Self-Shading Façade Geometries to Control Summer Overheating in UK Passivhaus Dwellings for Current and Future Climate Scenarios

Thesis Submitted in Accordance with the Requirements of the University of Liverpool for the Degree of Doctor in Philosophy

By

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Declaration

I hereby declare that this thesis constitutes my own work, that where the language of others is set forth, quotation marks so indicate, and that appropriate credit is given where I have used the language, ideas, expressions or writings of another.

I declare that the thesis describes original work that has not previously been presented for the award of any other degree of any institution.

Signed	Yahya Lavaf. p
Date	30 July 2017

Abstract

The German Passivhaus building standard, with its emphasis on airtightness and very high levels of insulation, has become well known. It is widely applied to produce buildings that have a very low heating energy demand in winter whilst providing thermal comfort. However, there have been, over the last decade, instances of summertime overheating in Passivhaus buildings. Research has shown that the high internal air temperatures during summer in Passivhaus dwellings are mainly due to excessive solar gain through large south-facing glazing and a lack of natural ventilation. A number of well-established passive adaptation measures have received a great deal of research attention, and several have been implemented in to Passivhaus designs to reduce summer discomfort. Some of these approaches, such as window opening and blinds, are user-dependent, while other interventions, such as overhangs, are truly passive and do not require the occupants' attention. Although thermal mass is not a user-dependent intervention, it typically works in conjunction with night purge ventilation, which is controlled by building users.

The research presented here investigated a less examined passive approach to reducing overheating - the potential implementation of the envelope shape as an environmental design strategy to self-shade. This approach is architectural in nature, and so could have both aesthetic and environmental consequences. The research tested if altering the geometric form of a UK Passivhaus (by tilting the south facade to give self-shading) might be capable of passively protecting the house from the excessive solar gain in summer, both for current and future climate scenarios. This study used probabilistic climate change scenarios from the UK Climate Change Projections to determine the overheating risk in an existing Passivhaus dwelling under a high emission 50-percentile scenario in London. Dynamic thermal simulation modelling software (DesignBuilder) was used to examine the impact of various inclinations of the south façade of the Passivhaus dwelling to make use of the self-shading that this form created. A sensitivity analysis of internal temperatures and thermal comfort conditions in the dwelling as a function of building facade inclination and prevailing climatic conditions was undertaken.

The research found that implementing an optimum angle tilted façade would moderate indoor temperature variations between day and night in summer and could potentially act as an effective shading device and reduce overheating by a significant amount while still being practical for collecting solar gains in winter. The proposed inclined façade could eliminate the risk of overheating for current climates; however, it was found that using only the geometric considerations would not solely be fully capable of eradicating the risk of future thermal discomfort overheating, particularly for UK climate scenarios of the 2080s. The suggested tilted façade was then analysed alongside other conventional approaches, such as overhangs and reduced window to wall ratios, to compare their relative effectiveness in reducing overheating risk. Manipulating the tilt of the south facing façade will clearly have other impacts on, for instance, winter heating demand, daylighting and natural ventilation air flows, and these parameters have also been examined using the lighting and computational fluid dynamics CFD algorithms in DesignBuilder. The consequences of a slight tilt of the south façade on daylight levels and airflows through the dwelling were apparent but not overly large. The research noted a concurrent increase in the heating demand and artificial lighting, but it was concluded that this increase was an acceptable trade-off compared to the reduced summer overheating risk.

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Chapter One

1 Introduction

1.1 The stimuli for this study

"The global climate is changing, with greenhouse gas emissions from human activity the dominant cause. The global increase in temperature of 0.85°C since 1880 is mirrored in the UK climate, with higher average temperatures and some evidence of more extreme weather events." (Committee on Climate Change, 2016)

It is agreed that buildings are responsible for a substantial amount (about 33%) of global greenhouse gas (GHG) emission. It is believed they are the largest potential for reducing the GHG in the future (Levermore, 2008a). The Paris Agreement (UN, 2015) highlighted the urgent need for further a ction to prevent increases in global warming, while the UK Climate Change Risk Assessment report (Committee on Climate Change, 2016) addressed the top six areas of inter-related climate change risks for the UK. The risks were identified as being of low, medium and high risk and which risks required more action. Amongst the greatest risks was that for people's health, wellbeing and productivity from high temperatures. Heat waves in the UK are expected to occur more often in the future and the number of heat-related illnesses are predicted to triple by the 2050s. Therefore, ways to mitigate high indoor temperatures and improve wellbeing in the domestic sector is essential.

Figure 1-1 shows the UK's energy consumption by different sector. Buildings and, in particular, the domestic sector, are responsible for a large proportion of energy consumption and greenhouse gas (GHG) emissions in the UK. The UK government has introduced measures to reduce GHG and CO_2 emissions. Some research has focused on climate change mitigation and adaptation measures, and how these measures may affect the indoor environment, human wellbeing and indoor air quality. Recent cases of overheating in buildings have created a substantial amount of research attention. Such research regards overheating as a new challenge for the housing sector in the UK. Overheating is seen as a direct negative impact of global warming, and is linked to an increase in thermal insulation levels, which was originally introduced to reduce heating demand.

In the current trend towards mitigating summer overheating in the UK, a specific role is played by shading strategies. Future developments require more options than the conventional shading devices such as blinds and overhangs. The façade, as the largest component of the building, has a significant influence on the energy exchange between indoor and outdoor environments. Windows and solar shading devices play a central role in the total energy optimization.

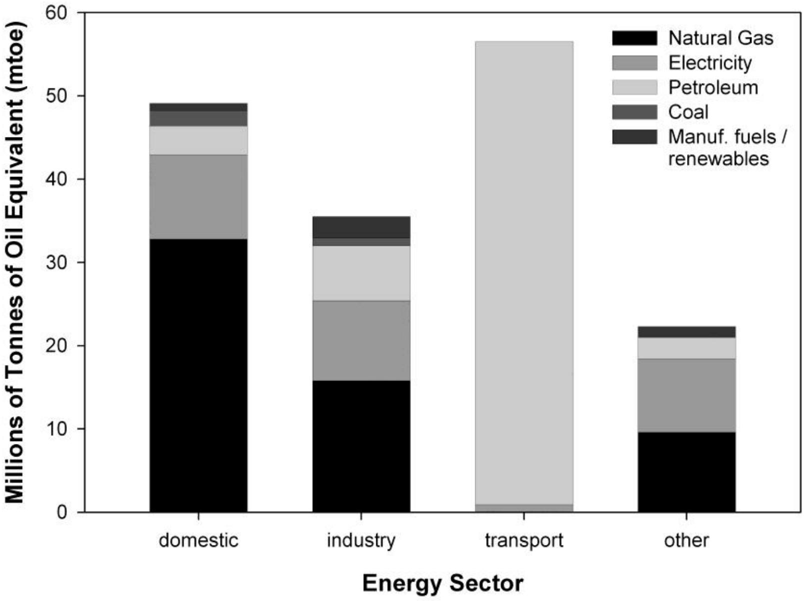


Figure 1-1 UK energy consumption (Kaluarachchi, et al., 2005)

1.2 Background of the study

(Socrates, as quoted by Xenophon. in Memorabilia, book III, chapter VIII. Section 9.)

"Is it pleasant to have it cool in summer and warm in winter? Now, in houses with a southern aspect, the sun's rays penetrate into the porticoes in winter, but in summer, the path of the sun is right over our heads and above the roof so that there is shade. If

then this is the best arrangement, we should build the south side loftier to get the winter sun and the north side lower, to keep out the cold winds. In short: the house in which the dweller can find a pleasant retreat at all seasons and store his belongings safely, is presumably at once the pleasantest and the most beautiful" (Xenophon, 1923)

Socrates, and later Vitruvius, were early thinkers on how to address climatic and sustainable building design. However, up until the Industrial Revolution, it did not seriously influence architectural design considerations. Even in modern times thermal comfort and designing vis-à-vis sustainability were largely an academic question and rarely arose in practice. In reality, when it was cold, a fire was lit to ameliorate the condition and active mechanical cooling was used to avoid overheating (Szokolay, 1985).

In the last few decades the need to develop energy efficient buildings has led to research and developments in many areas. For example, hi-tech materials (Holstov, et al., 2015), sophisticated mechanical devices (Barozzi, et al., 2016), new low energy HVAC systems, bio-inspired designs, and building integration of natural energy systems (Ferrara, et al., 2017). Nowadays, new approaches in designing climate responsive building skins, adaptable facade systems and intelligent building envelopes (Aschehoug, et al., 2005) are rapidly advancing vis-à-vis optimisation of solar energy, shading and daylight. It can be concluded that this movement in architecture emerged for so called "sun-control purposes" (Fiorito, et al., 2016).

The energy crisis of 1973 accelerated attempts to find advanced methods and tools for the design and evaluation of architectural solutions. The development started with the Computer Aided Design (CAD) tools regarding insulation, shadings and determination of solar rights. Nevertheless, many of the dwellings with energy efficiency-label looked like boxes, and featured windows covered in matted galvanised roller blinds; often it seems that the architect simply forgot to design the place and rather concentrated all the attention on overcoming the negative impact of the outdoor climate. A recent development was the Passivhaus standard, one of the leading standards in low energy architecture, which adopted performance-based standards, and which mainly suggests engineering-based approaches to architecture. Figure 1-2 shows some examples of the new passive houses in the UK.

Figure 1-2 Examples of UK Passivhaus: clockwise from top left Sunnyside Passivhaus, Denby Dale Passivhaus, Larch House, Wimbish Passivhaus, Totnes Passivhaus and Lime House

For many years, high-profile architects were not particularly interested in engineered fixes i.e. super insulation, avoiding thermal bridge, using mechanical heat recovery systems, PV panels, etc. However, this is changing rapidly and there are some very interesting low-energy buildings developing these days (Figure 1-3).

Figure 1-3 Design Studio 2x2 (left) and Crossway Passivhaus

Recently, Stride Treglown Architects have designed a series of innovative passive house schemes in North Bristol (see Figure 1-4). Form, shape, building orientation, and innovative material have brought attractive design alongside passive design principles. The roof is designed in a wraparound form, which encloses a highly glazed south-facing elevation, and take full advantage of solar gain. The design of the roof forms a striking focal point and produces an intricate design reminiscent of an origami fold effect (fc&a magazine, 2015).

Figure 1-4. 42a Gloucester Road by Stride Treglown Architects

1.3 The focus of this thesis

Geometry is the fundamental science of forms and a central characteristic of any architectural design. Throughout the history of architecture geometric rules have been mainly based on the ideas of proportions and harmony and geometry has been considered as a general aesthetic matter in architecture.

In order to find the optimum building envelope many different criteria must be taken into account. Thermal indoor comfort and lighting comes first in many given context. Architectural issues such as scale, proportion, aesthetic, and facade configuration also play a big role in achieving a successful optimum building design. Most individual research studies that focused on a limited selection of optimization interventions have concluded that a global optimisation is impossible – there is usually a trade-off between conflicting criteria, which are based on context and priorities (Aschehoug, et al., 2005).

Thermal performance in buildings has become one of the most important aspects for comfort and quality of life. Buildings are now designed to use less energy and to avoid indoor discomfort conditions.

"Increasing numbers of buildings are being designed with the aims of balancing optimum user comfort and with conservation of natural resource …. However, there is

still often a gap between environmental and architectural quality". (Gauzin-Müller, 2002)

Sustainable design is an approach and not a style of architecture and there are no physical scale barriers to its adoption. It is a philosophy that simply seeks to enhance the quality of the built environment i.e. creating better buildings for people whilst minimising or eliminating the negative impact on the natural environment. In general, sustainable design is simply expanding the definition of good design to one in which a wider set of criteria are considered. Sustainable architecture is adequately responsive to the natural environment and adds more layers to the architecture design (McLennan, 2004).

Many standards and codes have emerged from the sustainable movement in architecture, such as Zero Energy Buildings, eco-friendly, energy efficient buildings and standards such as LEED, BREEAM, Green Star and Passivhaus. All these codes and standards aim to improve the building envelope, with a focus on insulation, glazing, and introducing passive and environmental-friendly design strategies.

Current developments advocate that the thermal performance of a building can be predicted with reasonable accuracy and that each individual building ultimately can control and moderate its indoor condition using passive means (Szokolay, 1985). Shading the walls and windows are amongst the most important design parameters to achieve good indoor conditions. Shading should be carefully designed to avoid overheating, overshadowing, and a rise in peak heating or cooling demand. For instance, in a low-storey building it is possible to shade the walls and windows by the mass of the building, such as by using a roof design that can be extended to form wide verandas to protect the building from rain and wind (Givoni, 1998). New facade solutions are a key area for research and development. A large share of energy exchange in the domestic sector takes place at the building envelope interface, primarily the facade and roof (Kaluarachchi, et al., 2005).

Shading devices are not an addition to the building; they are one of the components of the building envelope suitable for a variety of actions. These include integration of renewable energy systems (e.g. PV integrated facades), a systematic facade to control daylight or a static architectural mass which has a practical use, like integrated shading devices, concave, convex, curved, or self-shading facades

It has become increasingly evident that buildings contribute significantly to the serious environmental problems of the planet. Nearly half of the total energy consumption and 40% of global CO_2 emissions are due to the operation of buildings (EPBD article 4, 2010). There is a growing scientific interest towards the optimization of the energy performance of buildings to reduce their CO_2 emissions and fossil fuel consumption. In the UK carbon emission reduction, and the associated reduced energy consumption, is one of the key priorities of the government (The Climate Change Act, 2008). The Environmental Audit Committee warned, "*As temperatures rise due to climate change there is an increased risk of overheating in buildings*" (Zero Carbon Hub, 2015). UK building regulations now contain detailed standards for energy use. Earlier regulations for energy efficiency prescribed certain physical properties and values for glazing, wall and other buildings elements. However the new regulations are performance-based rather than prescriptive. They measure overall energy consumption and carbon emissions. The newer regulations are believed to encourage more creativity in the design (Levermore, 2008b). The building regulations require architects and engineers to demonstrate additional calculations to address appropriate overheating risk criteria for new built homes, the need for cooling (both passive and mechanical) and performance prediction under a standardised climate data and calculation method (CIBSE TM36, 2005).

Several studies have approached energy-related design optimization. These include investigations of constructional materials (Ascione, et al., 2010); shading with attached overhangs and balconies (Hien & Istiadji, 2003); shading and daylight (Torres & Sakamoto, 2007); openable windows as a potential for natural ventilation, location and building orientation (Porritt, et al., 2012); relative compactness and energy use (Depecker, et al., 2001); window to wall ratio (WWR) (Bellia, et al., 2013); form and geometry of the building (Zerefosa, et al., 2012), and general overheating concern (Ji, et al., 2014).

In response to these environmental concerns, a number of energy efficient strategies have been employed in the UK housing sector, including the German Passivhaus standard. The Passivhaus strategy uses super insulation and airtightness to reduce the heat transfer through the building envelope. Many case studies have demonstrated that Passivhaus works well during European winter conditions in reducing heating energy demand whilst maintaining a high level of thermal comfort. However, some studies have found potential summer overheating problems, even for the relatively moderate summer climate of the UK (Zero Carbon Hub, 2015). Attempting to reduce this risk through the analysis of novel, self-shading building forms, was the focus of the research presented in this work.

1.4 Overarching structure of the research

Figure 1-5 illustrates the overarching procedure observed in this thesis. Further to the arguments which will be presented in the observation stage i.e. literature review, the research seeks a non-conventional arrangement to alleviate unwanted solar gain in a super insulated passive house, which often features a large glazing façade on the south elevation and has a box-shape design (stimuli). To start within a framework (scope) a case study which features the most common elements in a passive house and obtained a high level of accomplishment from the Passivhaus institute was chosen, namely “Larch House” and located in Ebbw Vale, UK (observation). The selection of an existing case study helps to replicate all the building components, such as external walls, slabs and partitions, windows, shading devices, HVAC system, etc. Another reason behind choosing the Larch House was the on-going monitoring analysis that was undertaken at the time (data collection).

The main method which is used throughout the research is the computer simulation modelling. To ensure that the model created is reliable for further analysis, it will be tested against both monitoring data and PHPP spreadsheets obtained from the design team (validation). Passive House Planning Package (PHPP) is a steady state worksheet software and works based on a set of over 30 linked Microsoft Excel spreadsheets. The software is the official tool for designing according to the Passivhaus standards.

Comparing the simulated model with PHPP and real data measurement will allow calibration of the model and fine-tunings of the data achieved from the initial simulations. The process of calibration will be repeated up until a satisfactory protocol is achieved that reflected on the existing data.

Once the model had been verified and validated in its original location i.e. Ebbw Vale, it was virtually moved to London, where a warming summer is more likely to affect thermal comfort. The extent of overheating risk in a super insulated Passivhaus with large glazing in London climate for current and future probabilistic climate scenarios was diagnosed. Data from initial analysis show that a similar building to the Larch House would experience overheating in summer and was at a high level of overheating risk under probabilistic future climate conditions (diagnosis).

To apply the proposed design solution, the research undertook an initial pilot study (application). The reason that the pilot unit was considered was mainly due to some limitations in creating forms in the Energyplus/Designbuilder software (at the time). Considering the fact that by changing the wall inclination all the internal zoning are effected and need to be re-setup, therefore, a single zone unit allowed examination of the geometry to be done more efficiently. Nonetheless, at the time, the reaction of the software to a tilt wall was unknown. A single zone, simple geometry envelope using the same template as the validated model was considered sensible to experiment with the form manipulation (pilot study).

Using the lessons learnt from the pilot study the effective tilt angle was then implemented to the case study model (implementation). The current and future performances of the proposed façade were analysed and relevant consequences were assessed (investigation).

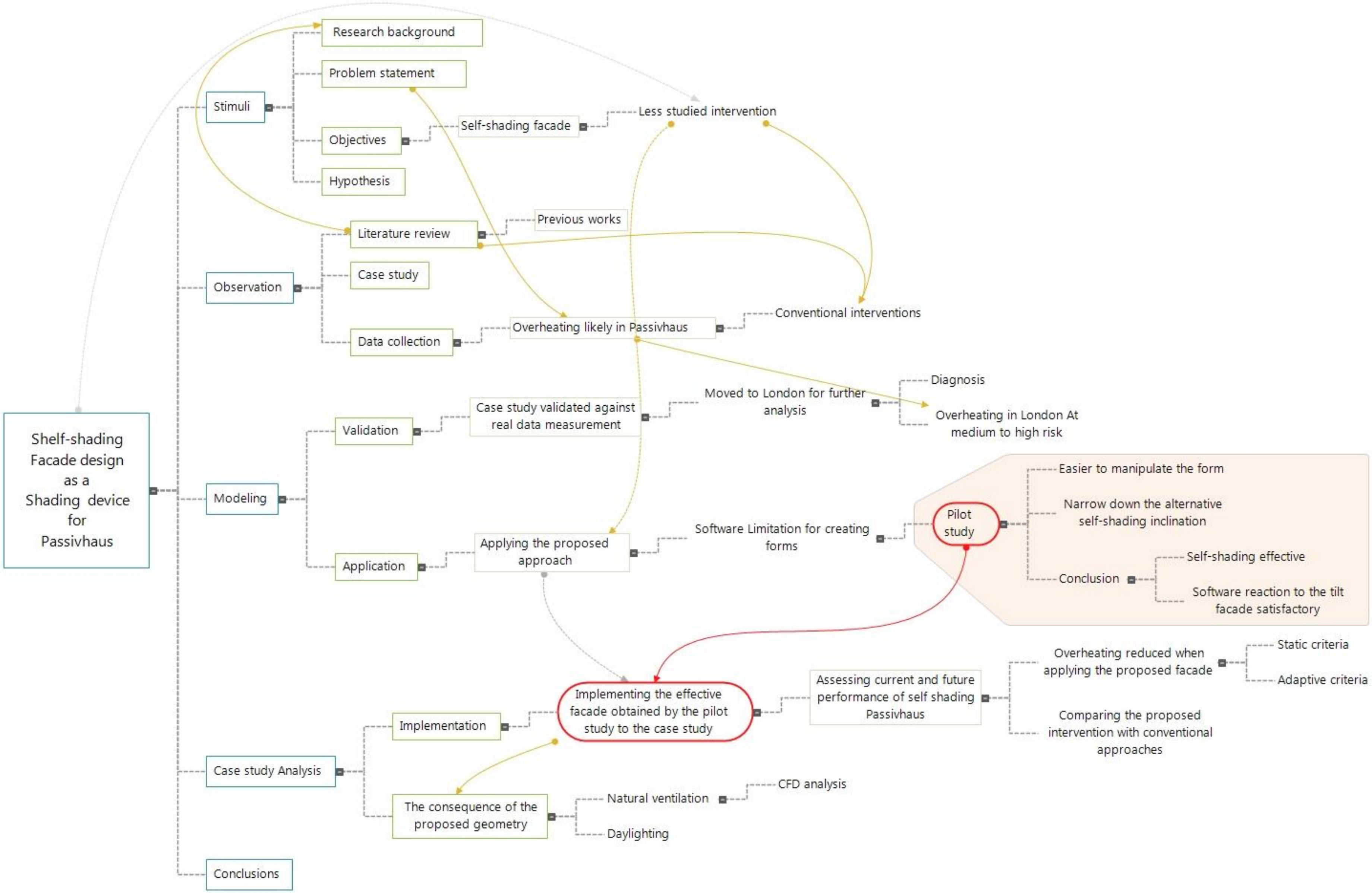


Figure 1-5 Overarching structure of the research

1.5 Aims and objectives of the study

This study has examined the potential of self-shading façades in Passivhaus designs to reduce summer overheating for current and future climatic conditions. London was chosen as the location for the study as it is the UK city most at risk from overheating, due to a combination of urban heat island and climate change impacts. The aim of the study was to investigate the potential of geometrical façade forms to increase comfort hours in a warming summer, thereby reducing or eliminating the potential need for air-conditioning installations in the London housing stock.

The main objectives of the study were as follows:

1) To assess the extent of overheating risk in a super insulated Passivhaus in London under a warming climate.
2) To investigate the influence of different façade inclination angles on building performance, including overheating percentage and heating demand, and to establish an optimal façade tilt range.
3) To compare the effectiveness of the proposed strategy against existing and more conventional interventions in reducing overheating.
4) To analyse the consequences of the proposed geometry on daylighting levels and natural ventilation air flows.

1.6 Research questions

Based on the aforementioned objectives, the main questions this research was seeking to answer are:

1) Is there a strong correlation between the Passivhaus envelope shape and its energy performance?
2) To what extent can the façade geometry eliminate or reduce an overheating risk?

3) What are the energy use implications of a self-shading approach when compared with strategies that are more conventional?
4) What is the impact of the self-shading façade on heating demand, natural ventilation and daylighting?

1.7 Hypothesis

Different inclination angles created by a tilted façade will change the sun's angle of incidence and consequently effect the direct solar radiation gain. This will reduce the amount of excessive solar gain in summer when the sun angle of incidence is higher. However, the extent of the overheating reduction and the trade-offs it may have on heating demand, daylighting or natural ventilation are unknown.

