$ and $1.4m^2$, achieved by inclusion of two side hung windows and four top-hung windows respectively with 10° maximum angle of opening, have been considered as a representative of the low and high openable window area in the scenario development.

C: Solar gain in SD:

C1: Glazing area in SD: With regards to the south facing glazing area, although a decrease in the percentage of glazing area within the studied range indicates a continued reduction in the annual frequency of internal temperature over 25°C, the decline in overheating risk based on the CIBSE criteria seems to be stopped beyond 32% glazing area. However, since the variation in these parameters show the potential of influencing the overheating risk, 25 and 35 parentages which are the minimum and maximum of the BRE recommendation range (Mcleod et al, 2011) for this design factor are included in scenario modelling as low and high south facing glazing area.

C2: g-value in SD: Figure 5.10 also indicates that using the glazing with the g-value, beyond the recommendation of the Passivhaus Standard, has a potential influence in exacerbating the overheating risk. Therefore, a value of 0.5 which is recommended minimum value for the glazing g-value by the Passivhaus standard (Feist et al., 2012)) and 0.63 which is recommended value by building regulation (ODPM, 2013) representative of low and high g-values are considered in scenario modelling.

D: Thermal mass in SD: Increasing the total heat capacity of the building fabric components also shows the potential of thermal mass in controlling the overheating risk based on both adaptive and Passivhaus criteria. Hence, this parameter is also required to be included in scenario modelling in order to study the potential effects of thermal mass level in combination with the other factors and in the selected location. In addition to the lightweight component used in base models, medium weights construction as described in Table 5.8 is also used for the purpose of scenario development. Although the heavy weight construction can offer a further improvement in overheating control, medium weight construction is used to represent the improved thermal mass level since the heavy weight construction is achieved by traditional construction.

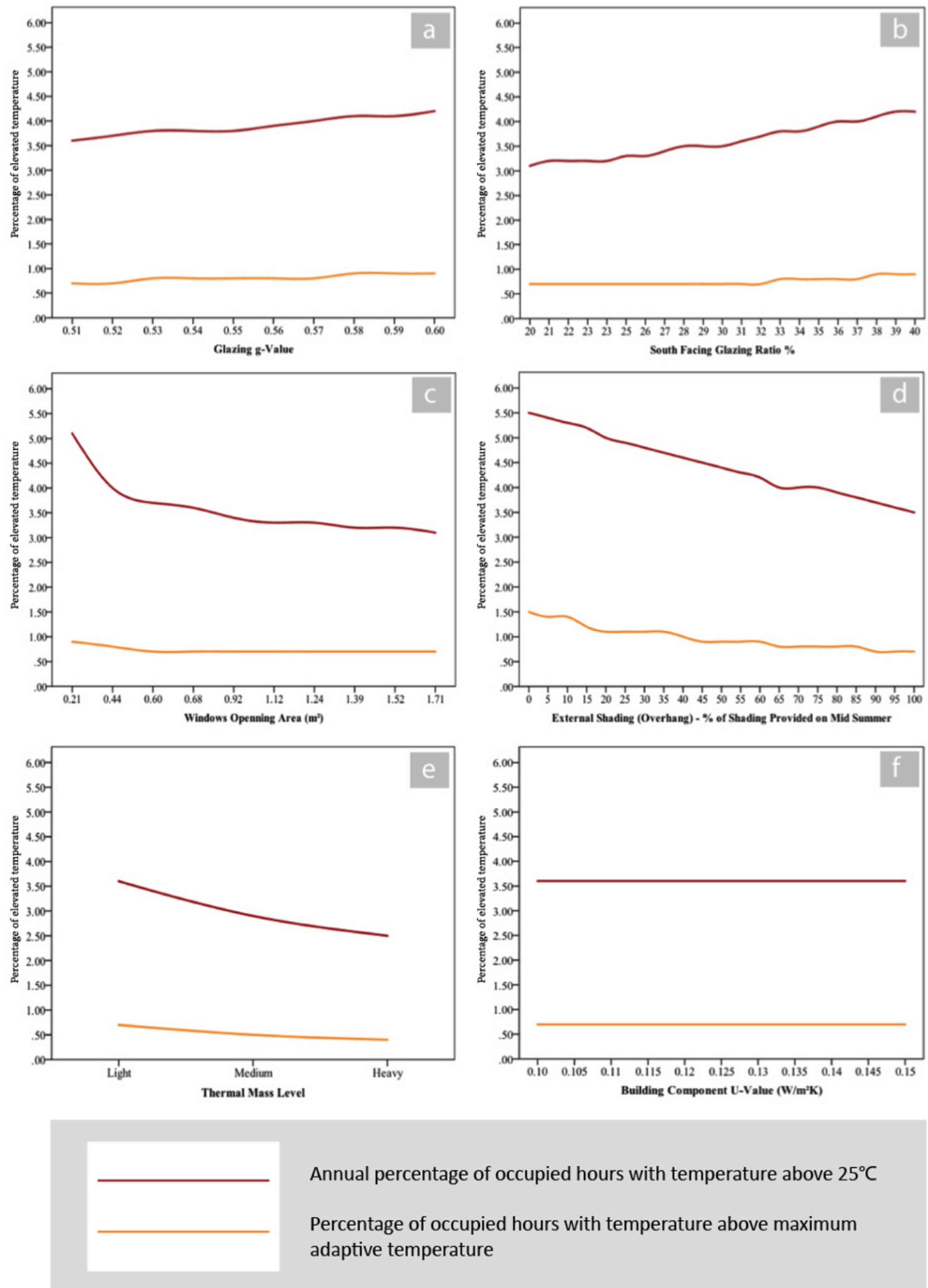


Figure 5.10 Parametric study results for design parameters (glazing g-value (a), south facing glazing ratio (b), windows opening area (c) external shading (d), thermal mass (e) and building component U-value (f))

A summary of the all input parameters with their related variations used in the planning and design scenario modelling is presented in Table 5.11.

Table 5.11 Selected variables for design scenario modelling

Parameter	Variation in scenario modelling	Related value	
Thermal Mass Level	Light	External Wall	35.5 KJ/(m^2K)
		Ground Floor	46.2 KJ/(m^2K)
		Roof	36.1 KJ/(m^2K)
		Internal Floor	24.2 KJ/(m^2K)
		Internal partition	24 KJ/(m^2K)
	Medium/High	External Wall	137.5 KJ/(m^2K)
		Ground Floor	176.4 KJ/(m^2K)
		Roof	141.6 KJ/(m^2K)
		Internal Floor	138.6 KJ/(m^2K)
		Internal partition	81.9 KJ/(m^2K)
Glazing g-Value	Low (Minimum)	0.5	
	High	0.6	
South Facing Glazing Ratio	Low (Minimum)	25%	
	High (Maximum)	35%	
External Shading	No	No Overhang	
	yes	Optimum Overhang	
Windows Opening Area	Low	0.45m^2(Equivalent to 2.6% of south facing façade)	
	High	1.4m^2 (Equivalent to 8.2% of south facing façade)	

5.4.2.2 Occupants parameters in Scenario development (SD)

Figure 5.11a-e illustrate the variation in the risk of overheating based upon the changes in operational factors. Results demonstrate that all of these five selected occupant behaviour factors have influence on the risk of overheating.

A: Ventilation factors affected by occupants in SD: Window opening threshold represents the most pronounced influence on both Passivhaus and adaptive overheating criteria. While window opening beyond the 22°C (CIBSE TM59 recommendation) does not seem to have any effect on reducing overheating risk, delay in opening the window has a significant effect on exacerbating the overheating risk. In this example, Passivhaus and adaptive overheating criteria show a considerable jump when the window opening delays by 2 and 3°C respectively. In order to include the pronounced effect of the window opening threshold in behavioural scenario modelling, 22°C and 25°C are assumed as low and high opening threshold in scenario development. Benefiting from the MVHR by pass mode and also natural cross flow ventilation, affecting the amount of air change rate is one the most effective way to control overheating by CIBSE TM37 (CIBSE, 2006b). Allowing the flat to benefit from these two ventilation types by the occupants shows mitigation in the overheating risk in this parametric study and therefore, both of these parameters are included in the operational scenario modelling as the influential factors in achievable ventilation rate.

B: Solar gain affected by Occupants in SD: Using the internal shading devices by the occupant with lower shading coefficient is also shown to have an impact on reducing the overheating risk. Hence, two operational conditions, one with the use of white cotton curtain with 0.54 SC (as a representative and example of internal shading device) and one with the assumption that occupants do not prefer to use any internal shading device, are modelled and included in occupant behaviour scenario modelling.

C: Internal gain –affected by Occupant in SD: With regards to the internal gain, it has been discussed that the specified values in CIBSE TM 59 (CIBSE, 2017) are the standard and average values for overheating assessment in UK dwellings, and up to 50% reduction in these values are allowed in this parametric study to investigate the effect of using more highly energy efficient appliances in Passivhaus dwellings as recommended by the Passivhaus standard. In this particular model used for parametric study in this section, reduction in the internal gain values seems to have a negligible effect on the selected overheating criteria in comparison to the other parameters. However, stipulated values in CIBSE TM59 (CIBSE, 2017) and profiles with 50% reduction in the internal gain values are included in operational scenario development as representative of high and low internal gain.

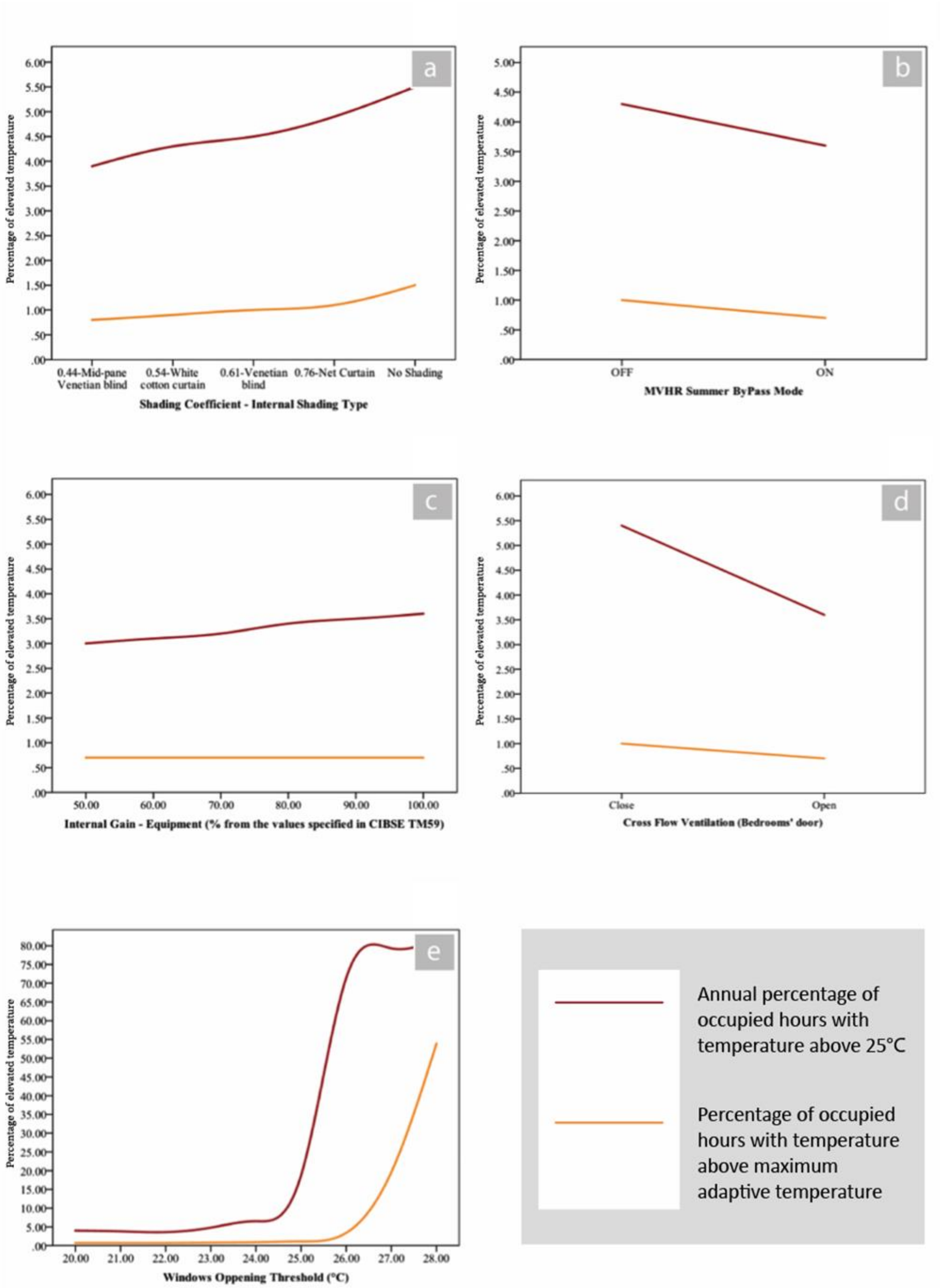


Figure 5.11 Parametric study results for occupant behaviour factors (Internal shading (a), use of MVHR Bypass Mode (b), internal gain (c) Cross flow ventilation (d), Windows opening threshold (e))

Table 5.12 summarises the selected parameters and variations used in occupant behaviour scenario modelling.

Table 5.12 Selected variables for occupant behaviour scenario modelling

Parameter	Variation in scenario modelling	Related value
Windows Opening Threshold	Low	22°C
	High	25°C
MVHR Summer Bypass Mode	On	
	Off	
Cross Flow Ventilation during the day (Bedrooms doors opening profile)	No	Doors Closed
	Yes	Doors open during the day
Internal Gain (Equipment Gain)	High	Values Specified in CIBSE TM59
	Low	50% of the Values Specified in CIBSE TM59
Internal Shading	Yes	Curtain with Shading Coefficient of 0.54
	No	No shading device

5.4.2.3. Design and occupant behaviour scenarios for overheating investigation

The process of identifying the effective parameters for both design and occupant behaviour scenario modelling has been discussed in the previous section. It has also been argued that an unlimited combination of the factors with possible range of values could result in an infinite number of design options or operational conditions. However, to conduct a comprehensive investigation of the overheating risk in UK social housing flats built to the Passivhaus standard, a limited number of design and operational scenarios has been defined in this study by a combination of identified effective factors. It is worth noting that whilst these scenarios are considered to present possible variations in design and occupant behaviour, it is acknowledged that various other options in each category are likely to happen. Therefore, the finding of this study should be viewed as a comparative analysis of a series of scenarios, which represent a wide range of possible design options or operational conditions, rather than a context specific deterministic study.

Following the discussion of the effective parameters in the previous section, five parameters for each category of scenario modelling were selected and described in Table 5.11 and Table 5.12. Also, for each parameter, 2 values (or modelling assumptions) are considered for scenario modelling to include the effect of variation in the selected factor. This will result in 32 number of scenarios for each category. Table 5.13 and Table 5.14 present the details and values of all defined design and occupant behaviour scenarios respectively.

All design and occupant behaviour scenarios are then modelled and simulated in all 4 selected locations for the purpose of overheating evaluation. Results from these simulations will be discussed in the following sections.

Table 5.13 Design scenarios based upon defined variable parameters and fix occupants behaviour

Scenario No.	**South Facing Glazing Ratio**	**External Shading**	**Thermal Mass Level**	**Windows Opening Area**	**Glazing g-Value**
Base Model	Medium (30%)	Optimum Overhang	Light	Medium	Low
1	Low	No Overhang	Light	Low	Low
2	Low	No Overhang	Light	Low	High
3	Low	No Overhang	Light	High	High
4	Low	No Overhang	Light	High	Low
5	Low	No Overhang	Medium	High	Low
6	Low	No Overhang	Medium	High	High
7	Low	No Overhang	Medium	Low	High
8	Low	No Overhang	Medium	Low	Low
9	Low	Optimum Overhang	Light	Low	Low
10	Low	Optimum Overhang	Light	Low	High
11	Low	Optimum Overhang	Light	High	High
12	Low	Optimum Overhang	Light	High	Low
13	Low	Optimum Overhang	Medium	Low	Low
14	Low	Optimum Overhang	Medium	Low	High
15	Low	Optimum Overhang	Medium	High	High
16	Low	Optimum Overhang	Medium	High	Low
17	High	No Overhang	Light	Low	Low
18	High	No Overhang	Light	Low	High
19	High	No Overhang	Light	High	High
20	High	No Overhang	Light	High	Low
21	High	No Overhang	Medium	High	Low
22	High	No Overhang	Medium	High	High
23	High	No Overhang	Medium	Low	High
24	High	No Overhang	Medium	Low	Low
25	High	Optimum Overhang	Light	Low	Low
26	High	Optimum Overhang	Light	Low	High
27	High	Optimum Overhang	Light	High	High
28	High	Optimum Overhang	Light	High	Low
29	High	Optimum Overhang	Medium	Low	Low
30	High	Optimum Overhang	Medium	Low	High
31	High	Optimum Overhang	Medium	High	High
32	High	Optimum Overhang	Medium	High	Low

Table 5.14 Occupant behaviour scenarios based upon defined variable options and fix design

Scenario No.	Internal Gain (Equipment)	MVHR ByPass	Cross Flow ventilation (Bedroom's Door)	Internal Shading	Windows Opening Threshold (^{0}C)
Base Model	**Standard**	**ON**	**Yes**	**NO**	**22**
1	Standard	ON	Yes	No	22
2	Standard	ON	Yes	No	24
3	Standard	ON	Yes	Yes	22
4	Standard	ON	Yes	Yes	24
5	Standard	ON	No	No	22
6	Standard	ON	No	No	24
7	Standard	ON	No	Yes	22
8	Standard	ON	No	Yes	24
9	Standard	Off	Yes	No	22
10	Standard	Off	Yes	No	24
11	Standard	Off	Yes	Yes	22
12	Standard	Off	Yes	Yes	24
13	Standard	Off	No	No	22
14	Standard	Off	No	No	24
15	Standard	Off	No	Yes	22
16	Standard	Off	No	Yes	24
17	Low	ON	Yes	No	22
18	Low	ON	Yes	No	24
19	Low	ON	Yes	Yes	22
20	Low	ON	Yes	Yes	24
21	Low	ON	No	No	22
22	Low	ON	No	No	24
23	Low	ON	No	Yes	22
24	Low	ON	No	Yes	24
25	Low	Off	Yes	No	22
26	Low	Off	Yes	No	24
27	Low	Off	Yes	Yes	22
28	Low	Off	Yes	Yes	24
29	Low	Off	No	No	22
30	Low	Off	No	No	24
31	Low	Off	No	Yes	22
32	Low	Off	No	Yes	24

5. 5 Results and analysis of scenario modelling

This section presents and discusses the scenario modelling developed for both design and occupant behaviour parameters, see Table 5.13 and Table 5.14, in order to investigate the risk of overheating in social housing flats built to the Passivhaus standard across the UK. For each location, a total of 65 scenarios, including base model scenario, have been modelled and simulated individually using 2020 weather data which is the representative of the current weather data (CIBSE, 2017). Given that heating demand is a core requirement for the Passivhaus standard, the result of simulations confirm that annual flat heating demands for both design and occupant behaviour scenarios are within the Passivhaus criteria and are less than 15KWh/m^2/year (Figure 5.12 and Figure 5.17). For this reason, all the scenarios can be a representative of a Passivhaus flat and can be used as a base for the overheating analysis. In the following sections the overheating risk in all these scenarios are investigated using both compliance criteria including Passivhaus and Adaptive Thermal Comfort (CIBSE TM 59). Adaptive Thermal comfort provides an opportunity to evaluate the risk of overheating in living room and bedroom for occupants with different level of vulnerability.

5.5.1 Simulation results for design scenarios

All the design scenarios were simulated under the weather data of 2020 in four locations across the UK to obtain indoor door temperature and consequently investigate the risk of overheating in the flats based on both Passivhaus and Adaptive overheating criteria. Results from all these scenario modellings are presented in tables B1 - B4, appendix B. It is notable that in all these design scenarios, occupant behaviour parameters are fixed based on the values considered in the base models.

The results obtained from simulation modelling is sorted based on annual percentage of living room occupant hours with a temperature over 25°C (Passivhaus overheating criteria). The results tabulated for scenarios modelling are ranked based on an increasing risk of overheating and show which design scenarios will lead to a higher risk of overheating. It is notable that if the sorting criteria alternate based on other overheating critera (Adaptive Thermal Comfort) or living spaces (bedrooms), the ranking of overheating risk for various design scenarios will change slightly. Despite the slight changes in the overall ranking of the overheating risk based on different overheating criteria and living spaces, Table B1-4, appendix B, represent the design scenarios with high overheating risks for all locations investigated in this study.

Annual heating demand has been determined in the study flats for all design scenarios. Figure 5.12 shows the variation of annual overheating demand for all locations simulated within this study. The figure compares the flat heating demand for each location to the Passivhaus standard limit. The results show that the overal annual heating demand for London is the least in comparison to the other three locations, while Edinburghh has the highest annual heating demand.

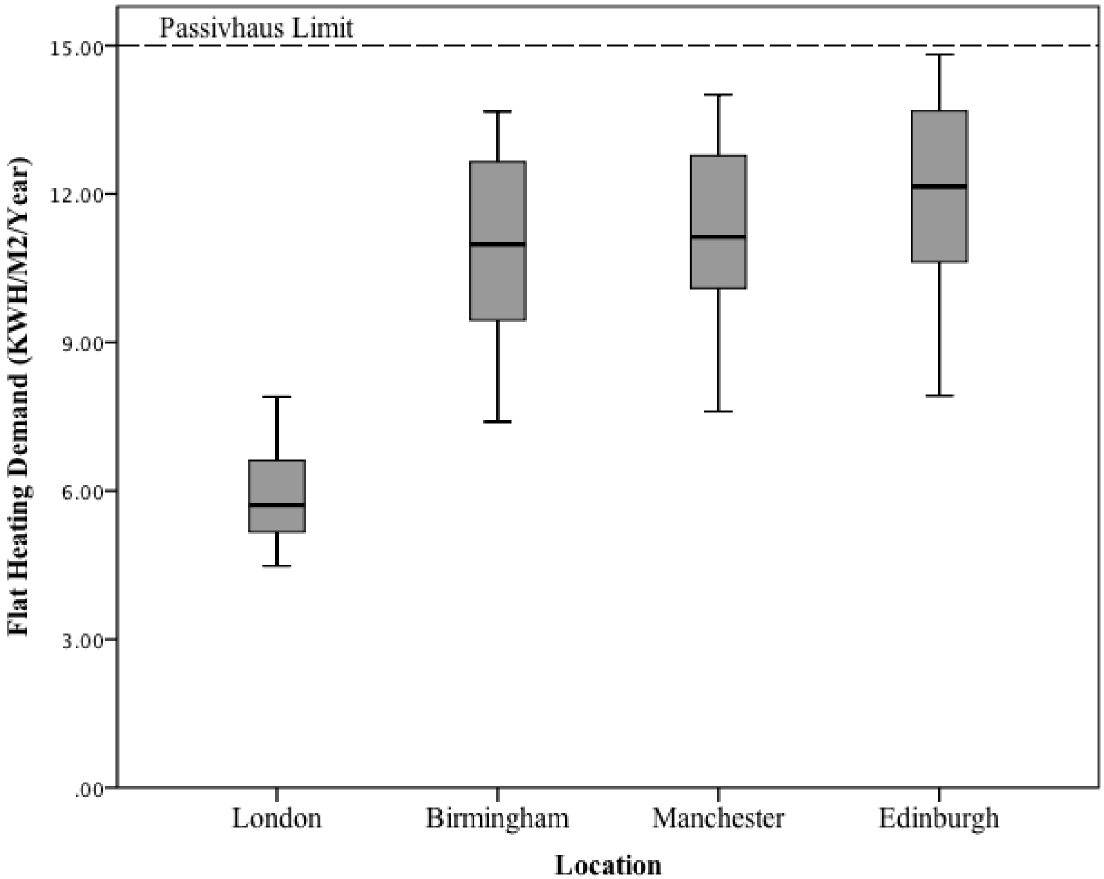


Figure 5.12 Flat heating demand in all design scenarios

Figure 5.13 presents the overheating risks based on Passivhaus criteria for all studied locations. The simulation results show that for the living room, which is the room with highest occupancy duration, annual percentage of occupied hours with temperature over 25°C have the highest values for the case of London. Figure 5.13 indicates that all scenarios simulated for the case of London have failed based on Passivhaus criteria. In the case of London, simulations show that between 10.5 – 23% of annual occupied hours, the living room temperature is above 25°C. The results show that for all other locations, the living room has passed Passivhaus overheating criteria, with worst design scenario options of 8.6% for Birmingham, 6.2% for Manchester and 3.3% for Edinburgh.

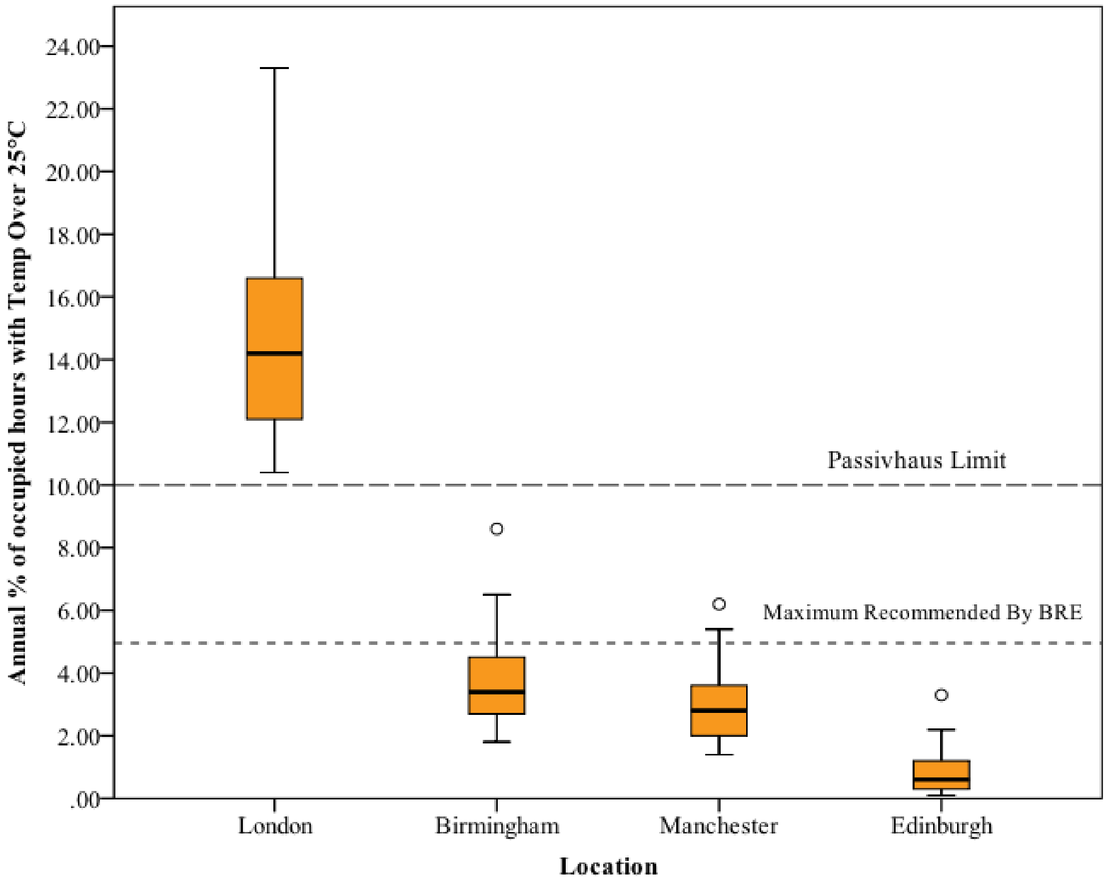


Figure 5.13 Overheating risk based on Passivhaus criteria in all design scenarios

Figure 5.14 presents adaptive thermal comfort (CIBSE TM59) overheating criteria for all design scenarios and locations investigated within this study. The figure shows the overheating risk in the living room for both vulnerable (CAT I) and normal (CAT II) occupants. The analysis of simulation results shows that in general, a higher risk of overheating exists for vulnerable occupants. For London, all design scenarios for vulnerable occupants have failed; however, only six scenarios comply with overheating criteria based on normal occupant type. The maximum percentage of occupied hours with temperature over maximum adaptive thermal comfort limits for the case of London is 15% for normal occupants and 18.5% for vulnerable occupants. The best design scenario for the case of London will pass overheating criteria with 1.9% for normal occupants, however, this design will fail for vulnerable occupants with 5%.

For all scenarios, assessment based on normal occupant type shows that risk of overheating does not exist for the case of Birmingham, Manchester and Edinburgh. The assessment of results based on vulnerable occupant type shows that 5, 4 and 1 of 33 scenarios in Birmingham, Manchester and Edinburgh have failed the overheating criteria respectively.

The analysis of simulation results shows that the percentage of occupied hours with temperature over maximum adaptive temperature range between 0 - 1.1% for normal occupants is in Edinburgh, with 27 scenarios where the internal temperature did not exceed the adaptive thermal comfort limit. This range is between 0 - 3.3% for vulnerable occupants in Edinburgh with 17 scenarios where the internal temperature did not exceed the adaptive thermal comfort limit.

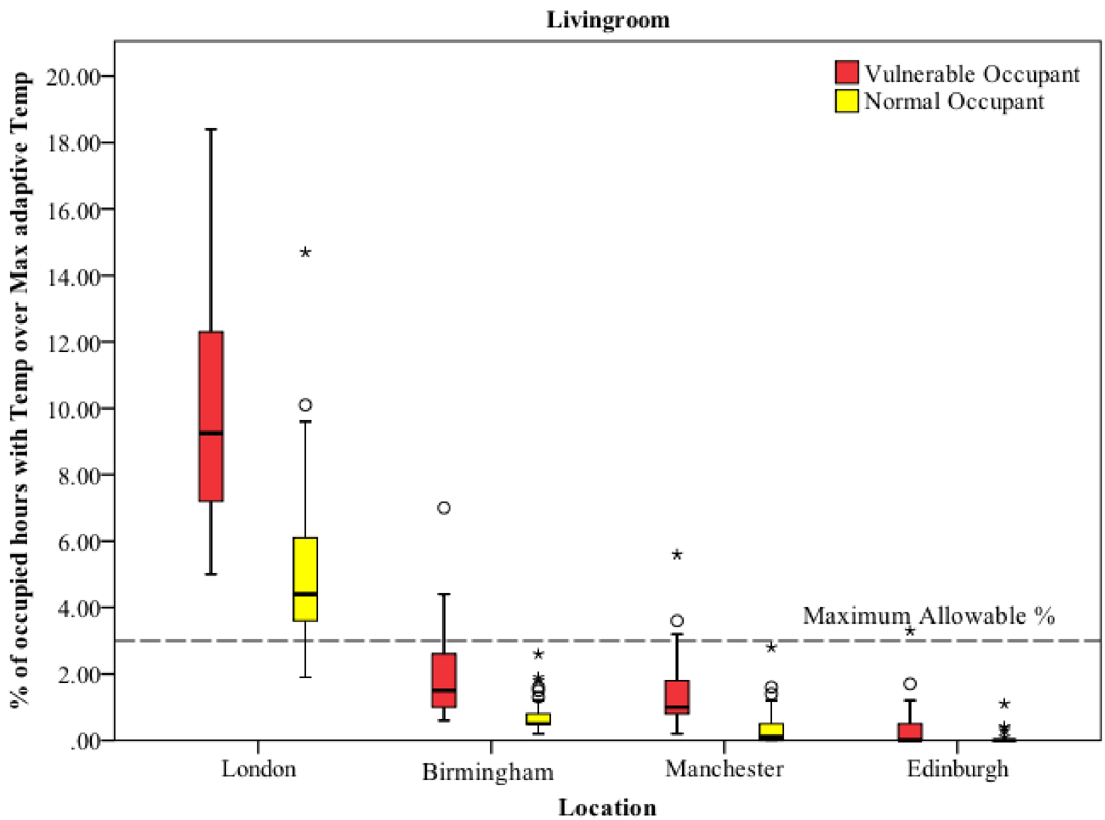


Figure 5.14 Living room overheating risk based on CIBSE Criteria in all design scenarios

As discussed in Chapter Three, the bedroom will meet the overheating compliances if the percentage of occupied hours with temperature over maximum adaptive temperature is less than 3% (Criteria a) and the maximum number of annual occupied hours with temperature over 26°C is below 32 hours (Criteria b). Figure 5.15 and Figure 5.16 represent the results of bedroom overheating assessment based on CIBSE criteria a and 2, respectively, for all design scenarios and study locations. These figures show the results for both bedroom 1 and 2.

The simulations for London shows that for bedrooms, the overheating assessment based on Criteria a (which described above) results in 3 and 23 failed scenarios for normal and vulnerable occupants respectively. However, the analysis of the results based on Criteria b shows that all scenarios failed. Hence, none of the scenarios in London met bedroom overheating compliances according to CIBSE TM59 (CIBSE, 2017).

For all other study locations, the assessment of simulation results show that bedrooms meet both Criteria a and b for both occupant types and therefore there is no risk of overheating in bedrooms based on CIBSE TM59 (CIBSE, 2017) compliances. For the case of Edinburgh, the results show that bedroom temperature never exceeded 26°C and maximum adaptive thermal comfort temperature for normal occupant. For Birmingham, bedroom temperature above 26°C varies between 2 - 21 hours, whilst this number varies between 0 - 25 hours in a year for the case of Manchester.

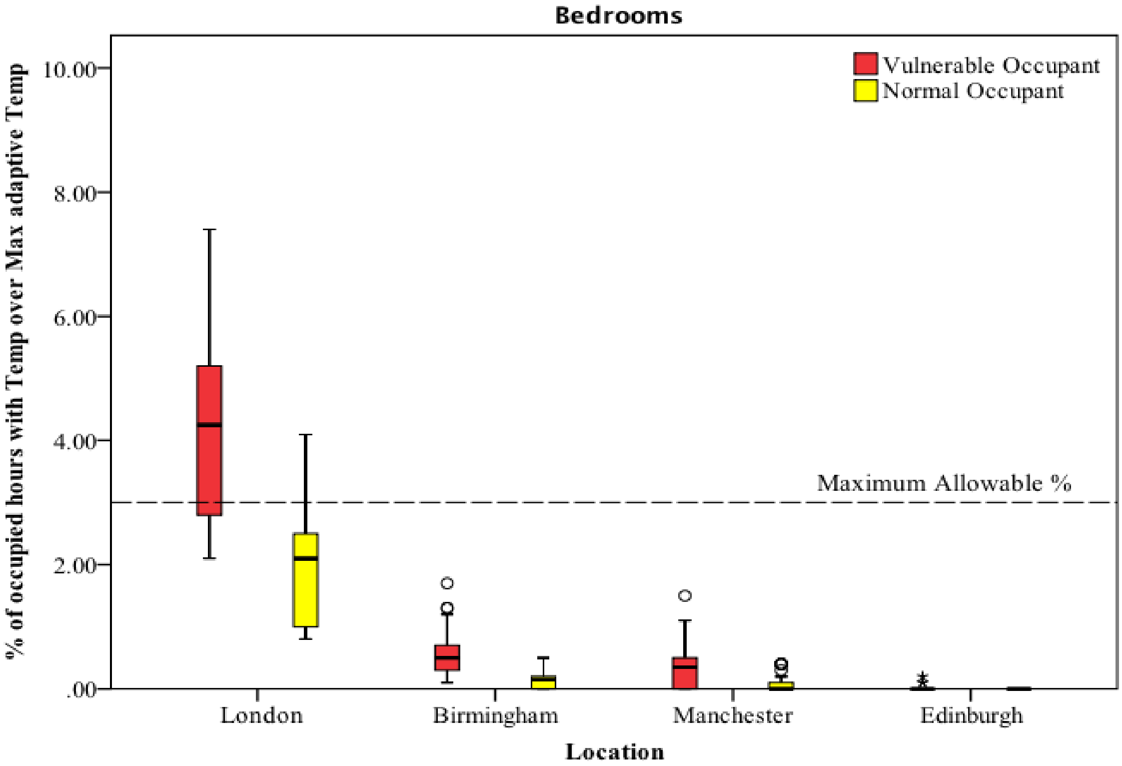


Figure 5.15 Bedrooms overheating risk based on CIBSE Criteria in all design scenarios - Criteria a

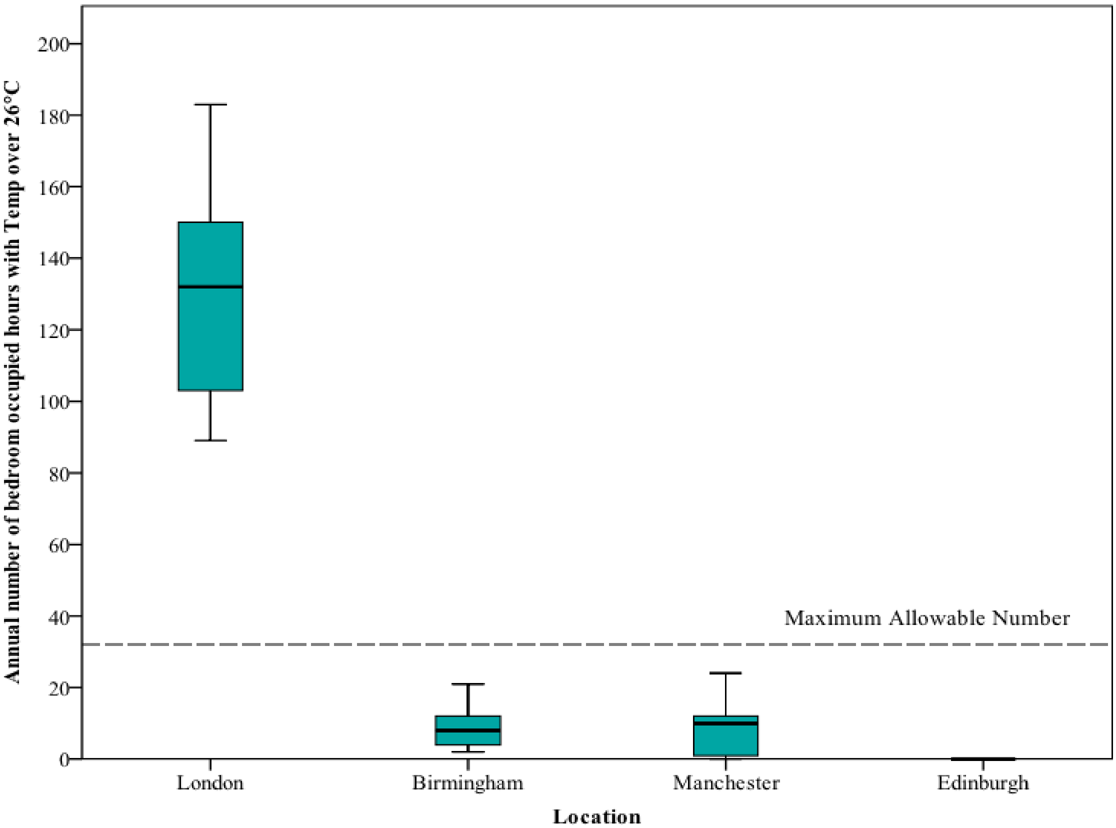


Figure 5.16 Bedrooms overheating risk based on CIBSE Criteria in all design scenarios - Criteria b

5.5.2 Simulation results for occupant behaviour

This section presents the results of simulation based on 32 occupant behaviour scenarios defined in Table 5.14. All the occupant behaviour scenarios were simulated under the weather data of 2020 in four loactions across the UK to obtain indoor temperature and consequently investigate the risk of overheating in the flats based on both Passivhaus and Adaptive overheating cariteria. It is notable that in all these occupant behaviour scenarios in each location, design parameters are fixed based on the related base model.