1.8 Scope of the study

The study focused on the tilted façade as a passive shading strategy to improve thermal comfort for a London Passivhaus dwelling. There is a broad area of research to investigate different façade geometries and their implications to reducing overheating. However, the scope of the presented study concentrated on self-shading envelopes. This research investigated the implementation of the tilted wall on the most dynamic façade i.e. south facade of an existing Passivhaus. The research was designed within a specific scope as follows:

1) Pilot building: a hypothetical single-zone building with Passivhaus standards was formulated and the inclination angles at 5° interval were tested from vertical to the feasible inclination angle (i.e. 55° beyond vertical)
2) Case study building: the design of an existing Passivhaus (Larch House by bere:architects) was chosen as the case study to be examined, and the main occupied areas (i.e. living room and master bedroom) were chosen for investigating the proposed strategy.
3) Weather data: London current and future (2030, 2050 and 2080) climates were employed for the simulations in this study

4) Simulations: the main research measures considered to address the study's questions were the room's average operative temperature, percentage discomfort overheating hour per occupied period, room's indoor air velocity and daylight factor.

1.9 Structure of the thesis

The structure of the thesis is as follows:

i. Introduction and background

The study is divided into nine main chapters. An introduction to the study, the research aims and the main research questions are given in Chapter One. Chapter Two presents the background to the study and introduces the fundamental principles of the Passivhaus standard. The basic knowledge of sustainable development and super insulated approach to Passivhaus standards are presented. This chapter also delivers a discussion over the possibly consequences of climate change and a warming climate.

ii. Literature review

Chapter Three reviews the main literature of the studied subject and discusses the definition of thermal discomfort according to different standards. Static and adaptive thermal methods were explained and interventions towards reducing thermal discomfort are presented. Chapter Four highlights the main stimulus of the study by presenting the literature and precedent works relating to geometric consideration in sustainable design and energy efficiency.

iii. Methodology and validation

In Chapter Five some of the available research methods for investigating the implication of the form and thermal assessment are reviewed. The chosen method for the simulations is presented by breaking down the research design. The selection of the case study and weather data and the reason for choosing the pilot study are explained. Chapter Six formulates the case study model validation, and the main input parameters for conducting dynamic thermal modelling simulations are established.

The modelled passive house is validated and then relocated to the London climate for investigating the overheating in worst-case scenarios.

iv. Results

Chapter Seven presents the main results and contributions of this study. Simulations on the pilot study are described and the proposed self-shading strategy and its principles are established. Following the established results from the pilot study, the results from the thermal analysis of the case study with proposed façade geometry are reported. Details of the range of the summer indoor temperature and peak temperatures in current and future climate scenarios are considered. The results of the proposed tilted façade are then compared with the results from the typical and more conventional interventions. In Chapter Eight the results of the consequent effect of the proposed strategy on daylighting and natural ventilation are assessed.

v. Conclusion

Finally, in Chapter Nine, the results obtained in the earlier chapters are discussed and the main conclusions to be drawn from this research are presented. The limitations of the study are discussed and possible further work to extend the geometric shading concept examined in this study is presented.

Additional information is provided in the appendices: Appendix A includes the software main data input regarding construction materials. Appendix B includes window blind operational schedule. Appendix C presents London future weather data. Appendix D shows example of PHPP spreadsheets obtained from the architect of the case study and Appendix E includes some of the published materials derived from the results of this research.

Chapter Two

2 Research Background

2.1 Introduction

The building sector accounts for over 40% of the UK's total energy consumption (Waters, 2016) and the residential category is responsible for 70% of that (UK Passivhaus Competition , 2012). Tens of thousands of buildings in the UK have been built with poorly insulated external envelopes, which create high levels of energy loss. Over the past decades, hundreds of environmental institutes have been involved in promoting highly insulated building skins to minimise thermal bridges, which is essential to reduce energy consumption. Highly insulated buildings with a high level of airtightness and energy recovery systems have been successful in reducing heating demand in the UK housing sector. One of the most successful and fastest growing standards to be implemented to the UK housing sector is the German Passivhaus standard, which reduce the energy consumption of a typical home about 85% compared to a typical construction (Trubiano, 2013). According to a government-sponsored study by Cambridge Architectural Research (Palmer & Cooper, 2012), the household energy consumption has gradually crept up from 1970 to 2004. However, the report showed that from 2004 the energy consumption had a descending trend, except in 2010 because of the harsh winter weather in that year.

The trend towards so-called low energy buildings, which has been at the centre of the focus of contemporary architecture for last few decades, has brought increased insulation, thermal storage and solar control to the buildings. These developments improve the reduction of energy use. Although there has been a positive point that the energy used in homes has changed enormously in the last decade due to the introduction of energy efficient standards, however, energy used by the housing stock rose by 5% from 1970 to 2011 (Palmer & Cooper, 2012).

2.2 Sustainable development and UK housing stock

Domestic homes in the UK are responsible for nearly 30% of the total national carbon emissions (BERR, 2007). Therefore, improvement in energy efficiency for the housing sector represents a major opportunity to cut energy consumption and meet the national target which was set to reduce 80% of CO_2 emission below 1990 levels by 2050 (The Climate Change Act, 2008). The UK building sector has been encouraging developers to invest in zero-carbon houses as an essential step to reducing greenhouse gas emission. As a result, a transition to zero-carbon new buildings was announced by UK government in December 2006 (DCLG, 2006), although this requirement was recently rescinded by the UK government (HM Treasury, 2015).

Until recently, the energy efficient development was focusing solely on the reducing of space heating in winter. However, the question of summer thermal comfort has been recently under examination for future climates. Although there have been several attempts towards energy efficient retrofit and new-build housing for future sustainable development, a report from the Technology Strategy Board (Gething, 2010) regarding the housing sector in its present condition recognised it to be inadequate to adapt to future climate change. It is now acknowledged that more research is required to investigate potential improvements in sustainable housing. Although the majority of buildings with an "Eco-Label" are dwellings, there is more research on office buildings’ energy performance than housing (Cody, 2006). Studies such as Mavrogianni, et al. (2009; 2010) and Gupta, et al. (2015; 2012) urged the importance of further work into the vulnerability of domestic buildings to summer overheating. Recently, a special issue of Building Research and Information on overheating (Lomas & Porritt, 2017) concentrated on the main questions regarding overheating and highlighted the rising level of concern and urgency about overheating in temperate climates.

With over 160,000 new homes, being built every year, the UK government has strengthened energy performance requirements in the Building Regulations for new homes. New homes are now required to be, on average, 30% more energy efficient, which means that consumers can save a substantial percentage on their fuel bills

(DCLG, 2014). Adaptation to these new requirements would benefit householders as, in dwellings, occupants are usually directly responsible for energy bills and they are concerned with rising energy costs. Home occupants also have a much more diverse range of age than any other building type from an infant to the very old, bearing in mind that older people are more at risk from thermal discomfort. Several studies have investigated thermal comfort in homes (Shove, et al., 2008; McLeod, et al., 2013; Isaksson & Karlson, 2006; Wright, et al., 2005). These studies contributed to provoking further debate on the current design intentions in sustainability and energy performance in the housing stock.

2.3 Passivhaus

Passivhaus (the German for passive house) was first established by Professor Feist at the Passivhaus Institute in 1990 (Passivhaus institute, 2010). It has been growing rapidly in Germany and other European countries, with over 37,000 buildings to date (2014) around the world, of which the majority were built in the last decade (United Welsh Housing Association, 2010). Passivhaus in the UK was first introduced by the Building Research Establishment (BRE). Until 2014, there were just over 200 completed Passivhaus in the UK (McGilla, et al., 2014). However this number has grown over the past 3 years to over 500 (Passivhaus Trust, 2017). Passivhaus is the fastest growing energy performance standards in the world (iPHA, 2013) and in the UK. Hundreds of successful Passivhaus homes have been built, including the first UK Passivhaus in London (Camden House) and the first zero carbon house – Level 6 Code for Sustainable Homes (Larch House) in Ebbw Vale, both designed by bere:architects. Passive houses are built using heavily insulated exterior envelopes, and often featuring large glazed facade to the south for maximising winter solar gain. To obtain Passivhaus certification a building needs to meet a few key criteria (Feist, 2012):

i. Maximum specific space heating demand to be no more than 15 kWhm^{-2} per year
ii. Total specific primary energy (PE) demand (referred to as Q_p in equations) to be no more than 120 kWhm^{-2} per year. PE consists of total electricity and gas

consumption including energy for heating, cooling, dehumidification, DHW, sockets, lights, cooker and electrical appliances, auxiliary loads, Mechanical Ventilation and Heat Recovery and boiler.

iii. This, and electricity on the following circuits:

iv. U-Value for all construction materials (envelope component) should be equal to or less than 0.15 $Wm^{-2}k$

v. U-Value for glazing and windows should be equal to or less than 0.8 Wm^{-2}

vi. Be free of thermal bridges

vii. An airtightness of maximum 0.6 h^{-1} at 50 Pa

viii. Living areas must not exceed 25°C for more than 10% of the occupied hours in a given year

ix. Incorporate the use of solar energy (solar heat gain) through south-facing large area of glazing

x. Comfortable indoor air quality in both winter and summer

xi. Efficient heat recovery ventilation system

There is also a maximum cooling demand for climates where active cooling is needed. However, this is for climates where the external air temperature does not drop low enough to create a benefit from night-time purge ventilation cooling. Therefore, for residual buildings the Passivhaus standard allows an annual cooling energy of 15 $kWhm^{-2}$ to be used (Passivhaus Institute, 2014). Table 2-1 summarises some post-occupancy monitoring data from Passivhaus dwellings in the UK.

Table 2-1 Monitoring data from some existing Passivhaus dwellings in the UK

Name	**Location**	**Annual heating demand (kWh/m^2)**	**Primary energy demand (kWh/m^2)**	**CO_2 emission (Kg/m^2)**	**Air-tightness h^{-1} @50 Pa**	**Reference**
Camden House	London	12.1	125	20.5	0.44	(Ridley, et al., 2013)
Larch House	Ebbw Vale	9.3	158	32	0.198	TSB 2014*
Lime House	Ebbw Vale	25.6	189.1	35.8	0.47	TSB 2014*

* (Technology Strategy Board, 2014)

One of the most advanced ventilation systems, which is used in all passive houses, is the Passivhaus certified Mechanical Ventilation with Heat Recovery (MVHR) system. The MVHR works with supply and extract terminals that are located inside the house (usually ceiling mounted) and intake and exhaust ducts facing onto the outdoors. The extract terminals return the warm air from the kitchen and shower room into the MVHR and the intake duct brings fresh air from outside into the MVHR unit. Filtered air from the MVHR system is introduced into the living areas by the supply terminals. Exhaust air will then be extracted from the building using the extract duct by a controlled volume of 0.3 ACH as a standard airflow rate (a schematic drawing of corresponding MVHR system can be seen later in Figure 6-2). There is also a boost ventilation mode, which is approximately 30% higher than the standard airflow rate (Clarke, 2015). This is for the extra ventilation that may be required after a long shower or excessive cooking. This system replaces the traditional way of ventilating the house using a fan i.e. a hole in the wall to send the stale air out and a supply system to provide with the fresh air e.g. typically window opening. Not all these traditional systems have a direct control of the amount of air out and in. The advantage of the MVHR system is that it controls the cubic metres of air delivered to the house and extracted from the house.

Airtightness is one of the main characteristics of all Passivhaus exterior components, including windows and doors, to ensure the air leakage of the openings when closed is equal or less than 2.25 m^3/hm at 100 Pascal or the airtightness result at 50 Pascal pressure does not exceed 0.6 air change per hour (McLeod, et al., 2014). In addition to the required airtightness, the U-value of the building envelope and glazing should be lower than 0.15 and 0.8 $Wm^{-2}K$ respectively. A variety of wall construction materials is available to Passivhaus that are capable of achieving the Passivhaus requirements within the 450 mm wall build-up. Some examples introduced include masonry with EIFS, polystyrene rigid foam insulated concrete form (ICF), ICF based on expanded concrete, prefabricated lightweight concrete element etc. Thermal bridging, which is common at the geometric junctions and connections between elements, is vastly reduced or eliminated in the Passivhaus. The heat loss associated with these thermal bridges is expressed as a linear thermal transmittance called the psi value (Ψ-value). Psi values should be equal to or less than 0.01 $Wm^{-1}K$ at any linear thermal bridges (McLeod, et al., 2014).

In brief, the main concern of the Passivhaus principles is to reduce substantially the requirements for space heating via introducing the *"fabric first approach"* to the design criteria i.e. using high levels of insulation in the thermal envelope. To reduce further heating demand, Passivhaus benefits from large glazing areas in south façades (in the northern hemisphere). According to the book *Passivhaus Primer: Designer's Guide* (McLeod, et al., 2014) *"A central part of the Passivhaus principle is to make use of solar gains in winter to reduce the heating demand"*. Solar gains consider a significant component to gain free heat gains available to a Passivhaus during heating period. The BRE Passivhaus primer also states *"In order to benefit from the useful solar gains a Passivhaus requires the glazing to be optimised on the south façade with reduced glazing the [other] façade[s]".*

According to Feist (2012), walls facing the east and west should have the lowest amount of glazing to avoid input from a low-angle sun. It is believed (Porritt, et al., 2012) that the greatest overheating occurs when the windows face west. Findings from a jointly report supervised by EA Technology Limited (Wright, et al., 1999), showed that comfort was much harder to achieve on a glazed east façade building. With glazing encapsulated in the south façade, solar gains make up a significant component of the free heat gains available to a Passivhaus during the heating season. Large windows themselves become radiators for the room (Feist, 2012) to offset some of the energy required for heating. In addition, large windows provide a good daylight and pleasant view (psychological comfort) for occupants.

Conversely, large south glazing with the increased level of super insulation and air tightness in Passivhaus dwellings, alongside the potentially elevated summer temperature in the future, can lead to an overheating risk. There is a clear need to take overheating into serious consideration for the future development of Passivhaus. Excessive insulation may be beneficial for currently north European climates but might also cause problems in future climate projections, contradicting the most popular definition of sustainability from the Brundtland Report (1987), which stated:

“Sustainable development is a development that meets the needs of the present without compromising the ability of future […].” Providing Passivhaus standards may consequently lead to conflict with the policy recommendation in EU Legislation (EPBD article 4, 2010), which states: *"Member States shall take the necessary measures to ensure that minimum energy performance requirements for buildings are set […] These requirements shall take account of general indoor climate conditions, in order to avoid possible negative effects”*. To avoid the negative effects of using super insulation the design decision should be modified to avoid overheating in summers.

Summer thermal comfort is achieved in Passivhaus using “*Professional Planning*” introduced by the Passivhaus Institute (2014), which refers to environmental design strategies such as relevant orientation, shading, and ventilation to overcome summer overheating risk.

There are a number of design approaches to mitigating the risk of overheating in Passivhaus dwellings, such as shading devices, reflective surfaces, and thermal mass, that have received a good deal of research attention in Passivhaus design. The present study has investigated a less examined arrangement by which dwellings have geometric forms that make the south-facing façades self-shading. This study examines the potential benefits of using different self-shading façade geometries to reduce thermal discomfort in Passivhaus standard dwellings for current and future UK climate scenarios.

It should be mentioned that a new sets of Passivhaus criteria with a revised structure and a more comprehensive procedure was introduced in 2015 (Passivhaus Institute, 2015). The new criteria comes with three standards including;

i. Passive House (Passivahaus) Standard (Classic, Plus, and Premium class)
ii. EnerPHit Standard (for refurbishment)
iii. PHI Low Energy Building Standard

The new procedure is based on Primary Energy Renewable (PER), which evaluates the first two standards i.e. Passive House and EnerPHit. In fact, the requirement for PER demand replaces the primary energy demand (PE) of the old method i.e. the method used in this research ($Q_p \leq 120$ kWh/m^{2}a) which may continue to be used only for PHI Low Energy Building Standard and the 'Classic' class of the Passive House standard (for more information on the classes refer to (Passivhaus Institute, 2015)). Renewable energy generation plants are also included in the Passivhaus and EnerPHit Criteria for the 'Plus' and 'Premium' classes.

For the EnerPHit standard the climatic zones are very important; for instance, the U-values of the building envelope differs for different climatic zones. There are also different U-values assigned to interior and exterior insulation of the envelope's construction materials (for more data see Passivhaus Institute, 2015 Table 2, p. 8). The EnerPHit criteria also has a different threshold depending on the climate zone and the airtightness can go to up to 1.0 ach^{-1} at 50 Pa.

The new criteria also allow buildings which do not fully meet the Passivhaus Standards to qualify for PHI Low Energy Building Standard which requires less strict criteria. The new edition now also focuses more on the occupant satisfaction for instance, priority must be given to user-operation for any automatic system including lighting, temporary shading devices, heating, ventilation and cooling systems. It also requires that all rooms with prolonged occupancy must have at least one operable window. The spaces which are not continuously used also must have ventilation (mechanical).

Frequency of overheating remained as per the old criteria i.e. the indoor temperature exceeding 25°C should not exceed 10% of total hours in a given year, however, it is recommended that it preferably remain below 5%.

2.3.1 Assets and liabilities of super insulation

For the last few decades insulation has been the most dominant and frequently used energy intervention for a range of building types in the UK (examples of well-established low energy standards are presented in Table 2-2). Much of the focus on the new build and refurbishment in the UK to date has concentrated on thermal comfort during the winter and on the reduction of space heating. The obvious reason is that the heating period is the dominant spell of the year and the space heating has the largest energy use rate for housing stock. However, as suggested by UK Climate

Projections from the Metrological Office (Murphy, et al., 2010), the increase in extreme weather events, such as heat waves, calls to attention the need to study the cooling period as well. Nevertheless, energy efficiency mostly is misunderstood and confused with the term low energy consumption. Energy efficiency does not only refer to the reduction of energy demand. It also addresses the relationship between the resource and usage (Schumacher, et al., 2010).

Table 2-2 Examples of low-energy standards used in the UK

Standards	**Heating and cooling**	**Primary energy demand**	**Airtightness @ 50Pa**	**Thermal bridging, y-value**	**U-values Wall-Windows ($Wm^{-2}K$)**
FEES Part L 2013	39-46* $kWhm^{-2}$	NA	5.4 $m^3/hr/m^2$	0.05 $Wm^{-2}K$	0.18-1.4
Passivhaus	15 $kWhm^{-2}$	120 kWh/m^2	0.6 h^{-1}	0.0 $Wm^{-2}K$	0.15-0.8

*39 $kWhm^{-2}$ for apartments and mid terrace- 46 $kWhm^{-2}$ for semi-detached and detached houses.

"The most important influencing parameter for the annual heating demand which decides whether the Passive House standard is achieved or not (i.e. not exceeding 15 kWh/m^{2}yr) is the thermal protection of the opaque external building components, particularly that of the roof and external walls. Howeve], it is often assumed that increasing the level of thermal protection would lead to increased problems with overheating in summer" (Passivhaus Institute, 2014). In the thermal analysis of the Darmstadt-Kranichstein Passivhaus conducted by the Passivhaus Institute, it was found that the frequency of overheating increased in summer with improved insulation. A study from the organisation Zero Carbon Hub (Dengel & Swainson, 2012) has also showed that Passivhaus can have a greater problem losing heat in summer than other houses. Poorly insulated building components easier remove the internal heat load and excessive solar gain in summer. This assessment for Passivhaus was in the case of exhaust air operating only i.e. the summer ventilation as an exhaust system with an air change of 0.4 h^{-1} (Passivhaus Institute, 2014). This may produce lower thermal comfort in summer. However, a higher thermal comfort is achieved by a "practically-oriented" summer ventilation strategy. Studies (Gupta & Gregg, 2012; Porritt, et al., 2012; Lomas & Kane, 2013) addressed the benefit of external wall insulation for achieving thermal comfort in summer. Although the benefit of super

insulation is well established, there is still uncertainty about the dispersion of heat in super insulated dwellings in summer. Porritt, et al. (2012) pointed out that, unlike external insulation, internal wall insulation has little impact on the summer thermal comfort and overall energy performance of the building. It is believed that in some cases insulation will lead to an increase of internal temperatures. Some studies found that excessive insulation could lead to a lower air quality and high risk of summer overheating. Table 2-3 shows the impact of the insulation thickness on the thermal transmittance coefficient for external wall of the Darmstadt-Kranichstein Passivhaus. Within the context of a warming climate, understanding the behaviour of super insulation is crucial for an accurate assessment of the dwellings for thermal comfort. There are a few studies that analysed the optimum and adequate insulation for improving building thermal performance in summer e.g. (Ballarini & Corrado, 2012; Al-Khawaja, 2004).

Table 2-3 Thermal transmittance of different thickness of insulation panel used in Darmstadt-Kranichstein Passivhaus external wall

Insulation panel thickness (mm)	**Thermal Transmittance coefficient ($Wm^{-2}K$)**
300	0.126
175	0.209
100	0.342
50	0.598

2.3.2 Ventilation in super airtight Passivhaus dwellings

Air entering a building can be due to infiltration through, for example, cracks around windows and doors or air flow through purpose-made ventilation openings i.e. windows and vents (Szokolay, 2004). The Passivhaus structure reduces the amount of the infiltration significantly where the maximum amount of air passes through cracks can be as low as 0.2 ac h^{-1} at 50 Pascal. This means that, unlike conventional buildings, there is almost no air change when windows are closed. Nevertheless, a high ratio of windows in Passivhaus is fixed and cannot be opened.

Insulation is mostly considered as an intervention to reduce space-heating demand. These materials are more capable of retaining the heat due to their low thermal conductivity. Greater insulation will reduce the transfer of the heat from inside to the outside in summer time, which may cause overheating during warm days if windows are kept closed or if windows are fixed.

For a hotter climate, when outside temperature is much above the thermal comfort, high insulation would be very effective as the hot outside temperature would not enter the building through the fabric elements and if mechanical cooling devices are operating the cooled inside air would not escape and would be retained inside the dwelling. For a milder and cold climate, however, where summer outside temperatures would not vary much from the comfort temperature, cooling systems are not operating and so a higher level of insulation may lead to overheating if adequate ventilation is not in action and solar heat is not controlled. Ultimately, ventilation interventions are normally behavioural changes, which should be modified by occupants. Ideally, people should open their windows during the night on summer days to make use of thermal mass as a cooling effect. If they do not open the windows at night in summer, the house would not benefit from night purge ventilation and on the following day the house is overheated after a few hours of solar gain. For a two-story detached house, windows are less likely to be open at night due to privacy and security. Porritt (2012) and Liddament (2001) pointed out that windows are more likely to be open at upper floors.

To bring the fresh air into a very airtight building, Passivhaus uses controlled mechanical ventilation thorough a MVHR system previously introduced (section 2.1). Passivhaus typically allows 0.3 air changes per hour (approximately 8 ach per day) for a dwelling to provide air quality and efficient refreshing effect. It controls the amount of air out and in through intake and exhaust terminals to ensure enough sanitary air change. This system is more effective in wintertime as heat does not escape in an uncontrolled manner like conventional houses. However, people sometimes prefer to switch off the mechanical ventilation and get control over the ventilation manually, especially in summer. Some studies suggest that in certain cases internal air quality is affected due to the relatively low air exchange from mechanical ventilation.

A study carried out by McGilla, et al. (2014) investigated indoor air quality for three mid-terraced Passivhaus dwellings in the UK. The houses had the most relevant Passivhaus features i.e. airtightness of less than 0.6 h^{-1} (n50), large triple glazed windows (mostly fixed) on south facade, shutter or blinds as a main mechanism for shading, and consuming the maximum 15 kWh/m^2a of energy. All the occupants were happy with the space heating and the energy bills they received in winter. The indoor temperature remained within satisfactory levels for most of the time, especially in winter. However, a lack of understanding about the MVHR ventilation system, the filter replacement and the boost mode function by some occupants was reported. Some occupant complained about the noise of the mechanical ventilation (MVHR system) and the supply and extract terminals. All the occupants tended to open windows day and night during the summer months and two of them said the indoor temperature was “too warm” in summer. The maximum recommended carbon dioxide level (1000 ppm) was exceeded most of the time, especially in summer. Overall, the summer indoor air quality was not significantly fresh and satisfactory based on occupant interviews.

Ventilation should be provided not only to provide fresh air for the occupants, necessary to maintain acceptable air-quality levels, but also to have a direct effect on the occupant thermal comfort (Santamouris & Asimakopoulos, 2013). Szokolay (2004) refers to air movement as a sensible air velocity that can provide physiological cooling. Natural ventilation through the windows can have a direct effect on occupant wellbeing. It is argued that ventilation based on natural forces should always be used over mechanical ventilation in summer, which is possible without any additional costs.

2.3.3 Overheating concern and future performance of super insulated Passivhaus

In response to the frequently raised question of summer overheating in very airtight dwellings, the Passivhaus Institute declares *“as [experience] showed Passivhaus have a pleasant (cool) indoor air temperature even during hot periods. However, this requires professional planning”* i.e. oriented towards the south, temporary shading devices (motorized external blind), night time ventilation for locations where active cooling typically do not require for residential buildings (Passivhaus Institute, 2014).

However, as previously mentioned, Zero Carbon Hub (Dengel & Swainson, 2012) felt that *"there is a growing body of evidence that modern energy efficient, i.e. well insulated, airtight, dwellings are suffering from overheating, and that in some cases this is resulting in adverse health effects for the occupants of these properties."*

There are several studies highlighting the benefits of Passivhaus standards to be considered for future developments. People living in these houses reported excellent feedback on thermal comfort. However, they highlighted that they receive a better thermal comfort in winter than in summer (Mlecnik, et al., 2012; Larch House's tenants, 2012; McGilla, et al., 2014). In their monitoring study, Baborska-Narożny, et al. (2017) found widespread overheating, with 44% of bedrooms and 28% of Living rooms exceeding CIBSE threshold during occupied hours. The Technology Strategy Board's monitoring data (2014) of two Welsh Passivhaus dwellings revealed that passive houses in summer were warmer than average UK standards. It is argued that very airtight homes are at risk of summer overheating even in the current climate (Dengel & Swainson, 2012). Nevertheless, CIBSE's future weather files show that the UK will experience hotter and more extreme summers in the coming decades and the risk of buildings overheating may become very significant in future climate scenarios. It is believed that buildings with south-facing windows are prone to a higher cooling load as they receive more direct solar radiation in summer (Chow & Levermore, 2010). In this context, large south glazing, as one of the characteristics of Passivhaus, may eventually lead to overheating in summer time. Zero Carbon Hub (2010) analysed different locations in the UK using computer modelling and they found that high insulation levels and reduced air leakage, coupled with enhanced solar gain, decreased space heating and increasing summer discomfort.

Buildings, particularly dwellings, are designed to last for several decades. The future performance of the housing stock under a warming climate, therefore, needs to be considered to ensure the longevity of the housing stock (CIBSE TM36, 2005). The real concern is that the likely adaptation responses from the occupant to hotter summers would be the widespread installation of air conditioning for occupant comfort. Consequently, this would increase potential energy use through active cooling systems (Collins, et al., 2010). Use of mechanical comfort cooling systems will hamper efforts to reduce greenhouse gas emissions and limit climate change (CIBSE TM36, 2005).

2.4 Climate change

"Climate change is an important topic for building services engineers, resulting in the UK in the new, performance-based Building Regulations Part L" (Levermore, 2008b).

It is already a reality acknowledged by the worldwide scientific and political communities. A warming climate is wildly accepted as the most likely outcome of climate change (Nicol, et al., 2009; Barrow & Hulme, 1997). The UK Climate Programme change scenarios report (UKCP02) (Hulme, et al., 2002) indicated that the annual average temperature for the UK climate may rise by up to 5°C in this century, and even an optimistic scenario suggests the climate will most likely increase by 1.4°C by 2080. The report added that winters are expected to be wetter and summers drier. The Intergovernmental Panel on Climate Change (IPCC) also stated that even in the most optimistic projection the Earth would experience at least a 1.8°C global average surface warming by the end of the century (IPCC, 2007). Extreme weather events such as flooding and heat waves are predicted to become more frequent.

High summer temperatures because of heat wave strikes are predicted to be more frequent, like the one that hit London and some parts of Europe in 2003, which caused more than 35,000 deaths. The UK's Department of Health (Department of Health & Health Protection Agency, 2008) predicted that a similar heat wave with a high temperature up to 27°C could result in more than 3000 heat related fatalities in the UK. During the 2003 heat wave period, the centre of London was up to 10°C warmer than the surrounding area in greater London (Nickson, et al., 2011). Figure 2-1 shows schematically the difference in external temperatures from rural district to the urban centre (the impact of the urban heat island). The summer of 2003 suggests that hot summers are more likely to occur in future years (CIBSE TM48, 2009).

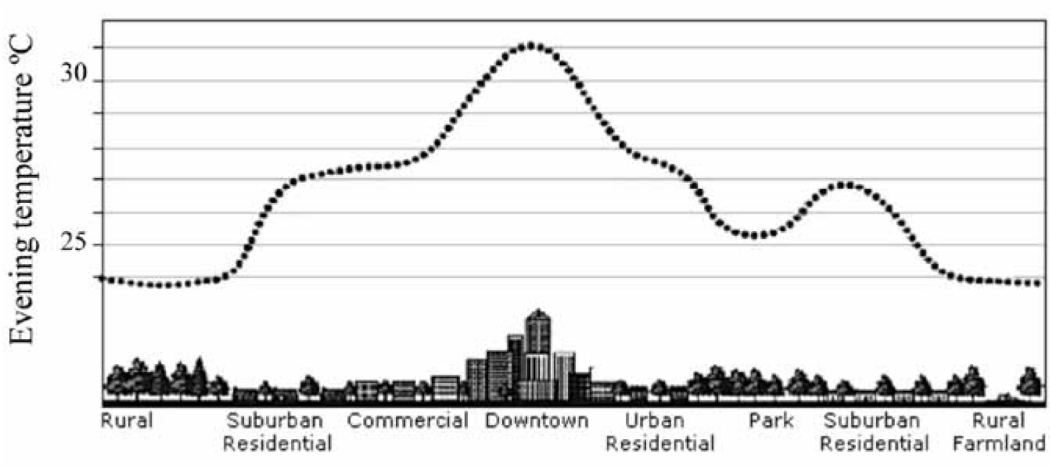


Figure 2-1 Urban heat island effect (Nickson, et al., 2011)

Data from UK Climate Projections (Murphy, et al., 2010) suggested that overheating is most likely to happen in the south east of the UK. Considering Greater London's climate, buildings are expected to be at high risk of overheating. In the context of the housing design, overheating would not necessarily result in more energy (electricity) consumption, but certainly in more human discomfort if no cooling equipment was provided.

Summer days at temperature higher than 27°C are expected to increase. The first three decades of the 21st century are predicted to experience a vulnerability period similar to the heat wave event of 2003. After 2030, however, the heat waves and days above 27°C temperature will increase, with the severity and intensity of heat wave events becoming more frequent and longer in duration after 2060 (Department of Health & Health Protection Agency, 2008).The 2003 heat wave lasted 12 days in London, with a maximum daily mean temperature of 29.3°C and absolute peaks of 37.4°C. Manchester experienced a 9-day heat wave period, with a maximum daily mean temperature of 25.4°C and a peak temperature of 32.1°C. Monitoring indoor temperatures at a variety of London dwellings during the August 2003 heat wave showed an average indoor temperature of 28.3°C, with the peak indoor temperature in a single room apartment reaching 39.2°C (Wright, et al., 2005). A London flat experienced a dangerous temperature of just below 38°C, which is higher than human core body temperature (37°C) (Lomas & Kane, 2013). The living room of one of the cases in Manchester reached 30°C and the bedroom exceeded 35°C.

In some European countries, heat waves have been more relevant than in the UK. In Italy, peak rates of electricity in the summer of 2006 were, for first time, higher than the energy consumption of the winter of the same year. The same event occurred in 2008, 2010 and 2011 (Caruso, et al., 2013). By the middle of the century UK heat waves are predicted to occur every three years (UKCP09, 2009). Johnson (2008) declared that by 2050 there would be more regular heat wave events similar to the 2003 heat wave. Eames, et al. (2011) predicted that a temperature like current heat wave events will be considered as relatively cool temperature by the 2080s. In these circumstances, high level of airtightness when natural ventilation is not adequate may accelerate the summer overheating. The risk of overheating in super insulated Passivhaus dwellings have been highlighted in a number of studies (Schmitt, et al., 2007; Isaksson & Karlson, 2006; Schnieders, 2009; Janson, 2010; Larsen & Jensen, 2011; McLeod, et al., 2013). A study in Sweden (Samuelson & Lüddeckens, 2009) showed that in the worst scenario – current climate, more than half of the Passivhaus dwellings experience warm indoor temperature during the summer time. These studies, mostly from northern Europe, emphasise the need for deeper investigation for UK Passivhaus dwellings since they have a relatively similar climate context. Nevertheless, current climate in south European countries can somehow represent the UK future climate. Building performance in current heat wave conditions also can be set as a performance benchmark for a typical summer condition in 2050s (Jentsch, et al., 2008).

Studies (Mavrogianni, et al., 2009; 2010; 2012; Wright, et al., 2005) have demonstrated that the London domestic building stock is likely to experience an increased risk of high temperatures during hot days of summer, especially under future climate probabilities. Mid-summer maximum temperatures in London are estimated to rise by up to 6.9°C above the 1961-1990 period (CIBSE TM36, 2005). CIBSE TM 36 shows the most frequent temperature for present climate condition in London is about 10°C while this number rises to about 12°C by the 2080s under a Medium-High emissions scenario.

Data from 1976 to 1996 in greater London showed that heat related mortality increased as external average daily temperature exceeded 19°C (Hajat, et al., 2002). The 2011 heat wave plan of the UK National Health Service (NHS, 2011) showed that an external temperature over 25°C led to an increase in heat-related deaths among elderly people and that women over 75 were especially at more at risk.

A warmer summer time is estimated to effect energy use patterns and comfort conditions of the UK dwellings throughout the century. In a hotter climate the risk of summer overheating intensifies. Zero Carbon Hub warned that newer homes built to satisfy a more demanding standard of energy efficiency might suffer in a warmer climate (Zero Carbon Hub, 2010). What is of concern in this study is the future performance of super insulated dwellings under a warming climate and to address to what extent will climate change increase overheating risk.

Chapter Three

3 Thermal Discomfort in Summer

Over the past few years much have been written on the risk of summertime overheating in UK dwellings, from studies that argued the risk of overheating is a major issue to studies regarding the risk as being marginal. Several studies used steady state or dynamic simulation modelling, ranking the overheating risk factors and examining the effect of urban heat island and probabilistic future weather scenarios. Most of these researchers made the effort to study the risk of overheating in low energy buildings. There is little monitored data from low energy housing in the UK (Ridley, et al., 2014; 2013). This makes the uncertainty over this issue even greater. Using highly insulated materials along with good basic design, providing comfortable condition has become relatively easy in the winter. With the current insulation standards, a challenge is to maintain the comfort in the summers without using any mechanical devices (Wright, et al., 2005).

3.1 Introduction

Overheating has been increasingly notable in new homes. The growing concern is a reflection on evidence that excessive heat degrades sleep and wellbeing among occupants. In the UK there is no universally agreed overheating criterion for residential buildings (CIBSE TM36, 2005). This is perhaps because in the UK the retention of heating has been the main focus of thermal design and so overheating has not historically been a concern (Lomas & Porritt, 2017). The definition of the term overheating is defined differently by different groups and it remains an area of uncertainty. Orme, et al. (2003) investigated overheating based on the definition that overheating occurred when indoor temperatures exceeded 27°C. Hacker, et al. (2005) set the absolute heat danger line to 35°C and indicated the “warm” and “hot” thermal discomfort threshold temperatures of 25 and 28°C respectively. Boardman, et al.

(2005) believed the risk of heart attack and stroke would increase as indoor temperatures exceeded 24°C.

Mavrogianni, et al. (2017) used maximum, minimum and mean temperature for living room and bedroom for overheating analysis (concerning the 28°C threshold for the living room and 26°C for bedroom). McGill, et al. (2017) used PHPP static criterion of 10% above 25°C and also CIBSE static criteria i.e. CIBSE Guide A 2006. They also looked at the adaptive criterion of CIBCE TM52 CatII, all three criteria, for living room only. Morgan, et al. (2017) analysed indoor temperature of the living room and the main bedroom based on the PHPP static criteria and also analysed percentage of average of whole house hourly temperatures over 25°C in each month. Baborska-Narożny, et al. (2017) used CIBSE static criteria of 1%/26°C bedrooms, 1%/28°C living rooms during occupied periods.

The Three Regions Climate Change Group (2008) recommended that indoor temperatures of 30°C and above must be avoided. Several studies are in agreement in some values, with 25°C seen as an acceptable warm and 28°C as unacceptable warm indoor temperatures underpinning the criteria for evaluating overheating risks.

The Housing Health and Safety Rating System from the Housing Act 2004 (Health and Safety Rating System , 2006) stated, "*a healthy indoor temperature is around 21 °C. As temperatures rise, thermal stress increases, initially triggering the body's defence mechanisms such as sweating. High temperatures can increase cardiovascular strain and trauma, and where 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*".

The English Housing Survey (2009), using the Standard Assessment Procedure (SAP), found 82% of dwellings were currently at "slight" risk of overheating assuming no adaptation strategies are taken. 41% were predicted to be at medium to high risk, but if the summer time temperature rose by 1.4°C then almost all properties (99%) were predicted to be at the medium to high level of vulnerability to overheating (SAP, 2010).

The UK Department of Health predicted that if a 9-day heat wave with an average temperature of 27°C occurred then it would result in over 3000 immediate heat-related deaths (Department of Health and the Health Protection Agency, 2008).

3.2 Definition of thermal discomfort and overheating according to British and International Standards

Thermal comfort is the pleasant environmental conditions that can provide ergonomic, physiological and psychological thermal performance for the human body. In this study, thermal comfort is the major criterion for assessing building performance. There are two ways of assessing summertime thermal comfort - static and adaptive – and these will be considered in the next section.

3.2.1 Static criteria (Steady state thermal comfort model)

a) CIBSE Guide A

Guide A from the Chartered Institution of Building Service Engineers (CIBSE Guide A, 2006; 2015) is widely used to assess thermal summer comfort in UK domestic sector (Lomas & Porritt, 2017; 2013; Mavrogianni, et al., 2017; Baborska-Narożny, et al., 2017). The Guide indicated two threshold temperatures to define warm discomfort indoor environment. A lower temperature threshold that defines the moment occupant will start to feel warm (25°C) and a higher threshold temperature predicting the moment occupants will start to feel hot (28°C for living room and 26°C for bedroom). It is pointed that to achieve thermal comfort temperature should not exceed 25°C for the living areas more than 5% of total occupied hours or/and should not exceed 28°C for the living room and 26°C for the bedroom more than 1% of total occupied hours (see Table 3-1).

Table 3-1 CIBSE “Guide A” overheating benchmark

Threshold	Living room	Bedroom	Criteria limit
Warm threshold	25°C	25°C	5% occupied hours over benchmark
Hot threshold	28°C	26°C	1% occupied hours over benchmark

CIBSE Guide A (2006) considered that the target comfort temperature for living rooms and bedrooms should be between 23 -25°C and in warm weather 25°C was acceptable. CIBSE 2006 defined the comfort temperature as the dry result temperature (DRT), which was based on a combination of air temperature and mean radiant temperature. However, Guide A 2006; 7th edition-issue 2, with corrections (2007) adopted operative temperature (Top; the average of mean radiant temperature and air temperature) as the indicator for comfort temperature, following the standards such as American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE, 2013) and European Standard (BS EN 15251, 2007). The definition of operative temperature excludes the influence of humidity. It is accepted that within the "comfort" range (say 20-26°C) humidity has a second order of importance (CIBSE Guide A , 2015). Although Relative Humidity (RH) can be a major factor to assess thermal comfort, especially for adaptive criteria, the CIBSE Guide A criteria do not consider RH as a primary key factor within thermal comfort for static criteria. In the Passivhaus criteria, also, the minimum humidity control only applies to warm humid climates and does not apply for cool-temperate climates. Furthermore, since this study focused on the reduction of unwanted solar gain to reduce temperature, the key factor for assessing the thermal comfort was taken as the Indoor Operative Temperature (Top). The shading strategy would not have much effect on the relative humidity.

The downside of CIBSE Guide A criteria is that there is no specific limitation or weight for the severity of overheating - for instance, one hour of 28.1°C and 1 hour of 32°C is considered as 1 hour above 28°C and the same level of overheating intensity.

CIBSE Guide A in the 2015 version refers to both static and adoptive criteria. It refers to a fixed definition of overheating and recommends that the operative temperature should not exceed 25°C for more than 5% and 28°C for more than 1% of occupied hours. It also refers to the CIBSE TM 52 (2013) which is based on the BS EN 15251 assessment and has a different approach (see adaptive criteria 3.2.2 section b). It regards that overheating in buildings that are free running has become an increasingly serious problem in Europe. A CIBSE-assembled group "Overheating Task Force" reconsidered the new approach to identifying the overheating of buildings. The method suggested the applicability of the categories and their associated acceptable temperature ranging from a high level of expectation (Category I), a normal expectation (Category II), a moderate expectation (Category III) , and outside criteria for a limited periods (Category IV). The aim was for new buildings and renovations to comply with category II.

CIBSE Guide A (2015) recommended that designers discuss the issue with client and choose the most appropriate approach. However, it also suggested that, regardless of any criteria, the internal operative temperature under free running conditions should never exceed 30°C.

b) Passivhaus Institute

The performance of a Passivhaus design is assessed using the Passive House Planning Package (PHPP). In the PHPP spreadsheets overheating hours are calculated for the occupied period when in the living areas (living room and bedrooms) temperatures exceed 25°C for more than 10% of the occupied hours (Feist, 2007). The kitchen is excluded because of the probability of miscalculation of overheating when catering equipment is being operated during occupied periods. Passivhaus tries to keep inside temperatures within the interval of 20 to 25°C during whole cycle of the year. There is a limit of 10% occupied hours having temperatures above 25°C. However, according to a revised PHPP (Passivhaus Institute, 2015) the overheating is "acceptable" for a Passivhaus if the indoor temperature of 25°C and above occurred only for 5-10% of the time i.e. if temperature during annual occupied hours do not exceed 25°C for more than 10% of the time then this means that the building complies with the Passivhaus criteria. However, Passivhaus regards a building as "excellent" only if the indoor temperature is above the threshold temperature for only 0-2% of time. PHPP defined overheating as "catastrophically unacceptable" if the indoor temperature of above 25°C occurs more than 15% of the time and "poor" if the warm temperature of 25°C occurs between 10-15% of the time in a given year (during annual occupied hours).

c) ASHRAE static criteria – Fanger

According to the American Society of Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE, 2013), thermal comfort is a state of mind which express satisfaction with the thermal environment. Satisfaction with the thermal environment in most cases has a similar condition, as the thermal environment is neutral (Fanger, 1982).

ASHRAE uses both steady state and adaptive models to predict thermal comfort. Static criteria employ the thermal sensation scale of Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) index. The PMV-PPD model (also known as the Fanger model) is based on a seven-point scale ranging from +3 (hot) to -3 (cold) i.e. +3 hot, +2 warm, +1 slightly warm, 0 neutral, -1 slightly cool, -2 cool, and -3 cold. The lowest discomfort (PPD) occurs when the PMV is at neutral point (0). The system uses heat balance equations and experimental studies for a wide range of parameters such as skin temperature, thermal complaints, clothing level, air speed, metabolism rate for calculating a combination of air temperature, mean radiant temperature and relative humidity to set a satisfied condition (thermal comfort), which is normally displayed on a psychrometric chart. It is widely used for design and thermal comfort assessment (ASHRAE, 2013). Experiments conducted by Fanger (1982) showed a slight adaptation to people preferring warmer or colder environments. Therefore, almost the same comfort conditions are applied regardless of the external air temperature.

ASHRAE also uses adaptive thermal comfort. Numerous studies (de Dear & Brager, 2001; Awbi, 2003a) have argued that people can adapt to changing condition in their environment. These researchers pointed that out that, contrary to the universality of the Fanger thermal model, cultural, climatic, social, and contextual aspects of comfort should not be ignored.

The use of fixed threshold temperature is an approach to establish the occurrence of overheating but cannot define severity of overheating (Nicol, et al., 2009). However, the adaptive method may be problematic because of the assumptions that occupants can adapt to the changing environment regardless of their physical conditions (Anderson, et al., 2013).

3.2.2 Adaptive thermal comfort

Adaptive thermal comfort was developed based on the hypothesis that people in different climate zones prefer different indoor temperatures (de Dear & Brager, 1998), contrary to the static thermal models addressed earlier, including CIBSE Guide A, Fanger and Passivhaus definitions, adaptive thermal models include individual adaptation to changing temperatures.

Static criteria (mentioned earlier) mean that the threshold temperatures above which overheating is considered do not adjust based to the changes in ambient temperature. However, assessing thermal comfort based on the static criteria allows researchers to focus and measure one specific parameter but, in reality, individuals will also adapt their behaviour to changing temperatures, such as controlling ventilation by opening or closing windows, creating more or less shading by curtains and blinds, drinking cold or hot beverages or wearing more or less clothing and being less or more active. A more comprehensive explanation is that people will acclimatize themselves. Therefore, adaptive thermal criteria may be more appropriate to assess future thermal conditions in homes. Some of the static comfort assumptions have tended to require energy-intensive environmental control to optimise the thermal acceptability of indoor environments. However, using adaptive thermal comfort could lead to significant energy savings. Dissatisfaction with static comfort temperature has promoted the focus on the adaptive comfort temperature where the outdoor temperature is believed to have a clear effect on the indoor comfort (de Dear & Brager, 2001). Adaptive thermal comfort also gives more accurate predictions for a naturally ventilated building (Brager & de Dear, 1998; de Dear, et al., 1991).

Also, there is an argument that the adaptive criteria of overheating were devised primarily from field studies of office workers and it is believed by some research that it should not be used to assess bedroom overheating. Zero Carbon Hub (ZCH, 2016) advises that while the adaptive approach can be used to assess field studies of office and living room, however, it suggests that the fixed 1% over 26°C criteria should be used for bedroom because adaptive analysis cannot be exercised without sleep disruption.

a) ASHRAE

An ASHRAE sponsored study (de Dear & Brager, 1998) developed adaptive models for free running buildings i.e. no heating and cooling required for winter and summer. Figure 3-1 shows the adaptive comfort standard for buildings with naturally ventilated spaces.