Results from all these scenario modellings presented in tables C1 - C4 , appendix C. The results tabulated for scenarios modelling are ranked based on increasing risk of overheating and show which occupant behaviour scenario will lead to a higher risk of overheating. The ranking presented in this section is similar to the procedure described in previous section.

Annual heating demand has been determined for the study flat for all occupant behaviour scenarios. Figure 5.17 shows the variation of annual overheating demand for all locations simulated based on occupant behaviour scenarios and compares the flat heating demand for each location to the Passivhaus standard limit.

The results show that the overall annual heating demand for all locations is below 10 kWH/m^2/year. For London, heating demand is the least amongst the four locations investigated within this study. All scenarios were simulated based on occupant behaviour scenarios for all locations are meeting the criteria for Passivhaus heating demand.

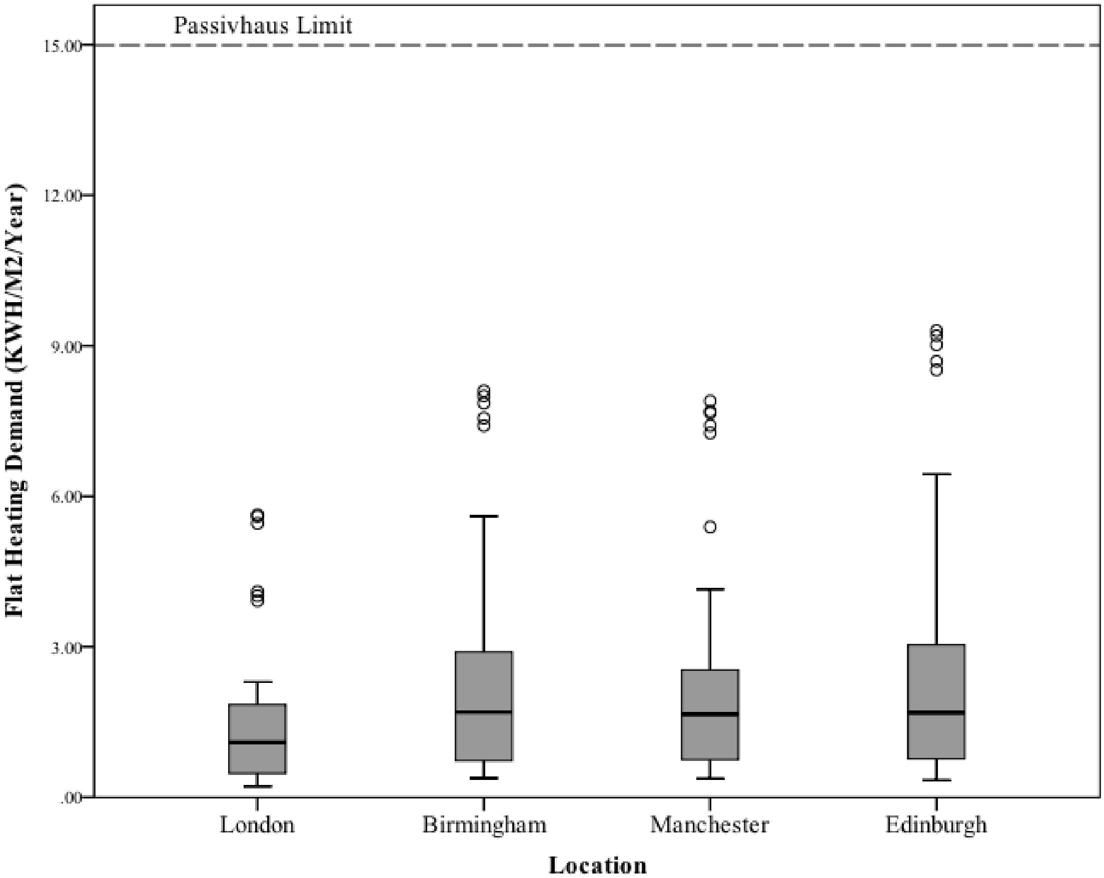


Figure 5.17 Flat heating demand in all occupant behaviour scenarios

Figure 5.18 shows the living room overheating risks based on Passivhaus criteria for all studied scenarios, based on occupant behaviour.

The simulation results show that for the living room, which is the room with highest occupancy duration, and an annual percentage of occupied hours with temperature over 25°C, London has the highest values.

All occupant behaviour scenarios except one have failed the Passivhaus overheating criteria for the case of London. The only scenario which passed the overheating limit showed 9.8% for annual occupied hours which is very close the 10% limit of the Passivhaus standard.

In the case of London, simulations show that between 9.8 - 24% of annual occupied hours, the living room temperature is above 25°C. For all other locations, the living room has passed Passivhaus overheating criteria, with the range of 2.1 - 7.6 % for Birmingham, 1.4 - 7% for Manchester and 0.1 - 3% for Edinburgh.

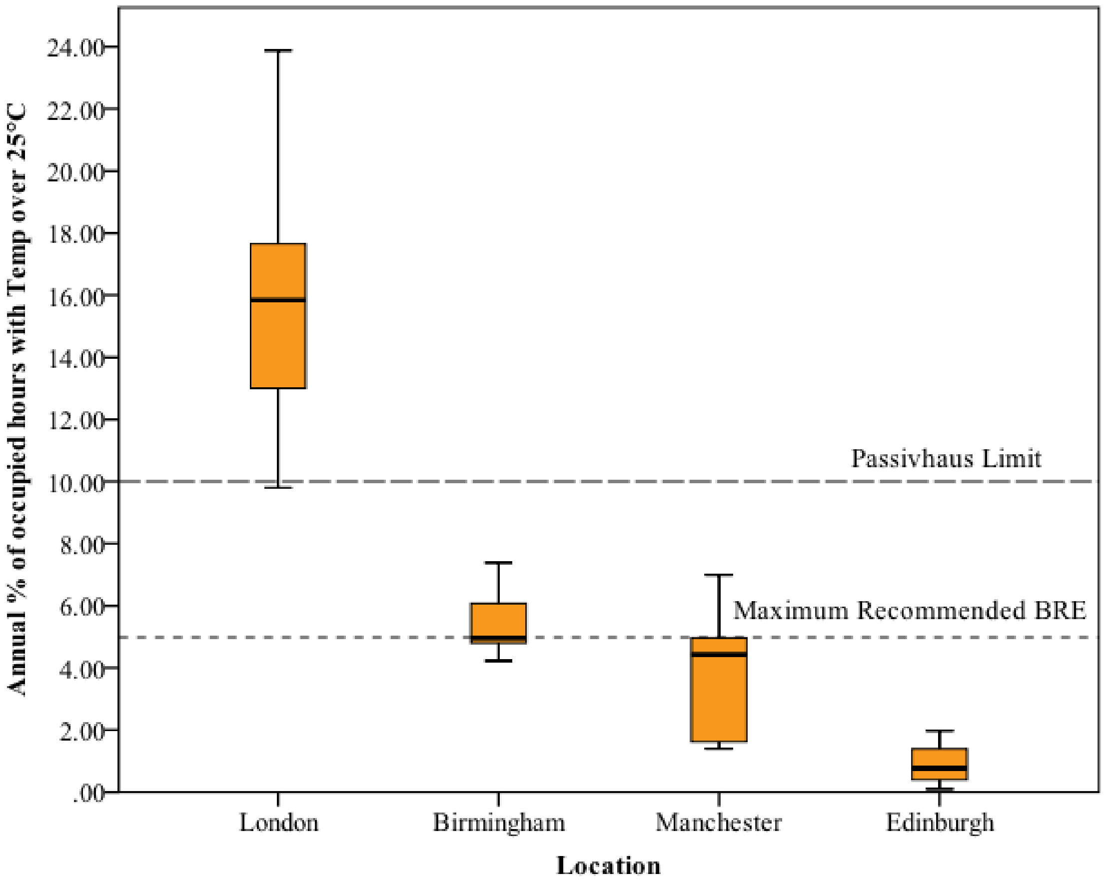


Figure 5.18 Living room overheating risk based on Passivhaus criteria in all occupant behaviour scenarios

Figure 5.19 presents adaptive thermal comfort (CIBSE TM59) overheating criteria for all occupant behaviour scenarios investigated within this study. The overheating risk in living room for both vulnerable (CAT I) and normal (CAT II) occupants are shown in this figure. As it was predictable, a higher risk of overheating exist for vulnerable occupants in all scenario modelling based on occupant behaviour.

For London, all design scenarios for vulnerable occupants have failed. Only three occupant behaviour scenarios have met the living room overheating criteria for normal occupant type. These three scenarios only passed the criteria with 2.9 and 2.8% which are very close to the 3% limit set out by CIBSE TM59 (CIBSE, 2017) guideline. The worst-case occupant behaviour scenario for London shows 24.5% for normal occupants and 18.4% for vulnerable occupants.

For Birmingham, only one scenario has failed for both occupant types and four scenarios failed only for the vulnerable occupant type. The percentage of occupied hours with a temperature over the maximum adaptive thermal comfort temperature range from 0.5 - 3.1% for normal occupant and 1 - 8% for vulnerable occupants in Birmingham.

For Manchester, only 3 scenarios failed for vulnerable occupants while all scenarios for normal occupant type have passed the overheating criteria for living room. The percentage of occupied hours with temperature over the maximum adaptive thermal comfort temperature, range from 0.0 - 1.2% for normal occupant and 0.6 - 5.3% for vulnerable occupants in Manchester.

For Edinburgh, all simulations based on occupant behaviour scenarios have passed overheating criteria for the living room. For six occupant behaviour scenarios in Edinburgh, the simulated living room temperature did not exceed the maximum adoptive thermal comfort temperature for both occupant types. In the worst-case scenario for Edinburgh, the simulated living room internal temperature exceeds the maximum adoptive thermal comfort temperature by 0.8% and 2.1% for normal and vulnerable occupants respectively.

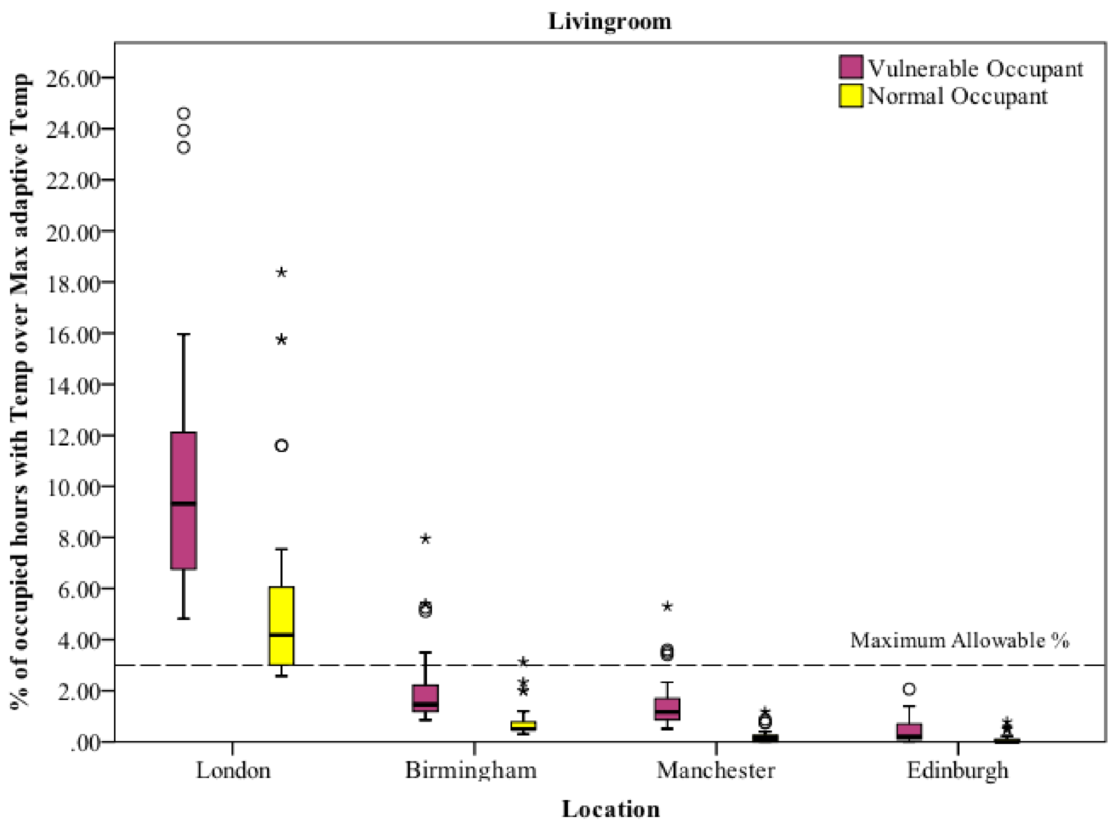


Figure 5.19 Living room overheating risk based on CIBSE Criteria in all occupant behaviour scenarios

Figure 5.20 and Figure 5.21 show overheating assessment for both bedrooms based on CIBSE TM59 method, as per the two criteria described in Chapter Three.

The simulation results for London show that out of 32 scenarios, in 24 scenarios for vulnerable and 3 scenarios for normal occupants, at least one of the bedroom passed overheating Criteria a. However, all flats assessed in London are overheated since they all failed Criteria b.

For occupant behaviour scenarios in Birmingham, bedrooms in 9 flats overheated as they failed Criteria b; however, only two of these 9 flats failed Criteria a only for vulnerable occupants. In Manchester, bedrooms in 10 flats overheated based on Criteria b, whilst no flat failed overheating Criteria a for both vulnerable and normal occupants. For the case of Edinburgh, the bedroom temperature never exceeded 26°C (Criteria b) and the maximum adaptive comfort temperature for normal occupants. For the vulnerable occupants, all bedrooms also met Criteria a with a maximum of 0.8% of hours above adaptive thermal comfort limit.

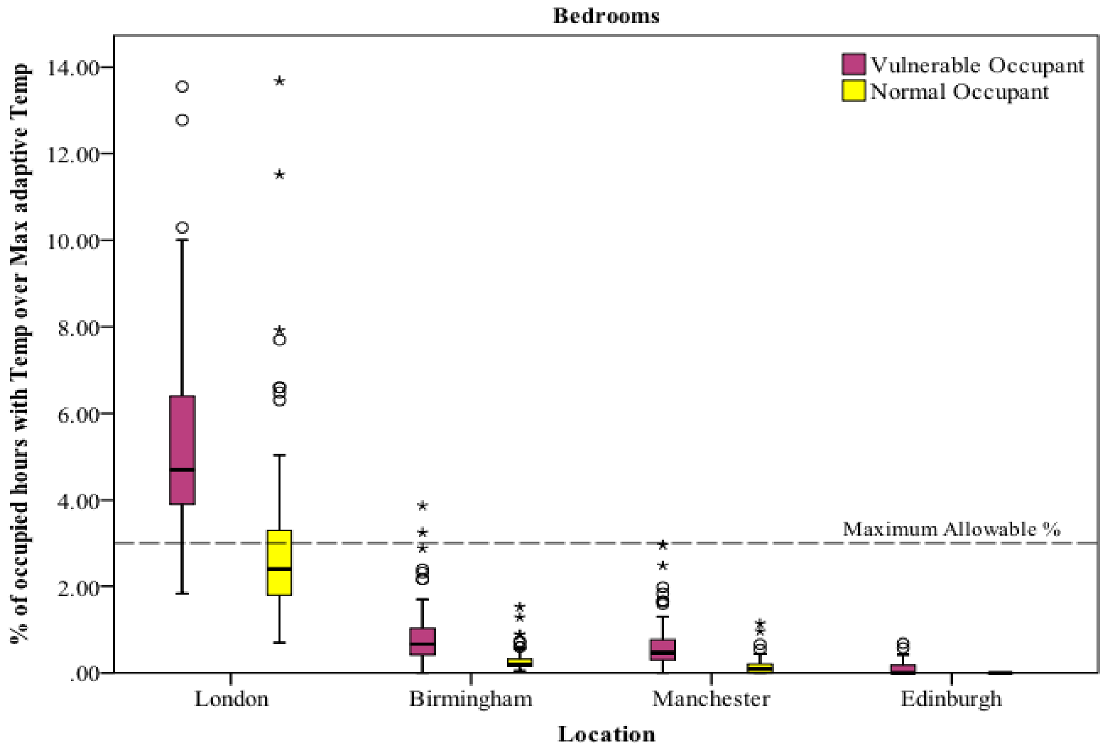


Figure 5.20 Bedrooms overheating risk based on CIBSE Criteria in all occupant behaviour scenarios - Criteria a

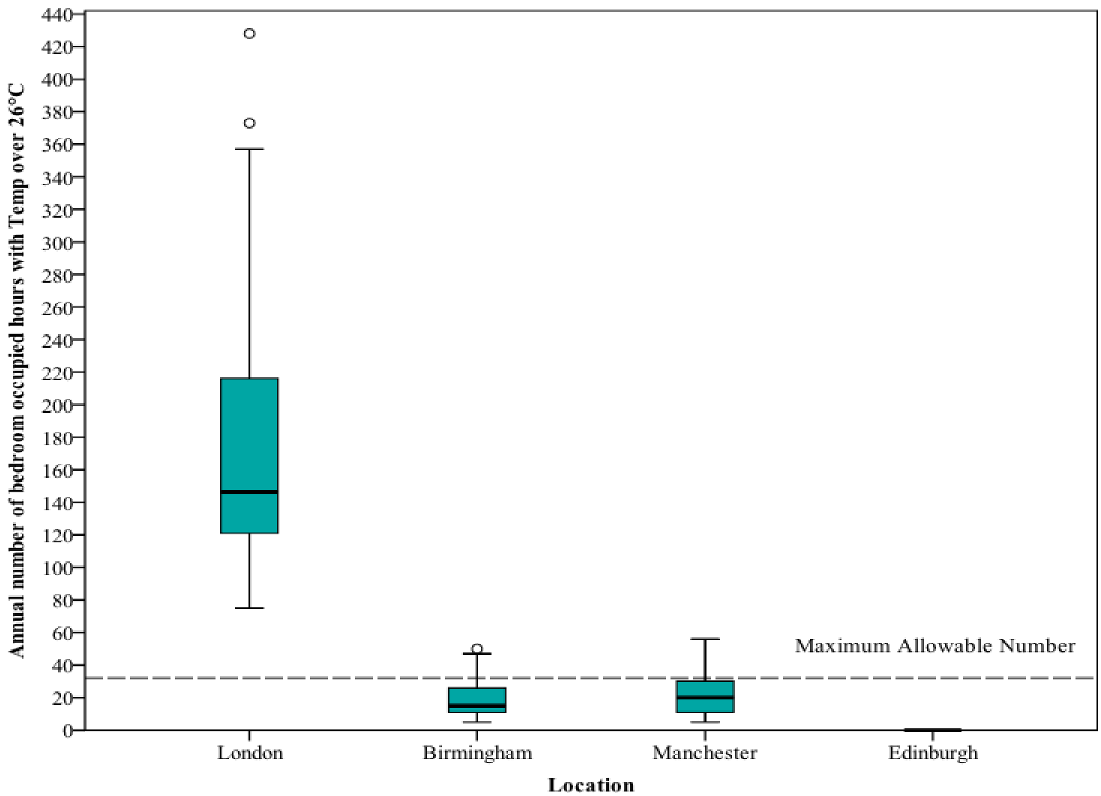


Figure 5.21 Bedrooms overheating risk based on CIBSE Criteria in all occupant behaviour scenarios - Criteria b

5.5.3 Statistical analysis and interpretations of simulation results

In order to investigate the impact of each design and occupant behaviour parameters on developing the risk of overheating, Firstly**,** two sets of graphs are prepared to illustrate the risk of overheating for all scenarios that only in one element of design or occupant behaviour parameters. In this section, the risk of overheating is evaluated based on the Passivhaus bench mark. Secondly a statistical analysis (T- test) was carried out between the risk of overheating of the scenarios that have similar design and occupant behaviour but are different in one elements of design or occupant behaviour parameters. In this section, the risk of overheating is evaluated based on both the Passivhaus and CIBSE benchmarks.

5.5.3.1 Illustration of the impact of design and occupant behaviour parameters

Figure 5.22, which contains five figures, illustrates the relative importance of five design parameters in developing the risk of overheating with use of the Passivhaus overheating benchmarks and BRE recommendations. The graphs compare the annual percentage of occupied hours with a temperature over 25°C in the living room based on variation in design parameters. These design parameters are glazing ratios, external shading and g-value which has influence on solar gain and window opening areas which has influence on ventilation rate and also the level of thermal mass.

- **The influence of solar gain:** Figure 5.22 (a) shows the overheating risk for variation of south facing glazing ratio for all study locations. The results indicate that scenarios with a high glazing ratio resulted in higher overheating risk in general. Figure 5.22 (b) compares the scenarios with variation of external shading. It is evident from this figure that optimum overhang will reduce the risk of overheating for all study locations. All the scenarios with optimum overhang (for all locations but London) not only met the Passivhaus limit but also fall below the BRE limit. Finally, Figure 5.22 (e) indicates that a lower glazing g-value will result in reduction of overheating risk.

- **The influence of thermal mass:** Figure 5.22 (c) shows the overheating risk for all scenarios with variation of thermal mass. The overheating risk reduced by increasing thermal mass level.

- **The influence of ventilation:** Figure 22 (d) shows that with the increase of windows opening area, the risk of overheating reduced. Overall, Figure 5.22 gives a comprehensive overview of the relative importance of design parameters in exacerbating or reduction of overheating risk.

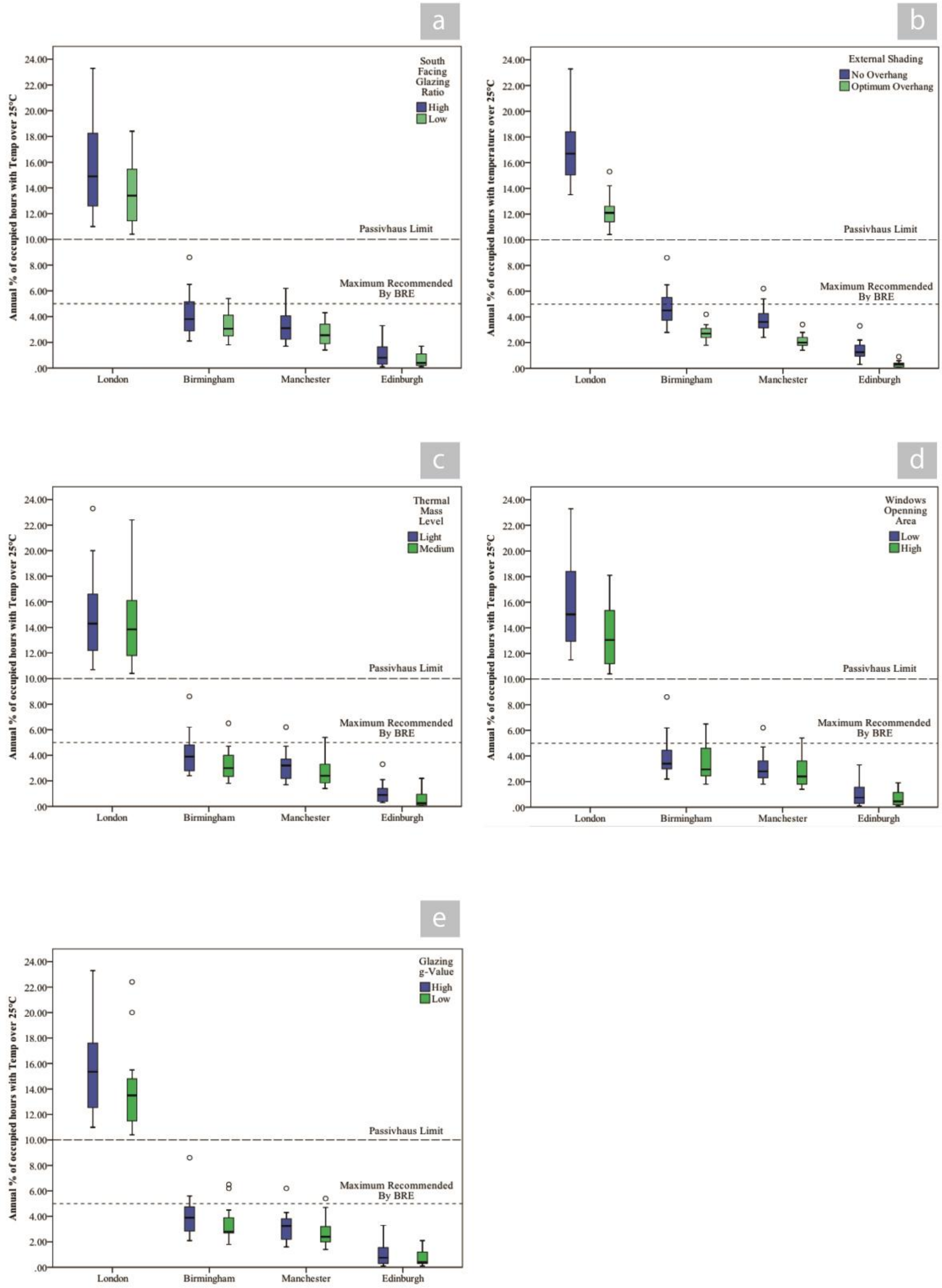


Figure 5.22 Effect of design parameters on flat overheating risk

Figure 5.23, which contains five graphs, shows the relative importance of five occupant behaviour parameters in developing the risk of overheating with use of the Passivhaus benchmark. The occupants' behaviours parameters are the use of MVHR by pass mode, operation of windows and shading devices and also the level internal gain.

- **The influence of occupants' behaviour on ventilation:** Figure 23 (b) indicates the importance of MVHR bypass mode in reduction of overheating risk in accordance with Passivhaus recommendations. Figure 5.23 (c) show the importance of cross flow ventilations during the day in reduction of overheating risk for all locations studied within the UK. Figure 5.23 (e) shows delay in window opening could increase the overheating risk.
- **The influence of occupants' behaviour on solar gain:** The results show that an internal shading device could reduce the overheating risk Figure 5.23 (d)
- **The influence of occupants' behaviour on internal gain:** Figure 5.23 (a), the results show that the risk of overheating in scenarios with low internal gain is slightly less than the scenarios with high internal gain.

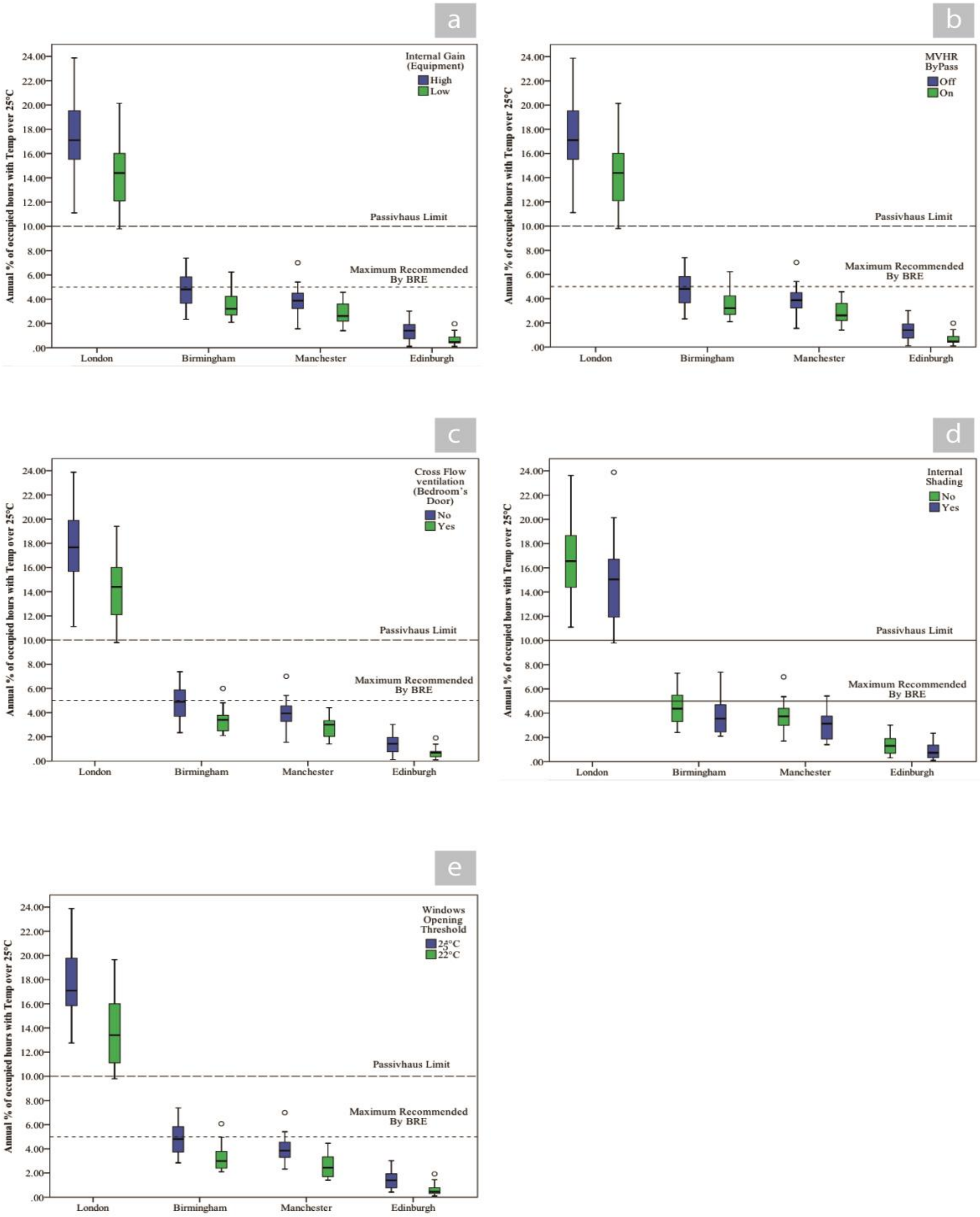


Figure 5.23 Effect of occupant behaviour parameters on flat overheating risk

As the result, Figure 5.22 and Figure 5.23 summarize the results of simulation modelling for design and occupant behaviour parameters. These two figures give an overall illustration of each parameter's effect on the overheating risk with use of the Passivhaus benchmark.

5.5.3.2 T-test and the impact of design and occupant behaviour parameters

A detailed statistical analysis has been carried out for each parameter in order to understand the importance of each parameter for different study locations. Tables D1 - D5, appendix D, presents the statistical analysis for design parameters and Tables D6 - D10, appendix D, show the statistical outcome for occupant behaviour parameters. These tables are comparing the results of statistical T-test analysis based on the Passivhaus overheating benchmark and CIBSE overheating benchmark for normal and vulnerable occupants. The statistical analysis has been performed with focus on the living room. The living room has been chosen for analysis due to the maximum occupied hours, south facing orientation and consequently higher risk of developing the risk of overheating. For design and occupant behaviour parameters, mean and standard deviation of benchmarking criteria are determined for each parameter's variation and the statistical measures for pair difference and their significance are presented.

Table 5.15 Summary of statistical analysis of the effect of all design and occupant behaviour parameters

Benchmark criteria	Location	Design parameters					Occupant behaviour parameters				
		South facing glazing area	External shading	Thermal mass	Window opening area	Glazing g- value	Internal gain	MVHR bypass	Cross flow ventilation	Internal shading	Window opening threshold
Passivhaus overheating benchmark	London	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Birmingham	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓
	Manchester	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓
	Edinburgh	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
CIBSE overheating benchmark (normal occupant)	London	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓
	Birmingham	✓	✓	✓	✗	✗	✓	✓	✓	✓	✓
	Manchester	✓	✓	✗	✗	✗	✓	✓	✓	✓	✓
	Edinburgh	✓	✓	✗	✗	✗	✓	✓	✓	✓	✓
CIBSE overheating benchmark (vulnerable occupant)	London	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Birmingham	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓
	Manchester	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓
	Edinburgh	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓

✓ Significantly effective ✗ Not significantly effective (in terms of affecting the overheating risk)

The result of the T-test shows the relative importance of each parameter for different benchmarking criteria for each study location. The summary of tables D1 - D10 (available in Appendix D) which present the results of statistical analysis using different benchmarking criteria, are presented in Table 5.15. Summarizing all the results for the design parameters, it is shown that south face glazing area and external shading parameters are significantly effective in controlling overheating for all locations using all overheating benchmarking criteria. The thermal mass parameter and glazing g-value show significant effectiveness in overheating when using the Passivhaus or CIBSE (vulnerable occupants) benchmarking criteria. When the CIBSE benchmark for normal occupants was adopted for assessing overheating, thermal mass was only effective in London and Birmingham. The analysis for the results show that windows' opening area has the least effectiveness in overheating in comparison to other design parameters.

For the case of occupant behaviour factors, the results indicate that all parameters selected in this study have significant effects on overheating risk in all locations regardless of which benchmarking is used to assess the overheating risk.

5.6 Future overheating investigations

This section focuses on investigating on the future overheating risk. In the first stage, the base model developed for each location was used to evaluate future overheating risk considering the various predicted future summer conditions using the Base Models. The outcome of first stage will provide an overview of future risks of overheating in UK social housing flats built to the Passivhaus standard. In the second stage, detailed investigation is carried out to understand the future risk of overheating in the selected design and occupant behaviour scenarios in various locations.

5.6.1 Base model simulations for various predicted future summers

For the purpose of presenting a comprehensive overview of future overheating risk, Base Models are simulated under various projected summer conditions which are a 'Moderate warm summer', a 'Short intense warm summer' and a 'Long-less intense Warm summer'. These summer conditions are selected as CIBSE TM 59 (CIBSE, 2017) recommended weather files DSY2 (i.e. Short-intense warm summer) and DSY3 (i.e. Long-less intense warm summer) should be should be used in simulation, as well as DY1 (i.e. Moderate warm summer) to further test the overeating risk where there is a particular concern (e.g. the presence of vulnerable occupants).

The Base model scenarios are considered since they are developed according to standard values and assumptions proposed by Passivhaus and CIBSE guidelines and consequently they can provide the most ideal cases for overheating assessment. The details of generation Base models for each location of Birmingham, Manchester, Edinburgh and London are available from section 5.2.4.

Future overheating risk in Base Models using Passivhaus benchmark under various summer conditions:

Figure 5.24 shows the future overheating risk in the living room based on the Passivhaus benchmark for various predicted summer conditions. It is evident from the graph that for all summer conditions, the overheating risk will increase until the 2080s. The results show that, for the case of London, the overheating risk is higher than other study locations and overheating happens for all predicted summer conditions. The simulation results show that, for the case of Edinburgh, the risk of future overheating is very low and for all summer conditions until the 2080s, overheating will not occur based on Passivhaus criteria. In Manchester, the results show that the risk of overheating is very low and only for a long, less intense summer condition in the 2080s the risk of overheating exist. For Birmingham, beyond the 2050s, overheating will occur for all summer conditions.

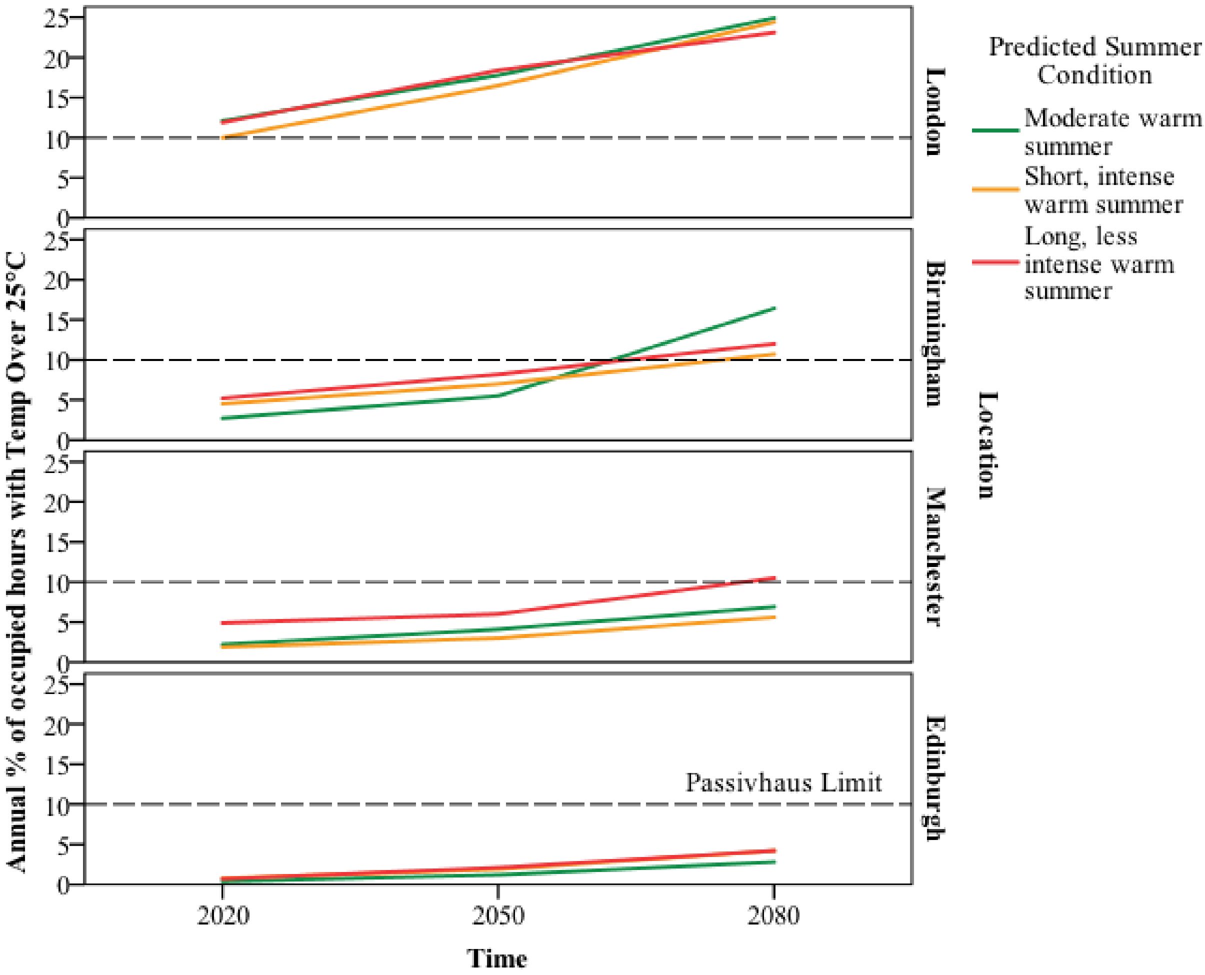


Figure 5.24 Future overheating risk in Living room based on Passivhaus benchmark under various predicted summer conditions using Base Models

Future overheating risk in the living rooms of the Base Models using CIBSE benchmark under various summer conditions:

Figure 5.25 shows the future overheating risk in the living room based on CIBSE TM59 (CIBSE, 2017) benchmark (adaptive thermal comfort) for various predicted summer conditions. The overall trend shows that the overheating risk increases by time. For the case of London, until the 2080s, the percentage of occupied hours with temperature over maximum adaptive temperature will reach 22.5% for vulnerable occupants and 16% for normal occupants.