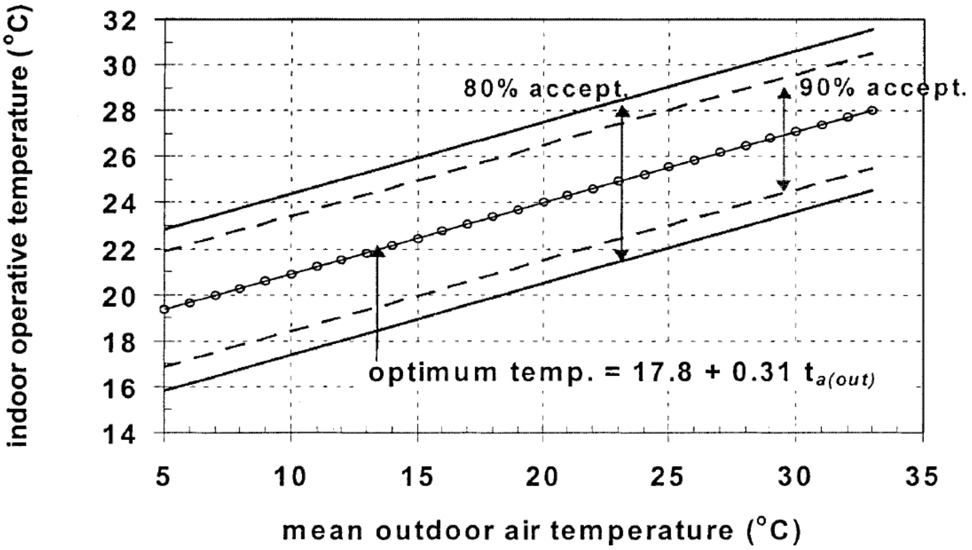


Figure 3-1 The adaptive comfort standards for naturally ventilated building (de Dear & Brager, 2001)

The study suggested the following equation (see Equation 3-1) for climates and buildings where cooling and heating are not required. For the UK summer climate, therefore, the model can be used to estimate the optimum indoor operative temperature based on the mean outdoor temperature. An extended study of the same research (de Dear & Brager, 2001) which carried on the analysis on the ASHRAE RP-884 project re-analysed the database of (de Dear & Brager, 1998) and set out to explain the adaptive model in more metrological terms, producing Equation 3-2 as the method of assessing the thermal comfort.

$$t_{oc} = 18.9 + 0.225\ \mathrm{t_{out}}$$

Equation 3-1 (de Dear & Brager, 1998)

$$t_{oc} = 17.8 + 0.31\ \mathrm{t_{out}}$$

Equation 3-2 (de Dear & Brager, 2001) where $\mathrm{t_{oc}}$ is the operative comfort temperature for naturally ventilated buildings and $\mathrm{t_{out}}$ is the mean outdoor air temperature.

The adaptive model indicates that for naturally ventilated buildings in various climate zones the preferred temperature increases by approximately one degree Celsius for every three-degree increase in mean monthly outdoor air temperature. The later adaptive comfort standard assessment (de Dear & Brager, 2001) comes fairly close to earlier attempts by Auliciems (Auliciems, 1983) (Equation 3-3) with the same coefficient of 0.31 found in the later study of ASHRAE (Dengel & Swainson, 2012) but the y-intercept of 17.6 was negligible cooler value by 0.2°C.

$$t_{oc} = 17.6 + 0.31\ \mathrm{t_{out}}$$

Equation 3-3 (Auliciems, 1983)

The later assessment was based on a more diverse set of building types. Although this study mainly used CIBSE Guide A static criteria, an attempt was made using methodology presented in De Dear and Brager (2001) to assess the adaptive thermal comfort in future weather scenarios (results are presented in Chapter Seven, section 7.5.2).

Figure 3-2 depicts the adaptive comfort temperature in naturally ventilated spaces. The upper and lower limit of the 90% and 80% acceptability comfort are 2.5°C and 3.5°C on either side of the optimum temperature respectively as follows: (de Dear & Brager, 2001).

$\text{Upper 80\% acceptable limit}\ \mathrm{t_{oc}} = (17.8 + 3.5) + 0.31\ \mathrm{t_{out}}$

$\text{Upper 90\% acceptable limit}\ \mathrm{t_{oc}} = (17.8 + 2.5) + 0.31\ \mathrm{t_{out}}$

$\text{Lower 80\% acceptable limit}\ \mathrm{t_{oc}} = (17.8 - 3.5) + 0.31\ \mathrm{t_{out}}$

$\text{Lower 90\% acceptable limit}\ \mathrm{t_{oc}} = (17.8 - 2.5) + 0.31\ \mathrm{t_{out}}$

The model is restricted to the extreme outdoor temperature rate. The linear trend of the model flattens when the mean monthly outdoor temperature is warmer than 32°C or cooler than 5°C (Figure 3-2).

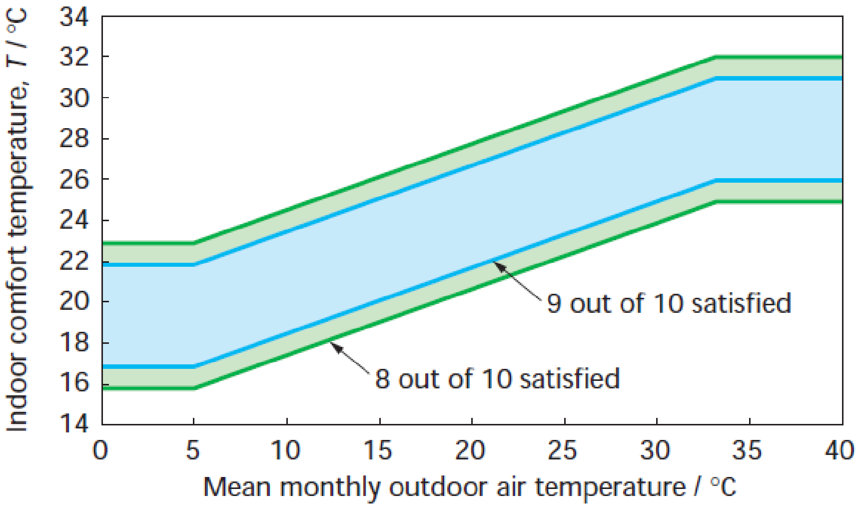


Figure 3-2 Adaptive thermal model (after ASHRAE 2013)

b) BS EN 15251 and TM52

British Standards European Norm (BSEN) 15251 (2007) defines the summer building comfort temperature in a free running mode based on the running mean of the outdoor temperature (T_{rm}) as seen in Equation 3-4.

$$T_{comf} \quad = \ 0.33\, T_{rm} + 18.8$$

Equation 3-4

where T_{comf} is the comfort temperature and T_{rm} is the mean outdoor temperature.

According to BSEN 15251, for a normal level of expectation (Class II building) the severity of overheating is defined based on the following criteria, where:

(i) Operative temperature does not exceed the comfortable temperature limit (Equation 3-4) by 1°C for more than 3% of the total occupied hours or 40 hours during summer.

(ii) The sum of the Weighted exceedance (We) should be less than 10 in a given day.

(iii) Operative temperature at any time should not exceed the threshold upper limit temperature (T_{upp}).

For class II building the maximum temperature (Tmax) and upper limit temperature (Tupp) are defined as indoor temperature being respectively 4 and 7°C higher than comfort temperature. A building is considered to have an acceptable level of overheating if it passes a minimum of two out of the three abovementioned criteria.

CIBSE TM52 (2013) which used the same methodology presented in BS EN 15251, suggested the following temperature ranges:

Upper limit $T_{max}\ (°\mathrm{C}) = 0.33\ \mathrm{T_{rm}}\ + 18.8 + K$

Lower limit $T_{max}\ (°\mathrm{C}) = 0.33\ \mathrm{T_{rm}}\ + 18.8 - K$

The suggested acceptable range (K) depends on four categories which indicates the level of expectation as fowwlows:

Category I (high level of expectation); $K = 2$
Category II (normal level of expectation); $K = 3$
Category III (moderate level of expectation); $K = 4$
Category IV (value outside criteria for limited time); $K = 5$
For a given category, a building or a room should pass two of the three criteria below:

Criterion 1: Number of hours $(\mathrm{H_e})$ that $\Delta T \geq 1\ \mathrm{K}$, should not exceed 3% of occupied hours between 1 May to 30 September.

Criterion 2 (severity of overheating): Daily limit for weighted exceedance $W_e \leq 6$ degree-hours (refer to TM52 (2013) p. 14 for more information)

Criterion 3 (upper limit temperature): absolute maximum temperature difference (ΔT) of $4\ \mathrm{K}$.

c) Standard Assessment Procedure

The Standard Assessment Procedure (SAP 2009, Appendix P) considers that when the threshold temperature is lower than 20.5°C then the risk of high summer internal temperatures is small. However, when the threshold temperature lies between 20.5-23.5°C the chance of high internal temperatures is slight to medium. When the threshold temperature exceeds 23.5°C the likelihood of overheating temperature becomes significant. Passivhaus tries to achieve a threshold temperature of 20°C.

Threshold temperature is calculated using Equation 3-5 to estimate the high summer internal temperature rate (SAP, 2010).

$$T_{threshold} = T_e^{summer} + \frac{G}{H} + \Delta T_{mass}$$

Equation 3-5

where T_e^{summer} is the external summer temperature (°C), G is the summer gains (W), and it is found by adding the summer solar gain (see Equation 3-7) and internal gain i.e. human metabolic, cooking, water heating and appliance use. H is the heat loss factor ($Wm^{-2}K$) which is the sum of the ventilation (see Equation 3-9) and fabric heat loss (not significant for a Passivhaus) and ΔT_{mass} indicates the thermal mass parameter (TMP) and it is defined as per Equation 3-6 - see SAP 2009 (2010) Table 1e for further details.

$$\begin{aligned} \Delta T_{mass} &= 2 - 0.007 \times TMP \qquad if\ TMP < 285 \\ \Delta T_{mass} &= 0 \qquad\qquad\qquad\quad\ \ if\ TMP \geq 285 \end{aligned}$$

Equation 3-6

3.2.3 Psychological comfort

ASHRAE suggest that human thermal adaptation is comprised of three distinct yet interrelated adaptive processes: behavioural, physiological (acclimatisation), and psychological (shifting expectations) (de Dear, et al., 1997). However, psychological comfort can also be described as wellbeing experienced by individuals. It can also concern other needs which are more complex and produced by environments and life styles (Pineau, 1982).

Apart from physiological comfort addressed above, psychological comfort is also very important in the modern society. In some cases, even successful applications of physiological comfort may experience an uncomfortable psychological condition. For instance, fixed windows may be useful in reducing energy consumption but will leave occupants psychologically uncomfortable. Controlled blinds can also bring an uncomfortable feeling for occupants – it has been reported in many cases that people switch off the automatic systems and prefer to use them it manually. Small windows, in contrast to large glazing, can bring uncomfortable feeling for occupants. They may reduce heat loss in winter and heat gain in summer but they are not ideal for providing psychological comfort. Also, reducing summer solar gain does not necessarily improve wellbeing. For example, a lack of sunlight and daylight in homes can lead to depression. Light intensity, direction, spatial and polar distribution, creation of light and shadow and the spectral composition can have an influential impact on human physiological and psychological wellbeing. This should be realized and recognized as part of the indoor comfort condition as a comfortable visual environment (Gugliermetti & Bisegna, 2006). The balance between receiving daylight and sunlight should be always considered from both energy and environmental perspectives.

Comfort psychological conditions can be achieved by window ventilation in some cases. The human body produces heat by metabolic processes. This heat must be dissipated to provide a comfortable feeling. Air flow can provide direct comfort and prevent discomfort due to wetted skin, which called health ventilation (Szokolay, 2004). Mechanical ventilation and heat recovery (MVHR) systems are designed to avoid uncontrolled ventilation. However, the psychological comfort of air velocity via windows is beneficial to dissipate heat from the skin.

3.3 Interventions towards overheating

Adapting to the negative impacts of climate change is becoming as important as mitigating the climate change itself (Gupta & Gregg, 2012; DCLG, 2010). Thus, the mitigation and adaptation are considered jointly as one attempt to overcome the negative impact of the climate hazard and its effect on people's wellbeing. A range of single and combined strategies or interventions may need to be used to eliminate discomfort overheating for current and future hot periods. The term ‘intervention’ covers a variety of actions on either buildings or occupants. Modifying building fabrics, additional physical changes to the building envelope, and behavioural changes of occupant all encompass three main strategies to tackle overheating - including insulation and thermal mass, solar control, and natural ventilation. Adjustments to solar shading, insulation and ventilation are believed to be the most effective interventions to mitigate summer overheating.

Findings from CIBSE indicate that domestic buildings in England are incapable of coping with climate change, and some are already failing to meet basic comfort criteria (CIBSE TM36, 2005). Therefore, it is important to develop carefully the housing sector to be compatible and adaptable for future weather projections. Part "L" of the UK's Building Regulations requires every new home in England to be assessed for potential overheating risk.

CIBSE TM36 used 4 terms to identify adaptation towards overheating: 1) switch off- which refers to reducing heat gain through controlling solar irradiation. 2) Absorb - to benefit from absorbing cool air (night) via higher thermal mass. 3) Blow away - intelligent ventilation such as night pure ventilation and window closing in peak hot hours. 4) Cool - which refers to use mechanical cooling system under future climate which might be inevitable for some buildings. For adaptation to overheating - in common with TM36 – Three Regions Climate Change Group (2008) also refers to the passive measure consisting reduction of internal heat gains, enhancing natural ventilation and reducing solar gain through windows.

Previous studies investigated the alternative passive interventions that can be used to reduce overheating during warm periods. Passive interventions, which by definition would not directly consume energy and, therefore, produce no extra carbon dioxide emissions, have been historically used in vernacular architecture and some have been integrated to modern building design.

The Energy Saving Trust Guide (2005) suggested appropriate design strategies to help reducing overheating in dwellings. These includes careful orientation of buildings and windows, and the best use of thermal mass in building. It also suggested adopting strategies such as:

- Orientating the building away from south will increase the amount of overheating and reduce winter solar gain when the building is rotated toward west
- Having no large west facing openings

- Protecting south facing windows
- Using overhanging eaves
- Setting back the facade to provide different degrees of shading
- Using overhangs and balconies

Further passive strategies to reduce overheating risk including conventional cross ventilation, night purge ventilation, thermal mass, and mechanical options i.e. MVHR systems. Table 3-2 summarises a list of different interventions in reducing overheating rate, the reference studies and the result of using that intervention.

Table 3-2 Review of literature involved in, but not limited to, passive interventions for reducing overheating in UK

Intervention	Source	Comments and Results
External Wall insulation	(Gupta & Gregg, 2012)	For 2030's: 31% reduction in overheating hours For 2050's: 21% reduction in overheating hours For 2080's: 4% reduction in overheating hours
	(Porritt, et al., 2012)	Reduction of overheating up to 51% for a south facing end terrace bedroom (with second wall east-facing)
Internal Wall insulation	(Porritt, et al., 2012)	Little reduction of overheating
Loft insulation	(Lomas & Kane, 2013)	Homes with loft insulation were cooler during summer
Increased thermal mass	(Gupta & Gregg, 2012), (Hacker, et al., 2008)	Best result when thermal mass is ventilated at night
Exposure on interior surfaces	(Peacock, et al., 2010)	Reduction of temperature swings Solid masonry wall homes had a better summer thermal comfort than lightweight dwellings
Light coloured coating (exterior)/ high albedo surface	(Givoni, 1998)	Absorptivity of a dark tile falls from a range of 0.89 to 0.3 for a white washed roof or wall Reduction of up to 3°C in peak indoor temperature (for Rome and Nice location)

	(Synnefa, et al., 2007)	8% decreasing in cooling load (Rome)
	(Porritt, et al., 2012)	Generally up to 20% reduction in overheating
External window blinds	(Porritt, et al., 2012)	Up to 39% reduction of overheating*
	(Steemers & Yun, 2009)	Window Blind Position, have a significant impact of cooling load
Louvered shading	(Gupta & Gregg, 2012)	For current climate: 100% of percentage reduction in overheating hours For 2030's and 2050s: 53% reduction in overheating hours For 2080's: 29% of percentage reduction in overheating hours
Window shutters		Roller shutters limited operation on windows opening outwards, and led to restriction on view outside
	(Porritt, et al., 2012)	For south and west-facing living rooms reduction of overheating by up to 71%
Internal window blinds		Less effective because much of the solar radiation is entered
Curtains		Heat gain will be trapped between the curtain and the glazing
Automatically controlled shading system	(Grynning, et al., 2014)	Wrong time shading increased energy demand
Solar reflective glazing and reflective screen	(Piccolo & Simone, 2009)	Electrochromic (EC) glazing Low E triple glazing
	(Bennet, et al., 2014)	13% cooling reduction by switching non-reflective blinds to interior reflective screens

* (Porritt, 2012) used high reflectivity blinds from DesignBuilder ready used database and set the schedule to closing the blind from 0900 to 1800. However, in reality this straight forward operation is less likely to function.

3.3.1 Fixed shading device – overhangs

Historically, protection from the sun and introducing fresh air have been two of the fundamental aspects of Architecture to provide comfort to inhabitants. According to BRE Building Technology Group (Dengel & Swainson, 2012), overheating may become an issue in airtight houses with little or no solar shading. Preventing excessive heat gain and providing natural ventilation are important tools in passive houses to enhance air quality and refresh building's mass.

The Passivhaus Institute (Passipedia, 2014) declared that overheating in residential buildings during the summer is mainly caused by high solar gains. Monitoring results from the Camden Passivhaus showed that summer overheating occurred between 3.00-7.00 pm, with the maximum at 5.00 pm (Ridley, et al., 2013), suggesting that the overheating happened perhaps due to the unnecessary solar gain.

Research (Gupta & Gregg, 2012; Defra, 2010; Laouadi, 2010) showed that shading proved to be the most effective single intervention for adapting homes for the future warming climate. Porritt, et al. (2012) examined a range of window shading interventions in London to observe the effect of the solar control interventions on summer thermal control. The effect of the overhang size was considered on the south, east, and west-facing windows. An overhang of the 1m depth (horizontal from the wall) was found to block most of the summer solar radiation for south-facing windows while still to be practical for collecting solar gain in winter. For east and west-facing windows a 2m overhang was effective in blocking the solar radiation. Tillson, et al. (2013) predicted that the overheating vulnerability of the housing stock without shading device would decrease from 75% to 42% if an overhang of about 1.3 m was added to the external glazing. Research (Encinas, 2012; SAP, 2010) used Equation 3-7 to calculate solar gain for the summer months. The building physics model behind this calculation is the same as for the major calculation programmes such as EnergyPlus. However, the difference between the static and dynamic models of calculations is that dynamic models perform at much more frequent time intervals. For instance, they calculate the effect of the thermal mass over the course of the day and night (hourly or sub-hourly intervals).

$$G_{Solar}^{summer} = \sum(0.9 \times A_W \times S \times g_\perp \times FF \times Z_{summer})$$

Equation 3-7

The constant 0.9 in Equation 3-7 is the ratio factor of average transmittance at normal incidence. A_W is the glazed area (m^2), S is the solar flux (radiation) on a glazing surface (Wm^{-2}), which depends on the latitude of the dwelling's region (see Table 6a in SAP, 2009 for London latitude), g is the total solar energy transmittance factor of the glazing, FF is the glazing frame factor and Z_{summer} is the summer solar access factor, which depends on the shading and is calculated according to Equation 3-8.

$$Z_{summer} = Z_{blinds}\,(Z + Z_{shading\ obstruction} - 1)$$

Equation 3-8

When energy savings are evaluated in relation to the use of shading devices and shading strategies the most significant parameters that should be taken into consideration include climate, geometrical characteristic of shadings and building envelope, the thermal transmittance of building component, and orientation. The professional planning addressed earlier, for instance, fixed balcony and roof overhangs above south-oriented glazing, can considerably reduce the solar heat gain in summer. With obstacles over the glazing area, reduction of heat gain will happen in both summer and winter. However, with the Passivhaus levels of insulation the heating demand will not significantly increase if the form and dimensions of the obstruction are correctly calculated according to the building location. For instance, the depth of an overhang [or angle of the self-shading facades] and the number of blades for louver are crucial for the energy performance in both summer and winter (Bellia, et al., 2013). The energy saving potential considered in a study (Bellia, et al., 2013) for three different cities in Italy, was found to be greater in the climate with warmer summers. However, it was observed that the overall annual energy demand was reduced when using shading device for all three climates.

Figure 3-3 from the Passivhaus Institute presents the effect of fixed shading elements on annual heating demand (Q_H) and overheating frequency (h_ϑ>25˚C) for the first Passivhaus building i.e. the Darmstadt-Kranichstein Passivhaus. Balconies overhangs were located on the south facade at a height of 0.59 m above the glazing edge. The curves in Figure 3.3 demonstrate that fixed shading had a notable impact on overheating frequency (h_{ϑ}). Also, the heating demand increased as the overhang grew horizontally. An overhang or a balcony of 1.5 m will dramatically drop the overheating rate from 26% down to 6% for the Darmstadt climate. The shading element will have a marginal impact as they increase beyond 2m. For this case the favourable length of the shading element is about 1.3m in order to effectively decrease the overheating frequency without a dramatic increase in heating demand. To additionally reduce overheating external blinds need to be operating in the summer time.

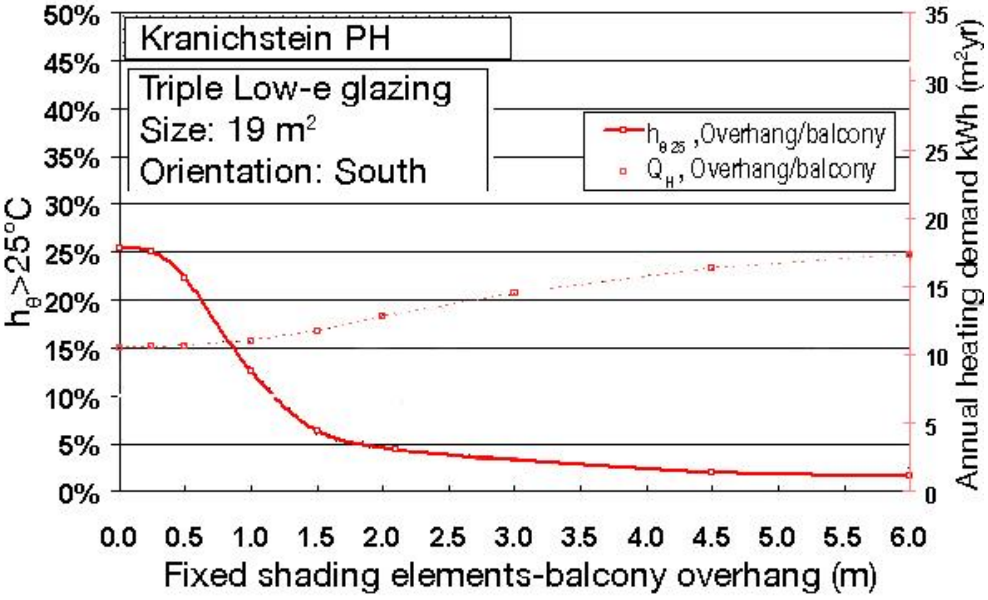


Figure 3-3 The influence of balconies/overhang on overheating and heating demand (Passipedia, 2014)

Although overhangs are one of the most effective interventions towards overheating, there are some consequences of having them on the façade of the building. Shading systems over glazing area will lead to a reduction in natural daylight and consequently increase in energy consumption needed for artificial lighting. They can also be solid objects that block air flow. According to an experimental study (Argiriou, et al., 2002) on the impact of the shading device on natural ventilation of a single-sided opening, it was found that attached shading devices would reduce ventilation rate by 30-50% compared to the opening without the shading device. Szokolay (2004) also regards that inlet opening accessories, such as shading devises outside of the opening before the air enters, will affect the direction of the indoor air stream.

3.3.2 Inside/outside roller blinds

Larger south facing windows lead to two conflicting objectives - reducing heating demand and increasing overheating risk (Porritt, et al., 2011). Research showed that the operation of blinds is mainly due to privacy or adjusting the view. A survey (Pigg, et al., 1996) showed 43% of the participants preferred to close their blind to reduce the direct light, and 37% closed them to reduce glare (more information on blind operation is given in section 3.3.7- occupant behaviour). It is necessary to assimilate shading strategies to mitigate overheating risk. In Passivhaus buildings internal or external blinds mostly control shading; however, this requires occupant attention and understanding. Figure 3-4 from the Passivhaus Institute shows that the building with external thermal insulation and no temporary shading device is at a slight risk of overheating. The overheating is eradicated if the external roller blinds are in operation. However, internal devices/blinds are not the most suitable option as they are not effective to control excess solar radiation before it hits the glass. In fact, the air will be trapped in between the inner surface of the window and the blind meaning the warm air is already inside the building. The data from the Darmstadt-Kranichstein Passivhaus showed that there was a significant difference when installing the roller blind outside the windows or between window panes. The frequency of overheating events ($h_{\vartheta>25^{\circ}C}$) dropped from 10.8% for the building with no blinds to 6.8% for internal blinds and dramatically dropped to 0.4% for external blinds.

Figure 3-4 The influence of temporary shading device on overheating (Passipedia, 2014)

The most influential problem that caused overheating in the Larch House case study was the operation of roller blinds (Technology Strategy Board, 2014). The Larch House PHPP analysis of overheating in summer (Newman, 2012) showed the overheating frequency would be 42% according to the Passivhaus definition (section 3.2.1b) without the external blinds, while this number reduced radically to 6% with external blinds operating. However, this analysis assumed that the occupants used the blinds to their best performance. What is not calculated in these statistics is the potential non-optimal use of the blinds by occupants. If the occupants used the blinds to only 70%-80% efficiency, then this would change the overheating frequency adversely.

In the Larch House, external automatic retractable blinds were fitted to the large south facing windows to avoid overheating in summer (Figure 3-5). A solar system was installed to lower the blind when there was sunshine to avoid relying exclusively on the occupants remembering to operate the blind. However, the report for the Technology Strategy Board (2014) stated "*Unfortunately, the solar sensor does not differentiate between summer and winter sun as expected at the design stage*". For this reason, tenants of the Larch House said *"the external blinds automatic function had at their request been disabled* (a point also on psychological comfort addressed in section 3.2.3). *This had been requested by the tenants due to the simplistic programming software in the blinds which, contrary to specification, were previously* *closing the blinds automatically when there was any sunshine, reducing the beneficial winter solar gains. Manual control of the blinds enabled the tenants to leave the blinds open in winter to enjoy the warming benefits of winter sunshine"* (Technology Strategy Board, 2014).

Figure 3-5 Larch House external blinds

Amongst internal window coverings, light coloured roller blinds and curtains were found to be relatively the most effective when different coloured curtain and venetian blinds were tested (SAP, 2010). However, the blinds with the darker colour were found to have a very small reduction in heating risk as lighter colours have a higher albedo. Curtain and blinds will block direct sunlight but will transmit the heat absorbed from the sun and affect the indoor temperature. The roller blinds' transmittance will reduce noticeably if they are installed outside of the window, yet they will still transmit some of the absorbed heat.

3.3.3 Reducing Window to Wall Ratio (WWR)

According to the Passivhaus Institute, the frequency of overheating increases sharply with a glazing area window to wall ratio of more than 20%. In the case of a window to wall ratio of less than 14%, the indoor temperature of a Passivhaus would not reach to 25°C even on warm summer days. However, larger windows are recommended for useful solar gain, daylight utilization, and enhanced natural ventilation and for a better view (Schneider, 2006).

A study at the Lighting Research Centre, Rensselaer Polytechnic Institute (Boyce, et al., 2003) demonstrated that people were finding the space more attractive if the indoor space received sufficient (plenty) daylight. A better view to outside highlight a more pleasant mood and a better well-being. Sufficient daylight have a positive perception of the space and on the mood. It helps to suppress melatonin and better circadian efficiency resulting in a better sleep quality and less fatigue. Results from the survey carried by (Aries, et al., 2010) showed that the view from the window was a very important factor to reach a satisfying level of comfort. However, the close distance to the window caused glare problems. It is scientifically proven that windows provide better health conditions. Viewing through glazing showed a positive physiological effect on people recovering from illness (Ulrich, 1984). A study by Küller and Lindsten (1992) showed windows improved the psychological conditions for children while studying, and it also improved work productivity for adults (Leslie, 2003).

The summer time analysis of the Kranichstein Passivhaus (Passipedia, 2014) revealed that in residential buildings possible overheating in summer is mainly because of *"too much"* high solar gain from glazing, but that this can be resolved with simple components of shading. Traditionally, passive house buildings in Europe used more than 50% of the wall area for glazing on the south façade, with important spaces e.g. living room, dining room and main bedroom designed to get most of the daylighting and pleasant view out. However, some new Passivhaus designs decided to reduce the south glazing to 25-30%. The design team of the Larch House (bere:architects) declared that a second Passivhaus next to the Larch House (Lime House) was designed using a 20% south glazed area, and was constructed using the lessons from the Larch House, aiming to reduce the peak heat load and cost associated with the large window and blinds (Ridley, et al., 2014). The Larch House had a 55% south glazed area, which was later described by the design team as oversized (Bere, 2014).

An investigation on the optimum window size and natural ventilation (Wright, et al., 1999) showed that, with external shading, blinds and night ventilation, a higher glazing ratio can achieve summertime comfort. For instance, in south east England, by implementing a 2m overhang to the design of a modern office building, in addition to blinds and a night ventilation rate of 6 air change per hour, the window to wall ratio for an office building (except north façade) can reach to 40% and ensure the condition to remain within the comfort level. It was found that a higher WWR required a higher ventilation rate to balance the amount of solar heat gain with heat loss through the windows. Orientation of the main facade with the most glazing is ideally to be towards the south, with the least possible deviation (maximum $\phi= \pm30°$). Other orientations would noticeably increase the overheating events.

3.3.4 Insulation and thermal mass

The work in collaboration with different disciplinary researchers at University College London (UCL) (Tillson, et al., 2013; Mavrogianni, et al., 2012; 2010), concerned that the issue of *"increased level of insulation and airtightness in dwellings as part of the CO_2 reduction target on summer time overheating level"*- needs to be reassessed. In broad term, it was found that insulation helped to reduce overheating and in some case, it led to an increase of internal temperature. Internal solid insulation may result to a higher indoor temperature if night time ventilation (purge cooling) is not provided. The study however regarded future study need to investigate the combined effect of insulation and thermal mass.

A study at Southampton University (James, et al., 2005) showed that annual space-heating load reduced from 130 to 30 kWhm^{-2} by replacing single glazing with e-low double glazing. However, the upper limit temperature (i.e. 27°C) doubled in south-west offices as a consequence of this refurbishment. Assuming the above-mentioned refurbishment, if a conventional A.C system were to be used to eliminate the secondary problem created by the refurbishment, this would create an additional 22 kWhm^{-2} cooling load (James, et al., 2005). This means that the approximate 100 kWhm^{-2}/yr energy saved in the first solution would decrease to 78 kWhm^{-2} /yr to offset the cooling load required. This also should be mentioned that there will be a risk of overusing and adapting to the mechanical cooling system because it would be accessible to use.

Two interesting pronounced outcomes from Tillson, et al. (2013) and SAP (2010) showed that building before 1930 are less likely to experience high temperature because of their solid wall constructions and those with cavity wall constructions (post 1930) were found to be more vulnerable to a higher summer temperature. All the dwellings built after 1983 – when Building Regulations suggested a higher level of insulation, were found to be at least at slight risk of overheating in the current climate. The research concluded the vulnerability to overheating varies with age and type of the building (Tillson, et al., 2013). Older buildings were found to be less vulnerable to overheating since they were built with more traditional materials like stone and brick with a higher thermal mass, which will moderate outside temperature due to their high heat capacity. It was also found that less insulated houses were easier to remove the heat. From Equation 3-5 (section 3.2.2) also it is clear that thermal mass plays a major role on internal temperature. A higher thermal mass i.e. materials with high heat capacity will have a lower threshold temperature as they moderate the high external temperature because of their capacity for thermal storage. The report from Standard Assessment Procedure (SAP, 2010) regarded that over 90% of the housing stock would be at risk of overheating if the thermal mass is lower than 50 kJ/m^{2}K. A higher thermal mass will constantly reduce the vulnerability risk to the point where the Thermal Mass Parameter (TMP) is equal to 285 kJ/m^{2}K. However, no further benefit was found if the thermal mass was higher than this (see Equation 3-6).

Research (AL-Turki & Zaki, 1991) also studied the effect of thermal insulation in hot climate. They used layers of insulation with the purpose of reducing cooling load for a conventional building. The insulation was found to be practical especially on the outer surfaces in reducing the average and peak cooling rate.

Overall, research on the insulation agreed that a certain amount of insulation is very effective in reducing heating and cooling load for both cold and hot climates. However, the uncertainty remains on the effect of super insulation on reducing overheating load in a temperate climate.

3.3.5 Enhancing natural ventilation

Natural ventilation is a deliberate attempt to provide air flow to a building through designed openings using natural wind and buoyancy forces. During recent decades natural ventilation has become a focus of researchers' attention as a single intervention to provide summer thermal comfort. Enhancing natural ventilation is not only effective to reduce high internal summer temperature but it provides a better indoor environmental quality and psychological user satisfaction. Natural ventilation can disperse the heat. The heat loss through ventilation in summer is defined using Equation 3-9.

$$H_V^{summer} = 0.33 \times n \times V$$

Equation 3-9

where n, is the air change rate and V the volume of the heated space inside the dwelling (m^3).

Depending on the location and ratio of building dimensions, natural ventilation can operate as cross-ventilation, single aspect ventilation and stack ventilation (Olgyay, 1963). Generally, natural ventilation in buildings occurs because of the wind-driven effects (Equation 3-10) or buoyancy-driven forces (Equation 3-11) (Allard, 1998). Wind-driven ventilation relies on wind force as the main mechanism while, the buoyancy or stack effect take place due to the temperature difference between indoor and outdoor environment (Szokolay, 2004). It is in fact, pressure differences (Δp) between two areas that force the air to move. The air will flow from a zone of high pressure towards a zone of low pressure. These pressure differences are mainly because of the wind and stack effect or a combination of two factors

$$Q_w = C_d A_w V_o \sqrt{\Delta C_p}$$

Equation 3-10

where Q_w (m^3/s) is the air flow rate of cross ventilation due to wind effect; C_d is discharge coefficient; A_w is obtained as $1/A_w^2$=$1/A_i^2 + 1/A_o^2$ where A_i and are the cross sectional area of inlet and outlet (m^2) ; V_o is outdoor wind speed (m/s), and ΔC_p is the different pressure coefficient between inlet and outlet

$$Q_s = C_d A \left(\frac{2\Delta T g H}{T_i}\right)^{0.5}$$

Equation 3-11

where Q_s (m^3/s) is the air flow rate of the cross ventilation due to stack effect; where Q_w (m^3/s); A is a cross sectional area of the opening (m^2); ΔT is temperature difference; g is gravitational acceleration; H is the distance between the midpoint of the inlet and outlet (m); and T_i is indoor air temperature. Actual airflow rate through an opening (Q) is given by vA , where v is air velocity (m/s) and A is the cross-sectional area of the opening (m^3).

For maximum cross ventilation, the major opening should face within 45° of the prevailing wind direction. Choosing the orientation of the building in favour of prevailing winds may influence the solar gain (Szokolay, 2004). With the south-facing wall if the wind comes from west or near-west, for example, a wing wall at the eastern end of the southern window would help to create positive pressure zone. At the same time, the difference in pressure can be obtained by placing a wing wall at the opposite end of the north wall to create negative pressure on the opposite wall (outlet).

Typically, Passivhaus have much lower air change rate in summer than conventional housing. A study on the impact of ventilation on summertime overheating (Tillson, et al., 2013) regarded, if the air change rate for dwelling was around 1 ACH, then 70% of the UK housing stock would be at risk of summer high temperature (Figure 3-6). However, the percentage decreases dramatically to 34% if the air change rate is doubled. In the case of four air change per hour or more, the risk of overheating could be eliminated. However, SAP (2010) states that an air change rate of four or more can only be achieved when the windows are fully open all the time. This is not applicable because of security, noise, privacy and because occupants would not wish to open their windows for excessive time periods to achieve a cooling effect, especially in low-rise detached dwellings (Tillson, et al., 2013). The combination of a higher ventilation rate (higher than typical) and a shading strategy, which does not interfere with air change rate, is a more applicable and practical way of eliminating the summer overheating risk. However, for extreme summer circumstances, where both shading strategies and natural ventilation fail to combat overheating, some supplementary cooling can be used to peak-lop in hot weather. This hybrid approach is the term “mixed mode” introduced by Cooper (1998).

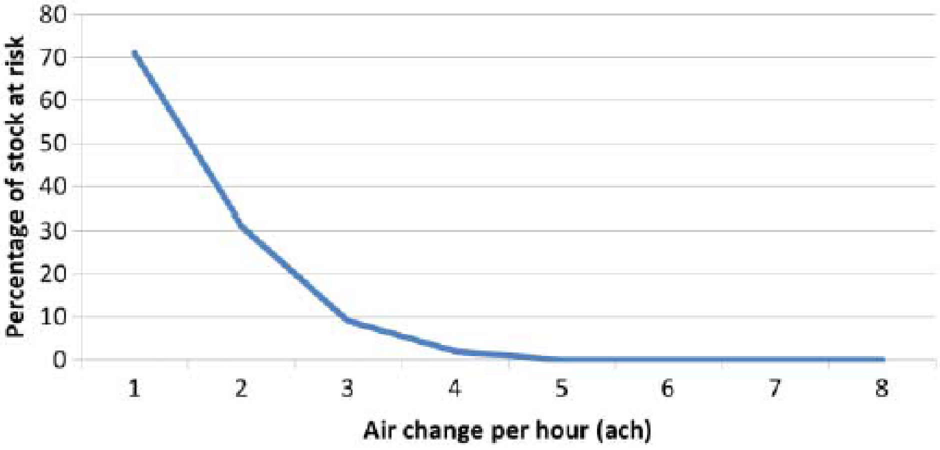


Figure 3-6 Effect of ventilation on vulnerability to overheating (Tillson, et al., 2013)

Santamouris, et al. (2010) used a range of different air change rate to efficiently ventilate buildings during the night for Greek weather, where mechanical air conditioning is used by many dwellings. The Greek weather file could potentially represent future UK climates under a higher emission scenario. The research found an average 26% decrease in cooling load when the building was efficiently ventilated during the night. A night ventilation rate of 10 ACH was estimated to be required to efficiently ventilate UK dwellings (Orme, et al., 2003).

Balaras (1996) investigated the effect of nocturnal ventilation and thermal mass in reducing summer indoor temperature. Kolokotroni, et al. (1998) highlighted the effectiveness of summer night ventilation for reducing indoor summer temperature for the next day. The results from Givoni (1993) showed a significant reduction of indoor temperatures during the day from coupling thermal mass and nocturnal ventilation.

Research (Seppänen, et al., 1999) determined that an increase of ventilation rate from 10 litres per second per person to, say, 20 litres/seconds/person in all building types improved the indoor air quality. It also will decrease Sick Building Syndrome (SBS) symptoms such as eye and nose irritation, dry skin, difficulty in breathing and tight chest, cough, headache, dizziness, mental fatigue and nausea (WHO, 1983). SBS can be significant for buildings with less than 10 litres per second per person ventilation. Based on health and hygiene consideration, the level of carbon dioxide below 1000ppm is harmless. CIBSE Guide B suggests that CO_2 levels of 800-1000 ppm indicates that the ventilation rate is adequate in a building (CIBSE Guide B, 2005).

In the assessment report of the world's first Passivhaus in Darmstadt (Passipedia, 2014), the indoor climate of the house was found to be comfortable in summer except for some days in mid-July and hot periods of late August through early September, in which temperatures of 25°C or more were prevalent, gradually increasing up to 30°C. The temperature was found to be considerably more favourable when additional window ventilation was operating. In each room of the house, a window was placed in the tilted position. It was found that the tilted position of the window led to a substantially higher average air change.

In the UK, where summer outdoor temperatures are normally comfortably pleasant, modification of natural ventilation can be crucial for providing summer thermal comfort in super insulated buildings, especially for a potentially warmer climate. Even in countries where external weather conditions could be very harsh during the hot periods of the year, many studies have examined the benefits from the potential use of natural ventilation in new house designs (Tantasavasdi, et al., 2001; Prajongsan & Sharples, 2012). In the UK, because of the relatively high wind speeds, outside temperature always feels cooler during summer than the actual dry-bulb temperature. This means the same temperature without the wind feels warmer. This happens in the area where the wind movement is restricted, such as inside buildings. In fact, what makes outside temperature feel a little bit cooler is the air movement (wind) and not solely the air temperature. Inside the building this wind movement will not be felt and if natural ventilation is not properly operating the building will suffer from overheating even with a relatively cool summer outdoor temperatures. Even in the future UK climates, with higher summer temperatures, if adequate natural ventilation is provided throughout the summer overheating risk reduces a great deal.

The potential need to install air conditioning equipment can be eliminated by enhancing natural ventilation and having night purge cooling. Natural ventilation offers potential for energy economy as it is arguably unacceptable that in northern Europe most mechanical cooling systems run while outside temperatures are lower than inside (van Moeseke, et al., 2005). A study carried out by Finnegan, et al. (1984) regarded that occupants in air-conditioned buildings suffered from lethargy, headache and dry skin.

3.3.6 Air conditioning

Cooling with mechanical systems is proposed as one of the adaptation options in the CIBSE climate change report (CIBSE TM36, 2005). With the warmer summer days as predicted by CIBSE future weather projections, air conditioning systems may become relevant for new developments and to avoid summer discomfort hours in passive houses. This is because active systems are often easier to design, for instance, natural ventilation is often more difficult to design than standard air conditioning (Levermore, 2008b). This has already been the case in warmer countries in southern Europe. In cold climates like Canada (Ontario) air-conditioning systems becoming commonplace in residential buildings and they increase the peak in electricity consumption (OPA, 2008). Growth in active cooling use in the building stock could potentially double the CO_2 emission by 2030, counteracting with the central Government's attempt to cut emissions by 80% by 2050.

Scientific reports cautioned against the installation of A.C units and urged improvement to the building envelope to reduce the need for active cooling and aid any air conditioning (Levermore, 2008a; 2008b). Littlefair (2005) pointed out that the use of air-conditioning systems in the UK is rising by 8% per year. It is estimated that even before the 2050's active cooling systems may become a relevant requirement for Passivhaus dwellings in the UK (McLeod, et al., 2013). Barclaya, et al. (2012) argued that providing a comfortable summertime indoor environment without a heavy reliance on mechanical cooling devices under future climate projection would be a major challenge for many parts of the UK. Peacock, et al. (2010) estimated that soon cooling might be needed for bedrooms for nearly four months of the year. This means that if no mitigating interventions are considered then overheating frequency will dramatically increase. Simulations carried by the Chartered Institution of Building Services Engineers (CIBSE TM36, 2005) considering a medium thermal mass houses with air conditioning operating for summer cooling, and showed a significant increase in carbon emissions.

Assuming mechanical cooling devices becoming common in the UK, these air conditioning units in the UK climate may not be used for a long period during a year, but most certainly will be used for hot summer spells. The acclimatization and adaptation to air-conditioning units in future could be significant. People could use air-conditioning for a thermal environment that they used to tolerate comfortably. With the growth in population and number of residential buildings, the cooling load through the course of a warm period may increase dramatically. Therefore, a reduction in peak electricity consumption is important to reduce energy costs and electricity generation and distribution capacity. Reduction of peak electricity demand reduces the demand for new power plants or importing electricity (OPA, 2012).

For a moderate climate such as the UK, air-conditioning should be avoided for the summer time. The building sector already produces about half of the UK’s total carbon dioxide emissions, and using air-conditioning systems will consequently increase the carbon dioxide emissions by 6 million tonnes per year by 2020 (Littlefair, 2005). Attempts to keep UK homes free-running in summer has encouraged researchers to endorse passive interventions to provide comfort for all types of buildings, especially the housing sector.

3.3.7 Occupant behaviour

A 15-year investigation of residential energy use by Emery and Kippenhan (2006) concluded that the impact of occupant's behaviour on overall household energy use was higher than the impact of a building's construction and insulation.

Occupant behaviour and their approach to controlling their building’s heat gains and losses accounts for a significant uncertainty in building modelling. Some studies (Baborska-Narożny, et al., 2017) conducted a survey to determine occupancy schedule and some studies used typical household schedules (normally built in the software's library). However, research questioned the suitability of the current assessment on overheating and highlighted difficulties facing the research (especially simulations) in applying the real occupied time scale. The special issue of Building Research and Information on overheating (Lomas & Porritt, 2017) highlighted the issue that the research struggled to precisely apply different overheating criteria due to difficulties to determine non-definitive parameters such as occupied hours, occupant behaviour, etc., and because there is no robust, defensible definition of overheating.

Bahaj and James (2007) compared the energy consumptions between nine identical homes. They found a large variation of up to 600% difference between energy use in the same identical homes with different occupancy schedules. Similarly, blind operation and window opening as a behavioural task is still a vague issue and little is known about the operation of windows in dwellings (Porritt, 2012). Passivhaus tries to avoid the smallest cracks, minimise thermal bridges and use the most of the thermal heat gain, but occupants may simply open the window even on the coldest days to refresh the indoor environment. Because of such behaviour, the heat loss coefficient could increase, the effort to reduce thermal conductivity is wasted and the value of the heat gain is misplaced, leading to extra fuel consumption.

Thermal dynamic modelling software are widely used to simulate building energy performance. These packages have sophisticated abilities in their modelling of deterministic features of building energy balance, with the most accurate computational calculating solvers supporting simultaneous solutions of thermal, electrical, and fluid dynamic equation sets (Clarke, 2001). But their ability to elaborately represent non-deterministic features, such as occupants' presence and their behaviour with environmental control, is very limited (Schweiker, et al., 2011), even though occupants' behaviour is one of the major parameters affecting a building's energy performance (Andersen, et al., 2007; Bahaj & James, 2007; Yao, et al., 2016). Furthermore, research (Hoes, et al., 2009) has highlighted that the impact of occupants' behaviour is more influential for passive buildings and energy efficient buildings.

Schweiker, et al. (2011) developed models of windows opening and Tanimoto et al. studied residents' activities relating to the use of HVAC systems. They developed a model with measured data where the occupants' switching of HVAC was predicted based on homogenous Markov Chain which was independent of the time and dependent on the indoor condition. They later altered the mode to a new stochastic model based on Multi-layered Artificial Neural Network (MANN), where the calculations depend on nine explanatory variables. These consisted of occupants' personal background, type of their job, groupings of time of day, whether the current day is a weekday or weekend, a comfort indicator, type of clothing, density of presence and time of arrival and leaving. This model better represented the occupants' behaviour and results to a closer predictive accuracy. (Refer to Robinson & Haldi, 2012; and Schweiker, et al., 2011 for more information).

Haldi and Robinson (2008; 2009; 2010) investigated the prediction of occupants' action in order to integrate more realistic operational schedules (occupants' behaviour) into dynamic building thermal simulation tools. Data from their studies show that occupants will lower the blinds during the day for a low indoor (and outdoor) illuminance until a peak of around 300 Lux and then, in some cases, they start to shut the blinds when the illuminance rises. Observation of the overall blind operation taking place in an office building in Lausanne, Switzerland indicated a high unshaded fraction - for more than two-thirds of the time the blinds were fully open and only for 5.2% of the total occupied time the blinds were fully closed. It was also found that blinds that do not interfere with the view, like blinds for upper window-panes, were more likely to be closed. This agrees with the point that people mostly operate the blinds due to the view and privacy rather thermal comfort.