The simulation shows that Birmingham is a high-risk location for vulnerable occupants in terms of overheating. The results show that for both Short, intense summers and Long, less intense summers, the overheating will occur from the 2020s onwards, for vulnerable occupants. Only for Moderate warm summers, the overheating will not take place until the 2050s for this category. It is evident from the figure that for all summer conditions beyond the 2050s, overheating will also take place for normal occupants in Birmingham.

In Manchester, the result of simulations shows that for vulnerable occupants, Long, less intense summers will always result in overheating and the risk will intensify from the 2050s onwards. For Moderately warm summer and Short, intense summers, the results indicate that overheating will not occur until the 2050s, however, after the 2050s all summer weather conditions have overheating risk for vulnerable occupants. For the case of normal occupants in Manchester, overheating will not happen for any summer weather condition, until the 2050s and only Long, less intense summer weather will result in overheating for simulations beyond 2050s. It is evident that by the 2080s, both Moderately warm and Short, intense summer conditions will reach the maximum allowable stipulated limits (i.e.3%) by CIBSE TM59 (CIBSE, 2017) for normal occupants.

In Edinburgh, the result of simulations show that for both occupant types and all summer weather conditions, the risk of overheating will be minimum until the 2080s in comparison to other locations, with a maximum overheating risk of 2.3% for vulnerable occupants for the case of Long, less intense summer conditions.

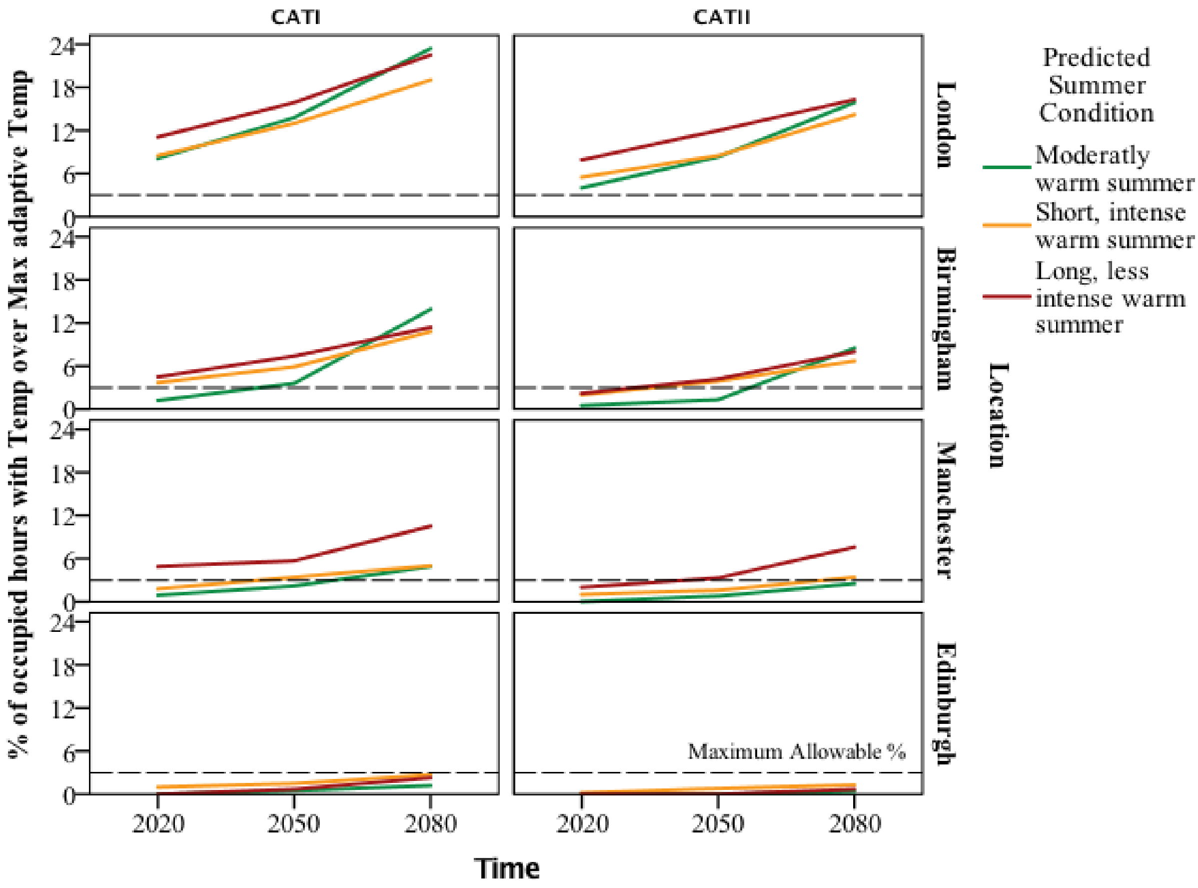


Figure 5.25 Future overheating risk in Living room based on CIBSE benchmark under various predicted summer conditions using Base Models

Future overheating risk in the bedrooms of the Base Models using CIBSE benchmark under various summer conditions:

Figure 5.26 and Figure 5.27 presents the future overheating assessment in bedrooms based on the two criteria proposed by CIBSE TM59 (CIBSE, 2017) under various predicted summers. For the case of future overheating assessment in bedrooms, simulations show that for both occupant types and in all summer conditions, London will fail CIBSE overheating criteria. The results show that in London, the numbers of annual occupied hours with temperature over 26°C could reach 530 hours by the 2080s.

For Birmingham, despite all summer conditions, the overheating risk is low until the 2050s based on Criteria a, but for short, intense and long, less intense summer weathers, Criteria b will fail from 2020 onwards. Moderately warm summers will also fail criteria b post 2050.

For Manchester, CIBSE overheating Criteria a shows satisfactory results for both occupant types until the 2050s and only Long, less intense summer weather will fail for vulnerable occupants from the 2050s onwards. However, based on CIBSE Criteria b, Long, less intense summer condition will fail from 2020s onwards and both Moderately warm and short, intense summer conditions will also fail from the 2050s.

Simulations for Edinburgh show that bedrooms for both occupant types and all summer weather conditions will pass Criteria a. Also, all summer weather conditions pass Criteria b until the 2080s where only Long, less intense summer condition fail this criteria by a maximum of 39 hours of over 26°C.

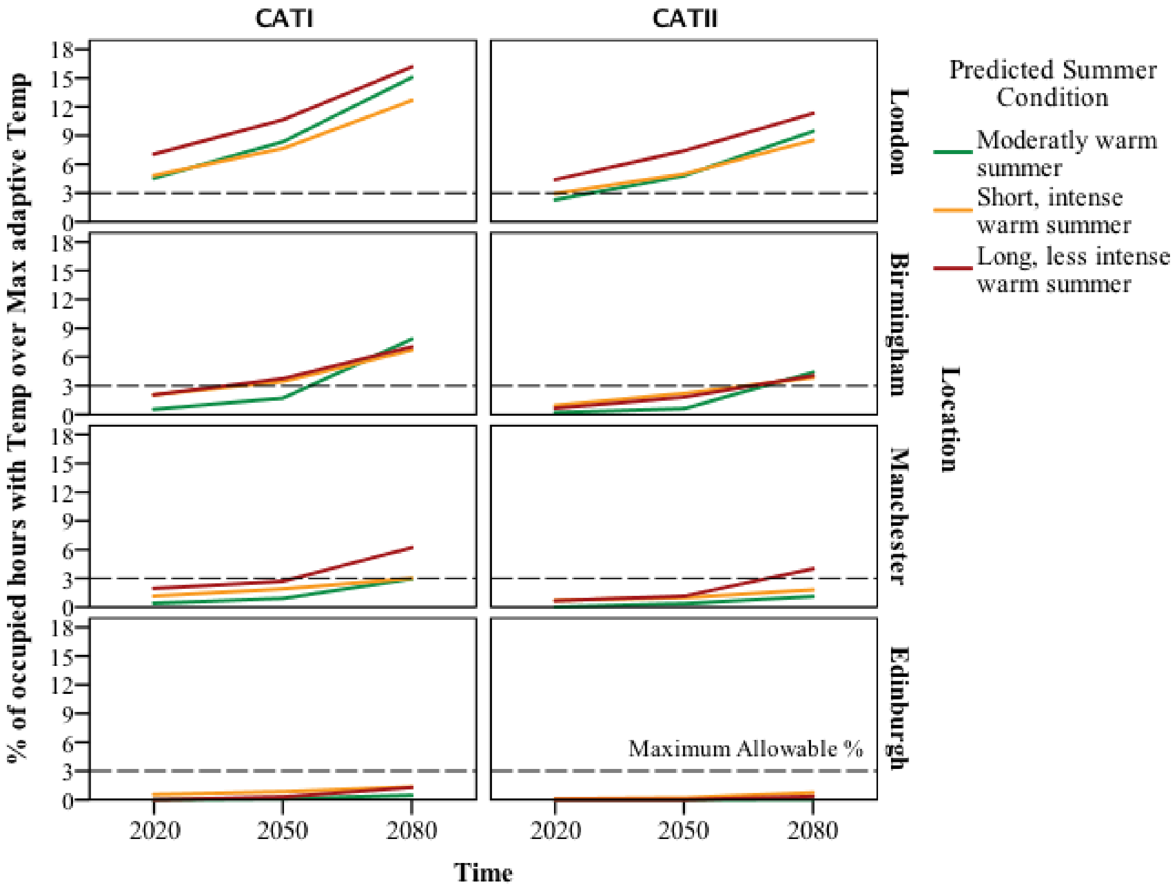


Figure 5.26 Future overheating risk in bedroom based on CIBSE benchmark under various predicted summer conditions using Base Models - Criteria a

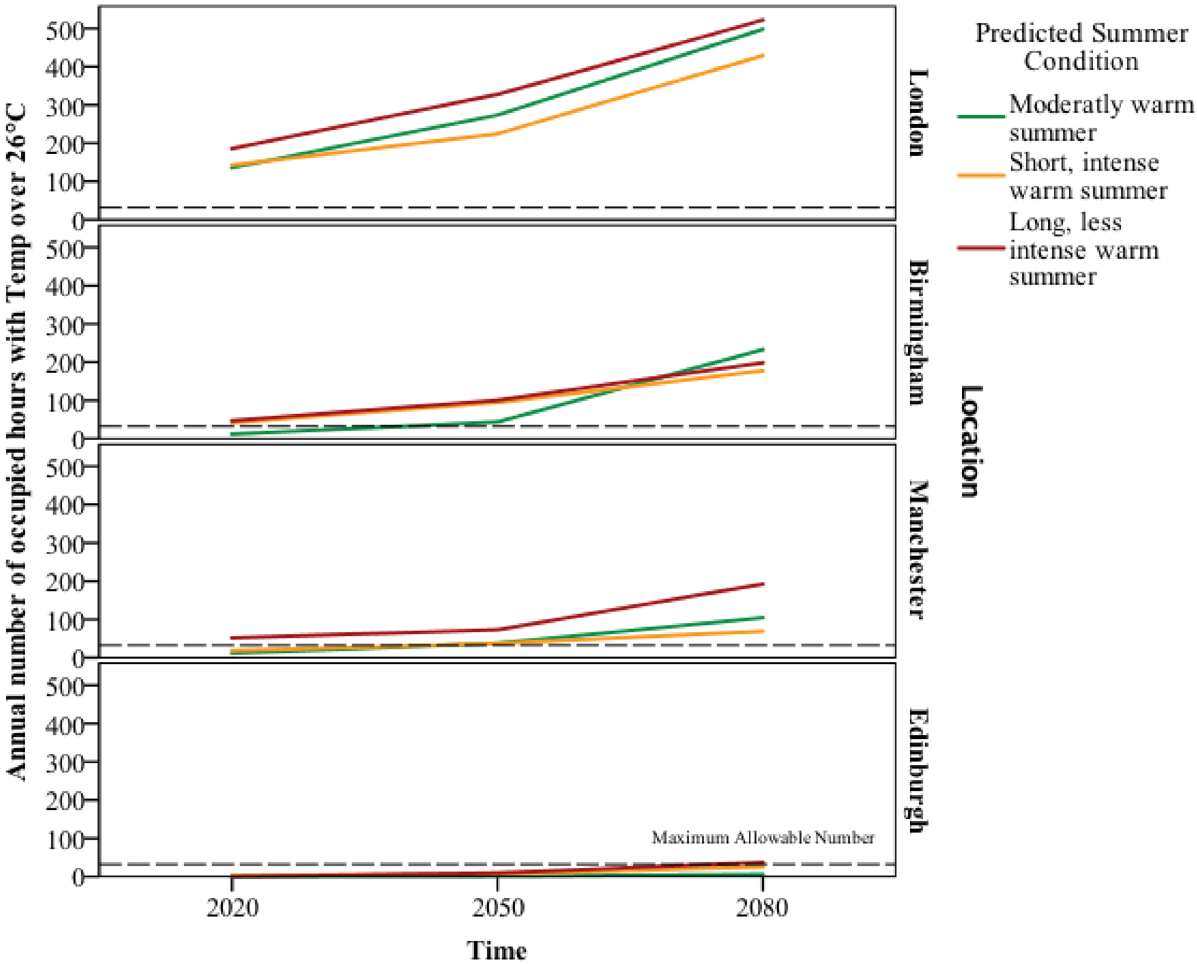


Figure 5.27 Future overheating risk in bedroom based on CIBSE benchmark under various predicted summer conditions using Base Models - Criteria b

5.6.2 Future Overheating investigation for the selected scenarios

The previous section presented an overview of future overheating risks under various projected summer weather conditions using the base models developed for all study locations. This section will study future overheating risk using representative design and occupant behavioural scenarios which have various levels of overheating risk. The outcome of this section not only provides a more comprehensive overview of future overheating risks by considering the possible flexibility in design and occupant behaviour, but also shows the importance of appropriate design and occupant behaviour in future overheating control.

5.6.2.1 Future overheating risk and design options

In this section, the impact of design options on the future risk of overheating in four locations of London, Birmingham, Manchester and Edinburgh are evaluated. For this reason, all 33 design options (32 design options + 1 base model) which were mentioned before (section 5.5.1) are simulated with a fixed occupants behaviour under the weather data of the 2020s and ranked based on the predicted percentage of living room occupied hours with temperature over 25°C (Passivhaus criteria). From all available design scenarios, four design scenarios as representatives of design options are selected for further overheating investigations in the future. Since BRE recommends targeting less than 5% of occupied hours with temperature over 25°C in designing any new Passivhaus dwellings (Mcleod et al, 2011), these four options are aimed to be selected in order to represent the cases with overheating risk of below 5, 4, 3 and 2%. Available ranges of overheating risk for Birmingham and Manchester cases, allowed the selection of scenarios as described above. However, for the case of London, the simulation results show the range of overheating risk between 10% to 23% based on Passivhaus criteria and as such the design options with the overheating risk of 10% and three other design options with higher overheating risks are selected for future overheating investigation for this location. Also, overheating risks in Edinburgh design scenarios fall between 0.1% to 3.3% and therefore four cases were selected within the range available for this location. Table 16 presents all the design options selected to investigate the risk of overheating in the future and their associated parameters. The four design options presented in Table 5.16 show a range of design scenarios with their risk of overheating under the climate conditions of the 2020s (A - D). Design options A in each location represent the selected Scenario with lowest overheating risk while Design options Bs, Cs and Ds are presenting scenarios with higher overheating risk in an increasing order. All the selected scenarios are then simulated under future weather data of the 2050s and the 2080s using Moderately warm summer which is the mandatory weather file for overheating assessment.

Table 5.16 Selected design options for future performance investigation using 2020s weather data

Location	Design Option	Scenario No.	South Facing Glazing Ratio	External shading	Thermal mass level	Windows Opening Area	Glazing g-Value	Percentage of Occupied Hours with temperature over $25^{0}C$			Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Vulnerable Occupant)			Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Normal Occupant)			Number of Occupied Hours with temperature over $26^{0}C$	
								B1	B2	L	B1	B2	L	B1	B2	L	B1	B2
London	**A_L**	16	Low	Optimum Overhang	Medium	High	Low	6.7	6.6	10.3	2.4	2.6	5	0.8	0.9	1.9	89	88
	B_L	BM	0.3	Optimum Overhang	Light	0.4	Low	8	8.2	12	4.4	4.7	8.1	2.2	2.4	4	138	134
	C_L	4	Low	No Overhang	Light	High	Low	8.3	8.6	14	4.8	5.4	11	2.4	2.6	5.5	150	143
	D_L	3	Low	No Overhang	Light	High	High	8.8	9.1	17	5.6	6	13	2.8	3	7.4	161	151
Birmingham	**A_B**	16	Low	Optimum Overhang	Medium	High	Low	0.9	0.9	1.8	0.2	0.3	0.6	0	0	0.3	2	3
	B_B	BM	0.3	Optimum Overhang	Light	0.4	Low	1.5	1.6	2.7	0.5	0.6	1.1	0.2	0.2	0.5	12	12
	C_B	4	Low	No Overhang	Light	High	Low	1.6	1.7	3.9	0.6	0.7	2	0.2	0.2	0.7	6	6
	D_B	3	Low	No Overhang	Light	High	High	1.7	2	4.8	0.7	1	2.7	0.2	0.4	1.3	11	6
Manchester	**A_M**	13	Low	Optimum Overhang	Medium	Low	Low	0.8	0.9	1.8	0	0	0.2	0	0	0	0	1
	B_M	25	High	Optimum Overhang	Light	Low	Low	1.4	1.6	2.8	0.4	0.5	1.3	0	0.1	0.2	13	14
	C_M	3	Low	No Overhang	Light	Low	High	1.6	2	3.7	0.5	0.7	2.2	0.1	0.2	0.8	12	8
	D_M	17	High	No Overhang	Light	Low	Low	1.8	2.2	4.7	0.7	1	3.6	0.2	0.4	1.6	21	20
Edinburg	**A_E**	13	Low	Optimum Overhang	Medium	Low	Low	0	0	0.1	0	0	0	0	0	0	0	0
	B_E	25	High	Optimum Overhang	Light	Low	Low	0.1	0.2	0.6	0	0	0.2	0	0	0	0	0
	C_E	23	High	No Overhang	Medium	Low	Low	0	0	1.4	0	0	0.3	0	0	0	0	0
	D_E	17	High	No Overhang	Light	Low	Low	0.2	0.3	2.1	0	0	1.7	0	0	0.4	0	0

Future overheating risk in selected design scenarios using Passivhaus benchmark:

Figure 5.28 illustrates the risk of future overheating in the living room based on Passivhaus criteria for the selected design options. As discussed earlier, none of the design options in London passed the Passivhaus overheating criteria under projected weather conditions of the 2020s, and it is evident from the graph that in all selected design options, overheating risks will increase in this location over the future years. For the case of Birmingham, the selected design options with overheating risk of less than 3% based on Passivhaus criteria will prevent the occurrence of overheating until the 2080s while the options with higher current overheating risk will fail to comply with the Passivhaus overheating benchmark beyond the 2050s. In Manchester, the overheating risk based on Passivhaus criteria will only occur for the selected design option that has the highest risk of overheating (with more than 4% of occupied hours with temperature above 25°C under projected 2020 weather condition) in the 2080s. The simulation results show that, for the case of Edinburgh, overheating will not occur based on Passivhaus criteria in all selected design options until the 2080s.

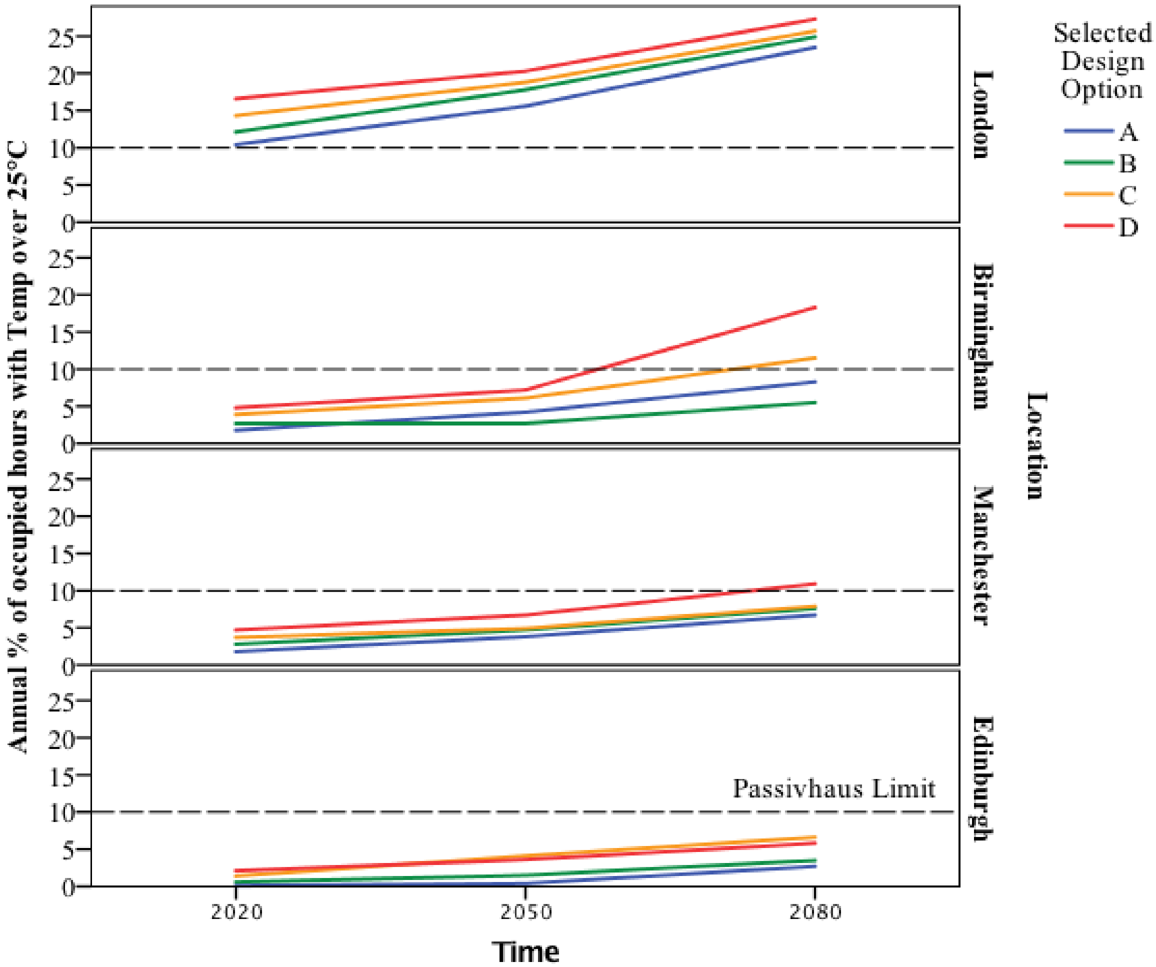


Figure 5.28 Future overheating risk assessment based on Passivhaus benchmark for the selected design scenarios (Living room)

Future overheating risk in living rooms of the selected design scenarios using CIBSE benchmark:

Figure 5.29 shows the future overheating risk (i.e. occupied hours with temperature over maximum adaptive temperature) in the living room based on CIBSE TM59 (CIBSE, 2017) benchmark (adaptive thermal comfort) for the selected design options in each location.

For the case of London, only the best design option (A_L) with respect to the overheating risk can provide a thermally comfortable condition for the normal occupant under the 2020s projected weather condition. It is evident from the graph that overheating will occur in all other selected design options in the 2020s and by the 2080s it will reach to 18% of overheating risk for normal and 28% of overheating risk for vulnerable occupants in the worst selected design option (D_L). Also, no design option provided thermally comfortable conditions for vulnerable occupants' type at any studied time in London.

The simulation results show that overheating risk in Birmingham and Manchester can be prevented in living room with selected design options A_B/A_m and B_B/B_m (design options with lower overheating risk) for vulnerable and normal occupants until the 2050s and the 2080s respectively. For the case of vulnerable occupants in Birmingham and Manchester, overheating will occur in all design options beyond 2050s based on CIBSE TM59 benchmark. In these two locations for the selected options with higher overheating risk (option C_B/C_M & D_B/D_M), the occurrence of overheating is predicted beyond the 2020s for vulnerable occupants and beyond 2050s for normal occupants.

For the case of Edinburgh, all selected design options with various overheating risks will provide thermally comfortable conditions for normal occupants until the 2080s in the living room, based on CIBSE TM59 benchmark. However, overheating risk for vulnerable occupants will be predicted in the 2080s for the selected design options of C_E & D_E with higher current overheating risk in comparison to the other available options in this location.

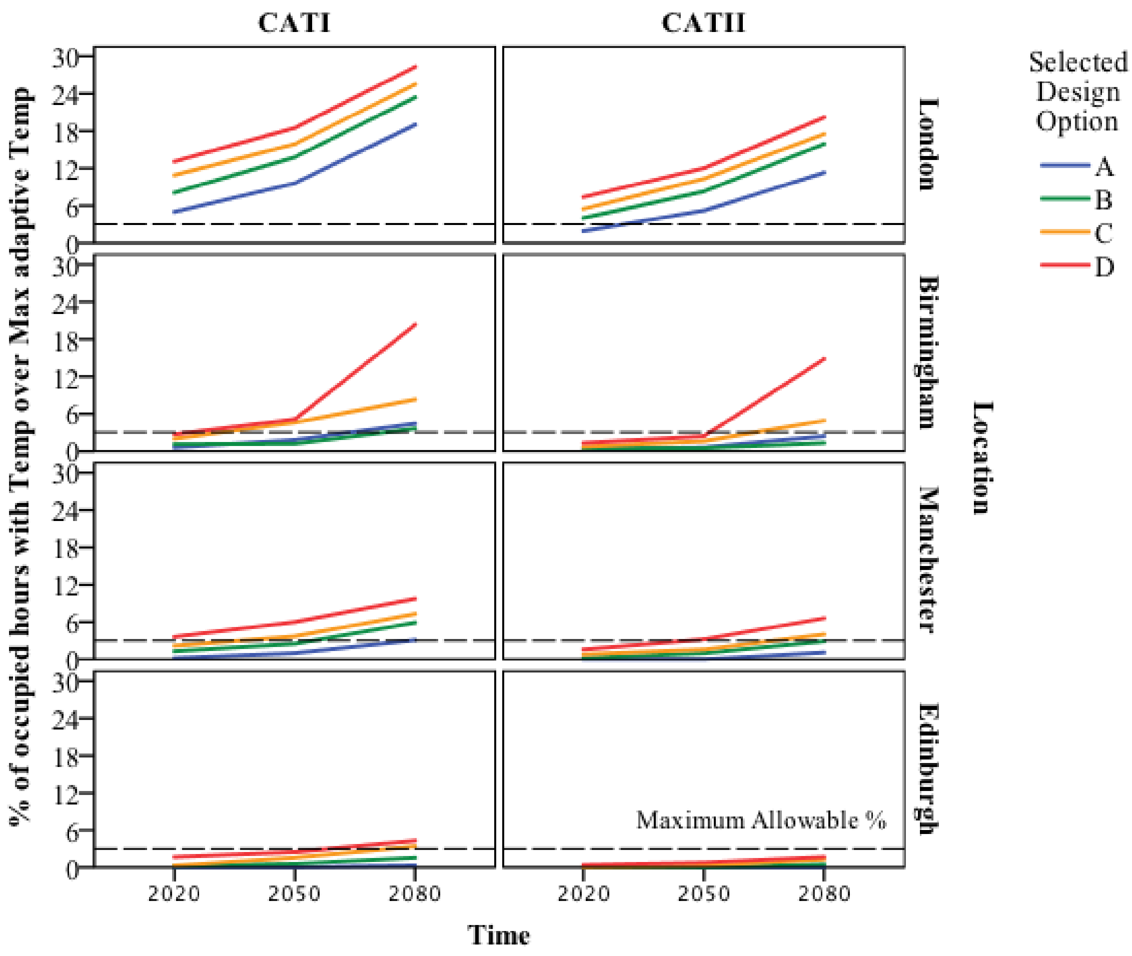


Figure 5.29 Future overheating risk assessment using CIBSE TM59 benchmark for the selected design scenarios (Living room)

Future overheating risk in bedrooms of the selected design scenarios using CIBSE benchmark:

Figure 5.30 and Figure 5.31 present the future overheating assessment in bedrooms based on the two criteria stipulated by CIBSE TM59 (CIBSE, 2017) for the selected design options.

Simulation results show that bedrooms for all selected design options in London will be classified as overheated spaces in any studied time as they will fail Criteria b.

For Birmingham, design options with lower overheating risk (A_B & B_B) are predicted to meet both Criteria a and b, and provide thermally comfortable spaces for both vulnerable and normal occupants in bedrooms until the 2050s. Other design options will fail Criteria b from the 2020s onwards.

In Manchester, while all selected design options pass Criteria a for vulnerable and normal occupants until the 2050s and 2080s respectively, only the best design option with respect to the overheating risk (A_M) will pass Criteria b until the 2050s. Therefore, overheating in bedrooms in this location will occur in all design options and for both occupant types post 2020s, except option A_M where the overheating risk is predicted from the 2050s onwards.

Simulation results for Edinburgh show that all selected design options will meet all bedrooms overheating criteria stipulated by CIBSE TM59 for both vulnerable and normal occupants.

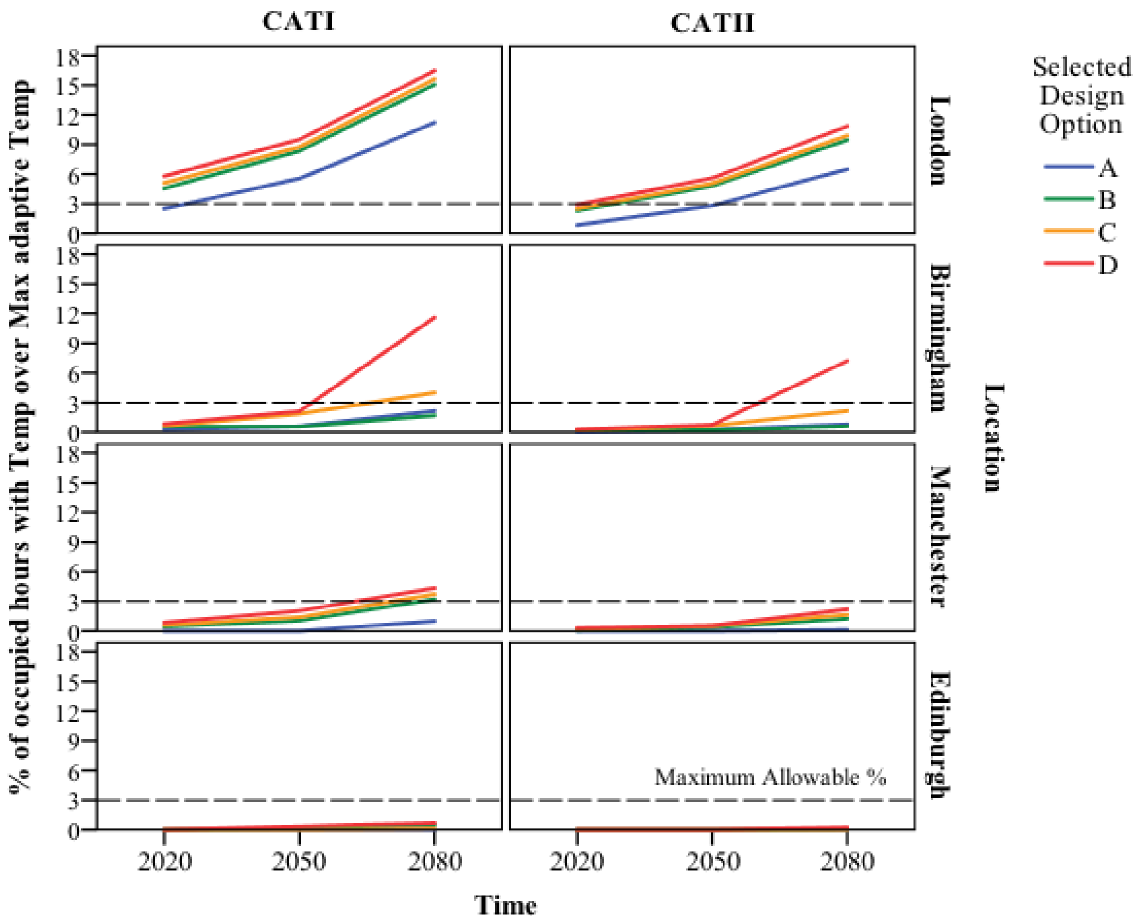


Figure 5.30 Future overheating risk assessment using CIBSE TM59 benchmark for the selected design scenarios (Bedroom) – Criteria a

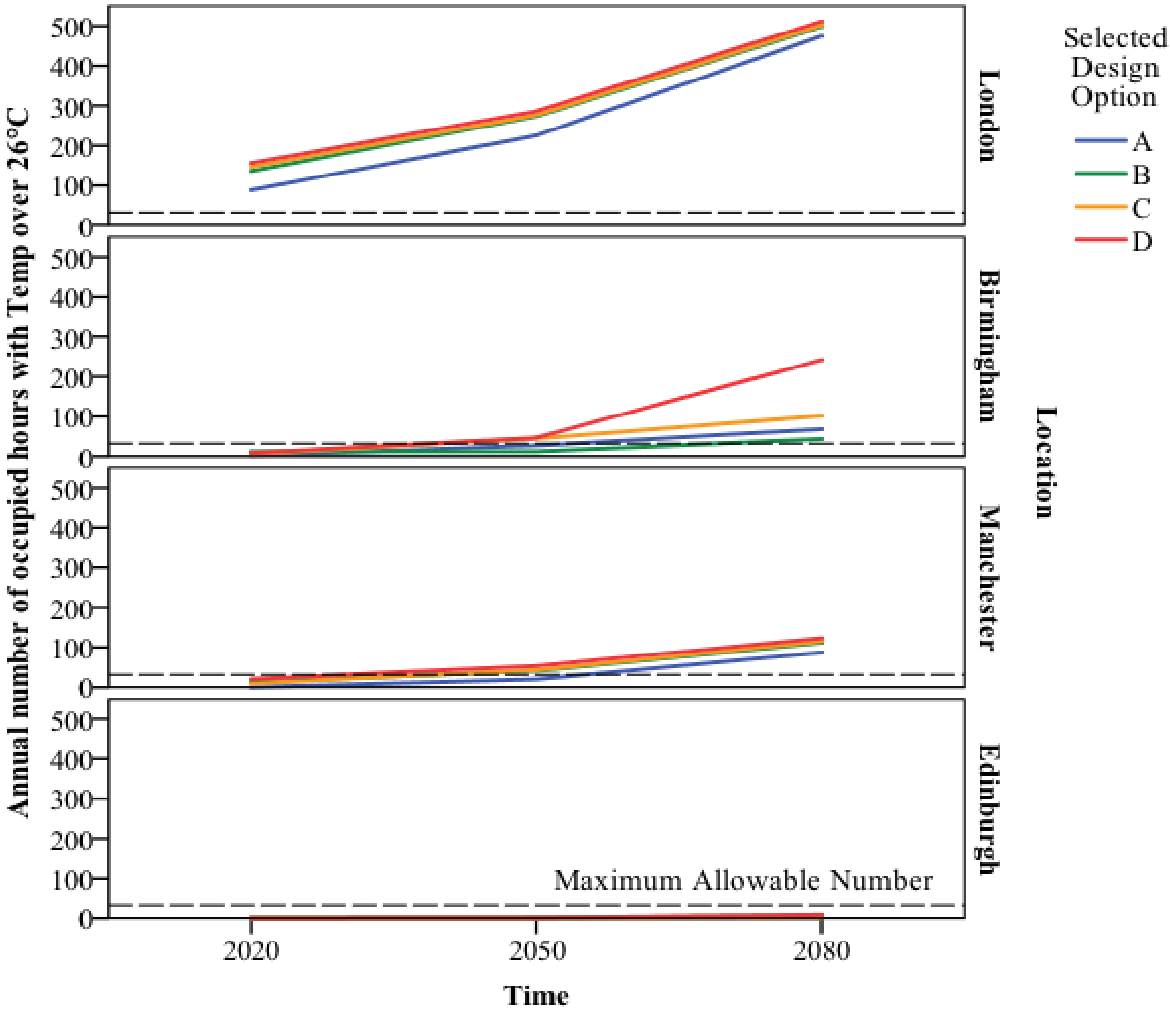


Figure 5.31 Future overheating risk assessment using CIBSE TM59 benchmark for the selected design scenarios (Bedroom) – Criteria b

5.6.2.2 Future overheating risk and occupant behaviour models

In this section the impact of occupant behaviours on the future risk of overheating in four locations of London, Birmingham, Manchester and Edinburgh are evaluated. For this reason, all 32 occupant behaviour models which were mentioned before (section 5.5.2) are simulated and ranked based on the predicted percentage of occupied hours with temperature over 25°C (Passivhaus criteria). Tables C1 - C4, appendix C, show that the ranking of overheating risks based on all defined occupant behaviour scenarios are the same in all study locations. Therefore, six scenarios (I-VI) were selected for further overheating investigations in the future. Table 5.17 shows the selected occupant behaviour models and their associated parameters, as well as the performances of each model in all study locations under a projected moderately warm (DSY1) 2020s summer condition. It is notable that model III in each location represents the base model. All occupant behaviour parameters in the base model are defined based on the standard values and assumptions in CIBSE TM 59 (CIBSE, 2017). Therefore, in each location and for future overheating assessment in this part, there are two scenarios (I and II) which represent better occupant behaviour options (with respect to the overheating risk) when compared to the base model (standard scenario for overheating assessment). Also, there are three scenarios (IV, V and VI) which represent the occupant behaviour options which lead to develop a higher risk overheating in compare to the base model. All the selected scenarios are then simulated under future weather data of the 2050s and 2080s using a Moderately warm summer which is the mandatory weather file for overheating assessment. Assessment of all these scenarios will show the influence of occupant behaviour in reducing or exacerbating the overheating risk in the future.