However, operating blinds at homes is significantly different from other buildings and from one home to another as well. In residential buildings privacy, sleeping and rest conditions are greater factors since occupants are not constrained by professional attire or activities. Occupants in residential buildings have more tasks that are flexible and a more diverse schedule than occupants in an office building. In residential buildings, the occupants are normally absent during the daytime in weekdays. They may forget to close or open the blinds before leaving the home and not operate the blinds during periods of greatest solar intensity. Conversely, occupants in offices are generally present during daylight hours. Bennet et al. (2014) monitored the blind use in a multi-unit residential building for different summer weather conditions in Ottawa, Canada. Among 370 homes it was observed that most occupants opened the shadings in the morning around 7:00 to 9:00, suggesting a morning schedule when the occupants woke up, open shades and then leave for work. However, the closing pattern showed no clear pattern but suggested closing generally occurred between 17:00 to 19:00. This could suggest a privacy closing or the arrival of residents after work. This is also in agreement with the study by Haldi and Robinson (2009) where they found that most shade movements occurred upon the occupant's arrival. The shade movement frequency showed a very unstable pattern. Some occupants had minimum interaction with shading (few movements during six days observed period) but some consistently moved their shades, with some having a consistent shading schedule. The study also showed that shade occlusion for the south façade increased at higher levels in the building. This was likely because of less shading from the neighbouring buildings. It was estimated that the incident window surface solar radiation on the south-east façade of the 7th floor was almost double that incident of windows 1st floor at the peak hours of solar intensity. These two different points of views suggest that top floors are more sensitive to the incident solar on a window. It was then concluded that "*personalised shading schedule"* may be the reason for some shade movement besides the factors which has been addressed, such as view, privacy and glare. Sutter, et al. (2006) reported that most occupants shut the blinds in a high luminance because of visual discomfort and they keep their blinds down until the luminance is very low. External view also turned out to be a major factor for operating the blinds. Porritt, et al. (2012) fond that even in the high temperature occupants might find closing the blinds unacceptable due to the loss of external view.

Findings from the monitored performance of the first London Passivhaus dwelling i.e. Camden Passivhaus, (Ridley, et al., 2013) also reported that occupants did not intend to change their window opening and blind operation use in future, despite the monitored data suggesting that temperatures were above the CIBSE thermal comfort criteria in several periods. It was also observed that the occupants of Larch House (the case study) did not use the blinds to their best advantage (Ridley, et al., 2014). The negative impact of the occupant's behaviour, like opening windows in winter, can seriously reduce the efficiency of a building. For example, in Lime House the measured space heating demand was double the predicted amount, surpassing the Passivhaus requirement (Technology Strategy Board, 2014). This under-performance of the house was due to occupants opening the windows in winter and extra heat loss being added to the dwelling. It was estimated that for each 0.1 ach^{-1} an extra heat loss of 11 W/k was added to the Passivhaus (Ridley, et al., 2014). An extensive study (Mahdavi, et al., 2008) observed little attempt from occupants to efficiently change the windows and blinds during the day. Although it has been confirmed that occupants controlling the window opening behaviour is not thermally efficient, it has been shown that it has an important psychological impact (refer to section 3.2.3) on overall comfort.

Behavioural factors, other than the aforementioned, may provide comfort for occupants. For instance, a NHS heat wave plan (NHS, 2011) suggested having more cold drinks or sitting next to an open window to combat overheating as simple solutions. Wearing cloth made from linen or cotton fabrics on a hot day can also help to keep a body cool.

3.4 Clustered interventions

Single interventions have been implemented in the UK housing stock to overcome the potential risk of overheating in warmer summers. It was found that external wall insulation and shadings were among the most effective single interventions to reduce the number of degree hours below CIBSE comfort threshold temperature. Night purge ventilation was found to be beneficial for summer thermal comfort. However, in summers for the period between 12:00 to 18:00, when the internal temperature might exceed comfort levels due to the intense solar gain, the research showed that shading the windows and, in particular, with external shutters, is the single most effective intervention. Internal curtains had a small overheating reduction and internal insulations in some cases caused a higher indoor temperature. However, to eradicate completely the overheating risk a combination of these interventions is required. Research showed that using successfully clustered interventions a reduction of up to 4.6°C internal average temperature can be achieved.

The combinations of the various adaptation measures available for analysis are endless, and it is believed that the multiple interventions can do passively what is feasible by using active cooling. Porritt et al. (2011) found that by using a combination of interventions e.g. solar shading and ventilation, the temperature in the living room of a typical Victorian terrace house could remain below the CIBSE overheating benchmark by 2080 (using Medium-High emission from UKCIP 02). In contrast, Gupta and Gregg (2012) tested different adaptation measures to reduce overheating in English homes. Overheating was reduced by a combination of interventions but no measures were found to eliminate entirely the risk of overheating in future climate especially in the 2080's (using high emission scenario from UKCIP 09). It was concluded, the adaptive measures can be combined with active cooling systems to eradicate overheating in future.

While there is a large body of evidence on the importance of the reduction of heating demand for a successful energy efficient development, reducing cooling needs and combatting overheating is also a prominent factor that has been less studied. Nevertheless, most of the existing data on reduction of cooling and overheating assessment focus on non-residential buildings such as office buildings, and only small number of researches have focused on the domestic sector (Tillson, et al., 2013). The issue of overheating is critical in the housing sector, especially for comfort in bedrooms, as people’s tolerance towards high temperatures is less during sleep time (Ji, et al., 2014). Sleep may be impaired for air temperatures above 24°C (CIBSE Guide A, 2006), causing poor performance on the following day at work (CIBSE TM36, 2005).

3.5 Discussion and conclusion

Improvements in energy efficiency for the UK housing sector is considered as a key objective in order to meet UK government targets for reducing greenhouse gases emissions. The residential category is responsible for 70% of total energy consumption in the UK building sector which accounts for 30% of total national carbon emissions, with nearly two-thirds of this used for space heating (BERR, 2007). Overheating as a new challenge has been studied in the last few years. Table 3-3 summarises precedent research results on different combination of interventions to prevent overheating.

Table 3-3 Review of some literature investigating the impact of increased summer temperature on the UK housing stock

Source	**Location/ Weather file**	**Results on reducing overheating**
(Orme, et al., 2003)	N/A	Night time purging the most effective Solar shading and ventilation effective
(Tillson, et al., 2013)	Entire UK	Combination of shutters and ventilation the most effective External overhangs very effective Light coloured curtain and blind effective
(Wright, et al., 1999)	South-east England	Comfort can only be achieved by using several passive interventions or active cooling Single passive intervention cannot eradicate overheating
(Hacker, et al., 2005)	London/ Manchester	Solar shading and ventilation most effective Air tightness and insulation successful
(Mavrogianni, et al., 2012)	London	Exposed thermal mass and effective ventilation would control overheating up to 2050s Internal insulation that masked thermal mass resulted to an increase in internal summer temperatures
(Porritt, et al., 2012)	London Heathrow 2003 heatwave	Orientation had a substantial impact High reflective solar coating on the walls the most effective External wall insulation very effective Internal wall insulation less effective External shutters very effective Internal blinds less effective Night ventilation effective Windows rules opening strategy not effective
(TRCCG* 2008)	London	Reflective façade, solar control, ventilation and enhanced air movement as a multiple intervention very effective
(Gupta & Gregg, 2012)	Oxford Future A1FI	Shading the glazing form incident solar radiation most effective High albedo external surface and external insulation effective

Source	**Location/ Weather file**	**Results on reducing overheating**
(CIBSE TM36, 2005)	Entire UK	Control of solar shading and internal gain and ventilation can achieve the target until 2050s
(Galasiu, et al., 2005)	Canada	Largest reduction in cooling energy (up to 70%) achieved by installing opaque exterior shades. **
(Bennet, et al., 2014)	Ottawa, Canada	Design of the building envelope (windows, shading type and exposed mass) has a profound impact on cooling load Interior shadings are not as effective as exterior shadings The effect of 1/2 WWR with no shading was very similar to internal shading
(Passipedia, 2014)	Darmstadt, Germany	Frequency of overheating events increases significantly for lightweight constructions. For the Darmstadt-Kranichstein Passivhaus if lightweight timber was used the highest daily mean temperature would have reached to 34°C in summer

*Three Regions Climate Change Group, 2008
**Shading device are fully closed during the sunshine

Beizaee, et al. (2013) presented one of the first national surveys of summer overheating risk based on the BS EN 15251 adaptive thermal comfort model and CIBSE's statistic criteria for UK dwellings. This survey was conducted during the cool summer of 2007 and considered the living room and bedroom temperatures of 207 homes in the UK. Overall observation indicated that older homes (pre-1919) were less at risk of overheating compared with well-insulated post-1990 homes. The results showed that despite the relatively cool summer of 2007, 80% of bedrooms in newer homes exceeded the CIBSE's static overheating criteria.

A study using SAP (Tillson, et al., 2013), tested the vulnerability of dwellings by type and age for the entire UK housing stock. For detached dwellings, the proportion of time with overheating in the pre-1900 dwellings with no adaptation measures was estimated to be 28%, while overheating for post-2006 dwellings was 100%. By taking into consideration the adaptation strategies, including overhangs and shutters, the overheating could be eliminated for pre-1900 buildings and reduced to only 3% for the newer dwellings under current climate conditions.

Generally, overheating occurs because of high solar irradiation or lack of air movement. Higher solar intensity in future summers and low air movement because of high air tightness in Passive houses may increase discomfort overheating frequency, especially in bedrooms. This could lead more home owners to install air-conditioning systems to avoid summer time thermal discomfort, an approach that is not going in the same direction as the UK government’s target of 'zero carbon' buildings.

As discussed earlier in this chapter, the definition of overheating is defined differently by different design Guides. Generally, adaptive thermal comfort models are believed to be more reasonable than static measures because people would acclimatize themselves depending on the external temperature. However, *“The adaptive approach does not allow the design to demonstrate explicitly the effect of variables [but] static model has the advantage of accepting a wider range of inputs”* (CIBSE Guide A , 2015). In this study overheating hours were calculated according to Passivhaus standards for lower threshold (25°C) and CIBSE Guide higher threshold (26/28 lower threshold), based on the ratio of hours the benchmark temperature is exceeded (section 3.2.1a).

Buildings in mild/cold climate have always been considered as being heat-dominated structures and, normally, shading devices have not been traditionally used. However, research (Grynning, et al., 2014) concluded that the cooling demand of a building with large glazing areas contributes significantly to the net energy demand and that providing shading is vital to reduce the cooling demand.

Design strategies to reduce excessive heat gain in summer have been reviewed in this chapter. The focus was on the passive interventions as they do not directly contribute to building energy demand and associated CO_2 emissions. Passive interventions for reducing overheating are mostly user dependent and include operations such as blinds and window openings. Automated shading devices have been used recently but they have their limitations. Studies (Stevens, 2001; Galasiu & Veitch, 2006) noted that user preferences often contradict automated shading control and occupants prefer to control the blinds manually or over-ride the automatic system. Occupants adjust their blinds more often on arrival [and departure] to create privacy or view. Therefore, user-dependent approaches to passive solar control may not properly function due to the occupants not interacting with them as planned. Other passive overheating control options, such as thermal mass and overhangs, are non-user dependent.

The problematic interaction between occupants and the solar overheating control systems was a stimulus for this study's investigation of an alternative non-user dependent intervention rather than the more conventional approaches such as overhangs and thermal mass. The idea was to test if altering the geometric form of a passive house (by tilting the south facade to give self-shading) might be capable of passively protecting the house from excessive solar gain in summer, both for current and future climate scenarios.

Chapter Four

4 Geometric Considerations

The original meaning of the term “passive” in building design refers to the idea that the design of the construction and the shape of the building play a major role in benefiting from “free energy”. This is, in fact, the term “passive design” which was used in vernacular architecture.

Passive design techniques in the early design stage represent important strategies towards decreasing energy demand in buildings. Dwellings should be designed to produce a comfortable indoor environment by adjusting and adopting the external climate. CIBSE TM48 (2009) regards *“A primary purpose of buildings is to act as climatic modifiers”.* Pearlmutter (2007) stated *“Climate inevitably produces certain effects on architectural forms. In its role as a provider of shelter, architecture intentionally modifies the climate on an immediate area, and traditionally its design has been shaped by the stresses and opportunities inherent in the regional climate”*. At the design stage, architects generally consider the geometry of the building as an aesthetic matter and miss the importance of geometry in energy consumption of the building. Research (Levermore, 2008b) warns about the current approach in designing buildings where individual items of a building are designed by separate individuals. For instance, the architect and the engineer work is not integrated in the design process. Integrated design process (IDP) in which the building is optimised by all the member of the design team can save a substantial amount of energy for building operation. Energy simulation is mostly conducted during the building stage and it is not integrated into design decision-making (Granadeiro, et al., 2013). It is perhaps because there is not a reliable methodology to assist design decision in terms of the building envelope geometry and its implication on energy performance and because of the time-consuming nature of energy simulation task.

4.1.1 Precedent studies on building form

There are some good examples of building geometry impacts on energy demand (Zerefosa, et al., 2012; Capeluto, 2003; Parasonis, et al., 2012; Loonen, et al., 2013). These researches have demonstrated that buildings with different external envelope areas but similar internal volumes can have different energy demands. When comparing the compactness, size and geometric efficiency of a building's shape the geometry of the building has the strongest effect on the energy demand. Ascione, et al. (2010) emphasized that controlling the radiative characteristics of a building's external surface will highly influence the space heating and cooling demands. Adamski and Marks (1993) investigated the shape optimization of buildings, taking into account minimum material and construction costs and minimum heating cost in the course of a year. These studies verified that the architectural design of the external building envelope can significantly improve the energy consumption of a building. Levermore (2008b) suggested that designers should use the buildings envelope as a "filter" to moderate the outside air and depending on the need for heating or cooling, accept or reject solar radiation. Mavrogianni, et al. (2012) concluded that "*the combination of geometry and construction age can function as reliable predictors of indoor overheating risk*".

In various academic studies, the expression "form" was described differently and in very broad terms. The word "form" is defined as the visible shape or configuration of something i.e. building (Oxford English Dictionary). This includes shape, proportion, scales, mass (size), rhythm and articulation. Form can denote formation processes in two dimensions. Form can also refer to the configuration of a building - relative compactness (RC), the proportion of the inner volume to the outside surface and the ratio and the size of the opening, all of which comprise the form of a building. These have been broadly studied and their effects on energy efficiency have been found. In this study the term "form" refers to the three-dimension geometrical configuration of the building envelope.

For instance, Figure 4-1 from *Passivhaus Primer: Designer's Guide* (McLeod, et al., 2014) shows that houses with the same area but different form of compactness results in an increase/decrease amount of required insulation and heating demand. A more complex form also is likely to have a higher proportion of thermal bridges and increased shading. Ourghi, et al. (2007) claimed a very strong correlation between the relative compactness (RC) of a building and its total energy consumption. It was found that the higher the building's RC then the lower is the exterior perimeter surface and the lower the heating and cooling requirements. Depecker, et al. (2001) agreed that energy consumption is inversely proportional to relative compactness for cold climates. However, for mild climates no recommendation on RC was concluded. Hence, building with smaller area of external envelope, while enclosing the same area, have smaller energy loss and consequently use less energy for heating and cooling.

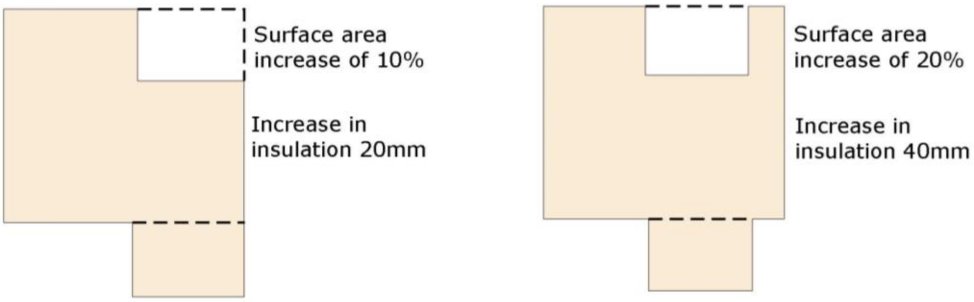


Figure 4-1 Effect of building compactness on insulation (McLeod, et al., 2014)

Other architectural features that can influence the indoor climate and energy consumption of the building include building layout, orientation, the shape of the building, colour of the opaque wall, window size, glazing type, material, shading device. However, there are several reports urging solutions to the problem of shape definition in energy saving buildings (Adamski & Marks, 1993). The result obtained by Parasonis, et al. (2012a) showed that changes in the shape of the building caused changes in energy demand. Zerefosa, et al. (2012) believed that energy consumption of two buildings with the same materiality, volume, wall area, openings and operating program, differs only due to the shape of their external envelopes. They examined the energy behaviour of a case study in Athens with polygonal and prismatic envelope shapes. The research pointed out that the prismatic formed building had lower solar gain compared to its orthogonal counterpart and consumed less energy in an annual cycle.

Capeluto (2003) and Shaviv (1999) used parametric analysis in an hourly dynamic simulation model to determine the energy consumption for heating, cooling and lighting for buildings with different shading requirements and orientations. Capeluto (2003) used the Solar Collection Envelope (SCE) by means of the computer model SustArc to generate self-shading envelopes to shade the building. Chan & Chow (2014) have also showed that inclined walls can attribute to the shading of the building envelope. The upside-down pyramidal shape case study in Capeluto's work (2003) is symmetrical with respect to the north-south axis. On the southern elevation an angle of 31° from the zenith was required while the northern elevation did not require any inclination. East and west facades of the building had the same inclination of 34° from the zenith. It should be mentioned that the case study was situated in a hot climate at 32°N latitude and 35°E longitude (city of Jerusalem).

4.1.2 Inclined facades and glazing

The greatest source of internal gain is solar radiation, which enters the building directly through windows. In addition to various shading approaches mentioned so far, inclined facades have also been implemented to create a shadow on the building's glazing and envelope.

Capeluto (2003) investigated the generation of a building's shape for a hot climate whereby the building's facades are self-shaded during a required period determined by the designer. The study revealed that sloped windows on east and west facade mitigate the penetration of direct solar radiation and reduce visual discomfort hours. It was observed that in the morning and late afternoon, when the angle of direct radiation is low, discomfort glare was reduced effectively. According to the case study climate (hot climate), the self-shading envelope would effectively remove most of the direct irradiation and no extra shadings were required for south-oriented windows. However, for East and West windows extra shading devices, such as roller blinds, can improve the energy performance of the building.

The incidence angle between the direct solar irradiation and the building surface differs because of changing orientations of the building or inclination of a building component. This will result in a different value of solar gain. For a tilted façade, the solar incident angle will decrease or increase depending on the inclination angle. In the case of the wall, tilting inside the living area the incidence angle is higher and when the wall leans outward, it tightens the solar incident angle, which will receive less solar radiation. The designer can check these issues using sun diagrams and manual calculations. The equation for working out solar heat gain on a surface is as follows:

With no obstacle and shading factor, the solar heat gains ($\Phi_{\mathrm{sol}}^{check}$) on a flat surface with a given tilt angle and orientation can be calculated using Equation 4-1.

$$\mathit{\Phi}_{sol}^{check} = \bar{\alpha}_s AT[I_d \rho(1 - cos \sum) + I_d(1 + cos \sum) + \frac{1}{\pi} I_b(cos \sum cos\, L^s + cos\, \psi\, sin \sum cos\, L^s \\ + \sqrt{Sin^2 \psi Sin^2 \sum + (cos \sum cos\, L^s + cos\, \psi\, sin \sum cos\, L^s)^2})]$$

Equation 4-1

where A (m^2) is the area of the flat surface, $\mathrm{I_b}$ and $\mathrm{I_d}$ are the direct and diffuse solar irradiance (Wm^{-2}) respectively, $\sum$ is the tilt angle of the surface and ψ is orientation angle. ρ is the reflection coefficient from the ground, and $\mathrm{L^s}$ is the equivalent latitude which depends on the specific month.

Some studies (Zerefosa, et al., 2012) used a simplified formula (Equation 4-2) to calculate the incident solar radiation (G) on a tilted surface.

$$G = Gh \times \cos INC \sin ALT + Gdh \times 1 + \cos TIL^2 + Gh \times r \times 1 - cos\, TIL^2$$

Equation 4-2

where Gh is the solar radiation on the horizontal plane, Gdh is the diffuse solar radiation on a horizontal plane, r is the reflectivity of the surface, ALT is the altitude of the sun, TIL is the tilt angle of the surface with the horizontal plane, INC is the angle of the surface.

However, using a computer-modelling tool makes it easier and faster to calculate and it is possible to evaluate large numbers of design alternatives. There are several examples of architects' attempts to self-shape the buildings to enhance thermal comfort in the building, such as Bank of Israel (A. and E. Sharon Architects), the city hall building of Bat Yam and Dubiner apartment house by (Neuman, Hecker, Sharon) Dallas city hall (I. M. Pei) Tempe City Hall (Michael and Kemper Goodwin) (Figure 4-2).

Figure 4-2 Clockwise from top left: Bat Yam town hall, Dallas City Hall, Dubiner apartment house, Tempe City Hall

These examples are mainly large-scale buildings – the research carried out on a dwelling's shape is much more limited. Topologically, homes have a larger surface area to volume and the different envelope design would have more pronounced impacts than for larger buildings but, understandably, the larger buildings get more attention in their envelope design because of commercial reasons.

4.1.3 Form Follows Energy

As discussed earlier, form can be referred to configuration of a building or its physical appearance. Hereby the term form mainly refers to the physical shape of the building. Different architectural styles have employed different languages of form, from constructivism, to modernism and now with hi-tech and fractal architecture the main concept always relies on the form. The focus on the form as a core concept has been the reason for aesthetic (e.g. in Classic architecture) or functionality (form follows function). Now, the question is how pronounced is the relationship between the form of the building and its energy performance. There are few dwellings where the architectural concept of the form has been driven from energy consideration. One reason for this may be the fact that the technology and the development of advanced engineering solutions (mechanical and electrical) are growing fast and the sustainability of a building can be optimised independent of the architectural style or concept and without exerting an influence on the intended architectural result (Gupta & Gregg, 2012). Because of this accelerated technologies in sustainable buildings many contemporary buildings in different parts of the world look very similar. In contrast, vernacular architecture took the benefit from different forms to acclimatize the building with its environment.

One example of geometric consideration in vernacular architecture is the dome. A domed roof shape is a good example for radiant cooling in hot climate. The spherical shape of the dome always has an area of shadow to minimize the radiant heating through the roof while the whole surface is exposed to the sky at night to make use of radiant cooling coupled with thermal mass. Domes also create different heights in the ceiling level, allowing the warm air to be trapped under the dome and a small vent in the apex of the dome exhausts the warm air. Caruso, et al (2013) calculated the optimal form of some existing buildings, such as the Hemisfèric in Valencia (designed by Santiago Calatrava, 1998) and the Bel-Air tower in Lausanne (1931) based on the same ground floor plan and volume (Figure 4-3). Although the concept behind the form of the Hemisfèric was not preliminary energy based, it was found that the form of the Hemisfèric is very close to the optimal form in terms of minimum direct solar irradiation gain, but the Bel-Air tower was found to be not compact enough and receives large amounts of excessive direct solar irradiation.