Table 5.17 Selected occupant behaviour models for future performance investigation using 2020 weather data

Location	Occupant Behaviour Model	Scenario No.	Internal Gain (Equipment)	MVHR ByPass	Cross Flow ventilation (Bedroom's Door)	Internal Shading	Windows Opening Threshold (^{0}C)	Percentage of Occupied Hours with temperature over 25^{0}C			Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Vulnerable Occupant)			Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Normal Occupant)			Number of Occupied Hours with temperature over 26^{0}C	
								B1	B2	L	B1	B2	L	B1	B2	L	B1	B2
London	I_L	19	Low	ON	Yes	Yes	22	6.7	6.9	9.8	3.2	3.6	5.7	1.4	1.7	2.8	115	110
	II_L	3	Standard	ON	Yes	Yes	22	7.6	7.4	11	3.9	4.3	6.7	2	2.1	3.5	129	122
	III_L	BM	Standard	ON	Yes	NO	22	8	8.2	12	4.4	4.7	8.1	2.2	2.4	4	138	134
	IV_L	9	Standard	Off	Yes	No	22	11	10	14	6.5	6.2	9.2	3.2	3.2	4.3	154	143
	V_L	2	Standard	ON	Yes	No	24	9.3	9.8	16	4.8	5.4	11	3.2	3.3	5.8	214	177
	VI_L	10	Standard	Off	Yes	No	24	13	13	19	7.1	7.1	12	3.5	3.6	6.3	240	201
Birmingham	I_B	19	Low	ON	Yes	Yes	22	1.1	1.2	2.1	0	0.4	1	0.1	0.1	0.5	8	5
	II_B	3	Standard	ON	Yes	Yes	22	1.4	1.4	2.4	0.4	0.5	1.1	0.1	0.2	0.5	11	11
	III_B	BM	Standard	ON	Yes	NO	22	1.5	1.6	2.7	0.5	0.6	1.2	0.2	0.2	0.5	12	12
	IV_B	9	Standard	Off	Yes	No	22	2	2.1	3.4	0.7	0.8	1.6	0.2	0.4	0.5	16	17
	V_B	2	Standard	ON	Yes	No	24	2.2	2.4	4.5	0.7	1	1.7	0.2	0.3	0.6	25	20
	VI_B	10	Standard	Off	Yes	No	24	3.2	3.2	6	1.6	1.7	2.7	0.4	0.4	0.8	34	26
Manchester	I_M	19	Low	ON	Yes	Yes	22	0.8	0.9	1.4	0	0.1	0.6	0	0	0	6	5
	II_M	3	Standard	ON	Yes	Yes	22	1.1	1.2	1.7	0.3	0.4	0.6	0	0	0	11	9
	III_M	BM	Standard	ON	Yes	NO	22	1.3	1.5	2.2	0.4	0.4	1	0	0	0	12	11
	IV_M	9	Standard	Off	Yes	No	22	2.2	2.2	3	0.5	0.6	1.3	0.1	0.2	0.2	29	21
	V_M	2	Standard	ON	Yes	No	24	2	2.3	3.6	0.5	0.7	1.3	0.1	0.2	0.2	28	22
	VI_M	10	Standard	Off	Yes	No	24	3.5	3.4	4.4	1.1	1.3	1.8	0.2	0.3	0.3	38	30
Edinburg	I_E	19	Low	ON	Yes	Yes	22	0	0	0.1	0	0	0	0	0	0	0	0
	II_E	3	Standard	ON	Yes	Yes	22	0	0.1	0.3	0	0	0	0	0	0	0	0
	III_E	BM	Standard	ON	Yes	NO	22	0.1	0.1	0.4	0	0	0.1	0	0	0.1	0	0
	IV_E	9	Standard	Off	Yes	No	22	0.1	0.2	0.7	0	0	0.2	0	0	0	0	0
	V_E	2	Standard	ON	Yes	No	24	0.3	0.4	1.3	0	0.2	0.7	0	0	0	0	0
	VI_E	10	Standard	Off	Yes	No	24	3.5	3.4	4.4	1.1	1.3	1.8	0.2	0.3	0.3	38	30

Future overheating risk based on the selected occupants' behaviour scenarios using Passivhaus benchmark:

Figure 5.32 shows the risk of future overheating in the living room based on Passivhaus criteria for the selected occupant behaviour models. For the case of London, only the best occupant behaviour scenario is predicted to meet Passivhaus criteria with only 0.02%

below the limit in the 2020s, but failed the limits for the 2050s and 2080s. All other options are predicted to not comply with Passivhaus overheating criteria in the 2020s and onwards, however, it is notable that, on average, there is about 10% difference in the percentage of occupied hours with temperatures over 25°C between the best and worst selected occupant behaviour models at each studied time in this location. In Birmingham, it is evident that only the occupant behaviour models with lower overheating risk (I_B and II_B) in comparison to the base model will meet the Passivhaus overheating criteria until the 2080s. In this location, the difference in the risk of overheating (i.e. percentage of occupied hour with temperature over 25°C) between the best (I_B) and worst (VI_B) selected occupant behaviour models is about 4% in the 2020s, but it is predicted to become double (around 8%) in the 2080s.

In Manchester, the simulation results show only the worst selected occupant behaviour (VI_M) model will fail the Passivhaus overheating criteria in the 2080s, and all other options are predicted to pass the criteria until the 2080s. In this location, the difference in the risk of overheating between the best (I_M) and worst (VI_M) selected occupant behaviour models is about 3% in the 2020s and it will reach to more than 5% in the 2080s.

For the case of Edinburgh, it is evident from the graph that all occupant behaviour models will meet the Passivhaus overheating benchmark until the 2080s. This location also presents the lowest difference in the Passivhaus overheating criteria between the best (I_E) and the worst (VI_E) selected occupant behaviour models. The differences are less than 2% and 5% in 2020s and 2080s respectively.

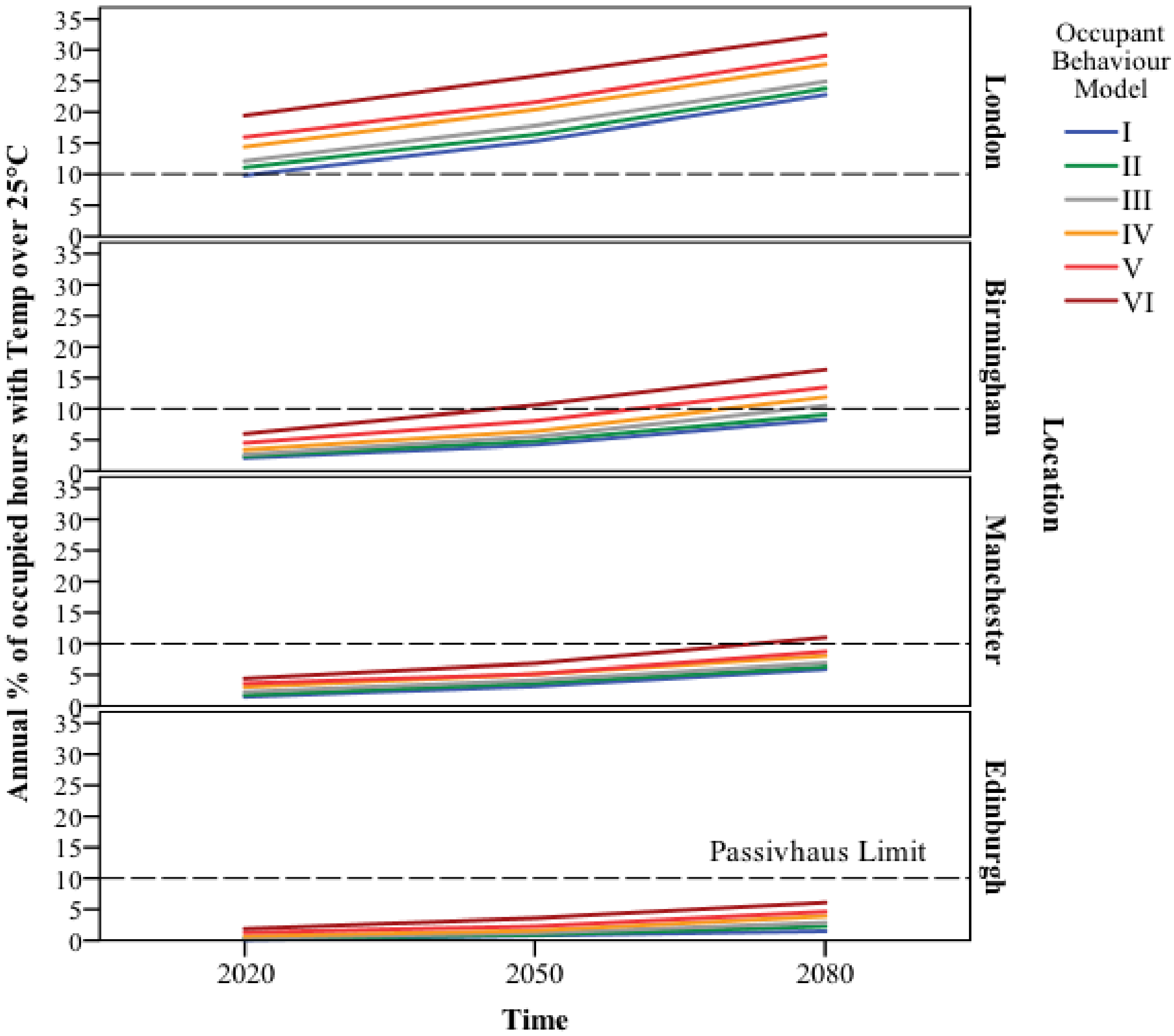


Figure 5.32 Future overheating risk assessment based on Passivhaus benchmark for the selected occupant behaviour scenarios (Living room)

Future overheating risk in living rooms of selected occupants' behaviour scenarios using the CIBSE benchmark:

Figure 5.33 presents the future overheating risk in living rooms based on the CIBSE TM59 (CIBSE, 2017) benchmark (adaptive thermal comfort) for the selected occupant behaviour models in each location. For the case of London, only the selected model with the best occupant behaviour (I_L) can meet the criteria for normal occupants under projected weather conditions of the 2020s. It is evident from the graph that overheating will occur in all other selected models for both normal and vulnerable occupants in the 2020s, and the overheating risk will intensify over the time significantly.

In Birmingham, the simulation results show while all occupant behaviour models meet the overheating criteria for vulnerable occupants in the 2020s, the overheating risk can only be prevented in the models with lower overheating risk (I_B and II_B) until the 2050s in the living room based on the CIBSE TM59 criteria. For normal occupants, the overheating risk is not predicted for all models until the 2050s but the risk can only be prevented in the models I_B and II_B post 2050s.

The simulation results show that in Manchester, the overheating risk in the living room is low for normal occupants according to the CIBSE TM59 benchmark, with four models predicted to pass the criteria until the 2080s. However, scenarios V_M and VI_M which represent the worst occupant behaviours will result in the occurrence of overheating for normal occupants in this location in the 2080s. For the case of vulnerable occupants, all models except the worst case one (VI_M) are predicted to provide thermally comfortable conditions in the living room until the 2050s based on CIBSE TM59 criteria. However, only the best model (I_M) can provide this condition post 2050s.

Finally, the simulation results in Figure 5.33 show that all scenarios with various occupant behaviour models in Edinburgh will pass the CIBSE TM59 overheating criteria for both vulnerable and normal occupants until the 2080s.

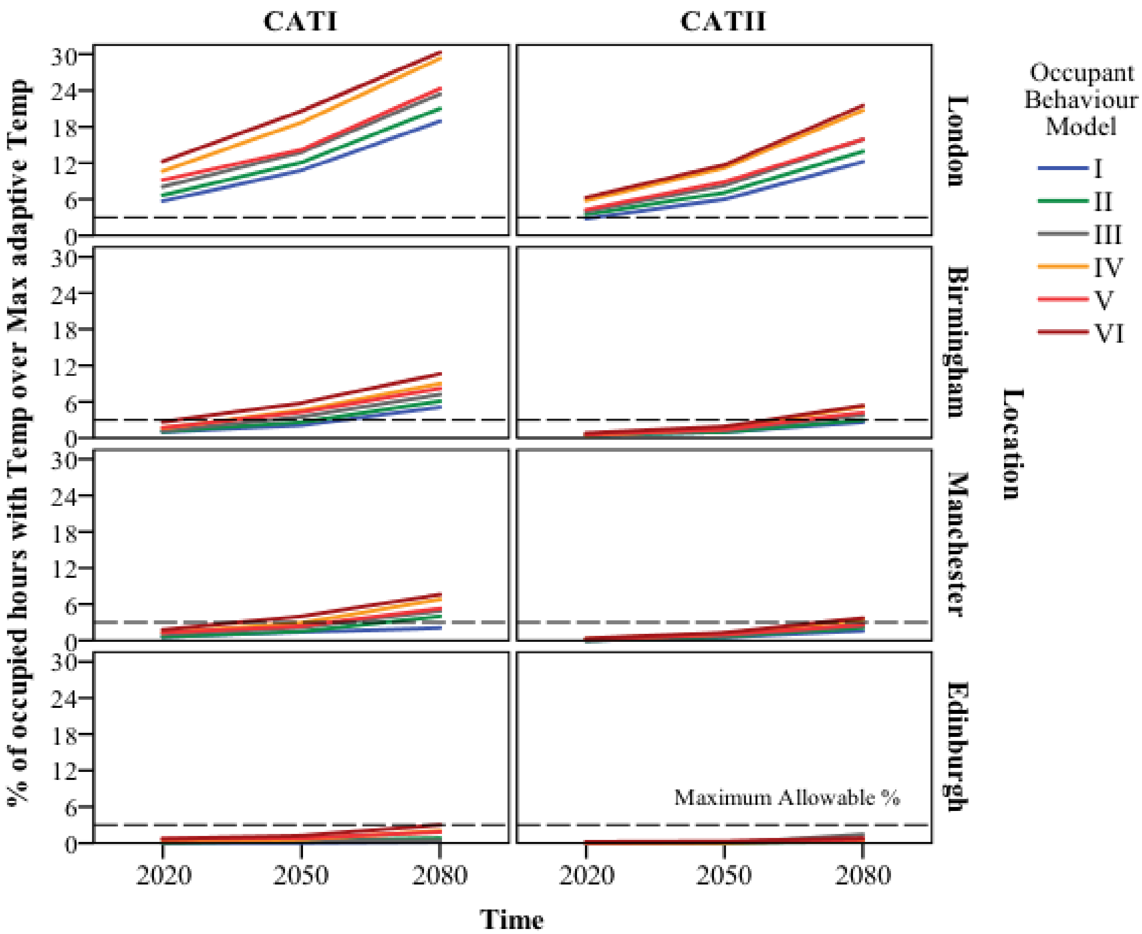


Figure 5.33 Future overheating risk assessment based on CIBSE TM 59 benchmark for the selected occupant behaviour scenarios (Living room)

Future overheating risk in bedrooms of the selected occupants' behaviour scenarios using CIBSE benchmark:

Figure 5.34 andFigure 5.35 show the future overheating risk in bedrooms based on the two criteria specified by CIBSE TM59 (CIBSE, 2017) for the selected occupant behaviour models. It is evident that in London, no occupant behaviour model passed Criteria b (Figure 5.35) in the 2020s and onward; therefore, bedrooms in all models are classified as overheated space for both occupant types in this location.

In Birmingham, all occupant behaviour models are predicted to meet Criteria a for normal occupants until the 2080s, and most options (5 out of 6) also will meet this criterion for vulnerable occupants until the 2050s (Figure 5.34). However, all models will fail to comply with Criteria b post 2020s. Hence, the compliances for bedroom overheating assessment cannot be met in any occupant behaviour model after the 2020s.

In Manchester, all selected occupant behaviour models will pass Criteria a for vulnerable and normal occupants until the 2050s and 2080s respectively. However, only the best occupant behaviour model with respect to the overheating risk (I_M) is predicted to pass Criteria b until the 2050s. Therefore, with the exception of one occupant behaviour scenario, all other models will not comply with CIBSE TM59 bedroom overheating criteria in Manchester post 2020s.

Simulation results for Edinburgh predicted that all selected occupant behaviour models will meet both bedroom overheating criteria stipulated by CIBSE TM59 for both vulnerable and normal occupants until the 2080s (Figure 5.34 and Figure 5.35).

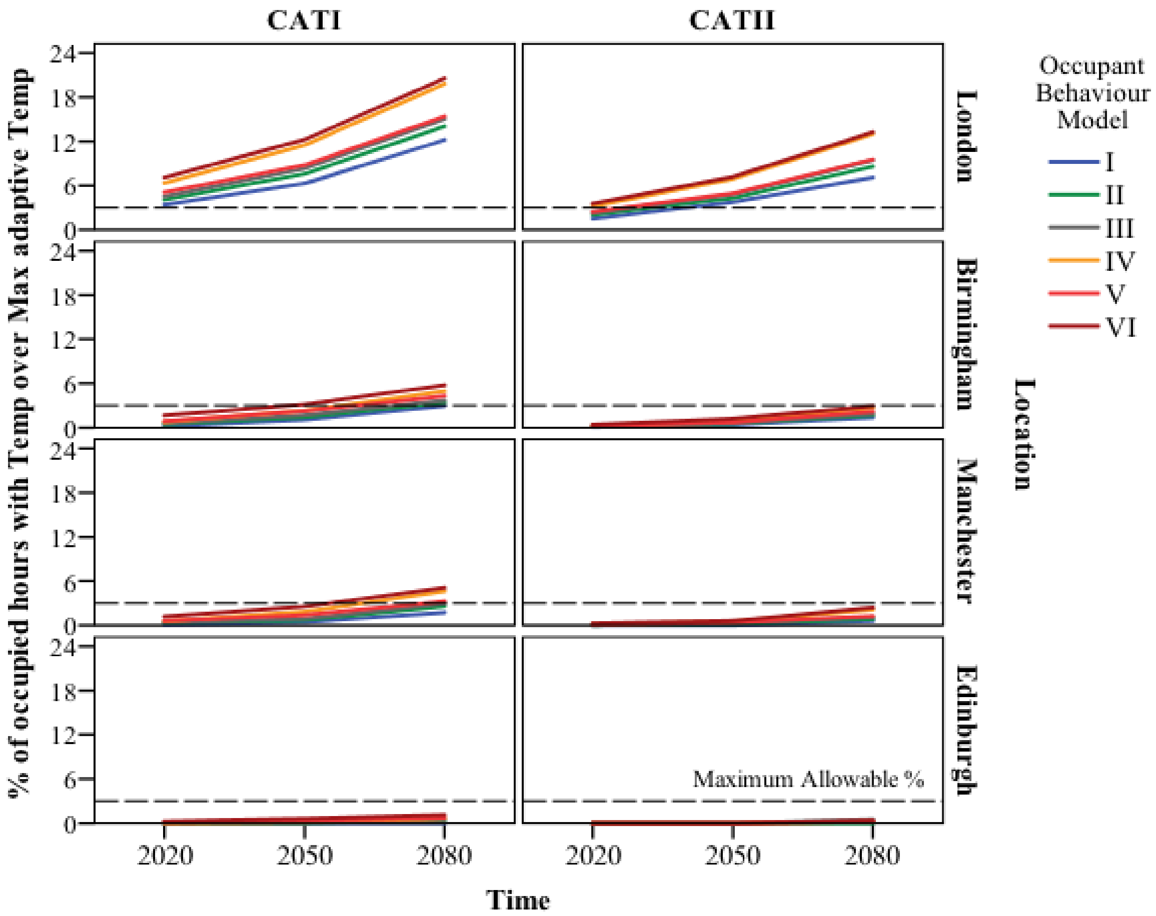


Figure 5.34 Future overheating risk assessment using CIBSE TM59 benchmark for the selected occupant behaviour scenarios (Bedroom) – Criteria a

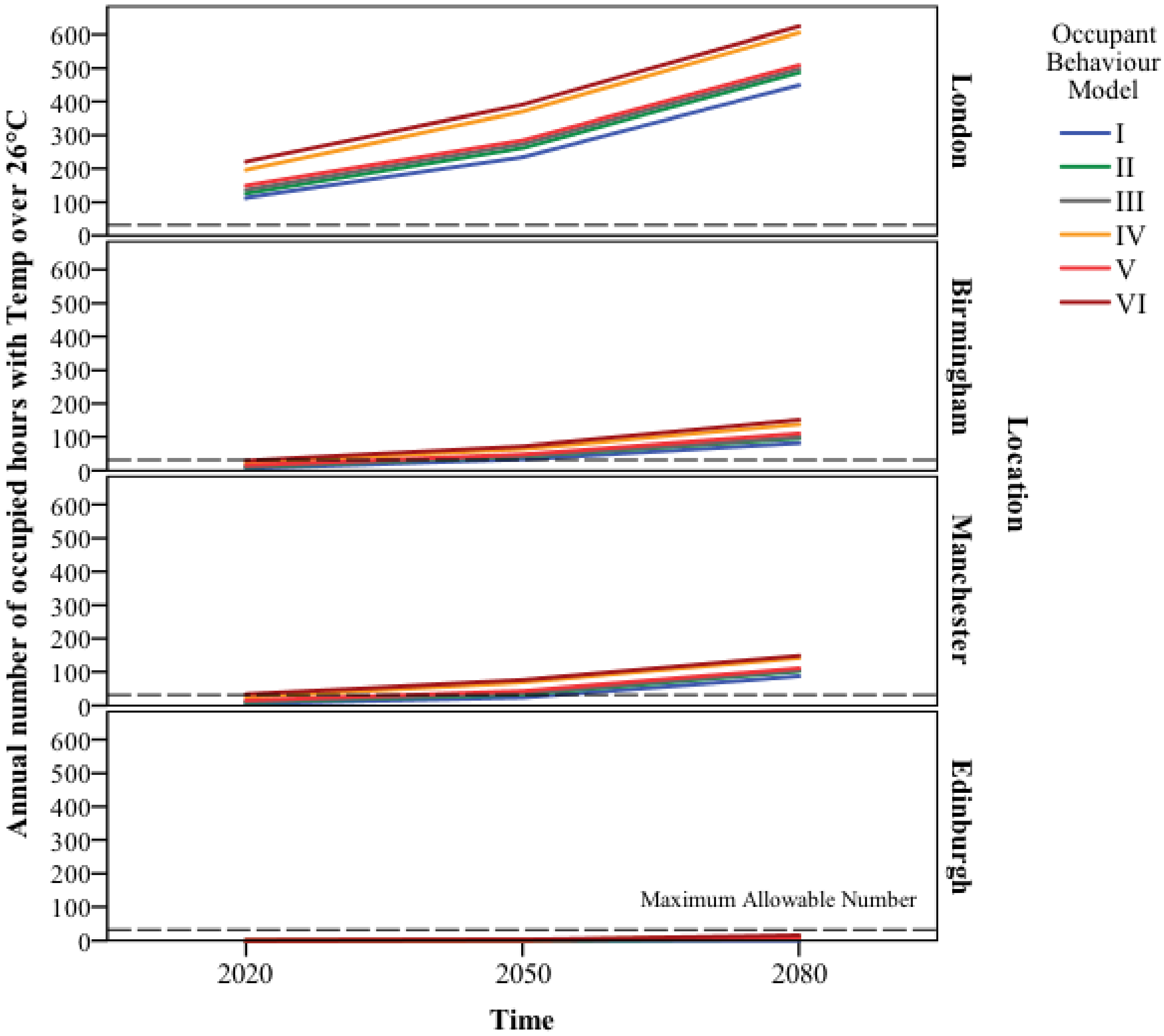


Figure 5.35 Future overheating risk assessment using CIBSE TM59 benchmark for the selected occupant behaviour scenarios (Bedroom) – Criteria b

5.7 Conclusion

This chapter presents an overview of the risk of overheating in the new UK social housing flats built to the Passivhaus standard using dynamic simulation. The use of simulation methods has been justified by comparing the data available from the presented case study in Chapter 4, and the data generated from the simulation of the case study block.

In this study, four out of the sixteen sites (with CIBSE available weather data for simulation) are selected for overheating assessment. London and Edinburgh are selected as representing the hottest and the coldest locations within the UK. Birmingham and Manchester are selected as they both represent moderate conditions.

Base Model block of flats have been developed in each location by incorporating all Passivhaus and UK social housing requirements and characteristics. The Base Models are also designed to comply with all the stipulated values and assumptions in CIBSE TM59 as the current UK methodology for overheating assessment in homes. As the result, four Base Models have been generated for the purpose of this study.

According to the available literature, the two factors of design and occupants' behaviours play a main role in developing the risk of overheating, in addition to the climate conditions. Each of these factors contains several sub factors. In this study a parametric study is conducted to investigate the influence of selected design and occupant behaviour sub factors on the risk of overheating.

In order to explore the influence of design and occupants' behaviours sub factors and investigate the suitability of constructing social housing flat built to the Passivhaus standard across the UK, a total of 64 scenarios are developed for each location, with the aid results from the parametric study. All scenarios are then simulated and the overheating risk assessed using CIBSE TM59 and Passivhaus Compliances criteria.

The result indicates that the overheating risk in London is found to be very significant while almost all scenarios failed to meet the compliances criteria. Edinburgh presents the best location for developing the Passivhaus flats, since no scenarios were found to be at risk of overheating. Although Birmingham and Manchester are shown to be low risk locations for developing the Passivhaus flats, careful design and occupant behaviour are essential in these two locations to ensure a comfortable condition in particular for vulnerable occupants.

Statistical analysis has been also conducted on the simulation results of all scenarios in all study locations to identify the relative influence of each selected design and occupant behaviour parameters on the risk of overheating. Results from statistical analysis indicate that all selected occupant behaviour parameters have significant effects upon the risk of overheating in all locations. Amongst the selected design parameters, south facing glazing and external shading have the most significant effects on the risk of overheating.

Future performance is investigated under various projected summer conditions to determine the long term suitability of Passivhaus with regards to the overheating risk.

Simulation results indicate that overheating risk will not occur for the case of Edinburgh until the 2080s under various predicted summer conditions. However, in Birmingham and Manchester, the occurrence of overheating is predicted in the 2020s for vulnerable occupants and in the 2050s for normal occupants under more extreme summer conditions. The results also indicate that flats in these two locations will not be able to provide thermally comfortable conditions for both occupant types almost in all summer conditions post 2050s.

Finally, the influence of design and occupant behaviour on future overheating risk have been investigated with the aid of selected design and occupant behaviour scenarios with various overheating risk. Apart from the case of London, where almost no design or occupant behaviour scenarios provided thermally comfortable flats, both design and occupant behaviour are shown to be effective in other locations in terms of preventing the occurrence of overheating risk in future years.

Chapter 6: Discussion

6.1 Introduction

Overheating is a fast-growing concern amongst the domestic design, construction and housing provider community. Overheating in domestic buildings has not always been a concern in the UK. However, the climate change and its inevitable effects on the building sector, ever-increasing urbanisation and construction of dense apartment blocks have all contributed in exacerbating the overheating risk. Also, adaptation of energy efficiency standards in recent decades to reduce winter energy demands and carbon emissions has led to higher indoor temperature during the summer time. Evidence and recent studies show the occurrence of overheating in the new UK energy efficient flats. Climate change may result in an increased risk of overheating in building sectors. This risk will be exacerbated due to the dense urbanization and increase of population in the future decades. The study shows that occupants' health and performance are in danger due to the risk of overheating and heat stress. Therefore, the building industry is facing the question of how to predict and mitigate this risk to maintain health and well-beings of the occupants. A clear understanding and definition of overheating and the identification of a suitable benchmark to evaluate this risk in any building is the main step to reduce and control the risk of overheating.

The Passivhaus standard is one of the fast-growing energy efficiency models that gained its popularity in the development of the energy efficient dwellings due to significant reduction of heating demand during winters. Although the energy efficient models that developed in the housing sectors claim to provide thermally comfortable conditions for occupants over the whole year, a recent study shows the occurrence in overheating in such energy efficient dwellings, as well as Passivhaus dwellings, is inevitable.

Recently, the social housing sector started adopting the Passivhaus standard to improve energy efficiency of their houses, to reduce energy consumption and hence reduce fuel poverty. The aim of this study is to help the building industry as well as social housing sectors to predict and mitigate the risk of overheating in the residential sector.

This chapter presents an overview of the suitability of different UK locations for developing the Passivhaus flats with respect to the current and future climate changes, followed by detailed discussion on how two elements of design and occupants can impact on overheating risk.

Suitability of available benchmarks in assessing the risk of overheating is also discussed in this chapter.

6.2 Considerable overheating risk in existing social housing flats built to the Passivhaus standard

In the first part of this study, the overheating risk in the current UK social housing flats built to the Passivhaus standard were investigated for existing case studies as discussed in Chapter Four. Table 6.1 shows the percentage of the overheated living rooms in each monitored summer period based on the two main benchmarks used for this study. The percentage of overheated living rooms is higher when the Passivhaus overheating benchmark is used, compared to the adaptive thermal comfort method which indicates that the level of risk based on CIBSE TM59 (CIBSE, 2017) Benchmark is not as high as the risk based on the Passivhaus Benchmark. Results also show that vulnerable occupants in more flats experienced thermally uncomfortable conditions over the case study monitoring periods. On average, more than half of the case study flats were overheated for the vulnerable occupants. Table 6.1 summarises the results of overheating investigation over the three monitoring periods.

Table 6.1 Percentage of overheated living rooms in the case study flats

Monitoring period	Passivhaus Benchmark	CIBSE TM59 Benchmark (Adaptive Thermal comfort)	
		Normal	Vulnerable
2011	73	27	36
2012	56	56	56
2013	100	80	100
Total	**72**	**48**	**56**

Given the higher percentage of vulnerable people living in the UK social housing compared to other sectors, the overheating risk is considered to be very significant in these type of flats. It is also notable that the effect of climate change can exacerbate this overheating risk in the future. Because of the recent uptake of the Passivhaus standard in the social housing sector, this study demonstrates the demand for comprehensive investigation into the overheating risk of this type of flats in different UK regions under the current and projected future climates. This is to establish the feasibility of such flats with respect to the overheating risk.

6.3 The impact of occupants' behaviour in developing the risk of overheating in existing social housing flats built to the Passivhaus standard

Results from the analysis of the recorded temperature in case study flats reveal significant variations in the elevated temperature in different living rooms. The percentage of hours with temperature over 25ºC vary from approximately 3% to 94% in 2011, 5% to 99% in 2012 and from 33% to 94% in 2013. In order to understand the relative influence of environmental factors (Outdoor temperature and solar radiation) on indoor temperature variation, statistical analysis has been conducted for each flat using recorded indoor and outdoor environmental factors. The result from statistical analysis shows that the influence of outdoor environmental factors on the indoor temperature varied from 5% to nearly 63% amongst different flats and in most cases, less than 50% of indoor temperature variations are explained by environmental factors. On average, for three monitoring periods and for 25 case study flats, only 32% of the variation of indoor temperature which is the main indicator of the overheating risk is affected by environmental factors, and 68% of the variation of indoor temperature is affected by occupant behaviour factors.

The results from this investigation therefore show that occupant behaviour has a significant impact on temperature variation and overheating. Also, comparison of the results in three monitoring periods shows that where the average daily percentage hours with elevated temperature is lower, the average impact of occupants behaviour on temperature variation is higher, which suggests that occupants have a considerable role in controlling overheating. Consequently, it is likely that occupant behaviour can increase the risk of overheating even in cases where the environmental factors are not very severe; it also suggests that even in cases when the environmental factors are severe, effective occupant behaviour can have a significant impact on reducing overheating risks in these flats.

Therefore, it is essential for the occupants to be familiar with methods of controlling the internal environment and reducing the risk of overheating in such energy efficient flats. This highlights the importance of the Post Occupancy Evaluation and educating occupants about their contribution towards reducing, and even eliminating, the risk of overheating.

6.4 Appropriateness of using CIBSE TM52 benchmark in evaluating the risk of overheating in social housing flats built to Passivhaus standard

A clear understanding and definition of overheating in any building is the main step to reduce and control the risk of overheating. To deal with the problem realistically, it is necessary to have the correct design benchmarks.

This study for the first time suggests the benefit of using the adaptive model in evaluating the risk of overheating in Social housing flats built to the Passivhaus Standard. Nearly one third of the occupants of these flats are more than 65 years old, which places them in the category of vulnerable groups. These groups are at a higher risk of suffering and health will deteriorate if exposed to high temperatures, compared to the normal occupants. The use of an adaptive model will highlight the risk of overheating in these groups and the urge to mitigate this risk through cautious design and promoting suitable adaptive behaviour.

This study carefully studied the suitability and applicability of the concept of adaptive thermal comfort model and use of TM52 (CIBSE, 2013) benchmark for evaluating the risk of overheating in in social housing flats built to the Passivhaus Standard. The study acknowledges the benefit of using an adaptive thermal comfort model in overheating assessment and the related benchmark at the time (i.e. TM52) but argues the application of the compliance criteria for assessing this risk specifically in the residential sector.

The study suggests in Chapter Four that criterion 2 of TM52 benchmark that considers the 6 degree hours as the allowable limit that indoor temperature can exceed the maximum adaptive threshold in each day, needs to be adjusted based on the actual occupancy hours of the space, as this limit is defined based on standard office occupancy hours. Following this suggestion, an overheating assessment was also conducted for all flat using the proposed revised criterion 2. Results show a considerable difference in the number of living areas which are categorised as overheated spaces based on the adaptation of a different limit. Therefore, the study suggests the need for a specific methodology for overheating assessment in residential sector. This result was published in Building and Environment Journal in the beginning of 2015. At the same time, the lack of specific methodology for overheating assessment in the UK residential sector has been highlighted by Zero Carbon Hub report (assessing overheating risk) in 2015 (ZCH, 2015). Following that, the CIBSE addressed this issue by publishing a new technical memorandum (TM59) in 2017, namely "overheating definition and assessment methodology for domestic building". In this methodology, meeting criterion 1 of the adaptive thermal comfort benchmark (as described in chapter 3) became the only compliance criteria for overheating assessment in domestic buildings (along with a fix benchmark for bedrooms only). This methodology has been adopted for further overheating assessment in this study (Chapter Five).

6.5 Overheating investigation in the new UK social housing flats built to the Passivhaus Standard

The first stage of this study demonstrates that the risk of overheating in UK social housing flats built to the Passivhaus standard is considerably high. However, there are a number of limitations in terms of investigating this risk in the UK using the case study flats. Firstly, all the case study flats are located in one location, to investigate the feasibility of constructing these flats across the UK considering various climate conditions. Secondly, all these flats mainly represent specific design and construction parameters, which limits investigation of the impact of a range of design parameters in developing the risk of overheating and to project what is happening. Thirdly, although the significant effect of occupants' behaviour on indoor temperature variation is established, there were lack of detailed data to explore the effect of associated parameters on developing the risk of overheating. Therefore, to address these limitations and provide a comprehensive investigation on the risk of overheating in such flats, various simulated scenarios have been developed to provide range of possible design and occupants behaviour options in different locations of the UK. In total, 64 scenarios have been developed in each study locations of London, Birmingham, Manchester and Edinburgh.

6.5.1 Overheating risk in new built Passivhaus flats in the social housing sector across the UK

In this study, an overheating assessment of new Passivhaus social housing flats has been conducted by modelling and simulation of a series of design scenarios in each location. In total, 32 design scenarios as well as the allocated Base Models of each location of London, Birmingham, Manchester and Edinburgh are simulated under the 2020 weather data.

Although these scenarios present possible variations in design parameters, it is notable that in reality there will be an infinite number of design options based on the combination of design parameters. However, these 132 scenarios are developed following a detailed investigation into the effectiveness of design parameters using parametric study. These scenarios were developed based on a range of various possible effective design parameters, with the aim of creating a full picture of variation in design choices.

To investigate the impact of design parameters on developing the risk of overheating, the occupant behaviour parameters of all the 132 developed design scenarios are defined and modelled in accordance with recommendations and standard values in CIBSE TM59: The UK standard methodology for overheating assessment in homes. The risk of overheating in these flats are investigated based on both Passivhaus and TM59 benchmarks using simulated data (Table 6.2).

As a result, it is evident that, there is a significant risk of overheating in the flats located in London as almost all the scenarios are predicted to be overheated based on both benchmarks and for both Normal and Vulnerable occupants. Therefore, London is not a suitable location for developing Passivhaus flats while the other locations are potentially appropriate. There is no risk of overheating in other locations for Normal occupants; however, the risk of overheating exists in the limited numbers of design scenarios for vulnerable occupants in other locations. For this reason, additional consideration at the design stage is required in designing such flats that aims to accommodate vulnerable occupants.

Table 6.2 Percentage of overheated flats in each location based on 132 scenarios simulated under 2020s weather condition

Location	Passivhaus Benchmark		CIBSE TM59 Benchmark (Adaptive Thermal comfort)			
			Vulnerable Occupant		Normal Occupant	
	Bedroom	Living room	Bedroom	Living room	Bedroom	Living room
London	0	100	100	100	100	82
Birmingham	0	0	0	15	0	0
Manchester	0	0	0	12	0	0
Edinburgh	0	0	0	3	0	0

6.5.2 Influence of occupant behaviour in developing the risk of overheating in new social housing flats built to the Passivhaus standard across the UK

The first part of this study demonstrated that occupant behaviour has a significant influence on developing the risk of overheating. Therefore, there is a need to investigate the effect of occupants' behaviour on reducing or exacerbating the risk of overheating. For this reason, in total, 32 occupant behaviour scenarios including the allocated Base Models of each location of London, Birmingham, Manchester and Edinburgh are simulated under the 2020 weather data.

In this part, all the developed Based Models have been modelled with the use of standard occupant behaviour defined based on recommended values and assumptions in CIBSE

TM59. However, the other 124 (31 in each location) scenarios are developed by combination of effective occupant behaviour parameters and their relative potential variations obtained from detailed Parametric Study of occupant behaviour factors, using the base simulation model. All of these scenarios are simulated and ranked based on the risk of overheating (details in Chapter Five and appendix C). In each location 25 out of 32 scenarios show a higher overheating risk compared to the risk of overheating at Base Models flats, while 6 out of 32 scenarios show lower overheating risk. These two sets of scenarios (which their occupants behaviours are better and worse compared to the occupant behaviours set for the Base Models) demonstrate the implication of occupant behaviour variations in comparison to the occupant behaviour that is recommended by CIBSE TM59 as standard occupant behaviour model.

Analysis of the result in this section not only provides a more comprehensive understanding of the overheating risk in Passivhaus social housing flats across the UK, but also shows the possibility of reducing or exacerbating the risk of overheating by occupant behaviour. Table 6.3 compares the risk of overheating in all scenarios with the allocated Base Models in each location.

For the case of London, significant overheating risk is predicted even for scenarios with improved occupant behaviour. Therefore, this location is shown to have such a high overheating risk which is unlikely to be reduced by improving the occupant behaviour.

This analysis shows that in Birmingham and Manchester, variation in occupant behaviour, compared to the standard model, can lead to the overheating risk in bedrooms for both occupant types, and in living rooms for vulnerable occupants in up to one third of flats. There is also a possibility of overheating in living rooms for normal occupants in Birmingham. This highlights the importance of occupant behaviour in these two locations (and locations with a similar climate), and the need for informing the occupants about the appropriate actions to avoid the occurrence of overheating.

Edinburgh (and locations with similar climate) is shown to be the ideal location for developing Passivhaus social housing flats, as no overheating risk is predicted for the Base Model with Standard occupant behaviour and also the variations in occupant behaviour are not predicted to result in occurrence of overheating.

Table 6.3 Comparison of the overheating risk based on the variation in occupant behaviour

Location	Occupant behaviour Model	Percentage of overheated spaces (%)					
		Passivhaus Benchmark		CIBSE TM59 Benchmark (Adaptive Thermal comfort)			
		Bed	Liv	Vulnerable Occupant		Normal Occupant	
				Bed	Liv	Bed	Liv
London	lower risk scenarios	% 0 F	**%80 F**	**%100 F**	**% 100 F**	**% 100 F**	**%80 F**
	BM_L (Standard occupant behaviour)	Pass	Fail	Fail	Fail	Fail	Fail
	Higher risk scenarios	**%100 F**	**%100 F**	**%100 F**	**%100 F**	**%100 F**	**%100 F**
Birmingha	lower risk scenarios	% 0 F	% 0 F	% 0 F	% 0 F	% 0 F	% 0 F
	BM_B (Standard occupant behaviour)	Pass	Pass	Pass	Pass	Pass	Pass
	Higher risk scenarios	% 0 F	% 0 F	**% 36 F**	**% 20 F**	**% 36 F**	**% 4 F**
Mancheste	lower risk scenarios	% 0 F	% 0 F	% 0 F	% 0 F	% 0 F	% 0 F
	BM_M (Standard occupant behaviour)	Pass	Pass	Pass	Pass	Pass	Pass
	Higher risk scenarios	% 0 F	% 0 F	**% 40 F**	**% 12 F**	**% 40 F**	% 0 F
Edinburgh	lower risk scenarios	% 0 F	% 0 F	% 0 F	% 0 F	% 0 F	% 0 F
	BM_E (Standard occupant behaviour)	Pass	Pass	Pass	Pass	Pass	Pass
	Higher risk scenarios	% 0 F	% 0 F	% 0 F	% 0 F	% 0 F	% 0 F

6.6 Effective design and occupant behavior parameters on overheating risk across the UK

In the previous sections, the roles of design and occupant factors in developing the risk of overheating in Passivhaus flats located across the UK is demonstrated. This section discusses a suitable approach to reducing the overheating risk by exploring the influence of design and occupant sub factors on developing this risk. The main factors that need to be considered to control the risk of overheating in a building, which are highlighted in the literature, are solar gain, thermal mass, internal gain and ventilation. A number of studies have been examined on the effect of these factors and their associated parameters on developing the overheating risk in buildings (details in section 2.7 Chapter Two). In this study, the effects of these factors on the overheating risk in Passivhaus flats across the UK are investigated by conducting statistical analyses on the pair wise design and occupant behaviour scenarios (discussed in section 5.5.3 Chapter Five).

With regards to the design parameters, results from this statistical analysis shows that solar gain (which is affected by south facing glazing area, external shading and glazing g-value) have higher effect on the risk of overheating in all study locations. The amount of ventilation (due to changes in window opening area) is shown to have the least effect in comparison to the other design factors and is mainly effective in reducing the overheating risk in London. The level of thermal mass also found to be effective in reducing the risk of overheating, in particular in locations with a warmer climate (London and Birmingham).

For this reason, there is a need for designers to control the unnecessary solar gain by considering effective external shading devices, an appropriate level of south facing glazing and specifying the appropriate glazing g-value, to reduce the risk of overheating. Since the solar gain plays a significant role in Passivhaus in reducing the heating load during the winter months, alterations to the mentioned factor should be conducted with careful consideration to ensure a balance between the heating demand target and overheating risk and not sacrificing one target at the expense of the other one.

In the flats which are considered for vulnerable occupants and are located in locations with a higher overheating risk, there is a need for further considerations at the design stage to reduce the risk of overheating, using a suitable thermal mass level that helps to store extra and unnecessary heat during the day and facilitate night time ventilation.

Statistical analysis is also conducted on the pair wise occupant behaviour scenarios. Occupant related ventilation factors (use of MVHR bypass mode, windows opening threshold and providing the opportunity for cross flow ventilation), occupant related solar gain factor (use of internal shading) and internal gain are included in this analysis. This study shows that all these occupant behaviour factors have significant effects on the overheating risk in all locations. The findings also emphasise the importance of occupant behaviour factors on controlling the risk of overheating and the need to educate and monitor their behaviours through Post Occupancy Evaluation.

6.7 Overheating assessment for projected future climatic conditions

6.7.1 Future overheating risk in Passivhaus social housing flats across the UK

According to CIBSE TM 59 (CIBSE, 2017), overheating assessment should be conducted under more extreme weather files as well as future climate files where there is a particular concern (e.g. vulnerable occupants); however, these further tests are not mandatory. In this study, due to the high level of vulnerable occupants in the social housing sector and also to provide a comprehensive overview of the risk of overheating in Passivhaus social housing flats across the UK, all Base Models are simulated and tested using all projected weather files of Moderate warm summer, Short, intense warm summer and Long less intense warm summer. Table 6.4 summaries the result of this investigation.

Table 6.4 Summary of the future overheating risk considering various projected summer conditions

Location	Future summer condition	Passivhaus Benchmark						CIBSE TM59 Benchmark (Adaptive Thermal comfort)											
								Normal Occupant						Vulnerable Occupant					
		Bedroom			Living room			Bedroom			Living room			Bedroom			Living room		
		2020	2050	2080	2020	2050	2080	2020	2050	2080	2020	2050	2080	2020	2050	2080	2020	2050	2080
London	Moderate warm summer	P	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
	Short, intense warm summer	P	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
	Long less intense warm summer	P	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
Birmingham	Moderate warm summer	P	P	F	P	P	F	P	P	P	P	P	F	P	P	P	P	F	F
	Short, intense warm summer	P	P	P	P	P	F	F	F	F	P	F	F	F	F	F	F	F	F
	Long less intense warm summer	P	P	P	P	P	F	F	F	F	P	F	F	F	F	F	F	F	F
Manchester	Moderate warm summer	P	P	P	P	P	P	P	F	F	P	P	P	P	F	F	P	P	F
	Short, intense warm summer	P	P	P	P	P	P	P	F	F	P	P	F	P	F	F	P	F	F
	Long less intense warm summer	P	P	P	P	P	F	F	F	F	P	F	F	F	F	F	F	F	F
Edinburg	Moderate warm summer	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
	Short, intense warm summer	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
	Long less intense warm summer	P	P	P	P	P	P	P	P	F	P	P	P	P	P	F	P	P	P

From the simulation of the Base Models and evaluating the risk of overheating in various locations in the UK and under different projected summer conditions, it can be concluded that:

- For London, regardless of benchmarking criteria, the simulations predicted overheating risk from the 2020s onwards for all living spaces (living and bedroom) and all occupant types (vulnerable and normal).
- For Birmingham, based on Passivhaus criteria, all conditions pass overheating benchmarks until the 2080s. Based on CIBSE benchmarking criteria for living rooms, overheating conditions will happen for vulnerable occupants in all conditions except for the case of projected Moderate summer condition in the 2020s. For normal occupants, living rooms will not be overheated until the 2020s

based on all projected summer weather conditions. From 2020s onwards, all summer conditions show overheating in living rooms for normal occupants and only Moderately warm summers did not result in overheating for normal occupants until the 2050s. For bedrooms, CIBSE overheating criteria will fail for both occupant types in all summer conditions, except for the case of Moderate summer condition in the 2020s.

- For Manchester, Passivhaus criteria for overheating was met for all conditions and weather files, except for Long, less intense summers in the 2080s. Based on CIBSE criteria for living rooms, for normal occupant types, overheating will only take place for Short, intense summers in the 2080s and Long, less intense summers from the 2050s onwards. The overheating risk in living rooms for vulnerable occupants and bedrooms for both occupant types is higher, and only meet the criteria for the case of Moderately warm and Short, intense summers until the 2020s.
- For Edinburgh, the simulation results confirm that it to be the best location for developing social housing flats built to the Passivhaus standard and with no overheating risk until the 2080s (except bedrooms in 2080s under very extreme summer condition).

Scenario modelling of various design options indicates that Birmingham and Manchester (and in general locations with similar climate) are low risk sites for developing Passivhaus social housing flats. However, results from further overheating investigation of the Base Models using projected future weather data, and also more extreme summer conditions, show that the risk of overheating is high in these locations in particular for the case of vulnerable occupants. Therefore, it is evident that extra considerations should be made in designing such flats in these locations and further overheating assessment, by the use of more extreme weather files and predicted future climate, are recommended for new flats in these locations. In the following sections, the potential of design and occupant behaviour in reducing this risk will be discussed.

6.7.2 Future overheating risk in Passivhaus social housing flats across the UK considering the design variations

The influence of design on reducing and exacerbating the future overheating risk is examined in this study. This investigation has been conducted by future overheating assessment of the range of design options with various overheating risk as described in section 5.6.2.1 Chapter Five. Table 6.5 summarises the results of this analysis.

Table 6.5 Summary of the future overheating risk considering the design variations

Location	Selected design option	Passivhaus Benchmark						CIBSE TM59 Benchmark (Adaptive Thermal comfort)											
								Normal Occupant						Vulnerable Occupant					
		Bedroom			Living room			Bedroom			Living room			Bedroom			Living room		
		2020	2050	2080	2020	2050	2080	2020	2050	2080	2020	2050	2080	2020	2050	2080	2020	2050	2080
London	A_L	P	F	F	P	F	F	F	F	F	P	F	F	F	F	F	F	F	F
	B_L	P	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
	C_L	P	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
	D_L	P	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
Birmingham	A_B	P	P	P	P	P	P	P	P	F	P	P	P	P	P	F	P	P	F
	B_B	P	P	P	P	P	P	P	P	F	P	P	P	P	P	F	P	P	F
	C_B	P	P	P	P	P	F	P	F	F	P	P	F	P	F	F	P	F	F
	D_B	P	P	F	P	P	F	P	F	F	P	P	F	P	F	F	P	F	F
Manchester	A_M	P	P	P	P	P	P	P	P	F	P	P	P	P	P	F	P	P	F
	B_M	P	P	P	P	P	P	P	F	F	P	P	P	P	F	F	P	P	F
	C_M	P	P	P	P	P	P	P	F	F	P	P	F	P	F	F	P	F	F
	D_M	P	P	P	P	P	F	P	F	F	P	F	F	P	F	F	F	F	F
Edinburg	A_E	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
	B_E	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
	C_E	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	F
	D_E	P	P	P	P	P	P	P	P	P	P	P	P	P	P	F	P	P	F

From the future overheating assessments of the various design options with different overheating risk, it can be concluded that:

- For London, overheating risk is predicted for all the selected design options based on both Passivhaus and CIBSE overheating criteria from the 2020s onwards for all living spaces (living room and bedroom) and all occupant types (vulnerable and normal).
- For Birmingham, selected design options (A & B) with lower overheating risk (options with less than 3% of occupied hours with temperature over 25°C under projected 2020s weather condition) are predicted to provide a thermally comfortable condition for occupants in the living room by the 2080s based on Passivhaus benchmark ,while other selected options with a higher overheating risk are predicted to fail the overheating benchmark post 2050s. For the case of overheating assessment based on CIBSE benchmarks, design option A and B will pass the compliances in the living room for normal occupants until the 2080s, for vulnerable occupants until the 2050s and also until the 2050s in bedrooms for both occupant types. In other selected design options with higher overheating risk, occurrence of overheating is predicted based on the CIBSE benchmarks from the 2020s onwards in bedrooms for both occupant types and in living rooms for vulnerable occupants.
- For Manchester, Passivhaus criteria for overheating will be met until the 2080s for all selected design options with less than 4% of occupied hours with temperature above 25°C under 2020s projected weather condition. Based on CIBSE criteria for living rooms, occurrence of overheating can only be prevented until the 2050s and the 2080s for vulnerable and normal occupants respectively, in the design options with less than 3 percent of hours with temperature above 25°C under 2020 weather conditions. For the case of bedrooms, and based on CIBSE overheating compliances, all selected design options will fail to meet the compliances post 2020s except the best design option (A) which will only comply with the benchmarking criteria until the 2050s.
- For Edinburgh, the simulation results show that all selected design options with various overheating risks can provide thermally comfortable conditions in living rooms by the 2080s based on Passivhaus benchmark and CIBSE criteria for

normal occupants. Also, all selected design options pass the CIBSE bedroom overheating compliances for both occupant types until the 2080s. The simulation results for Edinburgh show that the overheating will only occur for vulnerable occupants in selected design options of C & D in the 2080s.

6.7.3 Future overheating risk in Passivhaus social housing flats across the UK considering the effect of occupant behaviour

Finally, the influence of occupant behaviour for reducing and exacerbating the future overheating risk is also investigated in this study. This investigation has been conducted by future overheating assessment of the Base Model (scenarios with standard occupant behaviour) and also two and three other occupant behaviour scenarios with lower (scenarios I & II) and higher (scenarios IV, V & VI) overheating risk, respectively. Table 6.6 summarises the results presented in detail in section 5.6.2.2 Chapter Five.

Table 6.6 Summary of the future overheating risk considering occupant behaviour variations

Location	Occupant Behaviour Model	Passivhaus Benchmark						CIBSE TM59 Benchmark (Adaptive Thermal comfort)											
								Normal Occupant						Vulnerable Occupant					
		Bedroom			Living room			Bedroom			Living room			Bedroom			Living room		
		2020	2050	2080	2020	2050	2080	2020	2050	2080	2020	2050	2080	2020	2050	2080	2020	2050	2080
London	I$_{L}$	P	F	F	P	F	F	F	F	F	P	F	F	F	F	F	F	F	F
	II$_{L}$	P	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
	III$_{L}$ (BM$_{L}$)	P	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
	IV$_{L}$	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
	V$_{L}$	P	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
	VI$_{L}$	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
Birmingham	I$_{B}$	P	P	P	P	P	P	P	F	F	P	P	P	P	F	F	P	P	F
	II$_{B}$	P	P	P	P	P	P	P	F	F	P	P	P	P	F	F	P	P	F
	III$_{B}$ (BM$_{B}$)	P	P	P	P	P	F	P	F	F	P	P	F	P	F	F	P	F	F
	IV$_{B}$	P	P	P	P	P	F	P	F	F	P	P	F	P	F	F	P	F	F
	V$_{B}$	P	P	P	P	P	F	P	F	F	P	P	F	P	F	F	P	F	F
	VI$_{B}$	P	P	F	P	F	F	F	F	F	P	P	F	F	F	F	P	F	F
Manchester	I$_{M}$	P	P	P	P	P	P	P	P	F	P	P	P	P	P	F	P	P	P
	II$_{M}$	P	P	P	P	P	P	P	F	F	P	P	P	P	F	F	P	P	F
	III$_{M}$ (BM$_{M}$)	P	P	P	P	P	P	P	F	F	P	P	P	P	F	F	P	P	F
	IV$_{M}$	P	P	P	P	P	P	P	F	F	P	P	F	P	F	F	P	P	F
	V$_{M}$	P	P	P	P	P	P	P	F	F	P	P	P	P	F	F	P	P	F
	VI$_{M}$	P	P	P	P	P	F	P	F	F	P	P	F	P	F	F	P	F	F
Edinburg	I$_{E}$	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
	II$_{E}$	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
	III$_{E}$ (BM$_{E}$)	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
	IV$_{E}$	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
	V$_{E}$	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
	VI$_{E}$	P	P	P	P	P	P	P	P	P	P	P	P	P	P	F	P	P	P

From future overheating assessments of the scenarios with different occupant behaviour and various overheating risks, it can be concluded that:

- The overheating risk is predicted to be very significant in London. Simulation results show that, regardless of the occupant type, none of the selected occupant behaviour models can provide thermally comfortable conditions in both living rooms and bedrooms based on CIBSE TM59 overheating benchmark in the 2020s and onwards. Also, all occupant behaviour models (except the best selected model) failed the Passivhaus overheating criteria at any studied time. It is worth mentioning that the best occupant behaviour model only passed the Passivhaus criteria in the 2020s with a very small margin.
- In Birmingham, assessment of future overheating risk for different occupant behaviour models show that the occurrence of overheating in the living room can be delayed by the effect of occupant behaviour. Occupant behaviour models with less overheating risk compared to the Base Model (Models I and II) are predicted to prevent the occurrence of overheating based on Passivhaus criteria and CIBSE TM 59 benchmark for normal occupant until the 2080s, and for vulnerable occupant until the 2050s. However, the overheating risk in bedroom is shown to be more significant in this location while no model can meet the compliances post 2020s.
- In Manchester, the overheating risk is predicted to be low in accordance with the Passivhaus criteria and CIBSE TM59 benchmark for normal occupants in the living room. However, the occupant behaviour is shown to be effective in exacerbating this risk while the simulation results shows that the model with the highest overheating risk will not be able to meet the compliance in the 2080s. For the case of vulnerable occupants, the overheating risk is predicted to be significant after the 2050s and only the best model can prevent the overheating risk until the 2080s. Similar to Birmingham, the overheating risk in bedrooms is also predicted to be significant with all models failing to meet the compliances for both occupant types after the 2020s.
- Regardless of the benchmarking criteria, all selected occupant behaviour models with various overheating risk in Edinburgh are predicted to provide thermally

comfortable conditions in both living room and bedroom for both occupant types until the 2080s.

6.8 Appropriateness of the CIBSE TM59 overheating benchmarks

CIBSE TM59 (CIBSE, 2017) methodology for the assessment of overheating risks in residential buildings has been introduced in 2017 in response to the lack of specific guidelines for overheating assessment in homes.

Dynamic thermal modelling is the core of this new methodology. The main parameters and assumptions related to the occupant behaviour factors (e.g. window opening threshold and internal gain profiles) are defined in this guideline. While it is acknowledged that this approach provides a consistency in assessing the risk of overheating in residential sector, it should be noted that it cannot address a full picture of possible variations of occupant behaviour in reality. In this study, the importance of the occupant behaviour on reducing or exacerbating the risk of overheating is demonstrated in both case study analysis and simulations modelling. Results from this study shows that in some flats across the UK, where no overheating risk is predicted based on standard occupant behaviour parameters defined in this guideline, the occurrence of overheating risk can be developed as a result of variation in occupant behaviour parameters in particular for the case of vulnerable occupants. It is also arguable that in some cases the opportunity for the occupant to benefit from some actions, specified in this guideline, is not available. For example, in very noisy or polluted areas, window opening may be avoided by the occupants.

Therefore, this study recommends that detailed information about the assumptions associated to the modelling of occupant behaviour related parameters should be included in the overheating report. It is also essential that these factors and the associated required actions by the occupants to be included in any occupant education package.

Alternatively, where there is a particular concern about the abilities of occupants to follow the recommended actions (e.g. vulnerable occupants) or the possibility of following such recommendations (e.g. noisy and polluted areas), the wider effects of occupant behaviour factors should be considered at design and modelling stages. In this case, this study recommends that number of various occupant behaviour scenarios, with different overheating risks, should be developed and tested to ensure the suitability of design with respect to the overheating risk. This approach has been adopted in this research to provide a more comprehensive overview of the overheating risk in new social housing flats built to the Passivhaus standard across the UK.

6.9 Conclusion

This chapter discussed the main findings of this research. The appropriateness of the available overheating methodology and benchmarks are discussed in this chapter and the benefits and limits are highlighted. A full overview of the overheating risk in Passivhaus flats under current and projected future conditions across the UK are presented and the effects of design and occupant behaviour in reducing or exacerbating overheating risk in each study location are discussed. Overheating risk in London is found to be very significant and improving design or occupant behaviour are shown to have no effect on avoiding this risk. The finding of this research suggests that Edinburgh (and locations with a similar climate) is the best location for developing Passivhaus flats, with no overheating risk under current or future climate. Although Birmingham and Manchester (and other locations with similar climate) are shown to be low risk locations for developing the Passivhaus flats, to ensure delivering of thermally comfortable dwellings in particular for vulnerable occupants, there is a need for careful design and thermal modelling simulation in these locations. Also, the importance of occupants' awareness and education about the appropriate actions to control overheating risk in these locations are discussed.

The impacts of appropriate design and occupant behaviour in preventing the future overheating risk is demonstrated, however these factors have been found to only reduce the risk of overheating under certain climate scenarios and time scales. With regards to the design parameters, factors associated with solar gain (glazing area, external shading and glazing g-value) are found to have more significant impact on reducing the overheating risk which comply with other researches in this area. The findings in this chapter demonstrate that the work has answered all the key research questions and also the context of the literature used to underpin the research project.

Chapter 7: Conclusion

7.1 Introduction

This chapter provides the overall conclusion of this research in three sections. In the first section all the findings as the result of assessing the case study is explained. In the second section all the findings at the result of assessing the simulation models under current climate condition and in the third section all the findings as the result of assessing simulation models under future climate conditions are explained. These three sections demonstrate how the research questions, aim and objectives of the research have been fulfilled. The overall conclusions which were demonstrated in three sections, followed by a list of recommendations for the stakeholders and designers in social housing and building sectors in order to provide thermally comfortable conditions for their occupants. This chapter also proposes future works based on the findings and limitations of this study.

7.2 Overall conclusion

7.2.1 Case Study

Following are the list of findings from analysing case study data and overheating assessment:

- Considerable numbers of monitored case study flats have been overheated during all monitoring periods using both fixed (Passivhaus) and adaptive thermal comfort benchmark (CIBSE TM52). Therefore, significant risk of overheating in existing (recently built) UK social housing flats is highlighted in this study.
- Analysing the design aspect of the case study flats indicates that factors related to the solar gain are not carefully designed. In particular, the south facing glazing area is considerably higher than the recommended values and no external shading is designed for most of the glazing area. Given the importance of the solar gain in reducing the heating demand in Passivhaus design, this can suggest that meeting the heating demand might be achieved at the expense of the overheating risk. Also,

a high percentage of the overheated flats based on the Passivhaus criteria, demonstrates the performance gap in these certified Passivhaus flats. This indicates the inappropriateness of using Passivhaus planning package (PHPP) software for overheating analysis and also highlights the importance of dynamic thermal modelling for overheating assessment at design stage.

- Detailed analysis of the indoor temperature variation in all case study flats show the significant impact of occupant behaviour parameters on the recorded temperature in comparison to the external environmental factors. This suggests that occupant behaviour has a considerable role in controlling the overheating and highlights the importance of educating occupants about the suitable adaptive behaviours prior to being accommodated in highly insulated airtight energy efficient flats such as Passivhaus.
- The application of CIBSE TM52 second compliance criteria (limit in daily weighted exceedance) for overheating assessment in residential building needs to be reviewed to address the actual occupancy hours.

7.2.2 Simulated models under Current climate

From the findings of this study, the **current** risk of overheating in new social housing flats built to the Passivhaus standard across the UK and occupant behaviour influence on controlling the risk of overheating are as follow:

a) The current risk of overheating across the UK considering the possible design variations:

- Very significant risk of overheating in London for all occupant types. Therefore, this location is not recommended for developing Passivhaus flats.
- For other locations within the UK, which have a similar climate to Birmingham, Manchester and Edinburgh, there is no risk of overheating for normal occupants and such flats in these locations can provide thermally comfortable conditions as well as energy efficient homes. However, overheating risk potentially exists for vulnerable occupants in some design

options. According to the literature, vulnerable occupants demonstrate less effective behaviour in controlling their environment compared to normal occupants, therefore the importance of careful design and overheating assessment is recommended and essential in the flats that accommodate vulnerable occupants.

b) The effect of occupant behaviour on the current risk of overheating in new Passivhaus flats in social housing sector across the UK:

- Flats in London are shown to be at a high risk of overheating risk which cannot be reduced or avoided by improving the occupant behaviour.
- With the case of Birmingham and Manchester, while the overheating risk is predicted to be very low, occupant behaviour is shown to have influence on exacerbating this risk in particular for vulnerable occupants and in bedrooms. Therefore, while these two locations, and locations with similar climates, can be appropriate for developing Passivhaus flats, occupants' awareness and education about the appropriate actions to control and avoid overheating is very important in these areas.
- Edinburgh (and locations with similar climate) is shown to be the ideal location for developing Passivhaus flats since no overheating risk in all flats with various occupant behaviour scenarios (with different overheating potential) is predicted.

7.2.3 Simulated models under Future climate

Following are the list of findings about the future overheating risk considering various projected summer conditions and also potential of design and occupant behaviour in controlling the **future** risk of overheating in new Passivhaus flats in social housing sector.

a) Projected summer conditions and future risk of overheating across the UK:

- For the case of London, it is evident that while overheating is predicted to occur in current Moderately warm summer, this risk will increase under more extreme summer conditions and in future years. Hence, this location is at great risk of overheating and the construction of new Passivhaus social housing flats is not suggested.
- In Birmingham and Manchester, the risk of overheating is predicted for vulnerable occupants from the 2020s onwards and for normal occupants from the 2050s onwards in living rooms respectively. However, the overheating risk is predicted to occur in bedrooms for both occupant types from the 2020s onward. Therefore, it is strongly recommended that overheating risk, for any new Passivhaus flats (in particular dwellings with the presence of vulnerable occupants), in these locations to be carefully assessed at design stage using both current and projected future weather data as well as more extreme summer conditions. This will ensure the delivery of flats which will be able to provide thermally comfortable conditions over the life span of the building.
- The appropriateness of Edinburgh and locations with similar climate for developing such flats is also confirmed by this investigation where overheating risk is not predicted in almost all projected future summer conditions and for all occupant types.

b) Design considerations and future risk of overheating across the UK:

- For the case of London, it has been shown that no design option can provide thermally comfortable conditions in the current climate (2020s). Therefore, all the selected flats will be at risk of overheating under future climate conditions and this risk is much more significant in selected design options with higher risk of overheating.
- In Birmingham and Manchester, it has been shown that improving design can prevent the occurrence of overheating to a certain extent, based on occupant

vulnerabilities. According to the findings of this research, it is recommended that the designer should only allow the design options with less than 3% of occupied hours with temperature over 25°C under current climate in these locations and other UK locations with similar climate (it is notable that the target overheating risk by BRE Passivhaus designer guide is 5%). However, it is worth mentioning that while overheating risk can be prevented in living rooms for normal occupants until the 2080s, for vulnerable occupants in living rooms and in bedrooms for both occupant types, this risk can only be postponed until the 2050s. Arguably, this risk can be further prevented by improving the occupant behaviour or additional design consideration. In both cases, careful dynamic thermal simulation, to test the possibility of avoiding overheating risks, is recommended.

- For the case of Edinburgh is shown that design options, with more than 1% of occupied hours with temperature over 25°C under the current climate, can result in the occurrence of overheating in the 2080s for vulnerable occupants. However, this risk can be easily prevented by improving the design.

c) Occupant behaviour and future risk of overheating across the UK:

- While the risk of overheating in London is very significant, it is also shown that improving occupant behaviour cannot prevent the occurrence of overheating.
- In Birmingham and Manchester, improving the occupant behaviour is shown to be effective in reducing the future overheating risk to some extent based on occupant vulnerabilities. Delay in the occurrence of overheating by improving occupant behaviour can be achieved in these locations until the 2050s and the 2080s for vulnerable and normal occupants, respectively. However, the overheating risk in bedrooms is more significant and cannot be delayed after the 2020s.
- Testing different occupant behaviour scenarios, with various overheating risk, in Edinburgh also confirms the suitability of this location for developing the

Passivhaus flats while all selected models with higher overheating risk will also meet the overheating compliances by the 2080s.

7.3 Recommendations

This study urges housing developers willing to adopt Passivhaus models, to take on board the following recommendations regarding the location, design and occupants behaviour in order to control the risk of overheating for the life of the buildings.

a) Location considerations:

- Passivhaus flats should not be developed in London as there is a greater risk of overheating in this location. Developing such flats in this location will result in thermal discomfort and even heat stress for occupants during the summer months which can lead to health problems and also increase in energy consumption as a result of the demand for using mechanical cooling systems.
- Edinburgh and other locations with similar climate conditions in the UK can offer the ideal locations for developing the Passivhaus flats suggested, as the current and future overheating risk in these locations are negligible. Therefore, such flats in these locations can offer thermally comfortable conditions throughout the year as well providing very energy efficient homes.
- Developing Passivhaus flats in Birmingham and Manchester must be accompanied by a very careful design consideration as well as raising occupants' awareness of the necessary actions and behaviours to avoid the occurrence of overheating. This is mainly highlighted for the flats with the presence of vulnerable occupants. Therefore, careful thermal modelling, using current and projected future climate data, as well as using more extreme weather conditions, should be undertaken at design stage. Also, accommodating normal occupants in such flats should be prioritised in these locations and education of the occupants (e.g. the appropriate use of MVHR system during the summer) should be planned prior to the occupancy.

b) Design considerations:

Parameters related to reducing the unnecessary solar gain have found to be significantly effective in the occurrence of overheating risk. In the first instance, reducing the excessive solar gain should be achieved by determining a suitable level of south facing glazing area which could make a balance between the solar gain requirements during the winter and summer. It is notable that BRE recommendations for south facing glazing area in the UK for Passivhaus flats is between 25-35% (Mcleod et al, 2011). However, for example this percentage is higher in case study flats used for this study (around 60%) which could potentially have contributed to the occurrence of overheating. Selection of appropriate glazing g-value, which determines the capability of the glazing area to absorb the solar gain, should also be considered in the design stage and its effect on thermal performance and energy demand can be tested by the use of dynamic simulation. Finally, after careful consideration in designing the glazing area and specifying the appropriate glazing g-value, any unnecessary solar gain during the summer should be avoided through a well-designed shading device. CIBSE TM37 (CIBSE, 2006b) also suggests that preventing sunlight from reaching the windows is the most effective way to control the overheating risk. Number of research studies which were highlighted in this study (Chapter Five) suggested that movable external shading devices are not suitable for use in the UK as it will rarely be used by the occupants. Therefore, use of appropriate and well designed overhang, as a fixed external shading device which mainly reduce the solar gain during the summer months without sacrificing the view, is recommended in this study. The performance and effect of this shading system on overheating risk is also tested in this study by analysing the performances of various pairwise models and it is found to be significantly effective to reduce the overheating risk in all study locations.

For locations with a higher risk of overheating or where there is a particular concern (e.g. existence of vulnerable occupants), using a suitable level of thermal mass to store the unnecessary heat during the day and also designing more openable windows (or using window types with higher free area) which can facilitate the ventilation, are recommended.

This study also suggests that designer need to:

- Incorporating dynamic simulation for overheating assessment in Passivhaus design and also certifying process.
- Using specific UK data and assumptions (e.g. internal gains) in the process of Passivhaus design to reduce the performance gap.

- Testing future overheating risk in Passivhaus flats at design stage especially for the high risk locations specified in this study.

c) Occupant behaviour considerations:

With regard to the occupant behaviour factors, results from this study show that all tested parameters are significantly effective in the risk on developing or reducing the risk of overheating. Therefore, the following actions should be recommended to the occupants of these flats to be considered during the summer months to avoid the risk of overheating:

- Use of MVHR bypass mode
- Effective and on time window opening
- Promote cross flow ventilation by opening internal doors and windows
- Use of internal shading device during the hot sunny days
- Use of energy efficient appliances to reduce the internal gains

It is notable that Vulnerable occupants have certain limitations to be fully engaged with the buildings and apply all the above behavioural recommendations Hence, this study suggests that in order to secure this type of occupant, a higher investment need to be allocated in designing flats for this group and reduce the overheating risk through design rather than rely on them to control their environment effectively.

7.4 Limitation of the research

Although this study presents a detailed investigation of the overheating risk in the UK social housing flats built to the Passivhaus Standard, using both monitoring and simulation; there are a number of limitations associated with this study which must be acknowledged:

Limitations in evaluating the risk of overheating using case studies:

- All available case study flats are located in one location of the UK which has a moderate climatic condition in comparison to other UK locations. This limited the investigation of how the range of climatic conditions (i.e. from cold to warm) influence on the risk of overheating in real life scenarios, however, the implication of variations of climate conditions on the risk of overheating was investigated in the second stage of this study with the aid of simulation.

All case study flats are selected from one block which have similar design and construction characteristics. This limited the study on how design (i.e. layout, orientation, etc.) and construction (i.e. building fabric, glazing types, etc.) influence the risk of overheating, however, the implication of variation of design and construction on the risk of overheating was investigated in the second stage of this study with the aid of simulation.

- In the selected case studies access to the occupants for further investigation was restricted due to various reasons and only limited data was available about occupants' behaviour; however, the implication of occupants' behaviour on the risk of overheating was investigated in the second stage of this study with the aid of simulation.

Limitations in evaluating the risk of overheating using simulation:

Simulation techniques have been used in this research project to investigate the current and future overheating risk in the UK social housing flats considering the implication of design, occupants' behaviour and climate by developing various scenarios. Each of these factors has different parameters and each parameter has various possible ranges. Studying the impact of whole ranges of variables on the risk of overheating, would not be feasible given the time frame and limitation of this project. Therefore, certain criteria have been considered to select suitable variables and respective possible ranges to create a reasonable database of results for overheating investigation. The following are limitations in selecting variables:

- **Archetypical location:** UK regions for overheating assessment and scenario modelling in this study are limited to London, Birmingham, Manchester and Edinburgh. These represent, warm, moderates and cold climates respectively within the available climate conditions of the UK.
- **Weather file:** Different historic weather files based on duration and severity of hot events and also various future projected simulation weather files based on emission scenarios, probabilities and different predicted summer conditions are

available from CIBSE for the purpose of dynamic building simulation and overheating assessment. In this study, both mandatory and recommended weather files recommended in CIBSE TM59 for overheating assessment have been used; however, it should be acknowledged that considering a wider range of weather files (e.g. with lower or higher probability of occurrence or based on different emission scenarios) would present a more comprehensive overheating assessment.

- **Design and Occupants behaviour factors:** A series of design and occupant behaviour factors have been selected for the sensitivity analysis to understand how they influence the risk of overheating. Testing all the design and occupants behaviour variables was not feasible within the time frame of the project. A numbers of influential factors were selected based on the parameters highlighted in the literature as the effective factors on controlling or exacerbating the risk of overheating. It should be highlighted that the selected factors are beyond the factors which are suggested in Passivhaus design criteria.
- **Sensitivity analysis:** Birmingham represents the moderate climate in comparison to other case study locations. As such the sensitivity analysis for the selected factors has been only carried out using the Birmingham base model and also using the current climate condition.
- **Scenario development:** According to the results from the sensitivity analysis and identification of the effective factor on overheating risk, a limited number of design and operational scenarios have been defined in this study for overheating assessment in each location. Scenarios in each category (design and occupant behaviour) are defined by a combination of identified effective factors (using both maximum and minimum values in the possible range of available for each factor). It is worth noting that whilst these scenarios are considered to present a possible range of variations in design and occupant behaviour, it is acknowledged that various other options in each design and occupants behaviour category are likely to happen. Therefore, the findings of this study should be viewed as a comparative analysis of a series of scenarios, which represent a wide range of possible design options or operational conditions, rather than a context specific deterministic study.

7.5 Recommendation for future works

The following further research recommendations are proposed based on the findings and limitations of this study which would contribute to strengthening the finding:

- It is advisable that in further researches, Post Occupancy Evaluation (POE) are be carried out in completed social housing flats built to the Passivhaus standard across the UK. This will allow a better understanding of the current overheating risk in these flats and how occupants' behaviour and their vulnerability level influence the overheating risk. The POEs can also highlight the likely gap between design and actual performances and possible associated reasons.
- Based on the results from this study and highlighted overheating risk, it is recommended that similar study is carried out for different types of UK Passivhaus dwellings such as houses, high rise apartments and other type of accommodation which have occupants with different level of vulnerabilities (e.g. care home)
- Further research should be carried out to study the implication of neighbourhood (e.g. the effect of Urban Heat Island (UHI), shading from trees or adjacent buildings) in developing or preventing overheating risk in these kind of flats**.**
- Additional research could be carried out to investigate the overheating risk in the UK Passivhaus flats considering the impact of combining both design and occupant behaviour factors in preventing or exacerbating the overheating risk.
- It is advisable that further research to be carried out to investigate the overheating risk using a wider range of projected climate conditions (e.g. different predicted emission scenarios or different level of probabilities) particularly for the regions with a highlighted risk of overheating established in this study.
- Further research should be carried out to explore the optimum ranges for the effective design parameters to reduce the risk of overheating in various locations across the UK within the context of Passivhaus model. This can help the UK Passivhaus designers to minimise the risk of overheating while meeting the energy requirements.

- Further research is recommended to investigate the appropriate occupants' behaviour based on their vulnerability to reduce the risk of overheating in various locations across the UK within the context of Passivhaus model.
- CIBSE TM59 introduced a standard methodology for overheating assessment in UK homes, this has been used in this study for future overheating assessment. It is advisable that in further researches, field studies will be carried out to assess the suitability of this standard methodology in assessing the overheating risk in the UK social housing flats built to the Passivhaus standard and to explore if the thermal comfort perception of the occupants in Passivhaus flats are in line with the defined criteria.
- The majority of the overheated bedrooms in this study pass the adaptive thermal comfort criteria within CIBSE TM59 benchmarks but failed to meet the fixed benchmark criteria (limit of hours with temperature above 26°C). Therefore, further research to establish the reliability and suitability of the CIBSE TM59 bedroom fixed overheating criteria is recommended.
- This study has highlighted the higher risk of overheating in Passivhaus flats for vulnerable occupant. Therefore, it is advisable to develop number of standard occupant behaviour models which match to the vulnerable occupants ability to control their environment (in addition to the current standard assumptions and values stipulated in CIBSE TM59 with regards to the occupant behaviour parameters) to be used additionally in assessing the overheating risk in the cases with particular concern to the presence of vulnerable occupants.
- Further development in the PHPP overheating assessment to include adaptive thermal comfort model instead of fixed benchmark whilst considering occupant vulnerability level.

Performance standard and building simulation techniques are subjected to continued development over the time. Hence, the list of further research in this area is almost unlimited and the work done in this research project can be been seen as the important beginning and not the end of required works in development of the UK Passivhaus flats and its application in social housing sector.