The Greater London Authority (GLA) building by Norman Foster (Figure 4-4) was designed with one of the aims being to minimize direct solar radiation on a very large glazed facade. The oval shape of the building is inclined to the south and represents an optimal form. A distorted spherical shape was also calculated by Caruso, et al. (2013) and the optimum calculated form for the latitude of 51.5° (London) was very close to the GLA building shape. The study (Caruso, et al., 2013) found the distortion and inclination to the south provides an improvement in reducing direct solar compared to a rectangular boxed shaped form.

Figure 4-3 Hemisfèric and Bel-Air tower

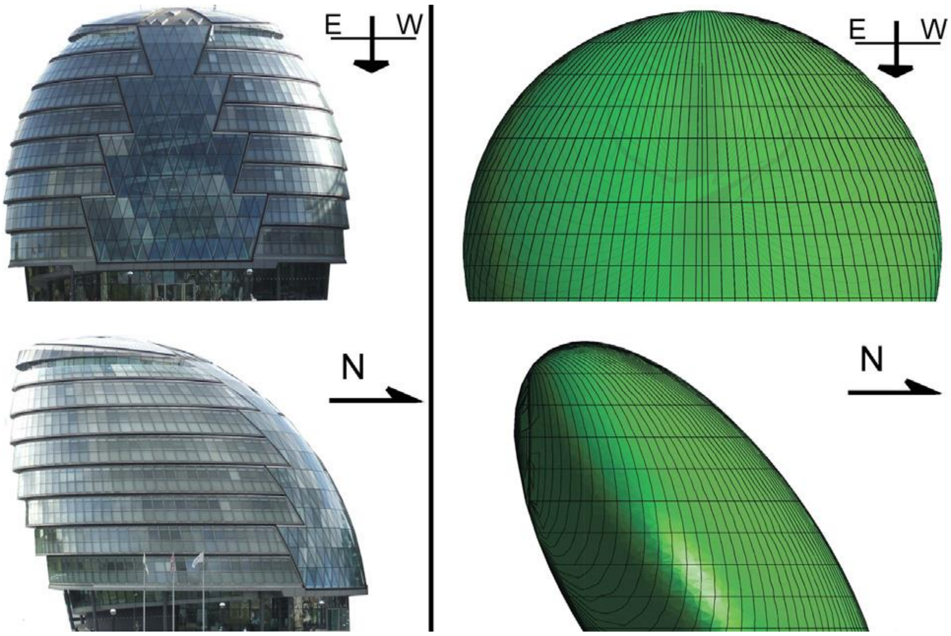


Figure 4-4 The Greater London Authority building (Caruso, et al., 2013)

In the design stage of the new opera house in Guangzhou (Figure 4-5) the interaction of incident solar radiation with the building skin was analysed to define the optimum solution for various modules with various positions in the building envelope. Depending on the orientation and tilt angle, the amount of annual solar incident radiation and the level of solar gain, the transparency of the modules and shading the internal spaces were calculated at the design stage (Cody, 2006).

Brian Cody (Cody, 2010) stated, *"The strategies to optimise the energy performance of the building can be architectural in nature and have far reaching consequences for the appearance of buildings".* He regarded that the emergence of a specific *"form language"* which is in direct relation to the energy efficiency is a potential concept which needs to be studied in depth to understand which design strategy does or does not have a pronounced impact on the overall energy performance of the building.

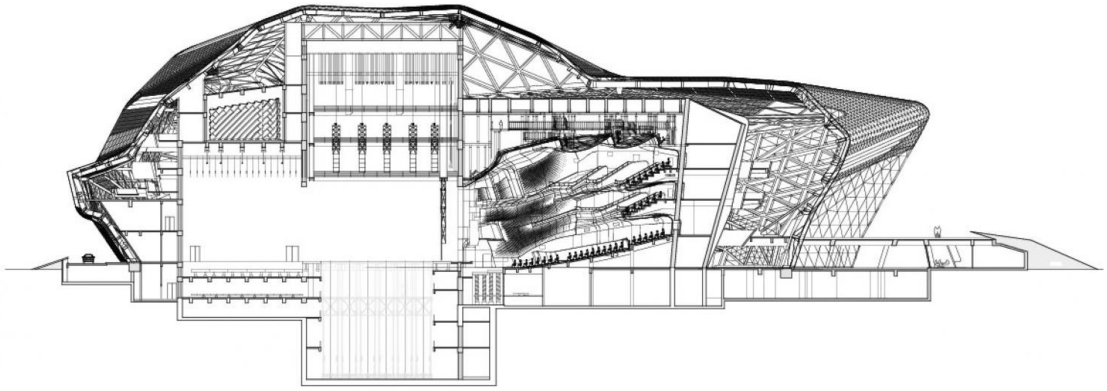


Figure 4-5 Guangzhou Opera House

The design for the Sunbelt Management Offices in San Diego, California was derived from the sun's movement (Figure 4-6). The shape of the building was primarily designed based on the interaction of solar radiation with the building envelope. The oval shape floor plan connected with a circular roof to create the tilt of the facade. The slope was created in different degree levels for each orientation, to optimise the building interaction with incident solar radiation. It was then found that the cooling load was significantly reduced compared to the identical building with conventional vertical facades in the same location (Cody, 2010).

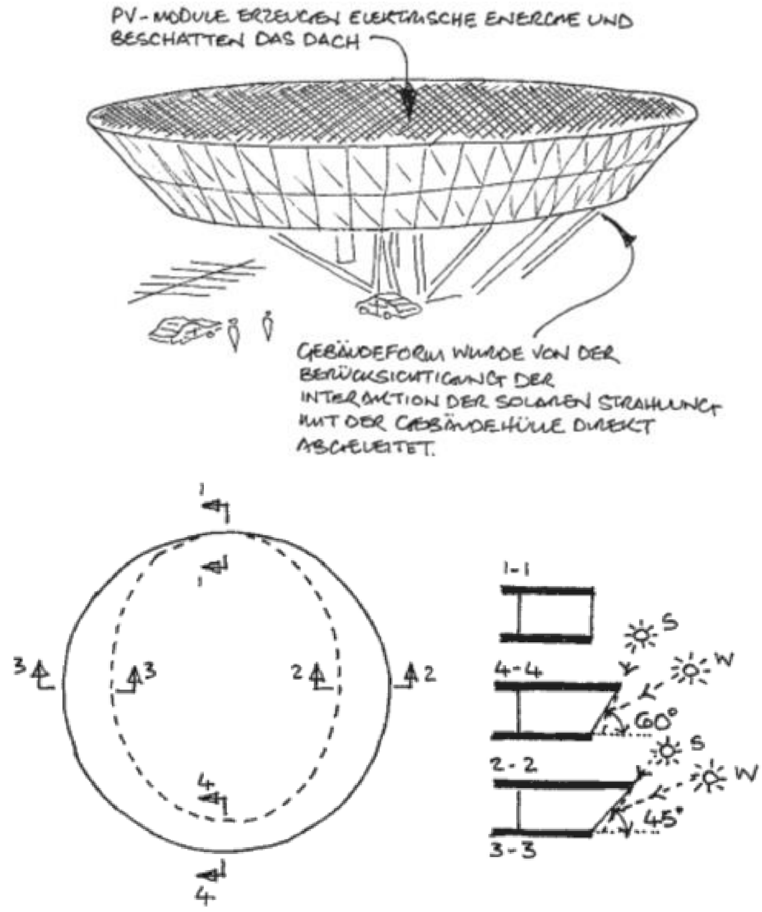


Figure 4-6 Sunbelt management office building (Cody, 2010)

As the solar angle of incidence is the main factor of solar transmission, the prismatic roof of the Geodynamic Institute of Athens (Figure 4-7) was divided into four parts with different slopes. The negative angles of the slanted roofs to solar radiation helped these parts receive less solar gain compared to a flat roof (Zerefosa, et al., 2012). Therefore, the roof with slanted surface heated less during the summer time. Each surface with a different inclination towards sun behaves differently through the year. Overall, a comparison suggested the advantages of the sloped roof over the flat one. The eastern façade, with an angle of 4° from the vertical axis, received less direct solar radiation compared with the orthogonal shape and consequently required less cooling energy. However, during the winter the inclined wall of the prismatic building also received lower solar radiation. Zerefosa, et al. (2012) concluded that, overall, the prismatic building performed better than a rectangular shape in terms of incident solar radiation and energy consumption. The calculations showed an 8% reduction in energy use in the prismatic building shape compared to its counterpart with an orthogonal shape.

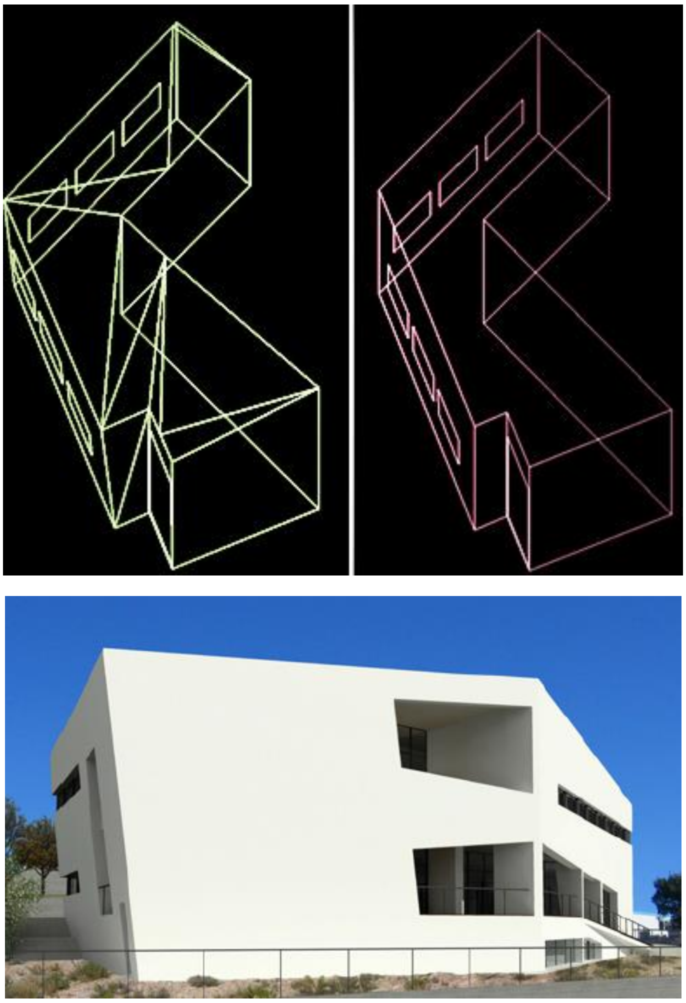


Figure 4-7 Geodynamic Institute of Athens (Zerefosa, et al., 2012)

Optimal form of a building can significantly reduce direct solar gain without reducing the total solar heat gain needed for mild and cold regions, in particular for buildings with large glazing area (Caruso, et al., 2013).

Although, the majority of the structures over the world are low-rise buildings (Ayata, 2009) the form of the building is less focused in small-scale structures and most of the small-scale buildings have a basic simple cubic shape. Historically, a house has been built in a cubical and rectangular shape. It is easier to build and the cost is lower. Another reason for box shaped low-energy housing is that the so-called A/V ratio (Area to Volume) of these forms are lower than for a more complex shape. The relationship of the building external area (A) to enclosed volume of the building (V) influences the energy demand of the building. A/V ratio is more pronounced in small sized building such as detached dwellings. Therefore, it is important to design very compact detached dwellings. The A/V factor has less impact on larger buildings - that is why they offer a greater freedom to design more complex geometries (McLeod, et al., 2014).

During the past decade, there has been an ongoing interest towards nonrectangular and prismatic building shapes (Zerefosa, et al., 2012). Buildings with prismatic forms have received great attention in architectural journals and have a big impact on the city where they are built. However, the form of the building has been always used as an aesthetic aspiration of design rather than from any energy efficiency concerns.

In the mid-20th century the core principle of the modernism architecture was that the shape of a building should be primarily based on its function – hence the phrase *“Form Follows Function”* which was coined by American architect Louis Sullivan. By that time, a building's intended use and its function were the most important criteria in designing the form of a building. The integration of the form and its relationship to the energy consumption brings a consideration where the whole issue of a building's use needs to be considered differently in a sustainable context (Cody, 2006). A new architectural language introduced by Professor Brian Cody (Cody, 2006) emphasised that the design of the building envelope was one of the key drivers for achieving energy efficiency in the built environment (*Form Follows Energy*). He argued how energy will become a new design parameter for future architecture.

The limitations and disadvantages of some existing shading strategies were described in section 3.3. Nevertheless, there is an architectural argument for some of the shading strategies implemented into the design of a low energy building (Figure 4-8).

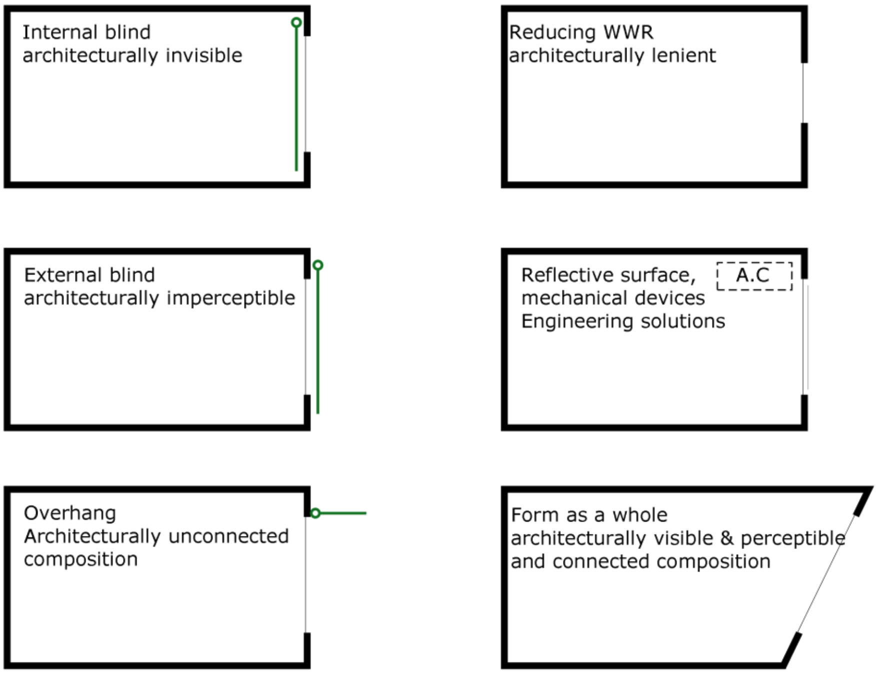


Figure 4-8 Architectural argument on shading strategies

For instance, an internal shading blind is architecturally invisible and taking or leaving it would not affect the architecture of the whole building. External roller blinds, as are mostly used in Passivhaus dwellings, are architecturally imperceptible. They cannot be considered as part of the main body of architecture and a concept of the design. Overhangs are not integrated in to the composition of the whole architectural geometry and they cannot be considered as a connected composition to the main body of the building. Reflective facades, computerised systems and mechanical conditioning devices are engineering solutions. However, form is architectural in nature. It is an architecturally visible, perceptible, integrated, and connected composition. It can be a strategy for obtaining a modification to the thermal comfort, which is so well integrated into the architectural concept of shelter.

4.1.4 Air movement around different building shape

The shape of the external building envelope will also affect the air flow patterns around and through a building and so, consequently, will have an impact on the natural ventilation of the building. Many studies have investigated wind behaviour and pressure coefficient distributions around and on the building envelope. Richards, et al. (2001) and Wiren (1986) investigated pressure profiles on buildings and Kim, et al. (2001) examined the impact of topography on wind flow around a building. Most of these studies focused on the influence of building geometry on outdoor conditions i.e. pedestrian level wind speeds and comfort levels around the building (Blocken, et al., 2012; Yoshie, et al., 2007)

Research (Kim, et al., 2011; Chungloo & Tienchutima, 2011; Montazeri & Blocken, 2013) concluded that added facade details, such as attached shading device, recessed walls, wing walls and balconies, have different impacts on the flow patterns and overall pressure distributions on the facade. Argiriou, et al. (2002) also suggested that shading device in front of an opening make an obstruction not only for solar radiation but will also form a boundary which interferes the mass airflow through the opening.

Kim, et al. (2011) used computational fluid dynamics (CFD) simulations integrated with a NURBS modelling program to optimize the building form at the early design stage in order to reduce adverse wind condition around the building. The experiment produced alternative building forms by integrating agent point modelling with genetic algorithm (GA) to generate building forms to find optimal or near-optimal solutions. Results showed that external envelope shape significantly affected wind behaviour and the speed of wind flow at different elevations around the building.

Montazeri and Blocken (2013) used sensitivity analysis with CFD simulations to evaluate the effect of building balconies on mean wind pressure distributions on the facade of the 4-story building. Validation took place based on wind-tunnel measurement. The results showed the building balconies caused significant changes in the wind pressure distribution since they produced flow separation and recirculation around the facade. Data from the experiment revealed that the presence of balconies on the middle floors leads to pressure increases on the balconies and the facade behind them. The pressure coefficient (Cp) on the first and last floor balconies decreased, especially for the side balconies, due to the flow separation.

Chungloo and Tienchutima (2011) examined the impact of facade components (obstructions), such as wing walls and balconies, on natural ventilation in a 6x6m residential room with a single sided opening. For a wind direction perpendicular to the opening (INC_{θ} =0°) the balcony caused an increase in the value of average air velocity coefficient (Cv); however, in the case of an oblique wind incidence i.e. INC_{θ}=15-75° the balcony reduced the wind entering the room. They suggested that a wing wall between two openings should be applied and any obstructions at the edge of the unit e.g. a balcony should be removed to increase the amount of airflow in the room. It was revealed that wing walls with a depth of 2 to 4 metres and a distance of 2-4 m between the openings would significantly increase the ventilation when the wind angle of incident is around 30-75°. The wing wall is suggested for single sided openings to produce the wind pressure difference between the windward and the leeward surface of the wing wall in order to cause the airflow in at the positive pressure and out at the negative pressure. According to Giovani (1994) implementing the wing wall will cause to three times more air velocity inside the room compared to those without wing walls.

Meinders, et al. (1998) analysed the flow patterns around a cube shaped object and Ikhwan and Ruck (2006) presented the flow patterns around a pyramid surface. The flow patterns around both objects were created in the form of a horseshoe where there was the most pronounced vortex. However, there were some significant differences in the flow pattern at the sides and in the corridors above the different geometries. The pyramidal geometries had a lower turbulence zone at the back than the rectangular forms.

Ayata (2009) investigated the form of a building component (i.e. roof) to protect the negative wind flow effect during the winter. The aerodynamic effect of the different shaped roofs showed that the velocity values decreased with the effect of the pyramidal roof. The highest velocities were observed at the upper part of the front facade of the house without pyramidal roof (the case with flat roof). This means that the heat loss of the houses with the pyramidal roof is less than the heat loss of the flat roof. The pressure distribution test on leeward and outward surfaces of different cases showed that, likewise, the pressure decreased with roof effect. The higher-pressure difference between front and rear wall suggested that a higher air infiltration would occur in the house with flat roof.

The aerodynamics of a building significantly influences the pressure distribution on building surface (Arens & Williams, 1977). The shape of an object plays an essential role in the drag force and free stream flow. The experiment conducted by Gemba (2007) investigated the effect an object's shape on drag force using wind tunnel technology. The results showed the most aerodynamic shapes had the lowest drag force value and consequently the shape which looked the least aerodynamic had the highest calculated values of drag coefficient.

The drag coefficient is a dimensionless value that gives the overall effects of the body geometry and inclination, which can be defined by Equation 4-3.

$$C_d = \frac{F_D}{0.5\rho V_\infty^2 A}$$

Equation 4-3

where F_D is the drag force; ρ is mass density of the fluid (air), V_∞ is the free stream velocity (m/s), and A is the projected reference area. Figure 4-9 indicates the measured drag coefficient of some regular forms.

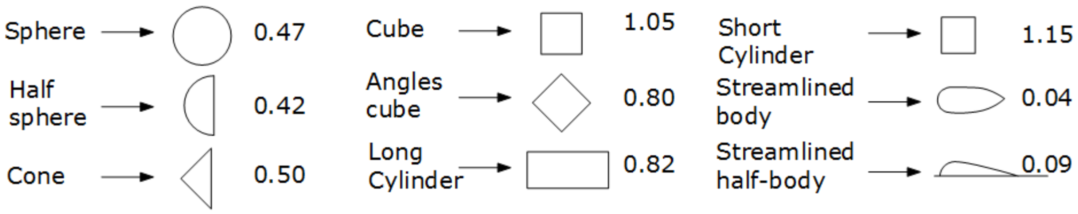


Figure 4-9 Drag coefficient of different geometries

The impact of the façade shape on thermal comfort and energy consumption has not been studied in the context of the Passivhaus dwelling. This is partly because there is no software combining shape generation and CFD analysis, and also software using batch file optimisation are very recent. Furthermore, simulation tools such as PHPP and SAP do not consider wind speed and direction in the calculation of heat dissipation. Although wind behaviour highly influences the building heat exchange rate (Arens & Williams, 1977) the air exchange rate due to ventilation is based on the building volume and existence of cross ventilation and window opening options and a typical constant value of air change per hour.

Chapter Five

5 Methodology

5.1 Introduction

There are several available methods that can be employed to answer the main research question i.e. can self-shading façades be considered as one of the successful shading strategies for future Passivhaus design. In this case, the methodology used should (i) reflect the form generation (tilt façade) and (ii) explore the thermal performance of the alternatives created. Here, some of the methods for generating forms and analysing thermal comfort found in literature will be addressed in more detail, bearing in mind that, in this study, thermal assessment is the main part of the research to examine overheating discomfort.

In the following section, methods available for (i) form generation research methodology (ii) thermal comfort assessment methods will be discussed. Then the method chosen for this study will be established.

5.2 Methods review

5.2.1 Form generation research methodology

The way Architects design a building's form has been changed in the last few decades, from planning on a drawing board to the basic Computer Aided Design (CAD) and nowadays – parametric design methods. Building parametric design is a novel design method based on algorithmic thinking where the final schematic form is generated through controlling the parameters and the relationship between elements. Many architects have applied this design method widely into more projects. However, architects using parametric design methods based on the philosophy to achieve eye-catching complex architectural forms and the energy efficiency method is neglected

(Li, et al., 2016) or overlooked. However, some studies tried to integrate Energy software into parametric design software (Li, et al., 2016).

There are different available methods to investigate the optimisation of building form. For instance, a sensitivity analysis of some specific parameters can be used to meet a set of criteria or arbitrary variables using a constraint-based approach can be considered to test different building geometries. Studies have also employed simplified analysis to predict the impact of the building shape by utilising several combinations of building geometry, glazing type, glazing area and climate and establishing a direct relationship between variables (Ourghi, et al., 2007). Yi and Malkawi (2009) implemented hierarchical geometry relations to obtain the most efficient and optimum buildings envelope shape. Caruso, et al. (2013) developed an analytical method to minimise unwanted solar radiation. They used a simplified model in the first stage to calculate the direct irradiation and this allowed formalising a mathematical approach based on the Calculus of Variants. Then a second more accurate model was developed to optimise the solar irradiation on the envelope with the aim that minimum direct solar radiation incident is getting to the building envelope. Building envelope optimization was also investigated with the numerical approach by using multi-criteria optimization (Wright, et al., 2002) and genetic algorithm (Tuhus-Dubrow & Krarti, 2010).

Most of the analytical approaches are mainly reliant on the primary method of solving problems (trial and error) and requires a significant number of variable optimisation. The probability of finding an optimal solution for the geometric form using a limited manual approach is small, especially if there is no reference building i.e. a case study as a starting point.