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Appendixes

Appendix A: Overhang performance analysis

Figure A1: Overhang Performance in London Base Model

Month				MORNING								AFTERNOON					
	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00
Jan					1%	9%	14%	16%	17%	16%	14%	9%	1%				
Feb					14%	21%	24%	26%	26%	26%	24%	21%	14%				
Mar				31%	37%	38%	39%	40%	40%	40%	39%	39%	37%	32%			
Apr				100%	84%	70%	64%	61%	61%	61%	64%	70%	85%	100%			
May					100%	100%	94%	87%	85%	87%	94%	100%	100%				
Jun					100%	100%	100%	100%	100%	100%	100%	100%	100%				
Jul					100%	100%	100%	97%	94%	97%	100%	100%	100%				
Aug				100%	100%	87%	76%	72%	71%	72%	76%	87%	100%	100%			
Sep				66%	54%	50%	49%	48%	48%	48%	49%	50%	53%	64%			
Oct				8%	22%	27%	30%	31%	31%	31%	30%	27%	22%	8%			
Nov					5%	13%	17%	19%	20%	19%	17%	13%	4%				
Dec						7%	12%	14%	15%	14%	12%	7%					

Figure A2: Overhang Performance in Birmingham Base Model

Month				MORNING								AFTERNOON					
	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00
Jan						9%	13%	16%	16%	16%	13%	9%					
Feb					13%	20%	24%	25%	26%	25%	24%	20%	13%				
Mar				31%	36%	38%	39%	40%	40%	40%	39%	38%	37%	32%			
Apr				100%	84%	69%	64%	61%	60%	61%	64%	70%	85%	100%			
May					100%	100%	93%	86%	84%	86%	93%	100%	100%				
Jun					100%	100%	100%	100%	100%	100%	100%	100%	100%				
Jul					100%	100%	100%	96%	93%	96%	100%	100%	100%				
Aug				100%	100%	86%	76%	72%	71%	72%	76%	86%	100%	100%			
Sep				65%	54%	50%	49%	48%	48%	48%	49%	50%	53%	64%			
Oct				8%	22%	27%	29%	31%	31%	31%	29%	27%	21%	7%			
Nov					4%	12%	17%	19%	19%	19%	16%	12%	4%				
Dec						6%	11%	13%	14%	13%	11%	6%					

Percentage of the shading provided by overhang on south facing glazing

- 0-20%
- 21-40%
- 41-60%
- 61-80%
- 81-100%
- No Solar radiation on South facing glazing
- N/A - Night time

Figure A3: Overhang Performance in Manchester Base Model

Month	MORNING										AFTERNOON						
	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00
Jan						8%	13%	15%	16%	15%	13%	8%					
Feb					13%	20%	23%	25%	26%	25%	24%	20%	13%				
Mar				31%	37%	38%	39%	40%	40%	40%	39%	39%	37%	32%			
Apr				100%	84%	70%	64%	62%	61%	62%	64%	70%	85%	100%			
May				100%	100%	100%	93%	86%	84%	86%	94%	100%	100%	100%			
Jun					100%	100%	100%	100%	100%	100%	100%	100%	100%				
Jul					100%	100%	100%	96%	94%	96%	100%	100%	100%				
Aug				100%	100%	87%	77%	72%	71%	72%	76%	86%	100%	100%			
Sep				66%	54%	51%	49%	48%	48%	48%	49%	50%	53%	65%			
Oct				7%	21%	27%	29%	31%	31%	31%	29%	27%	21%	6%			
Nov					3%	12%	16%	18%	19%	18%	16%	12%	3%				
Dec						5%	10%	13%	14%	13%	10%	5%					

Figure A4: Overhang Performance in Edinburgh Base Model

Month	MORNING										AFTERNOON						
	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00
Jan						6%	11%	14%	15%	14%	11%	6%					
Feb					11%	19%	23%	24%	25%	25%	23%	19%	11%				
Mar				30%	36%	38%	39%	40%	40%	40%	39%	39%	37%	31%			
Apr				100%	85%	70%	65%	62%	61%	62%	65%	71%	85%	100%			
May				100%	100%	100%	93%	87%	85%	87%	94%	100%	100%	100%			
Jun					100%	100%	100%	100%	100%	100%	100%	100%	100%				
Jul					100%	100%	100%	96%	94%	96%	100%	100%	100%				
Aug				100%	100%	87%	77%	73%	72%	73%	77%	87%	100%	100%			
Sep				67%	54%	51%	49%	49%	49%	49%	49%	51%	54%	65%			
Oct				5%	20%	26%	29%	30%	31%	30%	29%	26%	20%	4%			
Nov					0%	10%	15%	17%	18%	17%	15%	10%	0%				
Dec						3%	9%	11%	12%	11%	9%	3%					

Percentage of the shading provided by overhang on south facing glazing

- 0-20%
- 21-40%
- 41-60%
- 61-80%
- 81-100%
- No Solar radiation on South facing glazing
- N/A - Night time

Appendix B: Simulation results of all design scenarios under current climate

Table B1: Design Scenario results for London (Based on London Heathrow DSY1_2020High50Percentile Weather file)

Scenario No.	South Facing Glazing Ratio	External shading	Thermal mass level	Windows Opening Area	Glazing g-Value	Heating Demand (KWH/m^2.yr)	Percentage of Occupied Hours with temperature over 25^{0}C			Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Vulnerable Occupant)			Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Normal Occupant)			Number of Occupied Hours with temperature over 26^{0}C		Compliances: Passivhaus Heating	Compliances: Passivhaus Overheating	Compliances: CIBSE Overheating (Bedrooms)		Compliances: CIBSE Overheating (Living room)	
							B1	B2	L	B1	B2	L	B1	B2	L	B1	B2			Vulnerable occupant	Normal occupant	Vulnerable occupant	Normal occupant
16	Low	Optimum Overhang	Medium	High	Low	4.59	6.7	6.6	10.3	2.4	2.6	5	0.8	0.9	1.9	89	88	Pass	Fail	Fail	Fail	Fail	Pass
12	Low	Optimum Overhang	Light	High	Low	4.71	7.7	7.9	11	4.1	4.4	6.7	2.1	2.3	3.8	132	126	Pass	Fail	Fail	Fail	Fail	Fail
15	Low	Optimum Overhang	Medium	High	High	5.57	7	7.3	11	2.5	2.9	5.4	0.8	1	2.4	93	92	Pass	Fail	Fail	Fail	Fail	Pass
32	High	Optimum Overhang	Medium	High	Low	5.34	6.9	7.1	11	2.5	2.7	5.5	0.8	0.9	2.5	92	89	Pass	Fail	Fail	Fail	Fail	pass
11	Low	Optimum Overhang	Light	High	High	4.92	8	8.2	11	4.3	4.8	7.9	2.2	2.5	3.9	139	133	Pass	Fail	Fail	Fail	Fail	Fail
13	Low	Optimum Overhang	Medium	Low	Low	4.48	7	7.4	12	2.1	2.5	5.2	0.8	0.9	2.2	90	91	Pass	Fail	Fail	Fail	Fail	Pass
28	High	Optimum Overhang	Light	High	Low	5.11	7.9	8.1	12	4.3	4.6	8.1	2.2	2.5	3.9	136	131	Pass	Fail	Fail	Fail	Fail	Fail
31	High	Optimum Overhang	Medium	High	High	6.64	7.3	7.5	12	2.7	3	6.5	0.9	1	3.1	96	95	Pass	Fail	Fail	Fail	Fail	Fail
Base Model	Medium	Optimum Overhang	Light	Medium	Low	5.63	8	8.2	12	4.4	4.7	8.1	2.2	2.4	4	138	134	Pass	Fail	Fail	Fail	Fail	Fail
9	Low	Optimum Overhang	Light	Low	Low	4.60	8.1	8.3	12	4.2	4.7	7.8	2.1	2.4	4	139	137	Pass	Fail	Fail	Fail	Fail	Fail
14	Low	Optimum Overhang	Medium	Low	High	5.45	7.4	7.8	13	2.4	2.8	6	0.9	1	2.7	98	95	Pass	Fail	Fail	Fail	Fail	Pass
27	High	Optimum Overhang	Light	High	High	5.79	8.2	8.4	13	4.7	5.1	9	2.4	2.6	4.8	142	139	Pass	Fail	Fail	Fail	Fail	Fail
29	High	Optimum Overhang	Medium	Low	Low	5.17	7.2	7.6	13	2.3	2.6	6	0.8	1	2.7	95	92	Pass	Fail	Fail	Fail	Fail	Pass
10	Low	Optimum Overhang	Light	Low	High	4.82	8.4	8.7	13	4.7	5.3	9.6	2.3	2.5	4.8	149	145	Pass	Fail	Fail	Fail	Fail	Fail
5	Low	No Overhang	Medium	High	Low	5.66	7.5	7.7	14	2.6	3	7.7	0.9	1.1	3.6	98	99	Pass	Fail	Fail	Fail	Fail	Fail
25	High	Optimum Overhang	Light	Low	Low	4.88	8.2	8.5	14	4.6	5.1	9.7	2.2	2.5	4.8	147	144	Pass	Fail	Fail	Fail	Fail	Fail
30	High	Optimum Overhang	Medium	Low	High	6.47	7.8	8.1	14	2.6	3.1	8.1	1	1.1	3.3	103	104	Pass	Fail	Fail	Fail	Fail	Fail
4	Low	No Overhang	Light	High	Low	5.83	8.3	8.6	14	4.8	5.4	11	2.4	2.6	5.5	150	143	Pass	Fail	Fail	Fail	Fail	Fail
21	High	No Overhang	Medium	High	Low	6.96	7.7	7.9	15	3	3.3	9.5	1.1	1.2	4.4	106	104	Pass	Fail	Fail	Fail	Fail	Fail
8	Low	No Overhang	Medium	Low	Low	5.55	7.8	8	15	2.5	3	8.5	1	1.1	3.7	103	103	Pass	Fail	Fail	Fail	Fail	Fail
20	High	No Overhang	Light	High	Low	5.99	8.5	8.7	15	5.2	5.7	13	2.7	2.9	7	153	146	Pass	Fail	Fail	Fail	Fail	Fail
26	High	Optimum Overhang	Light	Low	High	5.57	8.7	8.9	15	5.2	5.7	11	2.5	2.8	6.1	156	153	Pass	Fail	Fail	Fail	Fail	Fail
6	Low	No Overhang	Medium	High	High	7.62	8.1	8.4	15	3	3.4	10	1.1	1.2	4.4	111	111	Pass	Fail	Fail	Fail	Fail	Fail
1	Low	No Overhang	Light	Low	Low	5.71	8.5	8.9	16	5	5.7	12	2.5	2.8	6.5	154	150	Pass	Fail	Fail	Fail	Fail	Fail
3	Low	No Overhang	Light	High	High	6.61	8.8	9.1	17	5.6	6	13	2.8	3	7.4	161	151	Pass	Fail	Fail	Fail	Fail	Fail
22	High	No Overhang	Medium	High	High	7.90	8.3	8.6	17	3.4	3.7	12	1.3	1.4	6.1	116	117	Pass	Fail	Fail	Fail	Fail	Fail
7	Low	No Overhang	Medium	Low	High	4.47	8.4	8.7	17	2.8	3.5	11	1.1	1.2	4.8	112	114	Pass	Fail	Fail	Fail	Fail	Fail
19	High	No Overhang	Light	High	High	6.74	9	9.3	18	5.9	6.4	16	2.9	3.3	9.5	164	158	Pass	Fail	Fail	Fail	Fail	Fail
2	Low	No Overhang	Light	Low	High	6.48	9	9.6	18	5.7	6.2	16	2.5	2.8	6.5	167	160	Pass	Fail	Fail	Fail	Fail	Fail
24	High	No Overhang	Medium	Low	Low	7.75	8.3	8.7	18	2.8	3.5	13	1.1	1.2	5.8	111	113	Pass	Fail	Fail	Fail	Fail	Fail
17	High	No Overhang	Light	Low	Low	5.83	9.1	9.6	20	5.8	6.3	18	2.9	3.4	10	167	161	Pass	Fail	Fail	Fail	Fail	Fail
23	High	No Overhang	Medium	Low	High	6.68	9	9.4	22	3.5	4.5	18	1.3	1.6	9.6	127	130	Pass	Fail	Fail	Fail	Fail	Fail
18	High	No Overhang	Light	Low	High	6.59	9.9	10	23	6.7	7.4	18.5	3.6	4.1	15	183	179	Pass	Fail	Fail	Fail	Fail	Fail

Table B2: Design Scenario results for Birmingham (Based on Birmingham DSY1_2020High50Percentile Weather file)

Scenario No.	South Facing Glazing Ratio	External shading	Thermal mass level	Windows Opening Area	Glazing g-Value	Heating Demand (KWH/m^2.yr)	Percentage of Occupied Hours with temperature over 25^{0}C			Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Vulnerable Occupant)			Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Normal Occupant)			Number of Occupied Hours with temperature over 26^{0}C		Compliances: Passivhaus Heating	Compliances: Passivhaus Overheating	Compliances: CIBSE Overheating (Bedrooms)		Compliances: CIBSE Overheating (Livingroom)	
							B1	B2	L	B1	B2	L	B1	B2	L	B1	B2			Vulnerable occupant	Normal occupant	Vulnerable occupant	Normal occupant
16	Low	Optimum Overhang	Medium	High	Low	7.62	0.9	0.9	1.8	0.2	0.3	0.6	0	0	0.3	2	3	Pass	Pass	Pass	Pass	Pass	Pass
15	Low	Optimum Overhang	Medium	High	High	9.73	1	1	2.1	0.2	0.3	0.7	0	0	0.3	4	4	Pass	Pass	Pass	Pass	Pass	Pass
32	High	Optimum Overhang	Medium	High	Low	9.36	0.9	1	2.1	0.2	0.3	0.7	0	0	0.3	4	3	Pass	Pass	Pass	Pass	Pass	Pass
13	Low	Optimum Overhang	Medium	Low	Low	7.40	0.9	1	2.2	0.1	0.2	0.6	0	0	0.2	3	3	Pass	Pass	Pass	Pass	Pass	Pass
12	Low	Optimum Overhang	Light	High	Low	7.95	1.4	1.5	2.4	0.5	0.6	1.1	0.2	0.2	0.5	12	11	Pass	Pass	Pass	Pass	Pass	Pass
31	High	Optimum Overhang	Medium	High	High	12.43	1	1.1	2.5	0.3	0.3	0.8	0	0	0.4	4	4	Pass	Pass	Pass	Pass	Pass	Pass
11	Low	Optimum Overhang	Light	High	High	10.57	1.5	1.6	2.6	0.5	0.7	1.2	0.2	0.2	0.5	12	12	Pass	Pass	Pass	Pass	Pass	Pass
14	Low	Optimum Overhang	Medium	Low	High	9.45	1	1.1	2.6	0.1	0.2	0.7	0	0	0.2	5	4	Pass	Pass	Pass	Pass	Pass	Pass
28	High	Optimum Overhang	Light	High	Low	9.98	1.5	1.5	2.7	0.5	0.6	1.2	0.2	0.2	0.5	12	12	Pass	Pass	Pass	Pass	Pass	Pass
29	High	Optimum Overhang	Medium	Low	Low	9.09	0.9	1	2.7	0.1	0.2	0.7	0	0	0.4	3	3	Pass	Pass	Pass	Pass	Pass	Pass
Base Model	Medium	Optimum Overhang	Light	Medium	Low	7.9	1.5	1.6	2.7	0.5	0.6	1.1	0.2	0.2	0.5	12	12	Pass	Pass	Pass	Pass	Pass	Pass
5	Low	No Overhang	Medium	High	Low	9.88	1	1.1	2.8	0.3	0.3	1	0	0	0.5	2	2	Pass	Pass	Pass	Pass	Pass	Pass
9	Low	Optimum Overhang	Light	Low	Low	7.69	1.5	1.7	2.8	0.5	0.6	1.1	0.1	0.2	0.5	12	12	Pass	Pass	Pass	Pass	Pass	Pass
27	High	Optimum Overhang	Light	High	High	12.30	1.5	1.7	3.1	0.6	0.7	1.6	0.2	0.2	0.7	12	13	Pass	Pass	Pass	Pass	Pass	Pass
30	High	Optimum Overhang	Medium	Low	High	12.06	1	1.1	3.2	0.1	0.3	0.9	0	0	0.4	6	6	Pass	Pass	Pass	Pass	Pass	Pass
8	Low	No Overhang	Medium	Low	Low	9.53	1	1.1	3.3	0.1	0.3	1.1	0	0	0.5	2	2	Pass	Pass	Pass	Pass	Pass	Pass
10	Low	Optimum Overhang	Light	Low	High	10.12	1.6	1.8	3.4	0.5	0.7	1.5	0.2	0.2	0.5	13	14	Pass	Pass	Pass	Pass	Pass	Pass
21	High	No Overhang	Medium	High	Low	13.16	1.1	1.2	3.4	0.3	0.4	1.9	0.1	0.1	0.5	5	6	Pass	Pass	Pass	Pass	Pass	Pass
25	High	Optimum Overhang	Light	Low	Low	9.23	1.4	1.7	3.4	0.5	0.7	1.5	0.2	0.2	0.5	12	13	Pass	Pass	Pass	Pass	Pass	Pass
6	Low	No Overhang	Medium	High	High	13.06	1.1	1.2	3.6	0.3	0.3	1.9	0	0.1	0.5	2	2	Pass	Pass	Pass	Pass	Pass	Pass
4	Low	No Overhang	Light	High	Low	10.98	1.6	1.7	3.9	0.6	0.7	2	0.2	0.2	0.7	6	6	Pass	Pass	Pass	Pass	Pass	Pass
26	High	Optimum Overhang	Light	Low	High	11.94	1.7	1.9	4.2	0.7	0.9	2.1	0.2	0.3	0.9	16	15	Pass	Pass	Pass	Pass	Pass	Pass
1	Low	No Overhang	Light	Low	Low	10.72	1.7	1.9	4.3	0.6	0.8	2.6	0.2	0.3	0.8	8	6	Pass	Pass	Pass	Pass	Pass	Pass
7	Low	No Overhang	Medium	Low	High	12.66	1.2	1.3	4.4	0.3	0.3	2	0	0.1	0.5	2	2	Pass	Pass	Pass	Pass	Pass	Pass
20	High	No Overhang	Light	High	Low	12.48	1.6	1.8	4.5	0.7	0.8	2.9	0.2	0.4	1.2	16	14	Pass	Pass	Pass	Pass	Pass	Pass
22	High	No Overhang	Medium	High	High	13.67	1.2	1.3	4.5	0.3	0.4	2.5	0.1	0.1	0.7	8	8	Pass	Pass	Pass	Pass	Pass	Pass
24	High	No Overhang	Medium	Low	Low	13.05	1.2	1.3	4.7	0.3	0.3	2.6	0	0.1	0.6	7	8	Pass	Pass	Pass	Pass	Pass	Pass
3	Low	No Overhang	Light	High	High	13.12	1.7	2	4.8	0.7	1	2.7	0.2	0.4	1.3	11	6	Pass	Pass	Pass	Pass	Pass	Pass
2	Low	No Overhang	Light	Low	High	12.65	1.8	2.2	5.4	0.9	1.2	3.5	0.3	0.4	1.6	10	6	Pass	Pass	Pass	Pass	Fail	Pass
19	High	No Overhang	Light	High	High	13.26	1.9	2.1	5.6	0.9	1.2	4	0.4	0.5	1.9	19	16	Pass	Pass	Pass	Pass	Fail	Pass
17	High	No Overhang	Light	Low	Low	12.11	1.8	2.1	6.2	1	1.3	4.4	0.3	0.4	1.8	19	16	Pass	Pass	Pass	Pass	Fail	Pass
23	High	No Overhang	Medium	Low	High	12.24	1.4	1.6	6.5	0.4	0.5	4	0.1	0.1	1.5	10	10	Pass	Pass	Pass	Pass	Fail	Pass
18	High	No Overhang	Light	Low	High	12.89	2.1	2.4	8.6	1.3	1.7	7	0.4	0.5	2.6	21	20	Pass	Pass	Pass	Pass	Fail	Pass

Table B3: Design Scenario results for Manchester (Based on Manchester DSY1_2020High50Percentile Weather file)

Scenario No.	South Facing Glazing Ratio	External shading	Thermal mass level	Windows Opening Area	Glazing g-Value	Heating Demand (KWH/m^2.yr)	Percentage of Occupied Hours with temperature over 25^{0}C			Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Vulnerable Occupant)			Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Normal Occupant)			Number of Occupied Hours with temperature over 26^{0}C		Compliances: Passivhaus Heating	Compliances: Passivhaus Overheating	Compliances: CIBSE Overheating (Bedrooms)		Compliances: CIBSE Overheating (Livingroom)	
							B1	B2	L	B1	B2	L	B1	B2	L	B1	B2			Vulnerable occupant	Normal occupant	Vulnerable occupant	Normal occupant
16	Low	Optimum Overhang	Medium	High	Low	7.98	0.7	0.8	1.4	0	0	0.2	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
15	Low	Optimum Overhang	Medium	High	High	10.66	0.8	0.9	1.6	0	0	0.3	0	0	0	1	1	Pass	Pass	Pass	Pass	Pass	Pass
12	Low	Optimum Overhang	Light	High	Low	8.43	1.1	1.3	1.7	0.3	0.4	0.7	0	0	0	11	9	Pass	Pass	Pass	Pass	Pass	Pass
32	High	Optimum Overhang	Medium	High	Low	10.11	0.8	0.9	1.7	0	0	0.4	0	0	0	0	1	Pass	Pass	Pass	Pass	Pass	Pass
13	Low	Optimum Overhang	Medium	Low	Low	7.60	0.8	0.9	1.8	0	0	0.2	0	0	0	0	1	Pass	Pass	Pass	Pass	Pass	Pass
31	High	Optimum Overhang	Medium	High	High	12.96	0.8	1	1.9	0	0	0.5	0	0	0	1	1	Pass	Pass	Pass	Pass	Pass	Pass
11	Low	Optimum Overhang	Light	High	High	11.05	1.3	1.4	2	0.4	0.4	1	0	0	0	12	11	Pass	Pass	Pass	Pass	Pass	Pass
14	Low	Optimum Overhang	Medium	Low	High	10.15	0.9	1	2	0	0	0.5	0	0	0	1	1	Pass	Pass	Pass	Pass	Pass	Pass
29	High	Optimum Overhang	Medium	Low	Low	9.39	0.8	1	2	0	0	0.5	0	0	0	1	1	Pass	Pass	Pass	Pass	Pass	Pass
28	High	Optimum Overhang	Light	High	Low	10.09	1.3	1.4	2.1	0.4	0.4	1	0	0	0	12	10	Pass	Pass	Pass	Pass	Pass	Pass
Base model	Medium	Optimum Overhang	Light	Medium	Low	8.10	1.3	1.4	2.1	0.4	0.4	0.9	0	0	0	12	11	Pass	Pass	Pass	Pass	Pass	Pass
9	Low	Optimum Overhang	Light	Low	Low	8.07	1.3	1.5	2.2	0.4	0.4	0.9	0	0	0	12	12	Pass	Pass	Pass	Pass	Pass	Pass
5	Low	No Overhang	Medium	High	Low	10.42	0.9	1.1	2.4	0	0	0.8	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
27	High	Optimum Overhang	Light	High	High	12.53	1.4	1.5	2.4	0.4	0.5	1.3	0	0.1	0.3	12	12	Pass	Pass	Pass	Pass	Pass	Pass
30	High	Optimum Overhang	Medium	Low	High	12.46	1	1.2	2.4	0	0	0.8	0	0	0	1	3	Pass	Pass	Pass	Pass	Pass	Pass
10	Low	Optimum Overhang	Light	Low	High	10.52	1.5	1.7	2.7	0.4	0.5	1.2	0	0.1	0.2	14	15	Pass	Pass	Pass	Pass	Pass	Pass
8	Low	No Overhang	Medium	Low	Low	9.92	0.9	1.1	2.8	0	0	0.9	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
21	High	No Overhang	Medium	High	Low	13.34	1	1.1	2.8	0	0	1	0	0	0.1	1	3	Pass	Pass	Pass	Pass	Pass	Pass
25	High	Optimum Overhang	Light	Low	Low	9.62	1.4	1.6	2.8	0.4	0.5	1.3	0	0.1	0.2	13	14	Pass	Pass	Pass	Pass	Pass	Pass
6	Low	No Overhang	Medium	High	High	12.26	1.1	1.3	3.1	0	0	1	0	0	0.1	0	0	Pass	Pass	Pass	Pass	Pass	Pass
4	Low	No Overhang	Light	High	Low	11.13	1.4	1.6	3.2	0.5	0.5	1.6	0	0.1	0.5	10	8	Pass	Pass	Pass	Pass	Pass	Pass
26	High	Optimum Overhang	Light	Low	High	12.26	1.5	1.9	3.4	0.5	0.6	1.6	0.1	0.1	0.5	16	15	Pass	Pass	Pass	Pass	Pass	Pass
20	High	No Overhang	Light	High	Low	13.18	1.5	1.7	3.5	0.5	0.6	1.9	0.1	0.2	0.7	14	15	Pass	Pass	Pass	Pass	Pass	Pass
22	High	No Overhang	Medium	High	High	14.01	1.2	1.3	3.5	0	0.1	1.6	0	0	0.5	5	5	Pass	Pass	Pass	Pass	Pass	Pass
1	Low	No Overhang	Light	Low	Low	10.41	1.5	1.8	3.6	0.5	0.6	1.8	0.1	0.1	0.6	10	8	Pass	Pass	Pass	Pass	Pass	Pass
7	Low	No Overhang	Medium	Low	High	11.67	1.2	1.4	3.6	0	0	1.3	0	0	0.1	0	0	Pass	Pass	Pass	Pass	Pass	Pass
3	Low	No Overhang	Light	High	High	13.42	1.6	2	3.7	0.5	0.7	2.2	0.1	0.2	0.8	12	8	Pass	Pass	Pass	Pass	Pass	Pass
24	High	No Overhang	Medium	Low	Low	13.34	1.2	1.4	3.9	0	0	1.9	0	0	0.3	4	5	Pass	Pass	Pass	Pass	Pass	Pass
19	High	No Overhang	Light	High	High	13.59	1.8	2	4.2	0.7	0.9	3.2	0.3	0.4	1.4	21	19	Pass	Pass	Pass	Pass	Fail	Pass
2	Low	No Overhang	Light	Low	High	12.77	1.8	2.1	4.3	0.7	0.9	3	0.2	0.4	1.2	12	12	Pass	Pass	Pass	Pass	Pass	Pass
17	High	No Overhang	Light	Low	Low	12.41	1.8	2.2	4.7	0.7	1	3.6	0.2	0.4	1.6	21	20	Pass	Pass	Pass	Pass	Fail	Pass
23	High	No Overhang	Medium	Low	High	12.53	1.5	1.8	5.4	0.1	0.2	3.2	0	0	1	7	7	Pass	Pass	Pass	Pass	Fail	Pass
18	High	No Overhang	Light	Low	High	13.21	2.2	2.4	6.2	1.1	1.5	5.6	0.4	0.4	2.8	24	25	Pass	Pass	Pass	Pass	Fail	Pass

Table B4: Design Scenario results for Edinburgh (Based on Edinburgh DSY1_2020High50Percentile Weather file)

Scenario No.	South Facing Glazing Ratio	External shading	Thermal mass level	Windows Opening Area	Glazing g-Value	Heating Demand (KWH/m^2.yr)	Percentage of Occupied Hours with temperature over 25^0C			Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Vulnerable Occupant)			Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Normal Occupant)			Number of Occupied Hours with temperature over 26^0C		Compliances: Passivhaus Heating	Passivhaus Overheating	CIBSE Overheating (Bedrooms)		CIBSE Overheating (Livingroom)	
							B1	B2	L	B1	B2	L	B1	B2	L	B1	B2			Vulnerable occupant	Normal occupant	Vulnerable occupant	Normal occupant
13	Low	Optimum Overhang	Medium	Low	Low	7.92	0	0	0.1	0	0	0	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
14	Low	Optimum Overhang	Medium	Low	High	10.98	0	0	0.1	0	0	0	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
15	Low	Optimum Overhang	Medium	High	High	11.53	0	0	0.1	0	0	0	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
16	Low	Optimum Overhang	Medium	High	Low	8.36	0	0	0.1	0	0	0	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
29	High	Optimum Overhang	Medium	Low	Low	10.02	0	0	0.1	0	0	0	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
31	High	Optimum Overhang	Medium	High	High	13.68	0	0	0.1	0	0	0	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
32	High	Optimum Overhang	Medium	High	Low	11.12	0	0	0.1	0	0	0	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
30	High	Optimum Overhang	Medium	Low	High	13.02	0	0	0.2	0	0	0	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
5	Low	No Overhang	Medium	High	Low	11.06	0	0	0.3	0	0	0	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
12	Low	Optimum Overhang	Light	High	Low	9.23	0.1	0.1	0.3	0	0	0	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
Base Model	Medium	Optimum Overhang	Light	Medium	Low	9.30	0.1	0.1	0.3	0	0	0	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
8	Low	No Overhang	Medium	Low	Low	10.63	0	0	0.4	0	0	0	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
9	Low	Optimum Overhang	Light	Low	Low	8.68	0.1	0.1	0.4	0	0	0	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
11	Low	Optimum Overhang	Light	High	High	12.15	0.1	0.1	0.4	0	0	0	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
28	High	Optimum Overhang	Light	High	Low	10.63	0.1	0.1	0.4	0	0	0	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
27	High	Optimum Overhang	Light	High	High	13.61	0.1	0.2	0.5	0	0	0.3	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
10	Low	Optimum Overhang	Light	Low	High	11.21	0.1	0.2	0.6	0	0	0.2	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
25	High	Optimum Overhang	Light	Low	Low	10.12	0.1	0.2	0.6	0	0	0.2	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
21	High	No Overhang	Medium	High	Low	13.98	0	0	0.7	0	0	0	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
6	Low	No Overhang	Medium	High	High	13.89	0	0	0.8	0	0	0	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
26	High	Optimum Overhang	Light	Low	High	12.97	0.1	0.2	0.9	0	0	0.4	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
4	Low	No Overhang	Light	High	Low	11.52	0.1	0.2	1.1	0	0	0.5	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
7	Low	No Overhang	Medium	Low	High	13.23	0	0	1.1	0	0	0	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
1	Low	No Overhang	Light	Low	Low	10.89	0.1	0.2	1.2	0	0	0.6	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
22	High	No Overhang	Medium	High	High	14.77	0	0	1.2	0	0	0.4	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
20	High	No Overhang	Light	High	Low	13.62	0.1	0.2	1.3	0	0	0.8	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
3	Low	No Overhang	Light	High	High	14.17	0.1	0.3	1.4	0	0	0.8	0	0	0.1	0	0	Pass	Pass	Pass	Pass	Pass	Pass
24	High	No Overhang	Medium	Low	Low	14.32	0	0	1.4	0	0	0.3	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
2	Low	No Overhang	Light	Low	High	13.78	0.2	0.3	1.7	0	0.1	1	0	0	0.3	0	0	Pass	Pass	Pass	Pass	Pass	Pass
19	High	No Overhang	Light	High	High	14.82	0.2	0.3	1.9	0	0.1	1.2	0	0	0.4	0	0	Pass	Pass	Pass	Pass	Pass	Pass
17	High	No Overhang	Light	Low	Low	12.73	0.2	0.3	2.1	0	0	1.7	0	0	0.4	0	0	Pass	Pass	Pass	Pass	Pass	Pass
23	High	No Overhang	Medium	Low	High	13.54	0	0	2.2	0	0	1.1	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
18	High	No Overhang	Light	Low	High	14.25	0.3	0.3	3.3	0	0.2	3.3	0	0	1.1	0	0	Pass	Pass	Pass	Pass	Fail	Pass

Appendix C: Simulation results of all occupant behaviour scenarios under current climate

Table C1: Occupant Behaviour Scenario results for London (Based on London Heathrow DSY1_2020High50Percentile Weather file)

Scenario No.	Internal Gain (Equipment)	MVHR ByPass	Cross Flow ventilation (Bedroom's Door)	Internal Shading	Windows Opening Threshold (^{0}C)	Heating Demand(KWH/m^2.yr)	Percentage of Occupied Hours with temperature over 25^{0}C			Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Vulnerable Occupant)			Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Normal Occupant)			Number of Occupied Hours with temperature over 26^{0}C		Compliances					
																		Passivhaus Heating	Passivhaus Overheating	CIBSE Overheating (Bedrooms)		CIBSE Overheating (Livingroom)	
							B1	B2	L	B1	B2	L	B1	B2	L	B1	B2			Vulnerable occupant	Normal occupant	Vulnerable occupant	Normal occupant
19	Low	ON	Yes	Yes	22	1.34	6.7	6.9	9.8	3.2	3.6	5.7	1.4	1.7	2.8	115	110	Pass	Pass	Fail	Fail	Fail	Pass
23	Low	ON	No	Yes	22	0.27	6.3	7.8	11	1.9	4.2	4.8	0.7	1.7	3	122	132	Pass	Fail	Fail	Fail	Fail	Fail
27	Low	Off	Yes	Yes	22	1.41	8	8.2	11	4.5	4.2	6.1	2.1	2.6	3.5	216	154	Pass	Fail	Fail	Fail	Fail	Fail
3	Standard	ON	Yes	Yes	22	4.10	7.6	7.4	11	3.9	4.3	6.7	2	2.1	3.5	129	122	Pass	Fail	Fail	Fail	Fail	Fail
17	Low	ON	Yes	No	22	2.32	6.8	6.6	11	3.3	3.3	6.7	1.3	1.6	3.5	123	94	Pass	Fail	Fail	Fail	Fail	Fail
11	Standard	Off	Yes	Yes	22	4.04	10	9.4	13	6.7	6.2	9.6	2.7	2.1	3.5	142	155	Pass	Fail	Fail	Fail	Fail	Fail
Base Model	Standard	ON	Yes	NO	22	5.63	8	8.2	12	4.4	4.7	8.1	2.2	2.4	4.0	138	134	Pass	Fail	Fail	Fail	Fail	Fail
1	Standard	ON	Yes	No	22	5.63	8	8.2	12	4.4	4.7	8.1	2.2	2.4	4.0	138	134	Pass	Fail	Fail	Fail	Fail	Fail
20	Low	ON	Yes	Yes	24	0.12	8.8	9	13	2.6	2.9	6.3	1.1	1.8	4.0	120	91	Pass	Fail	Fail	Fail	Fail	Fail
7	Standard	ON	No	Yes	22	0.29	8.4	11	13	3.3	5.1	9.5	1.1	1.8	2.9	156	139	Pass	Fail	Fail	Fail	Fail	Pass
21	Low	ON	No	No	22	0.24	7.2	8.2	14	1.8	3.3	9.9	1.1	1.2	2.9	114	101	Pass	Fail	Fail	Fail	Fail	Pass
9	Standard	Off	Yes	No	22	5.60	11	10	14	6.5	6.2	9.2	3.2	3.2	4.3	154	143	Pass	Fail	Fail	Fail	Fail	Fail
4	Standard	ON	Yes	Yes	24	0.52	11	11	15	4.6	5.3	7.2	2.4	2.6	3	82	103	Pass	Fail	Fail	Fail	Fail	Fail
31	Low	Off	No	Yes	22	0.25	9.3	9.6	15	3.7	4.4	11	1.6	1.3	4.3	127	139	Pass	Fail	Fail	Fail	Fail	Fail
18	Low	ON	Yes	No	24	0.21	9.3	9.6	16	3.7	4	7.2	2.4	1.9	3	75	94	Pass	Fail	Fail	Fail	Fail	Fail
28	Low	Off	Yes	Yes	24	0.18	12	11	16	4.6	4.4	6.8	3.2	2.6	3	133	125	Pass	Fail	Fail	Fail	Fail	Fail
24	Low	ON	No	Yes	24	0.09	10	13	16	3.7	5.3	5.8	0.8	1.9	2.6	82	116	Pass	Fail	Fail	Fail	Fail	Fail
25	Low	Off	Yes	No	22	2.28	10	13	16	3.7	4	6.1	2.4	2.6	3	120	121	Pass	Fail	Fail	Fail	Fail	Fail
5	Standard	ON	No	No	22	0.38	9.3	12	18	4.6	8	12	1.6	3.8	4.3	99	139	Pass	Fail	Fail	Fail	Fail	Fail
2	Standard	ON	Yes	No	24	1.10	9.3	9.8	16	4.8	5.4	11	3.2	3.3	5.8	214	177	Pass	Fail	Fail	Fail	Fail	Fail
12	Standard	Off	Yes	Yes	24	0.66	12	21	16	6.4	6.1	8.8	3.2	4.1	4.6	357	177	Pass	Fail	Fail	Fail	Fail	Fail
8	Standard	ON	No	Yes	24	0.06	12	15	17	5.2	9.1	10	2.4	6.6	4.6	246	177	Pass	Fail	Fail	Fail	Fail	Fail
26	Low	Off	Yes	No	24	0.29	11	10	17	4.8	4.7	8.1	3.2	3.3	4.6	325	166	Pass	Fail	Fail	Fail	Fail	Fail
29	Low	Off	No	No	22	0.29	9	9.5	17	4	4.4	15	2.4	2.5	12	349	193	Pass	Fail	Fail	Fail	Fail	Fail
22	Low	ON	No	No	24	0.07	9.6	12	18	3.6	5.4	9.7	1.6	3.3	4.1	206	150	Pass	Fail	Fail	Fail	Fail	Fail
15	Standard	Off	No	Yes	22	0.34	12	12	18	6.8	7.8	16	4	6.6	12	428	247	Pass	Fail	Fail	Fail	Fail	Fail
32	Low	Off	No	Yes	24	0.11	14	14	20	5.2	6.4	14	2.4	3.3	7.5	373	209	Pass	Fail	Fail	Fail	Fail	Fail
10	Standard	Off	Yes	No	24	1.16	13	13	19	7.1	7.1	12	3.5	3.6	6.3	240	201	Pass	Fail	Fail	Fail	Fail	Fail
13	Standard	Off	No	No	22	0.44	13	13	20	7.5	9	24	4.9	7.9	18	249	256	Pass	Fail	Fail	Fail	Fail	Fail
6	Standard	ON	No	No	24	0.07	13	16	20	5.7	10	16	2.8	6.5	7.4	156	186	Pass	Fail	Fail	Fail	Fail	Fail
30	Low	Off	No	No	24	0.07	16	16	22	6	9	25	2.1	5	16	227	216	Pass	Fail	Fail	Fail	Fail	Fail
16	Standard	Off	No	Yes	24	0.07	20	20	23	10	14	23	6.3	12	16	298	286	Pass	Fail	Fail	Fail	Fail	Fail
14	Standard	Off	No	No	24	0.07	22	22	24	13	16	24.5	7.7	14	18.4	333	327	Pass	Fail	Fail	Fail	Fail	Fail

Table C2: Occupant Behaviour Scenario results for Birmingham (Based on Birmingham DSY1_2020High50Percentile Weather file)

Scenario No.	Internal Gain (Equipment)	MVHR ByPass	Cross Flow ventilation (Bedroom's Door)	Internal Shading	Windows Opening Threshold (°C)	Heating Demand (KWH/m²-yr)	Percentage of Occupied Hours with temperature over 25°C			Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Vulnerable Occupant)			Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Normal Occupant)			Number of Occupied Hours with temperature over 26°C		Compliances: Passivhaus Heating	Compliances: Passivhaus Overheating	Compliances: CIBSE Overheating (Bedrooms)		Compliances: CIBSE Overheating (Livingroom)	
							B1	B2	L	B1	B2	L	B1	B2	L	B1	B2			Vulnerable occupant	Normal occupant	Vulnerable occupant	Normal occupant
19	Low	ON	Yes	Yes	22	2.9	1.1	1.2	2.1	0	0.4	1	0.1	0.1	0.5	8	5	Pass	Pass	Pass	Pass	Pass	Pass
23	Low	ON	No	Yes	22	0.593	1	1.4	2.3	0	0.5	0.8	0.1	0.1	0.5	9	6	Pass	Pass	Pass	Pass	Pass	Pass
27	Low	Off	Yes	Yes	22	3.058	1.3	1.4	2.3	0	0.5	1.1	0.2	0.2	0.6	15	7	Pass	Pass	Pass	Pass	Pass	Pass
3	Standard	ON	Yes	Yes	22	7.56	1.4	1.4	2.4	0.4	0.5	1.1	0.1	0.2	0.5	11	11	Pass	Pass	Pass	Pass	Pass	Pass
17	Low	ON	Yes	No	22	4.279	1.2	1.3	2.4	0.3	0.4	1.1	0.1	0.2	0.5	10	9	Pass	Pass	Pass	Pass	Pass	Pass
11	Standard	Off	Yes	Yes	22	7.444	1.4	1.5	2.5	0.7	0.7	1.6	0.1	0.2	0.5	12	14	Pass	Pass	Pass	Pass	Pass	Pass
Base Model	Standard	ON	Yes	NO	22	7.9	1.5	1.6	2.7	0.5	0.6	1.1	0.2	0.2	0.5	12	12	Pass	Pass	Pass	Pass	Pass	Pass
1	Standard	ON	Yes	No	22	7.9	1.5	1.6	2.7	0.5	0.6	1.1	0.2	0.2	0.6	11	9	Pass	Pass	Pass	Pass	Pass	Pass
20	Low	ON	Yes	Yes	24	0.229	1.7	1.6	2.8	0.3	0.4	0.9	0.1	0.2	0.5	10	8	Pass	Pass	Pass	Pass	Pass	Pass
7	Standard	ON	No	Yes	22	0.563	1.7	1.7	3	0.4	0.6	1.4	0.1	0.2	0.4	14	12	Pass	Pass	Pass	Pass	Pass	Pass
21	Low	ON	No	No	22	0.469	1.8	2	3.2	0.2	0.4	1.5	0.1	0.1	0.4	10	9	Pass	Pass	Pass	Pass	Pass	Pass
9	Standard	Off	Yes	No	22	8.0	2	2.1	3.4	0.7	0.8	1.6	0.2	0.4	0.5	16	17	Pass	Pass	Pass	Pass	Pass	Pass
4	Standard	ON	Yes	Yes	24	1.031	2	2.3	3.5	0.5	0.7	1.2	0.2	0.3	0.4	9	12	Pass	Pass	Pass	Pass	Pass	Pass
31	Low	Off	No	Yes	22	0.499	2.1	2	3.6	0.4	0.6	1.9	0.1	0.2	0.5	13	16	Pass	Pass	Pass	Pass	Pass	Pass
18	Low	ON	Yes	No	24	0.421	2.1	2	3.7	0.4	0.5	1.2	0.2	0.2	0.4	8	11	Pass	Pass	Pass	Pass	Pass	Pass
28	Low	Off	Yes	Yes	24	0.355	2	2.3	3.7	0.5	0.6	1.2	0.2	0.3	0.4	14	15	Pass	Pass	Pass	Pass	Pass	Pass
24	Low	ON	No	Yes	24	0.188	1.9	2.7	3.8	0.4	0.7	1	0.1	0.2	0.3	9	14	Pass	Pass	Pass	Pass	Pass	Pass
25	Low	Off	Yes	No	22	4.534	1.9	2.7	3.8	0.4	0.5	1.1	0.2	0.3	0.4	12	14	Pass	Pass	Pass	Pass	Pass	Pass
5	Standard	ON	No	No	22	0.754	2.1	2.5	4.2	0.5	1	2.1	0.1	0.5	0.5	10	16	Pass	Pass	Pass	Pass	Pass	Pass
2	Standard	ON	Yes	No	24	1.92	2.2	2.4	4.5	0.7	1	1.7	0.2	0.3	0.6	25	20	Pass	Pass	Pass	Pass	Pass	Pass
12	Standard	Off	Yes	Yes	24	1.154	2.9	5	4.6	0.9	1.1	1.4	0.2	0.4	0.5	42	20	Pass	Pass	Fail	Fail	Pass	Pass
8	Standard	ON	No	Yes	24	0.111	2.8	3.7	4.8	0.8	1.7	1.6	0.2	0.6	0.5	29	20	Pass	Pass	Pass	Pass	Pass	Pass
26	Low	Off	Yes	No	24	0.511	2.6	2.5	4.8	0.7	0.9	1.3	0.2	0.3	0.5	38	19	Pass	Pass	Fail	Fail	Pass	Pass
29	Low	Off	No	No	22	0.499	2.1	2.3	4.9	0.6	0.8	2.3	0.2	0.2	1.2	41	22	Pass	Pass	Fail	Fail	Pass	Pass
22	Low	ON	No	No	24	0.122	2.3	3	5	0.5	1	1.5	0.1	0.3	0.4	24	17	Pass	Pass	Pass	Pass	Pass	Pass
15	Standard	Off	No	Yes	22	0.588	2.8	3	5	1	1.4	2.5	0.3	0.6	1.2	50	28	Pass	Pass	Fail	Fail	Pass	Pass
32	Low	Off	No	Yes	24	0.189	3.3	3.5	5.7	0.8	1.2	2.2	0.2	0.3	0.8	44	24	Pass	Pass	Fail	Fail	Pass	Pass
10	Standard	Off	Yes	No	24	1.97	3.2	3.2	6	1.6	1.7	2.7	0.4	0.4	0.8	34	26	Pass	Pass	Fail	Fail	Pass	Pass
13	Standard	Off	No	No	22	0.742	3.1	3.4	6.1	1.7	2.2	5.3	0.6	0.9	2.3	35	33	Pass	Pass	Fail	Fail	Fail	Pass
6	Standard	ON	No	No	24	0.111	3	4	6.2	1.3	2.4	3.5	0.3	0.7	0.9	22	24	Pass	Pass	Pass	Pass	Fail	Pass
30	Low	Off	No	No	24	0.122	3.8	4	7.3	1.4	2.2	5.4	0.2	0.6	2	32	28	Pass	Pass	Pass	Pass	Fail	Pass
16	Standard	Off	No	Yes	24	0.111	4.8	5.1	7.4	2.3	3.2	5.1	0.7	1.3	2	42	37	Pass	Pass	Fail	Fail	Fail	Pass
14	Standard	Off	No	No	24	0.111	5.3	5.6	7.6	2.9	3.9	8	0.9	1.5	3.1	47	42	Pass	Pass	Fail	Fail	Fail	Fail

Table C3: Occupant Behaviour Scenario results for Manchester (Based on Manchester DSY1_2020High50Percentile Weather file)

Scenario No.	Internal Gain (Equipment)	MVHR ByPass	Cross Flow ventilation (Bedroom's Door)	Internal Shading	Windows Opening Threshold (^{0}C)	Heating Demand (KWH/m^2-yr)	Percentage of Occupied Hours with temperature over 25^{0}C			Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Vulnerable Occupant)			Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Normal Occupant)			Number of Occupied Hours with temperature over 26^{0}C		Compliances: Passivhaus Heating	Compliances: Passivhaus Overheating	Compliances: CIBSE Overheating (Bedrooms)		Compliances: CIBSE Overheating (Livingroom)	
							B1	B2	L	B1	B2	L	B1	B2	L	B1	B2			Vulnerable occupant	Normal occupant	Vulnerable occupant	Normal occupant
19	Low	ON	Yes	Yes	22	2.4	0.8	0.9	1.4	0	0.1	0.6	0	0	0	6	5	Pass	Pass	Pass	Pass	Pass	Pass
23	Low	ON	NO	Yes	22	0.491	0.8	1	1.6	0	0.1	0.5	0	0	0	6	6	Pass	Pass	Pass	Pass	Pass	Pass
27	Low	Off	Yes	Yes	22	2.531	1	1.1	1.6	0	0.1	0.6	0	0	0	11	7	Pass	Pass	Pass	Pass	Pass	Pass
3	Standard	ON	Yes	Yes	22	7.41	1.1	1.2	1.7	0.3	0.4	0.6	0	0	0	11	9	Pass	Pass	Pass	Pass	Pass	Pass
17	Low	ON	Yes	No	22	4.195	1	1.1	1.7	0.3	0.3	0.6	0	0	0	10	7	Pass	Pass	Pass	Pass	Pass	Pass
11	Standard	Off	Yes	Yes	22	7.297	1.5	1.5	2	0.5	0.6	0.9	0	0	0	12	11	Pass	Pass	Pass	Pass	Pass	Pass
Base Model	Standard	ON	Yes	NO	22	8.1	1.3	1.5	2.2	0.4	0.4	1	0	0	0	12	11	Pass	Pass	Pass	Pass	Pass	Pass
1	Standard	ON	Yes	No	22	8.1	1.3	1.5	2.2	0.3	0.3	1	0	0	0	11	9	Pass	Pass	Pass	Pass	Pass	Pass
20	Low	ON	Yes	Yes	24	0.223	1.4	1.6	2.3	0.2	0.2	0.8	0	0	0	10	7	Pass	Pass	Pass	Pass	Pass	Pass
7	Standard	ON	NO	Yes	22	0.547	1.4	2	2.4	0.3	0.4	1.2	0	0	0	14	11	Pass	Pass	Pass	Pass	Pass	Pass
21	Low	ON	NO	No	22	0.455	1.2	1.5	2.6	0.2	0.3	1.2	0	0	0	10	8	Pass	Pass	Pass	Pass	Pass	Pass
9	Standard	Off	Yes	No	22	7.7	2.2	2.2	3	0.5	0.6	1.3	0.1	0.2	0.2	29	21	Pass	Pass	Pass	Pass	Pass	Pass
4	Standard	ON	Yes	Yes	24	1.03	2.2	2.4	3.1	0.4	0.5	1	0.1	0.2	0.1	15	15	Pass	Pass	Pass	Pass	Pass	Pass
31	Low	Off	NO	Yes	22	0.498	1.9	2.1	3.2	0.3	0.4	1.5	0.1	0.1	0.2	24	20	Pass	Pass	Pass	Pass	Pass	Pass
18	Low	ON	Yes	No	24	0.421	1.9	2.1	3.3	0.3	0.4	1	0.1	0.1	0.1	14	14	Pass	Pass	Pass	Pass	Pass	Pass
28	Low	Off	Yes	Yes	24	0.354	2.5	2.4	3.3	0.4	0.4	1	0.1	0.2	0.1	25	18	Pass	Pass	Pass	Pass	Pass	Pass
24	Low	ON	NO	Yes	24	0.188	2.1	2.8	3.3	0.3	0.5	0.8	0	0.1	0.1	15	17	Pass	Pass	Pass	Pass	Pass	Pass
25	Low	Off	Yes	No	22	4.53	2.1	2.8	3.3	0.3	0.4	0.9	0.1	0.2	0.1	23	18	Pass	Pass	Pass	Pass	Pass	Pass
5	Standard	ON	NO	No	22	0.753	1.9	2.6	3.7	0.4	0.8	1.7	0.1	0.2	0.2	19	20	Pass	Pass	Pass	Pass	Pass	Pass
2	Standard	ON	Yes	No	24	1.98	2	2.3	3.6	0.5	0.7	1.3	0.1	0.2	0.2	28	22	Pass	Pass	Pass	Pass	Pass	Pass
12	Standard	Off	Yes	Yes	24	1.19	2.7	4.8	3.7	0.7	0.8	1.1	0.1	0.3	0.2	47	22	Pass	Pass	Fail	Fail	Pass	Pass
8	Standard	ON	NO	Yes	24	0.114	2.5	3.5	3.8	0.5	1.2	1.3	0.1	0.4	0.2	32	22	Pass	Pass	Pass	Pass	Pass	Pass
26	Low	Off	Yes	No	24	0.526	2.4	2.4	3.8	0.5	0.6	1	0.1	0.2	0.2	43	21	Pass	Pass	Fail	Fail	Pass	Pass
29	Low	Off	NO	No	22	0.515	1.9	2.2	3.9	0.4	0.6	1.8	0.1	0.2	0.4	46	24	Pass	Pass	Fail	Fail	Pass	Pass
22	Low	ON	NO	No	24	0.126	2.1	2.8	4	0.4	0.7	1.2	0.1	0.2	0.1	27	19	Pass	Pass	Pass	Pass	Pass	Pass
15	Standard	Off	NO	Yes	22	0.607	2.5	2.8	4	0.7	1	1.9	0.1	0.4	0.4	56	31	Pass	Pass	Fail	Fail	Pass	Pass
32	Low	Off	NO	Yes	24	0.195	3	3.4	4.5	0.5	0.8	1.7	0.1	0.2	0.3	49	26	Pass	Pass	Fail	Fail	Pass	Pass
10	Standard	Off	Yes	No	24	1.88	3.5	3.4	4.4	1.1	1.3	1.8	0.2	0.3	0.3	38	30	Pass	Pass	Fail	Fail	Pass	Pass
13	Standard	Off	NO	No	22	0.708	3.4	3.6	4.5	1.2	1.7	3.5	0.3	0.7	0.9	39	38	Pass	Pass	Fail	Fail	Pass	Pass
6	Standard	ON	NO	No	24	0.106	3.3	4.3	4.6	0.9	1.8	2.3	0.2	0.5	0.4	25	28	Pass	Pass	Pass	Pass	Pass	Pass
30	Low	Off	NO	No	24	0.116	4.1	4.3	5.4	0.9	1.7	3.6	0.1	0.4	0.8	36	32	Pass	Pass	Fail	Fail	Fail	Pass
16	Standard	Off	NO	Yes	24	0.106	5.3	5.4	5.4	1.6	2.5	3.4	0.4	1	0.8	47	43	Pass	Pass	Fail	Fail	Fail	Pass
14	Standard	Off	NO	No	24	0.106	5.7	6	7	2	3	5.3	0.4	1.1	1.2	53	49	Pass	Pass	Fail	Fail	Fail	Pass

Table C4: Occupant Behaviour Scenario results for Edinburgh (Based on Edinburg DSY1_2020High50Percentile Weather file)

Scenario No.	Internal Gain (Equipment)	MVHR ByPass	Cross Flow ventilation (Bedroom's Door)	Internal Shading	Windows Opening Threshold (^{0}C)	Heating Demand (KWH/m^2-yr)	Percentage of Occupied Hours with temperature over 25^{0}C			Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Vulnerable Occupant)			Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Normal Occupant)			Number of Occupied Hours with temperature over 26^{0}C		Compliances: Passivhaus Heating	Compliances: Passivhaus Overheating	Compliances: CIBSE Overheating (Bedrooms)		Compliances: CIBSE Overheating (Livingroom)	
							B1	B2	L	B1	B2	L	B1	B2	L	B1	B2			Vulnerable occupant	Normal occupant	Vulnerable occupant	Normal occupant
19	Low	ON	Yes	Yes	22	2.72	0	0	0.1	0	0	0	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
23	Low	ON	NO	Yes	22	0.56	0	0	0.1	0	0	0	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
27	Low	Off	Yes	Yes	22	2.87	0	0	0.1	0	0	0	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
3	Standard	ON	Yes	Yes	22	8.69	0	0.1	0.3	0	0	0	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
17	Low	ON	Yes	No	22	4.92	0	0.1	0.3	0	0	0	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
11	Standard	Off	Yes	Yes	22	8.56	0	0.1	0.4	0	0	0	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
Base Model	Standard	ON	Yes	NO	22	9.3	0.1	0.1	0.4	0	0	0.1	0	0	0.1	0	0	Pass	Pass	Pass	Pass	Pass	Pass
1	Standard	ON	Yes	No	22	9.3	0.1	0.1	0.4	0	0	0.1	0	0	0.1	0	0	Pass	Pass	Pass	Pass	Pass	Pass
20	Low	ON	Yes	Yes	24	0.27	0.1	0.1	0.4	0	0	0.1	0	0	0.1	0	0	Pass	Pass	Pass	Pass	Pass	Pass
7	Standard	ON	NO	Yes	22	0.66	0.1	0.1	0.4	0	0	0.1	0	0	0.1	0	0	Pass	Pass	Pass	Pass	Pass	Pass
21	Low	ON	NO	No	22	0.55	0.1	0.1	0.5	0	0	0.1	0	0	0.1	0	0	Pass	Pass	Pass	Pass	Pass	Pass
9	Standard	Off	Yes	No	22	9.20	0.1	0.2	0.7	0	0	0.2	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
4	Standard	ON	Yes	Yes	24	1.19	0.1	0.2	0.7	0	0	0.2	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
31	Low	Off	NO	Yes	22	0.58	0.1	0.2	0.7	0	0	0.2	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
18	Low	ON	Yes	No	24	0.49	0.1	0.2	0.8	0	0	0.2	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
28	Low	Off	Yes	Yes	24	0.41	0.1	0.2	0.8	0	0	0.1	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
24	Low	ON	NO	Yes	24	0.22	0.1	0.3	0.8	0	0	0.1	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
25	Low	Off	Yes	No	22	5.25	0.1	0.3	0.8	0	0	0.1	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
5	Standard	ON	NO	No	22	0.87	0.1	0.2	0.9	0	0	0.3	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
2	Standard	ON	Yes	No	24	1.74	0.3	0.4	1.3	0	0.2	0.7	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
12	Standard	Off	Yes	Yes	24	1.05	0.4	0.8	1.3	0	0.2	0.6	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
8	Standard	ON	NO	Yes	24	0.10	0.4	0.6	1.4	0	0.3	0.7	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
26	Low	Off	Yes	No	24	0.46	0.4	0.4	1.4	0	0.2	0.5	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
29	Low	Off	NO	No	22	0.45	0.3	0.4	1.4	0	0.2	1	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
22	Low	ON	NO	No	24	0.11	0.3	0.5	1.4	0	0.2	0.6	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
15	Standard	Off	NO	Yes	22	0.53	0.4	0.5	1.4	0	0.3	1	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
32	Low	Off	NO	Yes	24	0.17	0.4	0.6	1.6	0	0.2	0.9	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
10	Standard	Off	Yes	No	24	1.69	0.5	0.5	1.9	0.2	0.3	0.7	0	0	0.2	0	0	Pass	Pass	Pass	Pass	Pass	Pass
13	Standard	Off	NO	No	22	0.64	0.5	0.5	1.9	0.2	0.4	1.4	0	0	0.6	0	0	Pass	Pass	Pass	Pass	Pass	Pass
6	Standard	ON	NO	No	24	0.09	0.5	0.6	2	0.2	0.4	0.9	0	0	0.2	0	0	Pass	Pass	Pass	Pass	Pass	Pass
30	Low	Off	NO	No	24	0.10	0.6	0.6	2.3	0.2	0.4	1.4	0	0	0.5	0	0	Pass	Pass	Pass	Pass	Pass	Pass
16	Standard	Off	NO	Yes	24	0.09	0.8	0.8	2.3	0.3	0.6	1.3	0	0	0.5	0	0	Pass	Pass	Pass	Pass	Pass	Pass
14	Standard	Off	NO	No	24	0.09	0.8	0.9	3	0.4	0.7	2.1	0	0	0.8	0	0	Pass	Pass	Pass	Pass	Pass	Pass

Appendix D: Statistical analysis results for design and occupant behaviour parameters

Table D1: Statistical analysis result for pair wise models with different glazing g-value

Parameter	Glazing g-value	Pair Sample Statistic		Paired Differences				Location
		Mean	Std. Deviation	Mean	95% confidence interval of the difference: Lower	95% confidence interval of the difference: Upper	Sig. (2-tailed)	
Annual Percentage of Hours with Temperature Over 25ºC	Low	13.98	3.29	1.42	2.31	0.53	0.004	London
	High	15.40	3.28					
	Low	3.43	1.36	0.64	1.08	0.19	0.008	Birmingham
	High	4.08	1.61					
	Low	2.75	1.11	0.42	0.74	0.10	0.007	Manchester
	High	3.18	1.18					
	Low	0.69	0.60	0.31	0.52	0.09	0.008	Edinburgh
	High	1.00	0.90					
Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Normal Occupant)	Low	4.76	2.44	0.88	1.77	0.12	0.530	London
	High	5.64	3.04					
	Low	0.67	0.44	1.81	0.40	0.04	0.106	Birmingham
	High	0.85	0.67					
	Low	0.29	0.47	0.22	0.43	0.00	0.490	Manchester
	High	0.51	0.74					
	Low	0.03	0.10	0.09	0.20	-0.01	0.083	Edinburgh
	High	0.12	0.29					
Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Vulnerable Occupant)	Low	9.47	4.08	1.65	2.82	0.49	0.008	London
	High	11.13	4.45					
	Low	1.71	1.18	0.52	0.95	0.09	0.021	Birmingham
	High	2.23	1.60					
	Low	1.25	0.98	0.44	0.80	0.07	0.035	Manchester
	High	1.68	1.33					
	Low	0.28	0.46	0.24	0.48	0.00	0.052	Edinburgh
	High	0.52	0.86					

Table D2: Statistical analysis result for pair wise models with different windows opening area

Parameter	Windows Opening Area	Pair Sample Statistic		Paired Differences				Location
		Mean	Std. Deviation	Mean	95% confidence interval of the difference		Sig. (2-tailed)	
					Lower	Upper		
Annual Percentage of Hours with Temperature Over 25ºC	Low	15.93	3.65	-2.48	-1.49	-3.47	0.000	London
	High	13.45	2.46					
	Low	4.03	1.61	-0.56	0.09	-1.19	0.085	Birmingham
	High	3.48	1.38					
	Low	3.17	1.15	-0.41	0.09	-0.91	0.102	Manchester
	High	2.76	1.14					
	Low	1.03	0.92	0.35	-0.10	-0.60	0.008	Edinburgh
	High	0.66	0.55					
Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Normal Occupant)	Low	5.76	3.28	-1.13	-0.16	-2.09	0.024	London
	High	4.63	2.03					
	Low	0.78	0.65	-0.56	0.14	-0.25	0.545	Birmingham
	High	0.73	0.47					
	Low	0.48	0.77	-0.17	0.09	-0.42	0.180	Manchester
	High	0.31	0.44					
	Low	0.11	0.28	-0.08	0.02	-0.18	0.120	Edinburgh
	High	0.03	0.10					
Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Vulnerable Occupant)	Low	11.46	4.99	-2.31	-1.02	-3.61	0.002	London
	High	9.14	3.18					
	Low	2.13	1.67	-0.31	0.22	-0.86	0.229	Birmingham
	High	1.81	1.12					
	Low	1.61	1.35	-0.29	0.22	-0.79	0.243	Manchester
	High	1.32	0.94					
	Low	0.55	0.88	-0.30	0.01	-0.61	0.058	Edinburgh
	High	0.25	0.38					

Table D3: Statistical analysis result for pair wise models with different external shading

Parameter	External Shading (Overhang)	Pair Sample Statistic		Paired Differences				Location
		Mean	Std. Deviation	Mean	95% confidence interval of the difference		Sig. (2-tailed)	
					Lower	Upper		
Annual Percentage of Hours with Temperature Over 25ºC	Optimum Overhang	12.23	1.33	4.91	5.89	3.93	0.000	London
	No Overhang	17.15	2.84					
	Optimum Overhang	2.73	0.18	2.04	2.54	1.54	0.000	Birmingham
	No Overhang	4.78	0.64					
	Optimum Overhang	2.13	0.51	1.68	2.00	1.34	0.000	Manchester
	No Overhang	3.81	0.99					
	Optimum Overhang	0.31	0.24	1.06	1.38	0.76	0.000	Edinburgh
	No Overhang	1.38	0.75					
Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Normal Occupant)	Optimum Overhang	3.55	1.16	3.29	4.39	2.18	0.000	London
	No Overhang	6.85	2.91					
	Optimum Overhang	0.44	0.43	0.63	0.89	0.36	0.000	Birmingham
	No Overhang	1.07	1.47					
	Optimum Overhang	0.08	0.14	0.66	0.98	0.32	0.001	Manchester
	No Overhang	0.73	0.74					
	Optimum Overhang	0.00	0.00	0.15	0.30	0.01	0.070	Edinburgh
	No Overhang	0.14	0.29					
Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Vulnerable Occupant)	Optimum Overhang	7.35	1.86	5.89	7.33	4.45	0.000	London
	No Overhang	13.25	3.99					
	Optimum Overhang	1.06	0.61	1.81	2.42	1.22	0.000	Birmingham
	No Overhang	2.88	1.44					
	Optimum Overhang	0.77	0.43	1.38	1.88	0.88	0.000	Manchester
	No Overhang	2.16	1.27					
	Optimum Overhang	0.07	0.13	0.66	1.06	0.26	0.003	Edinburgh
	No Overhang	0.73	0.86					

Table D4: Statistical analysis result for pair wise models with different thermal mass level

Parameter	Thermal mass level	Pair Sample Statistic		Paired Differences				Location
		Mean	Std. Deviation	Mean	95% confidence interval of the difference		Sig. (2-tailed)	
					Lower	Upper		
Annual Percentage of Hours with Temperature Over 25º C	Light	15.12	3.47	-0.86	-0.13	-1.59	0.016	London
	Medium	14.26	3.20					
	Light	4.26	1.65	-1.01	-0.57	-1.44	0.000	Birmingham
	Medium	3.25	1.18					
	Light	3.33	1.24	-0.73	-0.49	-0.98	0.000	Manchester
	Medium	2.60	0.94					
	Light	1.13	0.82	-0.58	-0.36	-0.80	0.000	Edinburgh
	Medium	0.56	0.61					
Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Normal Occupant)	Light	6.45	2.91	-2.50	-1.52	-3.49	0.000	London
	Medium	3.95	1.95					
	Light	1.01	0.62	-0.51	-0.21	-0.80	0.002	Birmingham
	Medium	0.51	0.37					
	Light	0.64	0.72	-0.46	0.10	-0.83	0.150	Manchester
	Medium	0.17	0.41					
	Light	0.12	0.28	-0.09	0.07	-0.26	0.253	Edinburgh
	Medium	0.03	0.10					
Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Vulnerable Occupant)	Light	11.94	4.31	-3.28	-2.20	-4.35	0.000	London
	Medium	8.66	3.69					
	Light	2.50	1.55	-1.05	-0.52	-1.59	0.001	Birmingham
	Medium	1.44	1.05					
	Light	1.96	1.25	-1.00	-0.54	-1.45	0.000	Manchester
	Medium	0.96	0.85					
	Light	0.65	0.81	-0.50	-0.08	-0.92	0.022	Edinburgh
	Medium	0.15	0.43					

Table D5: Statistical analysis result for pair wise models with different south facing glazing ratio

Parameter	South-facing glazing ratio	Pair Sample Statistic		Paired Differences				Location
		Mean	Std. Deviation	Mean	95% confidence interval		Sig. (2-tailed)	
					Lower	Upper		
Annual Percentage of Hours with Temperature Over 25ºC	Light	13.67	2.54	2.13	3.22	1.04	0.001	London
	Medium	15.80	3.91					
	Light	3.31	1.08	0.99	1.53	0.45	0.001	Birmingham
	Medium	4.30	1.80					
	Light	2.64	0.91	0.69	1.07	0.32	0.001	Manchester
	Medium	3.34	1.35					
	Light	0.65	0.52	0.43	0.75	0.12	0.010	Edinburgh
	Medium	1.09	0.95					
Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Normal Occupant)	Light	9.02	3.20	2.27	4.23	1.32	0.001	London
	Medium	11.80	5.07					
	Light	1.55	0.87	0.91	1.49	0.32	0.005	Birmingham
	Medium	2.46	1.77					
	Light	1.12	0.78	0.77	1.21	0.33	0.002	Manchester
	Medium	1.89	1.44					
	Light	0.21	0.34	0.44	0.79	0.09	0.016	Edinburgh
	Medium	0.64	0.90					
Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Vulnerable Occupant)	Light	4.30	1.65	1.96	3.22	0.71	0.005	London
	Medium	6.26	3.42					
	Light	0.59	0.39	0.37	0.57	0.16	0.002	Birmingham
	Medium	0.96	0.69					
	Light	0.23	0.37	0.38	0.65	0.12	0.007	Manchester
	Medium	0.62	0.79					
	Light	0.03	0.08	0.10	0.23	0.03	0.012	Edinburgh
	Medium	0.13	0.30					

Table D6: Statistical analysis result for pair wise models with different use of MVHR ByPass system

Parameter	Summer MVHR ByPass	Pair Sample Statistic: Mean	Pair Sample Statistic: Std. Deviation	Paired Differences: Mean	95% confidence interval of the difference: Lower	95% confidence interval of the difference: Upper	Sig. (2-tailed)	Location
Annual Percentage of Hours with Temperature Over 25ºC	On	14.43	2.99	3.78	5.10	2.47	0.000	London
	Off	18.21	4.79					
	ON	3.54	1.15	1.49	1.94	1.04	0.000	Birmingham
	Off	5.03	1.92					
	On	2.83	0.97	1.10	1.41	0.79	0.000	Manchester
	Off	3.93	1.13					
	On	0.74	0.54	0.65	0.83	0.47	0.000	Edinburgh
	Off	1.38	0.79					
Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Normal Occupant)	On	3.85	1.28	5.03	8.23	1.84	0.004	London
	Off	8.89	6.65					
	ON	1.44	0.64	1.13	2.14	0.54	0.003	Birmingham
	Off	2.78	2.03					
	On	1.07	0.46	0.88	1.38	0.38	0.002	Manchester
	Off	1.94	1.13					
	On	0.25	0.30	0.47	0.69	0.25	0.000	Edinburgh
	Off	0.72	0.61					
Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Vulnerable Occupant)	On	8.55	2.87	5.82	9.13	2.51	0.002	London
	Off	14.37	8.50					
	ON	0.48	0.15	0.59	1.01	0.17	0.009	Birmingham
	Off	1.07	0.85					
	On	0.09	0.11	0.28	0.42	0.14	0.001	Manchester
	Off	0.37	0.34					
	On	0.04	0.07	0.12	0.26	-0.01	0.042	Edinburgh
	Off	0.16	0.27					

Table D7: Statistical analysis result for pair wise models with different bedrooms' door opening profile

Parameter	Bedroom Doors	Pair Sample Statistic		Paired Differences				Location
		Mean	Std. Deviation	Mean	95% confidence interval of the difference		Sig. (2-tailed)	
					Lower	Upper		
Annual Percentage of Hours with Temperature Over 25ºC	Open	14.14	2.68	4.36	5.76	2.95	0.000	London
	Close	18.50	4.73					
	Open	3.45	1.10	1.67	2.16	1.18	0.000	Birmingham
	Close	5.13	1.87					
	Open	2.77	1.29	1.22	1.55	0.90	0.000	Manchester
	Close	3.99	0.32					
	Open	0.73	0.51	0.67	0.86	0.47	0.000	Edinburgh
	Close	1.39	0.79					
Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Normal Occupant)	Open	3.92	1.04	4.88	8.17	1.59	0..006	London
	Close	8.81	6.75					
	Open	1.34	0.42	1.54	2.43	0.65	0.002	Birmingham
	Close	2.88	2.01					
	Open	0.96	1.27	1.09	1.63	0.54	0.001	Manchester
	Close	2.06	0.10					
	Open	0.22	0.26	0.54	0.77	0.31	0.000	Edinburgh
	Close	0.76	0.59					
Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Vulnerable Occupant)	Open	7.87	1.85	7.18	10.83	3.54	0.001	London
	Close	15.06	8.22					
	Open	0.49	0.12	0.57	1.00	0.13	0.014	Birmingham
	Close	1.06	0.86					
	Open	0.10	0.35	0.26	0.41	0.11	0.002	Manchester
	Close	0.36	0.43					
	Open	0.03	0.06	0.15	0.28	0.01	0.021	Edinburgh
	Close	0.17	0.26					

Table D8: Statistical analysis result for pair wise models with different internal shading

Parameter	Internal Shading	Pair Sample Statistic		Paired Differences				Location
		Mean	Std. Deviation	Mean	95% confidence interval of the difference		Sig. (2-tailed)	
					Lower	Upper		
Annual Percentage of Hours with Temperature Over 25ºC	Yes	14.93	3.71	2.78	3.66	1.89	0.000	London
	No	17.71	4.67					
	Yes	3.71	1.45	1.14	1.38	0.89	0.000	Birmingham
	No	4.85	1.84					
	Yes	2.95	1.17	0.85	1.07	0.64	0.000	Manchester
	No	3.81	1.25					
	Yes	0.81	0.64	0.50	0.60	0.40	0.000	Edinburgh
	No	1.31	0.77					
Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Normal Occupant)	Yes	4.98	3.67	2.76	4.46	1.07	0.003	London
	No	7.75	6.47					
	Yes	1.63	1.03	0.96	1.54	0.38	0.003	Birmingham
	No	2.59	1.98					
	Yes	1.17	0.71	0.66	1.01	0.34	0.001	Manchester
	No	1.84	1.26					
	Yes	0.34	0.43	0.30	0.43	0.18	0.000	Edinburgh
	No	0.64	0.58					
Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Vulnerable Occupant)	Yes	9.45	4.77	4.02	6.05	2.01	0.001	London
	No	13.48	8.19					
	Yes	0.62	0.43	0.32	0.57	0.07	0.017	Birmingham
	No	0.94	0.83					
	Yes	0.15	0.20	0.17	0.26	0.08	0.001	Manchester
	No	0.31	0.34					
	Yes	0.04	0.13	0.11	0.22	0.01	0.037	Edinburgh
	No	0.16	0.25					

Table D9: Statistical analysis result for pair wise models with different window opening threshold

Parameter	Windows Opening Threshold	Pair Sample Statistic		Paired Differences				Location
		Mean	Std. Deviation	Mean	95% confidence interval of the difference		Sig. (2-tailed)	
					Lower	Upper		
Annual Percentage of Hours with Temperature Over 25ºC	22	14.16	3.02	4.39	5.59	3.19	0.000	London
	24	18.55	4.46					
	22	3.37	1.15	1.83	2.20	1.46	0.000	Birmingham
	24	5.20	1.75					
	22	2.67	1.01	1.41	1.65	1.18	0.000	Manchester
	24	4.09	1.12					
	22	0.65	0.53	0.81	0.95	0.67	0.000	Edinburgh
	24	1.46	0.71					
Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Normal Occupant)	22	5.44	4.45	1.85	2.87	0.83	0.002	London
	24	7.29	6.15					
	22	1.71	1.06	0.78	1.36	0.21	0.011	Birmingham
	24	2.50	2.01					
	22	1.23	0.75	0.54	0.87	0.22	0.003	Manchester
	24	1.78	1.27					
	22	0.28	0.42	0.41	0.52	0.29	0.000	Edinburgh
	24	0.69	0.55					
Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Vulnerable Occupant)	22	9.98	4.83	2.96	4.99	0.93	0.007	London
	24	12.94	8.39					
	22	0.68	0.51	0.18	0.37	0.01	0.041	Birmingham
	24	0.87	0.81					
	22	0.15	0.24	0.16	0.21	0.10	0.000	Manchester
	24	0.31	0.31					
	22	0.05	0.15	0.09	0.19	0.01	0.047	Edinburgh
	24	0.14	0.25					

Table D10: Statistical analysis result for pair wise models with different internal gain profile

Parameter	Internal Gain (Equipment)	Pair Sample Statistic		Paired Differences				Location
		Mean	Std. Deviation	Mean	95% confidence interval of the difference		Sig. (2-tailed)	
					Lower	Upper		
Annual Percentage of Hours with Temperature Over 25ºC	Low	15.27	3.66	2.08	3.09	1.08	0.000	London
	Standard	17.36	4.89					
	Low	3.81	1.41	0.94	1.23	0.65	0.000	Birmingham
	Standard	4.76	1.94					
	Low	3.05	1.15	0.66	0.85	0.48	0.000	Manchester
	Standard	3.71	1.34					
	Low	0.84	0.63	0.44	0.55	0.33	0.000	Edinburgh
	Standard	1.27	0.80					
Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Normal Occupant)	Low	2.00	3.66	2.74	4.48	1.00	0.004	London
	Standard	7.74	6.48					
	Low	1.63	1.10	0.95	1.53	0.39	0.003	Birmingham
	Standard	2.59	1.95					
	Low	1.20	0.75	0.62	0.96	0.27	0.002	Manchester
	Standard	1.81	1.26					
	Low	0.34	0.42	2.87	0.43	0.15	0.000	Edinburgh
	Standard	0.63	0.59					
Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Vulnerable Occupant)	Low	9.40	4.96	4.14	6.09	2.17	0.000	London
	Standard	13.53	8.05					
	Low	0.61	0.42	0.33	0.58	0.08	0.021	Birmingham
	Standard	0.94	0.83					
	Low	0.16	0.20	0.15	0.24	0.05	0.005	Manchester
	Standard	0.30	0.34					
	Low	0.04	0.13	0.11	0.22	0.01	0.037	Edinburgh
	Standard	0.16	0.25					

Appendix E: Simulation results for Base Models under various projected future summer conditions

Table E1: Future performance of London Base Model under various predicted summer conditions

Weather File	Year	Heating Demand (KWH/m^2.yr)	Percentage of Occupied Hours with temperature over 25^{0}C			Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Vulnerable Occupant)			Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Normal Occupant)			Number of Occupied Hours with temperature over 26^{0}C		Compliances					
														Passivhaus Heating	Passivhaus Overheating	CIBSE Overheating (Bedrooms)		CIBSE Overheating (Livingroom)	
			B1	B2	L	B1	B2	L	B1	B2	L	B1	B2			Vulnerable occupant	Normal occupant	Vulnerable occupant	Normal occupant
DSY1	2020	5.63	8.0	8.2	12.1	4.4	4.7	8.1	2.2	2.4	4.0	138	134	Pass	Fail	Fail	Fail	Fail	Fail
DSY1	2050	4.61	13.1	13.3	17.8	8.1	8.6	13.8	4.6	5.0	8.3	280	267	Pass	Fail	Fail	Fail	Fail	Fail
DSY1	2080	3.74	20.4	20.5	24.9	14.8	15.3	23.4	9.3	9.6	15.9	506	490	Pass	Fail	Fail	Fail	Fail	Fail
DSY2	2020	10.00	7.0	7.3	10.1	4.8	4.9	8.5	2.9	3.0	5.5	145	141	Pass	Fail	Fail	Fail	Fail	Fail
DSY2	2050	9.04	12.1	12.4	16.5	7.5	7.8	13.0	5.0	5.0	8.5	228	221	Pass	Fail	Fail	Fail	Fail	Fail
DSY2	2080	7.96	19.5	19.6	24.4	12.5	12.8	19.0	8.4	8.6	14.2	440	418	Pass	Fail	Fail	Fail	Fail	Fail
DSY3	2020	10.35	9.1	9.2	11.9	7.0	7.1	11.1	4.2	4.6	7.9	189	183	Pass	Fail	Fail	Fail	Fail	Fail
DSY3	2050	10.97	13.9	14.0	18.4	10.5	10.8	15.9	7.3	7.5	12.0	332	323	Pass	Fail	Fail	Fail	Fail	Fail
DSY3	2080	7.73	19.5	19.4	23.1	16.0	16.3	22.5	11.2	11.4	16.3	530	514	Pass	Fail	Fail	Fail	Fail	Fail

Table E2: Future performance of Birmingham Base Model under various predicted summer conditions

Weather File	Year	Heating Demand (KWH/m^2.yr)	Percentage of Occupied Hours with temperature over 25^{0}C			Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Vulnerable Occupant)			Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Normal Occupant)			Number of Occupied Hours with temperature over 26^{0}C		Compliances					
														Passivhaus Heating	Passivhaus Overheating	CIBSE Overheating (Bedrooms)		CIBSE Overheating (Livingroom)	
			B1	B2	L	B1	B2	L	B1	B2	L	B1	B2			Vulnerable occupant	Normal occupant	Vulnerable occupant	Normal occupant
DSY1	2020	7.9	1.5	1.6	2.7	0.5	0.6	1.1	0.2	0.2	0.5	12	12	Pass	Pass	Pass	Pass	Pass	Pass
DSY1	2050	7.65	3.1	3.3	5.5	1.5	1.9	3.6	0.6	0.6	1.3	45	42	Pass	Pass	Fail	Fail	Fail	Pass
DSY1	2080	7.16	11.9	12.0	16.4	7.5	8.2	13.9	4.4	4.4	8.5	238	228	Pass	Fail	Fail	Fail	Fail	Fail
DSY2	2020	11.25	2.8	3.1	4.5	2.0	2.1	3.7	0.9	1.0	2.0	43	41	Pass	Pass	Fail	Fail	Fail	Pass
DSY2	2050	10.36	5.0	5.3	7.0	3.3	3.6	5.9	2.2	2.2	3.9	95	94	Pass	Pass	Fail	Fail	Fail	Fail
DSY2	2080	9.03	8.4	8.5	10.7	6.6	6.8	10.8	3.7	4.0	6.7	180	175	Pass	Fail	Fail	Fail	Fail	Fail
DSY3	2020	12.40	3.2	3.4	5.2	1.9	2.2	4.5	0.5	0.8	2.2	48	46	Pass	Pass	Fail	Fail	Fail	Pass
DSY3	2050	11.22	5.4	5.5	8.2	3.5	4.0	7.4	1.6	2.0	4.2	103	98	Pass	Pass	Fail	Fail	Fail	Fail
DSY3	2080	10.19	8.9	9.0	12.0	6.9	7.2	11.4	3.8	4.3	8.0	203	194	Pass	Fail	Fail	Fail	Fail	Fail

Table E3: Future performance of Manchester Base Model under various predicted summer conditions

Weather File	Year	Heating Demand (KWH/m^2,yr)	Percentage of Occupied Hours with temperature over 25^{0}C			Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Vulnerable Occupant)			Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Normal Occupant)			Number of Occupied Hours with temperature over 26^{0}C		Compliances: Passivhaus Heating	Compliances: Passivhaus Overheating	Compliances: CIBSE Overheating (Bedrooms)		Compliances: CIBSE Overheating (Livingroom)	
			B1	B2	L	B1	B2	L	B1	B2	L	B1	B2			Vulnerable occupant	Normal occupant	Vulnerable occupant	Normal occupant
DSY1	2020	8.1	1.3	1.4	2.1	0.4	0.4	0.9	0.0	0.0	0.0	12	11	Pass	Pass	Pass	Pass	Pass	Pass
DSY1	2050	7.37	2.8	3.0	4.1	0.8	1.0	2.2	0.3	0.4	0.8	38	36	Pass	Pass	Fail	Fail	Pass	Pass
DSY1	2080	6.53	5.3	5.4	6.9	2.9	3.0	4.9	1.0	1.2	2.5	106	103	Pass	Pass	Fail	Fail	Fail	Pass
DSY2	2020	12.35	1.2	1.3	1.9	1.1	1.2	1.8	0.7	0.7	1.0	18	18	Pass	Pass	Pass	Pass	Pass	Pass
DSY2	2050	10.99	2.0	2.0	3.0	1.8	2.0	3.4	0.9	1.1	1.6	37	37	Pass	Pass	Fail	Fail	Fail	Pass
DSY2	2080	10.12	3.6	3.7	5.6	2.9	3.1	5.0	1.7	1.9	3.4	69	68	Pass	Pass	Fail	Fail	Fail	Fail
DSY3	2020	12.71	3.2	3.4	4.9	1.8	2.1	4.9	0.5	0.8	2.0	54	49	Pass	Pass	Fail	Fail	Fail	Pass
DSY3	2050	11.39	4.2	4.4	6.0	2.5	2.9	5.7	1.0	1.3	3.3	73	72	Pass	Pass	Fail	Fail	Fail	Fail
DSY3	2080	9.05	8.4	8.6	10.5	6.1	6.3	10.5	3.8	4.2	7.6	199	186	Pass	Fail	Fail	Fail	Fail	Fail

Table E4: Future performance of Edinburgh Base Model under various predicted summer conditions

Weather File	Year	Heating Demand (KWH/m^2,yr)	Percentage of Occupied Hours with temperature over 25^{0}C			Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Vulnerable Occupant)			Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Normal Occupant)			Number of Occupied Hours with temperature over 26^{0}C		Compliances: Passivhaus Heating	Compliances: Passivhaus Overheating	Compliances: CIBSE Overheating (Bedrooms)		Compliances: CIBSE Overheating (Livingroom)	
			B1	B2	L	B1	B2	L	B1	B2	L	B1	B2			Vulnerable occupant	Normal occupant	Vulnerable occupant	Normal occupant
DSY1	2020	9.3	0.1	0.1	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
DSY1	2050	8.91	0.4	0.5	1.2	0.0	0.2	0.5	0.0	0.0	0.0	1	1	Pass	Pass	Pass	Pass	Pass	Pass
DSY1	2080	8.23	1.1	1.3	2.8	0.4	0.5	1.2	0.0	0.1	0.4	5	6	Pass	Pass	Pass	Pass	Pass	Pass
DSY2	2020	11.90	0.3	0.4	0.8	0.5	0.6	1.0	0.1	0.1	0.2	3	3	Pass	Pass	Pass	Pass	Pass	Pass
DSY2	2050	11.54	0.8	1.0	1.9	0.8	0.9	1.5	0.1	0.3	0.8	6	7	Pass	Pass	Pass	Pass	Pass	Pass
DSY2	2080	10.21	2.4	2.5	4.2	1.3	1.4	2.7	0.7	0.8	1.3	25	25	Pass	Pass	Pass	Pass	Pass	Pass
DSY3	2020	10.70	0.4	0.5	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
DSY3	2050	9.43	1.0	1.1	2.1	0.2	0.4	0.7	0.0	0.0	0.0	9	9	Pass	Pass	Pass	Pass	Pass	Pass
DSY3	2080	8.50	2.7	2.8	4.2	1.2	1.4	2.3	0.3	0.4	0.7	39	35	Pass	Pass	Fail	Fail	Pass	Pass

Appendix F: Simulation results for selected design options under future climate

Table F1: Selected Design Options for future performance investigation

Location	Design Option	Scenario No.	South Facing Glazing Ratio	External shading	Thermal mass level	Windows Opening Area	Glazing g-Value	Heating Demand (KWH/m^2.yr)	Percentage of Occupied Hours with temperature over 25^0C			Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Vulnerable Occupant)			Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Normal Occupant)			Number of Occupied Hours with temperature over 26^0C	
									B1	B2	L	B1	B2	L	B1	B2	L	B1	B2
London	$\mathbf{A_L}$	16	Low	Optimum Overhang	Medium	High	Low	4.59	6.7	6.6	10.3	2.4	2.6	5	0.8	0.9	1.9	89	88
	$\mathbf{B_L}$	L	0.3	Optimum Overhang	Light	0.4	Low	5.63	8	8.2	12.1	4.4	4.7	8.1	2.2	2.4	4	138	134
	$\mathbf{C_L}$	4	Low	No Overhang	Light	High	Low	5.83	8.3	8.6	14	4.8	5.4	11	2.4	2.6	5.5	150	143
	$\mathbf{D_L}$	3	Low	No Overhang	Light	High	High	6.61	8.8	9.1	17	5.6	6	13	2.8	3	7.4	161	151
Birmingham	$\mathbf{A_B}$	16	Low	Optimum Overhang	Medium	High	Low	7.62	0.9	0.9	1.8	0.2	0.3	0.6	0	0	0.3	2	3
	$\mathbf{B_B}$	B	0.3	Optimum Overhang	Light	0.4	Low	7.90	1.5	1.6	2.7	0.5	0.6	1.1	0.2	0.2	0.5	12	12
	$\mathbf{C_B}$	4	Low	No Overhang	Light	High	Low	10.98	1.6	1.7	3.9	0.6	0.7	2	0.2	0.2	0.7	6	6
	$\mathbf{D_B}$	3	Low	No Overhang	Light	High	High	13.12	1.7	2	4.8	0.7	1	2.7	0.2	0.4	1.3	11	6
Manchester	$\mathbf{A_M}$	13	Low	Optimum Overhang	Medium	Low	Low	7.60	0.8	0.9	1.8	0	0	0.2	0	0	0	0	1
	$\mathbf{B_M}$	25	High	Optimum Overhang	Light	Low	Low	9.62	1.4	1.6	2.8	0.4	0.5	1.3	0	0.1	0.2	13	14
	$\mathbf{C_M}$	3	Low	No Overhang	Light	Low	High	13.42	1.6	2	3.7	0.5	0.7	2.2	0.1	0.2	0.8	12	8
	$\mathbf{D_M}$	17	High	No Overhang	Light	Low	Low	12.41	1.8	2.2	4.7	0.7	1	3.6	0.2	0.4	1.6	21	20
Edinburg	$\mathbf{A_E}$	13	Low	Optimum Overhang	Medium	Low	Low	7.92	0	0	0.1	0	0	0	0	0	0	0	0
	$\mathbf{B_E}$	25	High	Optimum Overhang	Light	Low	Low	10.12	0.1	0.2	0.6	0	0	0.2	0	0	0	0	0
	$\mathbf{C_E}$	24	High	No Overhang	Medium	Low	Low	14.32	0	0	1.4	0	0	0.3	0	0	0	0	0
	$\mathbf{D_E}$	17	High	No Overhang	Light	Low	Low	12.73	0.2	0.3	2.1	0	0	1.7	0	0	0.4	0	0

Table F2: Future Performance of the selected design options in London based on *DSY1 High50Percentile* Weather files

Design Option	Year	Heating Demand (KWH/m^2.yr)	Percentage of Occupied Hours with temperature over 25^0C			Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Vulnerable Occupant)			Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Normal Occupant)			Number of Occupied Hours with temperature over 26^0C		Compliances					
														Passivhaus Heating	Passivhaus Overheating	CIBSE Overheating (Bedrooms)		CIBSE Overheating (Livingroom)	
			B1	B2	L	B1	B2	L	B1	B2	L	B1	B2			Vulnerable occupant	Normal occupant	Vulnerable occupant	Normal occupant
A_L	2020	4.59	6.7	6.6	9.8	2.4	2.6	5	0.8	0.9	1.9	89	88	Pass	Pass	Fail	Fail	Fail	Pass
A_L	2050	3.67	13	13	16	5.4	5.7	9.6	2.7	2.9	5.2	231	220	Pass	Fail	Fail	Fail	Fail	Fail
A_L	2080	3.26	20	20	24	11	12	19	6.3	6.7	11	481	468	Pass	Fail	Fail	Fail	Fail	Fail
B_L	2020	5.63	8	8.2	12	4.4	4.7	8.1	2.2	2.4	4	138	134	Pass	Fail	Fail	Fail	Fail	Fail
B_L	2050	4.61	13	13	18	8.1	8.6	14	4.6	5	8.3	280	267	Pass	Fail	Fail	Fail	Fail	Fail
B_L	2080	3.74	20	21	25	15	15	23	9.3	9.6	16	506	490	Pass	Fail	Fail	Fail	Fail	Fail
C_L	2020	5.83	8.3	8.6	14	4.8	5.4	11	2.4	2.6	5.5	150	143	Pass	Fail	Fail	Fail	Fail	Fail
C_L	2050	4.69	13	13	19	8.6	8.9	16	4.8	5.3	10	283	270	Pass	Fail	Fail	Fail	Fail	Fail
C_L	2080	4.29	20	21	26	16	16	26	9.7	10	18	508	495	Pass	Fail	Fail	Fail	Fail	Fail
D_L	2020	6.61	8.8	9.1	17	5.6	6	13	2.8	3	7.4	161	151	Pass	Fail	Fail	Fail	Fail	Fail
D_L	2050	5.39	14	14	20	9.2	9.8	19	5.3	5.9	12	291	281	Pass	Fail	Fail	Fail	Fail	Fail
D_L	2080	4.87	21	21	27	16	17	28	11	11	20	516	506	Pass	Fail	Fail	Fail	Fail	Fail

Table F3: Future Performance of the selected design options in Birmingham based on *DSY1 High50Percentile* Weather files

Design Option	Year	Heating Demand (KWH/m^2.yr)	Percentage of Occupied Hours with temperature over 25^0C			Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Vulnerable Occupant)			Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Normal Occupant)			Number of Occupied Hours with temperature over 26^0C		Compliances					
														Passivhaus Heating	Passivhaus Overheating	CIBSE Overheating (Bedrooms)		CIBSE Overheating (Livingroom)	
			B1	B2	L	B1	B2	L	B1	B2	L	B1	B2			Vulnerable occupant	Normal occupant	Vulnerable occupant	Normal occupant
A_B	2020	7.62	0.9	0.9	1.8	0.2	0.3	0.6	0	0	0.3	2	3	Pass	Pass	Pass	Pass	Pass	Pass
A_B	2050	6.23	2.4	2.5	4.2	0.6	0.6	1.8	0.2	0.3	0.6	27	27	Pass	Pass	Pass	Pass	Pass	Pass
A_B	2080	5.55	5.3	5.5	8.3	2.1	2.2	4.4	0.7	0.9	2.4	69	67	Pass	Pass	Fail	Fail	Fail	Pass
B_B	2020	7.9	1.5	1.6	2.7	0.5	0.6	1.1	0.2	0.2	0.5	12	12	Pass	Pass	Pass	Pass	Pass	Pass
B_B	2050	6.32	1.5	1.6	2.7	0.5	0.6	1.2	0.2	0.2	0.5	12	12	Pass	Pass	Pass	Pass	Pass	Pass
B_B	2080	5.68	3.1	3.3	5.5	1.5	1.9	3.6	0.6	0.6	1.3	45	42	Pass	Pass	Fail	Fail	Fail	Pass
C_B	2020	10.98	1.6	1.7	3.9	0.6	0.7	2	0.2	0.2	0.7	6	6	Pass	Pass	Pass	Pass	Pass	Pass
C_B	2050	8.97	3.2	3.3	6.1	1.7	2	4.6	0.6	0.7	1.6	46	43	Pass	Pass	Fail	Fail	Fail	Pass
C_B	2080	7.86	6.5	6.7	12	3.8	4.2	8.3	2	2.3	4.9	105	98	Pass	Fail	Fail	Fail	Fail	Fail
D_B	2020	13.12	1.7	2	4.8	0.7	1	2.7	0.2	0.4	1.3	11	6	Pass	Pass	Pass	Pass	Pass	Pass
D_B	2050	12.21	3.4	3.5	7.2	2	2.2	5.1	0.7	0.8	2.4	48	45	Pass	Pass	Fail	Fail	Fail	Pass
D_B	2080	10.75	12	13	18	11	12	20	7	7.4	15	248	235	Pass	Fail	Fail	Fail	Fail	Fail

Table F4: Future Performance of the selected design options in Manchester based on *DSY1 High50Percentile* Weather files

Design Option	Year	Heating Demand (KWH/m^2.yr)	Percentage of Occupied Hours with temperature over 25^{0}C			Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Vulnerable Occupant)			Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Normal Occupant)			Number of Occupied Hours with temperature over 26^{0}C		Compliances: Passivhaus Heating	Compliances: Passivhaus Overheating	Compliances: CIBSE Overheating (Bedrooms)		Compliances: CIBSE Overheating (Livingroom)	
			B1	B2	L	B1	B2	L	B1	B2	L	B1	B2			Vulnerable occupant	Normal occupant	Vulnerable occupant	Normal occupant
A_M	2020	7.60	0.8	0.9	1.8	0	0	0.2	0	0	0	0	1	Pass	Pass	Pass	Pass	Pass	Pass
A_M	2050	6.16	2.3	2.5	3.8	0	0	1	0	0	0	21	19	Pass	Pass	Pass	Pass	Pass	Pass
A_M	2080	5.46	5.3	5.4	6.7	0.9	1.1	3.1	0	0.2	1.1	87	87	Pass	Pass	Fail	Fail	Fail	Pass
B_M	2020	9.62	1.4	1.6	2.8	0.4	0.5	1.3	0	0.1	0.2	13	14	Pass	Pass	Pass	Pass	Pass	Pass
B_M	2050	8.06	3	3.2	4.7	0.9	1.2	2.5	0.3	0.4	1	42	40	Pass	Pass	Fail	Fail	Pass	Pass
B_M	2080	7.12	5.4	5.6	7.6	3	3.4	5.9	1.1	1.4	2.9	113	110	Pass	Pass	Fail	Fail	Fail	Pass
C_M	2020	13.42	1.6	2	3.7	0.5	0.7	2.2	0.1	0.2	0.8	12	8	Pass	Pass	Pass	Pass	Pass	Pass
C_M	2050	10.96	3.1	3.2	4.9	1.3	1.5	3.7	0.5	0.5	1.6	45	41	Pass	Pass	Fail	Fail	Fail	Pass
C_M	2080	9.85	5.5	5.7	7.9	3.5	3.9	7.3	1.5	1.8	4	119	111	Pass	Pass	Fail	Fail	Fail	Fail
D_M	2020	12.41	1.8	2.2	4.7	0.7	1	3.6	0.2	0.4	1.6	21	20	Pass	Pass	Pass	Pass	Fail	Pass
D_M	2050	10.21	3.5	3.8	6.7	1.8	2.3	6	0.5	0.6	3.2	54	53	Pass	Pass	Fail	Fail	Fail	Fail
D_M	2080	9.36	6	6.1	11	4.1	4.5	9.7	2	2.4	6.6	124	121	Pass	Fail	Fail	Fail	Fail	Fail

Table F5: Future Performance of the selected design options in Edinburgh based on *DSY1 High50Percentile* Weather files

Design Option	Year	Heating Demand (KWH/m^2.yr)	Percentage of Occupied Hours with temperature over 25^0C			Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Vulnerable Occupant)			Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Normal Occupant)			Number of Occupied Hours with temperature over 26^0C		Compliances					
														Passivhaus Heating	Passivhaus Overheating	CIBSE Overheating (Bedrooms)		CIBSE Overheating (Livingroom)	
			B1	B2	L	B1	B2	L	B1	B2	L	B1	B2			Vulnerable occupant	Normal occupant	Vulnerable occupant	Normal occupant
A_E	2020	7.92	0	0	0.1	0	0	0	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
A_E	2050	6.33	0	0.1	0.4	0	0	0	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
A_E	2080	5.86	0.7	0.8	2.7	0	0	0.3	0	0	0	0	1	Pass	Pass	Pass	Pass	Pass	Pass
B_E	2020	10.12	0.1	0.2	0.6	0	0	0.2	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
B_E	2050	8.25	0.5	0.7	1.5	0.1	0.2	0.6	0	0	0	1	1	Pass	Pass	Pass	Pass	Pass	Pass
B_E	2080	7.53	1.2	1.3	3.5	0.5	0.5	1.6	0.1	0.1	0.5	7	7	Pass	Pass	Pass	Pass	Pass	Pass
C_E	2020	14.32	0	0	1.4	0	0	0.3	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
C_E	2050	12.06	0.2	0.3	4.1	0	0	1.6	0	0	0.3	0	0	Pass	Pass	Pass	Pass	Pass	Pass
C_E	2080	10.87	0.9	1	6.6	0	0.2	3.4	0	0	1.3	1	1	Pass	Pass	Pass	Pass	Fail	Pass
D_E	2020	12.73	0.2	0.3	2.1	0	0	1.7	0	0	0.4	0	0	Pass	Pass	Pass	Pass	Pass	Pass
D_E	2050	10.62	0.6	0.7	3.6	0.3	0.4	2.5	0	0	0.8	1	1	Pass	Pass	Pass	Pass	Pass	Pass
D_E	2080	9.56	1.4	1.6	5.8	0.6	0.8	4.3	0.2	0.3	1.7	9	8	Pass	Pass	Pass	Pass	Fail	Pass

Appendix G: Simulation results for selected occupant behaviour models under future climate

Table G1: Selected Occupant Behaviour Models for future performance investigation

Location	Occupant Behaviour	Scenario No.	Internal Gain (Equipment)	MVHR ByPass	Cross Flow ventilation (Bedroom's Door)	Internal Shading	Windows Opening Threshold (^{0}C)	Heating Demand (KWH/m^2.yr)	Percentage of Occupied Hours with temperature over 25^{0}C			Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Vulnerable Occupant)			Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Normal Occupant)			Number of Occupied Hours with temperature over 26^{0}C	
									B1	B2	L	B1	B2	L	B1	B2	L	B1	B2
London	$\mathbf{I_L}$	19	Low	ON	Yes	Yes	22	1.34	6.7	6.9	9.8	3.2	3.6	5.7	1.4	1.7	2.8	115	110
	$\mathbf{II_L}$	3	Standard	ON	Yes	Yes	22	4.10	7.6	7.4	11	3.9	4.3	6.7	2	2.1	3.5	129	122
	$\mathbf{III_L}$	Base Model	Standard	ON	Yes	NO	22	5.63	8	8.2	12	4.4	4.7	8.1	2.2	2.4	4	138	134
	$\mathbf{IV_L}$	9	Standard	Off	Yes	No	22	5.60	11	10	14	6.5	6.2	9.2	3.2	3.2	4.3	154	143
	$\mathbf{V_L}$	2	Standard	ON	Yes	No	24	1.10	9.3	9.8	16	4.8	5.4	11	3.2	3.3	5.8	214	177
	$\mathbf{VI_L}$	10	Standard	Off	Yes	No	24	1.16	13	13	19	7.1	7.1	12	3.5	3.6	6.3	240	201
Birmingham	$\mathbf{I_B}$	19	Low	ON	Yes	Yes	22	2.9	1.1	1.2	2.1	0	0.4	1	0.1	0.1	0.5	8	5
	$\mathbf{II_B}$	3	Standard	ON	Yes	Yes	22	7.56	1.4	1.4	2.4	0.4	0.5	1.1	0.1	0.2	0.5	11	11
	$\mathbf{III_B}$	Base Model	Standard	ON	Yes	NO	22	7.9	1.5	1.6	2.7	0.5	0.6	1.2	0.2	0.2	0.5	12	12
	$\mathbf{IV_B}$	9	Standard	Off	Yes	No	22	8	2	2.1	3.4	0.7	0.8	1.6	0.2	0.4	0.5	16	17
	$\mathbf{V_B}$	2	Standard	ON	Yes	No	24	1.92	2.2	2.4	4.5	0.7	1	1.7	0.2	0.3	0.6	25	20
	$\mathbf{VI_B}$	10	Standard	Off	Yes	No	24	1.97	3.2	3.2	6	1.6	1.7	2.7	0.4	0.4	0.8	34	26
Manchester	$\mathbf{I_M}$	19	Low	ON	Yes	Yes	22	2.4	0.8	0.9	1.4	0	0.1	0.6	0	0	0	6	5
	$\mathbf{II_M}$	3	Standard	ON	Yes	Yes	22	7.41	1.1	1.2	1.7	0.3	0.4	0.6	0	0	0	11	9
	$\mathbf{III_M}$	Base Model	Standard	ON	Yes	NO	22	8.1	1.3	1.4	2.1	0.4	0.4	0.9	0	0	0	12	11
	$\mathbf{IV_M}$	9	Standard	Off	Yes	No	22	7.7	2.2	2.2	3	0.5	0.6	1.3	0.1	0.2	0.2	29	21
	$\mathbf{V_M}$	2	Standard	ON	Yes	No	24	1.98	2	2.3	3.6	0.5	0.7	1.3	0.1	0.2	0.2	28	22
	$\mathbf{VI_M}$	10	Standard	Off	Yes	No	24	1.88	3.5	3.4	4.4	1.1	1.3	1.8	0.2	0.3	0.3	38	30
Edinburgh	$\mathbf{I_E}$	19	Low	ON	Yes	Yes	22	2.72	0	0	0.1	0	0	0	0	0	0	0	0
	$\mathbf{II_E}$	3	Standard	ON	Yes	Yes	22	8.69	0	0.1	0.3	0	0	0	0	0	0	0	0
	$\mathbf{III_E}$	Base Model	Standard	ON	Yes	NO	22	9.30	0.1	0.1	0.4	0	0	0.1	0	0	0.1	0	0
	$\mathbf{IV_E}$	9	Standard	Off	Yes	No	22	9.20	0.1	0.2	0.7	0	0	0.2	0	0	0	0	0
	$\mathbf{V_E}$	2	Standard	ON	Yes	No	24	1.74	0.3	0.4	1.3	0	0.2	0.7	0	0	0	0	0
	$\mathbf{VI_E}$	10	Standard	Off	Yes	No	24	1.88	3.5	3.4	4.4	1.1	1.3	1.8	0.2	0.3	0.3	38	30

Table G2: Future Performance of the selected occupant behaviour models in London based on *DSY1 High50Percentile* Weather files

Occupant Behaviour Model	Year	Heating Demand ($KWH/m^2.yr$)	Percentage of Occupied Hours with temperature over 25^0C			Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Vulnerable Occupant)			Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Normal Occupant)			Number of Occupied Hours with temperature over 26^0C		Compliances: Passivhaus Heating	Compliances: Passivhaus Overheating	Compliances: CIBSE Overheating (Bedrooms)		Compliances: CIBSE Overheating (Livingroom)	
			B1	B2	L	B1	B2	L	B1	B2	L	B1	B2			Vulnerable occupant	Normal occupant	Vulnerable occupant	Normal occupant
I_L	2020	1.34	6.7	6.9	9.8	3.2	3.6	5.7	1.4	1.7	2.8	115	110	Pass	Pass	Fail	Fail	Fail	Pass
I_L	2050	1.32	11	11	15	6.3	6.3	11	3.6	3.9	6	242	226	Pass	Fail	Fail	Fail	Fail	Fail
I_L	2080	1.32	19	19	23	12	12	19	7	7.2	12	459	439	Pass	Fail	Fail	Fail	Fail	Fail
II_L	2020	4.1	7.6	7.4	11	3.9	4.3	6.7	2	2.1	3.5	129	122	Pass	Fail	Fail	Fail	Fail	Fail
II_L	2050	3.86	13	13	16	7.3	7.9	12	4.2	4.4	7.1	267	256	Pass	Fail	Fail	Fail	Fail	Fail
II_L	2080	3.13	20	20	24	14	14	21	8.3	8.9	14	497	477	Pass	Fail	Fail	Fail	Fail	Fail
III_L	2020	5.63	8	8.2	12	4.4	4.7	8.1	2.2	2.4	4	138	134	Pass	Fail	Fail	Fail	Fail	Fail
III_L	2050	4.61	13	13	18	8.1	8.6	14	4.6	5	8.3	280	267	Pass	Fail	Fail	Fail	Fail	Fail
III_L	2080	3.74	20	21	25	15	15	23	9.3	9.6	16	506	490	Pass	Fail	Fail	Fail	Fail	Fail
IV_L	2020	5.6	11	10	14	6.5	6.2	11	3.2	3.2	5.8	214	177	Pass	Fail	Fail	Fail	Fail	Fail
IV_L	2050	4.84	17	16	20	12	11	19	7	6.8	11	399	341	Pass	Fail	Fail	Fail	Fail	Fail
IV_L	2080	3.43	24	23	28	20	19	29	13	13	21	632	579	Pass	Fail	Fail	Fail	Fail	Fail
V_L	2020	1.1	9.3	9.8	16	4.8	5.4	9.2	2.3	2.6	4.3	154	143	Pass	Fail	Fail	Fail	Fail	Fail
V_L	2050	1	15	15	22	8.6	9	14	4.7	5.2	8.9	289	280	Pass	Fail	Fail	Fail	Fail	Fail
V_L	2080	0.69	22	23	29	15	16	24	9.4	9.7	16	516	502	Pass	Fail	Fail	Fail	Fail	Fail
VI_L	2020	1.16	13	13	19	7.1	7.1	12	3.5	3.6	6.3	240	201	Pass	Fail	Fail	Fail	Fail	Fail
VI_L	2050	0.9	19	19	26	12	12	21	7.3	7.1	12	423	359	Pass	Fail	Fail	Fail	Fail	Fail
VI_L	2080	0.81	17	26	33	21	20	30	14	13	22	655	595	Pass	Fail	Fail	Fail	Fail	Fail

Table G3: Future Performance of the selected occupant behaviour models in Birmingham based on *DSY1 High50Percentile* Weather files

Occupant Behaviour Model	Year	Heating Demand (KWH/m^2.yr)	Percentage of Occupied Hours with temperature over 25^{0}C			Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Vulnerable Occupant)			Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Normal Occupant)			Number of Occupied Hours with temperature over 26^{0}C		Compliances					
														Passivhaus Heating	Passivhaus Overheating	CIBSE Overheating (Bedrooms)		CIBSE Overheating (Livingroom)	
			B1	B2	L	B1	B2	L	B1	B2	L	B1	B2			Vulnerable occupant	Normal occupant	Vulnerable occupant	Normal occupant
I_B	2020	2.9	1.1	1.2	2.1	0	0.4	1	0.1	0.1	0.5	8	5	Pass	Pass	Pass	Pass	Pass	Pass
I_B	2050	2.57	2.4	2.6	4.2	1	1.1	2.1	0.4	0.4	1	35	32	Pass	Pass	Fail	Fail	Pass	Pass
I_B	2080	2.31	5.5	5.7	8.3	2.9	3	5.1	1.3	1.4	2.6	85	79	Pass	Pass	Fail	Fail	Fail	Pass
II_B	2020	7.56	1.4	1.4	2.4	0.4	0.5	1.1	0.1	0.2	0.5	11	11	Pass	Pass	Pass	Pass	Pass	Pass
II_B	2050	6.21	2.9	3	4.8	1.2	1.6	2.6	0.5	0.6	1	45	40	Pass	Pass	Fail	Fail	Pass	Pass
II_B	2080	5.85	6.1	6.4	9.1	3.3	3.5	6.1	1.6	1.7	3	96	95	Pass	Pass	Fail	Fail	Fail	Pass
III_B	2020	7.9	1.5	1.6	2.7	0.5	0.6	1.2	0.2	0.2	0.5	12	12	Pass	Pass	Pass	Pass	Pass	Pass
III_B	2050	7.62	3.1	3.3	5.5	1.5	1.9	3.5	0.6	0.6	1.3	45	42	Pass	Pass	Fail	Fail	Fail	Pass
III_B	2080	7.12	6.4	6.7	11	3.5	3.9	7.2	1.7	2	3.8	102	97	Pass	Fail	Fail	Fail	Fail	Fail
IV_B	2020	8.0	2	2.1	3.4	0.7	0.8	1.6	0.2	0.4	0.5	26	20	Pass	Pass	Pass	Pass	Pass	Pass
IV_B	2050	7.52	4	4	6.4	2.3	2.3	4.6	0.8	0.9	1.6	71	58	Pass	Pass	Fail	Fail	Fail	Pass
IV_B	2080	7.26	8.1	8	12	4.9	5	9	2.6	2.7	5.2	148	127	Pass	Fail	Fail	Fail	Fail	Fail
V_B	2020	1.92	2.2	2.4	4.5	0.7	1	1.7	0.2	0.3	0.6	16	16	Pass	Pass	Pass	Pass	Pass	Pass
V_B	2050	1.91	4.1	4.4	8.1	2.1	2.4	4.3	0.7	0.7	1.4	49	47	Pass	Pass	Fail	Fail	Fail	Pass
V_B	2080	1.7	7.8	8.3	14	4.1	4.5	8.2	2	2.3	4.2	112	107	Pass	Fail	Fail	Fail	Fail	Fail
VI_B	2020	1.97	3.2	3.2	6	1.6	1.7	2.7	0.4	0.4	0.8	34	26	Pass	Pass	Fail	Fail	Pass	Pass
VI_B	2050	1.95	5.7	5.8	11	3.1	3.2	5.8	1.1	1.3	1.9	79	66	Pass	Fail	Fail	Fail	Fail	Pass
VI_B	2080	1.71	10	10	16	5.7	5.8	11	2.9	2.9	5.4	163	139	Pass	Fail	Fail	Fail	Fail	Fail

Table G4: Future Performance of the selected occupant behaviour models in Manchester based on *DSY1 High50Percentile* Weather files

Occupant Behaviour Model	Year	Heating Demand (KWH/m^2.yr)	Percentage of Occupied Hours with temperature over 25^{0}C			Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Vulnerable Occupant)			Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Normal Occupant)			Number of Occupied Hours with temperature over 26^{0}C		Compliances					
														Passivhaus Heating	Passivhaus Overheating	CIBSE Overheating (Bedrooms)		CIBSE Overheating (Livingroom)	
			B1	B2	L	B1	B2	L	B1	B2	L	B1	B2			Vulnerable occupant	Normal occupant	Vulnerable occupant	Normal occupant
I_M	2020	2.4	0.8	0.9	1.4	0	0.1	0.6	0	0	0	6	5	Pass	Pass	Pass	Pass	Pass	Pass
I_M	2050	2.32	2.1	2.2	3.1	0.4	0.5	1.4	0	0	0.5	25	23	Pass	Pass	Pass	Pass	Pass	Pass
I_M	2080	1.98	4.7	4.7	5.9	1.6	1.9	2.1	0.6	0.6	1.6	89	84	Pass	Pass	Fail	Fail	Pass	Pass
II_M	2020	7.41	1.1	1.2	1.7	0.3	0.4	0.6	0	0	0	11	9	Pass	Pass	Pass	Pass	Pass	Pass
II_M	2050	7.14	2.5	2.7	3.6	0.6	0.8	1.5	0.1	0.3	0.6	34	33	Pass	Pass	Fail	Fail	Pass	Pass
II_M	2080	6.42	5.1	5.1	6.3	2.5	2.7	4	0.8	0.9	2.1	103	100	Pass	Pass	Fail	Fail	Fail	Pass
III_M	2020	8.1	1.3	1.5	2.2	0.4	0.4	1	0	0	0	12	11	Pass	Pass	Pass	Pass	Pass	Pass
III_M	2050	7.32	2.8	3	4.1	0.8	1	2.2	0.3	0.4	0.8	38	36	Pass	Pass	Fail	Fail	Pass	Pass
III_M	2080	6.95	5.3	5.4	6.9	2.9	3	4.9	1	1.2	2.5	106	103	Pass	Pass	Fail	Fail	Fail	Pass
IV_M	2020	7.7	2.2	2.2	3	0.5	0.6	1.3	0.1	0.2	0.2	29	21	Pass	Pass	Pass	Pass	Pass	Pass
IV_M	2050	7.32	4.2	4.1	5.1	1.8	1.9	2.9	0.5	0.5	1.1	77	60	Pass	Pass	Fail	Fail	Pass	Pass
IV_M	2080	7.06	6.8	6.4	8	4.8	4.5	6.8	2.1	2.2	3.4	151	132	Pass	Pass	Fail	Fail	Fail	Fail
V_M	2020	1.98	2	2.3	3.6	0.5	0.7	1.3	0	0.1	0.1	16	15	Pass	Pass	Pass	Pass	Pass	Pass
V_M	2050	1.82	3.5	3.9	5.1	1.2	1.6	2.4	0.4	0.4	1	44	43	Pass	Pass	Fail	Fail	Pass	Pass
V_M	2080	1.54	6	6.3	8.7	3.1	3.4	5.3	1.1	1.4	2.6	112	109	Pass	Pass	Fail	Fail	Fail	Pass
VI_M	2020	1.88	3.5	3.4	4.4	1.1	1.3	1.8	0.2	0.3	0.3	38	30	Pass	Pass	Pass	Pass	Pass	Pass
VI_M	2050	1.72	5.4	5.3	6.8	2.4	2.7	4	0.5	0.7	1.3	84	67	Pass	Pass	Fail	Fail	Fail	Pass
VI_M	2080	1.69	8.2	8.1	11	5.1	5.1	7.6	2.4	2.4	3.7	159	138	Pass	Fail	Fail	Fail	Fail	Fail

Table G5: Future Performance of the selected occupant behaviour models in Edinburgh based on *DSY1 High50Percentile* Weather files

Occupant Behaviour Model	Year	Heating Demand (KWH/m^2.yr)	Percentage of Occupied Hours with temperature over 25^{0}C			Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Vulnerable Occupant)			Percentage of Occupied Hours with Temperature over Maximum Adaptive Temperature (Normal Occupant)			Number of Occupied Hours with temperature over 26^{0}C		Compliances: Passivhaus Heating	Compliances: Passivhaus Overheating	Compliances: CIBSE Overheating (Bedrooms)		Compliances: CIBSE Overheating (Livingroom)	
			B1	B2	L	B1	B2	L	B1	B2	L	B1	B2			Vulnerable occupant	Normal occupant	Vulnerable occupant	Normal occupant
I_E	2020	2.72	0	0	0.1	0	0	0	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
I_E	2050	2.56	0.2	0.3	0.8	0	0	0	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
I_E	2080	2.45	0.5	0.6	1.5	0.2	0.2	0.5	0	0	0.2	0	0	Pass	Pass	Pass	Pass	Pass	Pass
II_E	2020	8.69	0	0.1	0.3	0	0	0	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
II_E	2050	7.68	0.4	0.4	0.9	0	0.1	0.4	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
II_E	2080	6.88	1	1.1	2.3	0.4	0.4	0.8	0	0	0.3	4	5	Pass	Pass	Pass	Pass	Pass	Pass
III_E	2020	9.3	0.1	0.1	0.4	0	0	0.1	0	0	0.1	0	0	Pass	Pass	Pass	Pass	Pass	Pass
III_E	2050	9.12	0.4	0.5	1.2	0	0.2	0.5	0	0	0	1	1	Pass	Pass	Pass	Pass	Pass	Pass
III_E	2080	8.87	1.2	1.3	2.9	0.5	0.5	1.4	0.1	0.1	0.4	8	8	Pass	Pass	Pass	Pass	Pass	Pass
IV_E	2020	9.20	0.1	0.2	0.7	0	0	0.2	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
IV_E	2050	8.84	0.6	0.7	1.6	0.1	0.2	0.6	0	0	0	2	1	Pass	Pass	Pass	Pass	Pass	Pass
IV_E	2080	8.63	1.6	1.6	3.9	0.7	0.6	2	0.2	0.2	0.5	13	9	Pass	Pass	Pass	Pass	Pass	Pass
V_E	2020	1.74	0.3	0.4	1.3	0	0.2	0.7	0	0	0	0	0	Pass	Pass	Pass	Pass	Pass	Pass
V_E	2050	1.68	0.8	0.9	2.3	0.3	0.4	0.8	0	0	0.2	1	1	Pass	Pass	Pass	Pass	Pass	Pass
V_E	2080	1.61	1.7	2	4.6	0.6	0.8	1.8	0.2	0.3	0.6	8	8	Pass	Pass	Pass	Pass	Pass	Pass
VI_E	2020	1.88	0.5	0.5	1.9	0.2	0.3	0.7	0	0	0.2	0	0	Pass	Pass	Pass	Pass	Pass	Pass
VI_E	2050	1.61	1.1	1.2	3.6	0.5	0.7	1.2	0	0	0.3	3	3	Pass	Pass	Pass	Pass	Pass	Pass
VI_E	2080	1.52	2.8	2.8	6.1	1.1	1.1	3	0.3	0.4	0.8	17	14	Pass	Pass	Pass	Pass	Pass	Pass