Kampf and Robinson (2010) introduced a more sophisticated method of using constrained evolutionary algorithms (hybrid CMA-ES and HDE) to find an optimised urban geometry for a hypothetical city to utilise the most of the solar irradiation. In addition, the research sought to determine an optimum roof shape of a mansion to increase the photovoltaic efficiency of the roof-integrated PV. The optimal values obtained after 12000 evolutions and it was concluded that the solar energy available for utilisation might increase by up to 20% (compared with initially chosen form). The method, however, has its limitations and some of the parameters disregarded. It is also noteworthy to mention that it is likely to find an optimum solution within a reasonable period and many evolutions but cannot be confident that a globally optimised solution is obtained. The paper also suggested an alternative study by using a similar method in which irradiation can be reduced by producing self-shading configurations. Caruso and Kampf (2015) built on this suggestion and used the same methodology to optimise the three-dimensional form of buildings to reduce solar irradiation in two locations. It was observed the tilt angle of the optimum forms for minimising solar irradiation and air-conditioning needs was very close to the altitude angle of the point of maximum cumulated solar radiation and altitude angle of the maximum algebraic solar irradiation.

However, as mentioned earlier the focus of this study is not creating a hypothetical optimum form as a complex geometry. Rather is to investigate if a slight change in the form (south-façade inclination) of an existing building could be considered as a reliable shading method.

Concerning the objectives, in this study for generating different facade inclination a simplified method was used. Variables (tilt angle) in the form of parameters were modified to alter building design and create different façade alternatives. The initial single-zone pilot study was undertaken with a simple cube shape to narrow down the number of input parameters. This boxed-shape single thermal-zone unit allowed enhancing controllability on the form generation and testing the performance of the software regarding the alterations on the wall inclination. The Inclination angle of the south façade ($Tilt_{\theta south}$) of the pilot unit (variables) was manipulated to test the effectiveness of the façade inclination at 5° increments starting from 90° (vertical façade) to 145° (55° beyond the vertical). Afterwards, the results of the pilot study were used to implement smaller number of parameters to the existing case study, which have complex and realistic thermal zones. The chosen method will be expanded in the next section (Section 5.3).

5.2.2 Thermal analysis research methodology (thermo-analytical methods)

Thermal behaviour in a building and the performance of shading strategies for improving summer thermal comfort on the building can be assessed by (i) real data measurement (monitoring) or (ii) simulation modelling methods.

Monitoring data is widely accepted because it represents realistic situations of relative measures. Monitoring and evaluation of a building post occupancy, in general, helps to observe if a significant “performance gap” has been experienced. What is substantial about monitoring compared to simulations is that unexpected occupants’ behaviour can be discovered. However, this method is very time-consuming and more expensive than simulation methods. Monitoring performance is also dependent on the outdoor weather conditions of the particular year that the monitoring was carried whereas, in the simulation modelling, weather data can be easily changed and even the predicted future climates can be applied.

Dynamic and static simulation programmes have been developing since the 1970s to calculate the physics of a building. Several sophisticated software packages that can simulate a building’s energy and environmental performance (e.g. EnergyPlus, DesignBuilder, IES VE, PHPP, and Ansys Fluent) provide an accurate estimation of building performance. Although simulation studies have been extremely useful to predict buildings energy performance, it has been stated in many modelling studies (Robinson & Haldi, 2011; Wright, et al., 1999; Lomas & Porritt, 2017) that it is difficult to assess the absolute variability of occupant behaviour. There are also some limitations on ventilation potential and solar control schemes, which are again very dependent on the residents’ lifestyle. In contrast, real measurements can capture the full variability of such measures. However, there are also, limitations for the real data measurements including sensor failure and abnormal values for a specific time because of problems with the internal clock etc. (Lomas & Kane, 2013).

Since this study investigated different form alternatives under different weather scenarios, many input parameters will result in a significant number of combinations and so computer simulation modelling was the most suitable method to consider.

The dynamic modelling software DesignBuilder was chosen over static simulation packages such as SAP and PHPP, which have very significant limitations on calculating complex geometries. They also have limitations on hourly thermal calculation because they do not calculate frequent time intervals in the calculation process. These steady state calculation methods give average daily mean temperatures which then will not effectively take into account building characteristics such as thermal mass on frequent hourly intervals. Whereas dynamic model simulations such as EnergyPlus the calculation over thermal mass parameters includes the time intervals and it is possible to look at day to night time temperature variations.

5.3 The chosen methodology for the study

The main method used for this study was computer numerical thermal simulation as a substitute for direct measurement and experimentation. The methodology was originated on a basis of a multi-step application via dynamic simulations. Sensitivity analysis approach was adopted to assess alterations on the Passivhaus south façade. Five interrelated steps were taken to examine the impact of the tilted south façade on Passivhaus performance and comfort:

i. Selection of an existing Passivhaus dwelling in the UK
ii. Modelling and validation of the dwelling’s performance
iii. Selecting weather data for simulations
iv. Conducting an initial pilot study to narrow down the inclination variables and choose effective façade geometries (tilt angle interval)
v. Case study thermal analysis –Assessing the impact of the introduced geometry to future performance of the Passivhaus

5.3.1 Selection of an existing Passivhaus dwelling in the UK

An existing Passivhaus dwelling with available thermal analysis and monitoring data was considered as a reference case to validate the model. The building chosen for the case study was the Larch House, a three bedroom, 87m^2 floor area, timber frame detached house with certified CSH Level 6 Passivhaus standards in Ebbw Vale, Wales.

The house was one of the social housing prototypes built for the United Welsh Housing Association (UWHA, n.d.) in co-operation with the Welsh Assembly Government (WAG, n.d.), Building Research Establishment (BRE, n.d.) and the works team at Blaenau Gwent County Borough Council (BGC, n.d.), who worked collaboratively with bere:architects and Pendragon (Design & Build) Limited. The social housing prototype was part of the master plan consisting of offices, a school, a hospital, leisure centre, housing, eco-homes, and other buildings located over an area of 200 acres at Ebbw Vale. The target for the site was to have a 60% reduction in CO_2 emissions against building regulations. It was proposed to develop several sustainable houses in accordance with the Passivhaus principles to have excellent comfort conditions in both winter and summer (United Welsh Housing Association, 2010).

Larch House comprises a living room on the ground floor with south-facing windows, together with windows on the side (east) and at the rear (north). A south-facing kitchen and dining area are on the west side of the floor plan and a staircase leads to the three bedrooms on the first floor. The main bedroom (Bedroom No.1) is located on the south facade and bedroom No.2 at the rear of the building and bedroom No.3 is south-facing on the west side (see Figure 5-1, 5-2 and 5-3).

The building was the first Code Level 6 (Code for Sustainable Homes) zero carbon Passivhaus dwelling in the UK (McLeod, et al., 2012) . It was designed based on the strategy to maximize the benefit of solar heat gains (Ridley, et al., 2014) and achieved an outstanding draught-free construction with an air tightness result of just below 0.2 ac/h @ n50 surpassing the Passivhaus requirement of minimum 0.6 ac/h at 50 Pascal.

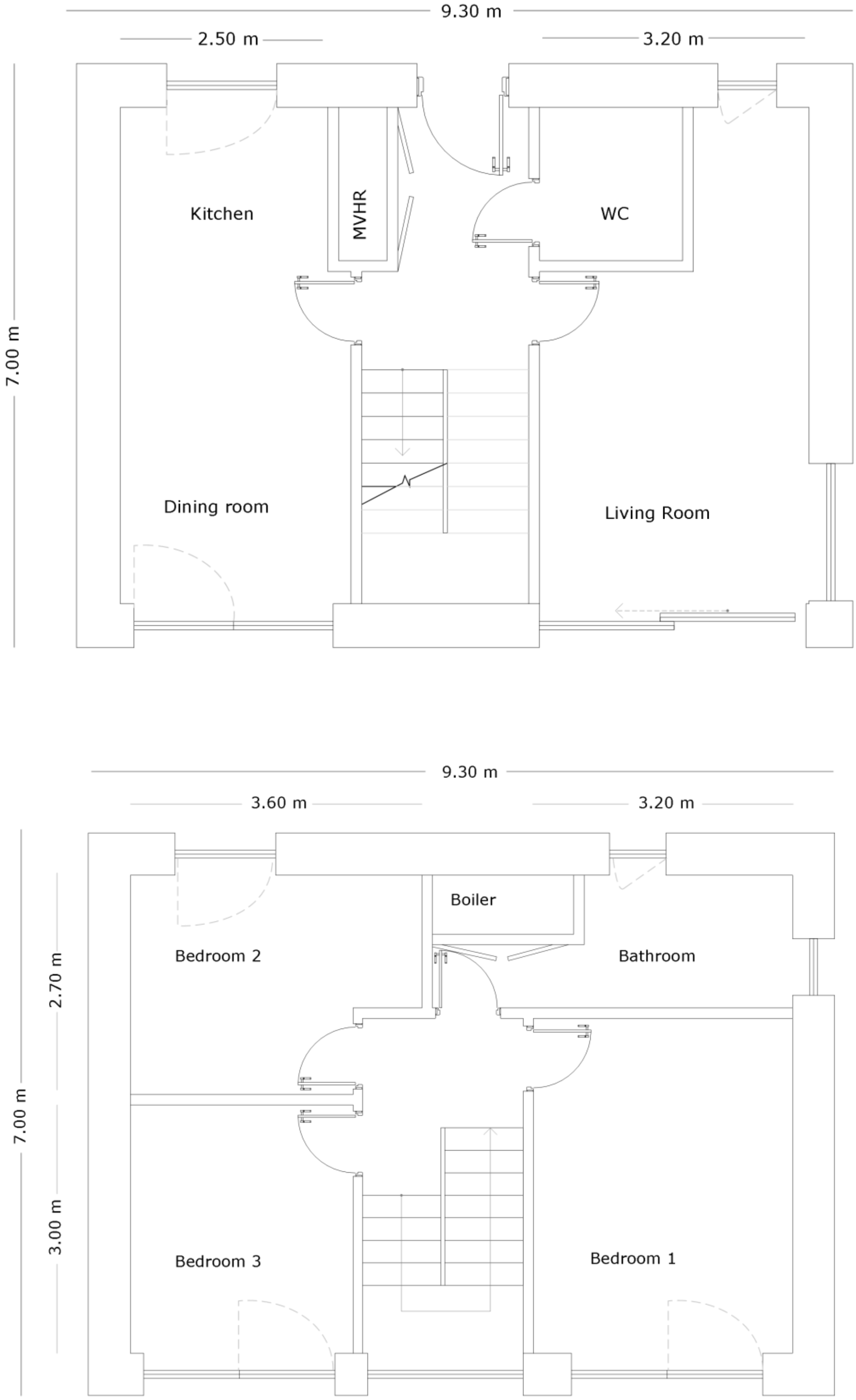


Figure 5-1 Ground floor (top) and first floor (bottom) plans of Larch House

Figure 5-2 South (left) and North (right) elevations of the Larch House

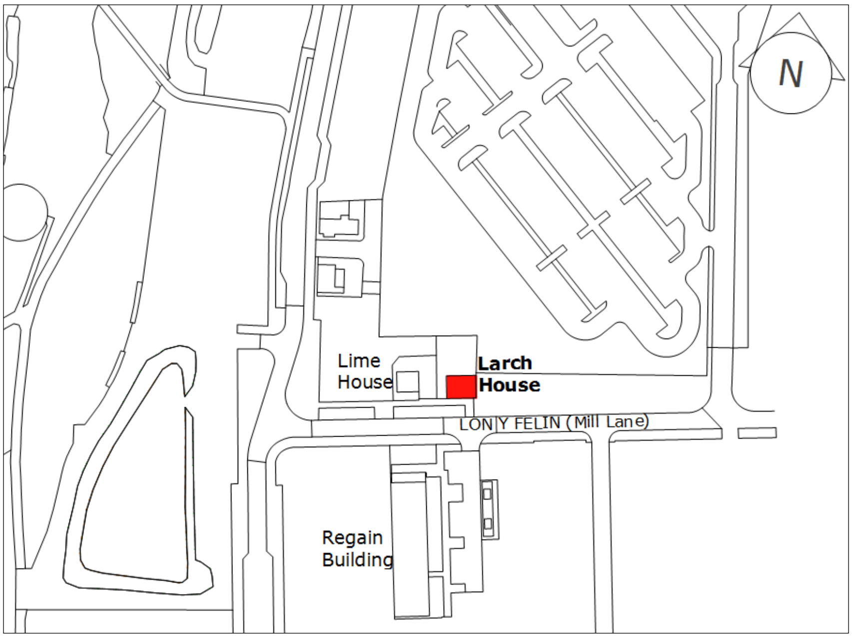


Figure 5-3 Location plan of the Larch House- Ebbw Vale

Large south-facing windows, super insulation, and closed-panel timber framing were used to minimize draughts and photovoltaic panels added to the zero-carbon footprint of the property. The building uses external roller blinds (see Figure 3-5) to prevent summer overheating. It should be noted that the blinds were assumed to be operated by the occupants in the summer time. Like many Passivhaus dwellings, Larch House has a large glazing area on the south elevation (55 % of the façade area) and external and internal blinds for controlling the shading.

Another reason for choosing Larch House as a case study for this research was the complaints of overheating that arose during monitoring of the house. Computerised shading devices had been provided, but studies in the house revealed that user preferences often contradicted automated shading control actions and occupants preferred to control the blinds manually or over-ride the automatic system. The malfunction of the blinds use and window openings in the Larch House case study is believed to be the main reason for overheating problems during summer months (Technology Strategy Board, 2014).

5.3.2 Modelling and validation of the dwelling's performance

The building case study was modelled using the dynamic thermal simulation package DesignBuilder –integrated EnergyPlus engine– version 3.4 (later some analysis was conducted using v.4.2 and v.5.0). DesignBuilder has been validated by reliable energy calculation standards i.e. EN ISO 13790 Standards (DesignBuilder Test Results, 2012), ASHRAE, and EnergyPlus validation testing result (ENERGYPLUS, 2014) verifies the robustness of the software. However, to ensure confidence in the results of the DesignBuilder model, it was necessary to compare the simulation results with the values provided by the architect – bere:architects, who used the steady state Passive House Planning Package (PHPP) for simulation of the house. The predicted results from the PHPP file were used to validate the model. Later, when the monitoring data were available monitoring data were also used for verifying the simulation data and mark out unexpected occupant's behaviour. However, due to some significant differences on some of the measures between predicted PHPP file and monitoring data this study referred to the monitoring data. Chapter 6 will elaborate on the process of modelling and validation.

5.3.3 Selecting weather data for simulations

This study used London (UK) climate data to investigate current and future summer overheating. Considering the fact of a warming climate, there are three options to approximate the future weather conditions. The first one is to use current weather file from a European Location in lower latitudes such as Italy, Spain, Greece, etc. The second option is to use current heat-wave period to approximate the future summer conditions; and third one, which was used in this study, is to use future predicted UK weather data.

To date (2014) the latest climate change projection for the UK is CIBSE's Climate Change Projection 2009 (UKCP09). The PROMETHEUS team (Eames, et al., 2011) based at Exeter University have developed ready future weather files in EnergyPlus format (.epw) using UKCP09 weather generator. These hourly weather data files are available under low, medium and high emission scenarios with different percentile probabilities (i.e. 10, 33, 50, 67 and 90 percentiles) for both Test Reference Year (TRY) and Design Summer Year (DSY) weather data. A 10% probability level represents the weather that the summer temperatures is very unlikely to be less than and 90% marks the weather that very unlikely to be greater than. 50% is a representative of central estimation for a given climate projection (timeslise). The TRY is generated using the most average months within the 20-some years of data including drybulb temperature (DryT), global solar irradiation (GlRad) and wind speed (WS). The selection of the most average months is based on the cumulative distribution functions of daily mean values of the aforementioned climatic parameters –for more detail refer to Levermore and Parkinson (2006). DSY also takes some 20 years of weather data but, unlike TRYs, which consider all months in the years, the DSY takes daily mean DryT for months April to September of each considered year (Levermore & Parkinson, 2006). Both TRY and DSY are available for 3 future intervals i.e. 2030's, 2050's and 2080's. Where DSY tends to give warmer summer days and TRY is more representative of the whole year. TRY-morphed years are based on typical months from a number of years, avoiding extreme month and heat wave periods, like the one in August 2003. DSY, on the other hand, contain hot summer days. Figure 5-4 shows a probabilistic climate profile (ProCliP) for summer London future climate.

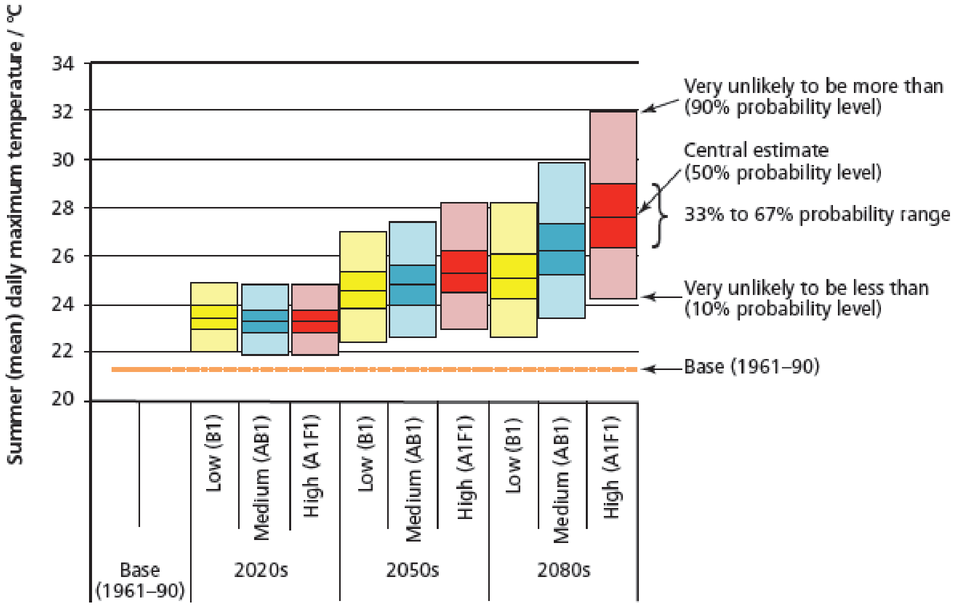


Figure 5-4 Probabilistic climate profile (ProCliP); London summer (Jun, July, Aug) mean daily maximum temperatures (CIBSE Guide A , 2015)

Many researchers to date have used medium to high emission future weather data with the central estimate (50% medium scenario) e.g. Mavrogianni, et al. (2012). Others used the worst-case scenario of high emission 90 % probability (A1FI 90%) where the changes are very unlikely to be greater than e.g. Gupta and Gregg (2012). Gupta and Gregg (2012) argued that the most robust design for future climate should be resilient to the worst-case scenario. On the other hand, some argued (Bere, 2014) that considering extreme worst-case scenario for building design is very costly and is unnecessary because it may be very unlikely to happen. The PHPP weather file used for designing Larch House was driven from ten-year worst-case weather data. The selection of the weather file was later objected to by the design team (bere:architects) as unnecessary and, instead, the average weather data should have been used. As a result, this led to significantly more south facing glazing and more insulation than would have been required under normal weather data (Bere, 2014). Mavrogianni, et al. (2012) used the warmest 5-day continuous period from the UKCP09 50 percentile medium scenario (A1B) of Design Summer Year (DSY) to examine overheating in future London dwellings. Although the UKCP09 recommends that all the emission scenarios be studied, findings from Raupach, et al. (2007) showed that the accelerating CO_2 emission during 2000 to 2004 was at a faster pace than the highest emission scenario of A1FI. Overall, studies (Porritt, et al., 2011) urge further investigation based on more extreme weather years where additional interventions are likely to be necessary.

Lomas and Porritt (2017) argued there remains work to be done on the selection of future weather data as it has a significant impact on the predicted intensity and duration of elevated internal temperature. For the modelling in this thesis an average pessimistic future scenario i.e. high emission 50 percentile probability (A1F1 50%) was chosen rather than the intermediate or worst case scenario (details on London weather data are presented in section 7.2.1). For the building design simulation, test reference years (TRYs) are often used when analysing the energy requirement and design summer years (DSYs) are generally used to asses mixed mode and natural ventilation in near-extreme summer condition (Levermore & Parkinson, 2006). Although this study focused on the summer thermal comfort but it also considered the whole year energy performance including the energy use for space heating in winter therefore, the Test Reference Year (TRY) data was used. Investigating the influence of shading on the energy requirements obviously mostly refers to the summer time. However, simulations should not be conducted only for summer time as shading affects both cooling and heating systems for a complete annual cycle. London (Islington) weather files were used to simulate the model as it is within an area of England projected to feel the greatest temperature rise and it is most likely to be affected by the impact of any UK climate change due to the urban heat Island (GLA, 2006). The situation in London can be an example for other big cities in the future since it is reported by the United Nations (UN, 2009) that the population in the urban settlements has grown from one-third of the world's total population to more than half.

CIBSE weather Guide (CIBSE Guide J, 2002) defines the summer period from April to September. DesignBuilder also defaults summer period being from April to September for UK climate indicating this period as "all summer" simulation option. Regarding the concern over summer thermal discomfort some studies (Wright, et al., 1999; Lomas & Kane, 2013) focused on the summer period from 1 July to 31 August and some of the more detailed analysis was carried for a shorter period i.e. 1st-7th of August. In this study the whole summer was considered, with the focus lying on the hottest summer months i.e. Jun, July, and August (considering April, May and September as shoulder months). The reason for this is that in some studies significant overheating was found during the adjacent months when solar angles are lower and shading less effective. For some of the analysis a summer design week or summer typical week were used to test the building performance for the hottest week (referred to as "summer design week" in DesignBuilder) or for an average representative of summer months (referred to as "summer typical week" in DesignBuilder).

5.3.4 Conducting an initial pilot study

After software reliability and the accuracy of the model had been tested against available real data series, a pilot unit was modelled using the specifications of the reference case. The pilot study was conducted to narrow down the inclination variables and choose the possible façade geometries for the case study (tilt angle interval). A sensitivity analysis approach on the pilot model was adopted to assess geometric alterations to the Passivhaus south facade.

To the best of the author's knowledge, the impact of a tilted façade has not been studied regarding thermal comfort and energy use for a Passivhaus design. In addition, the pilot study was conducted to examine the effectiveness of the software in response to changing the façade inclination. It is worth reminding that in DesignBuilder's current version when modifying the inclination of a wall, all the affected internal zones should be re-setup; therefore, a single-zone pilot unit was needed to conduct the initial analysis within a reasonable time frame.

Parametric analysis is a powerful new feature in the new version of DesignBuilder (V.4 and V.5) which can automatically run multiple simulations adjusting up to two variables to search for optimal design. For instance, the comfort (operative) temperature (as the main data) can be displayed based on changing two variables of say (i) window to wall ratio (in 20% increment i.e. 0%, 20%, 40%, 60% to 100%) and (ii) overhang depth (in a 0.5m interval i.e. 0.5,1.0,1.5 and 2m) . Alternatively, total energy consumption (as the main data) can be calculated based on changing one parameter of say glazing type. In the first example, the established operative temperature can define optimum window to wall ratio and overhang depth. For the second example, the lowest energy requirement can define the best glazing type among glazing options set to the programme. There is a list of variables and data display that can be chosen to reach optimisation in design (using current EnergyPlus engine in DesignBuilder). However, the software does not support geometrical alterations as variable options. Therefore, this should be conducted manually. If the software has had allowed to choose inclination of a façade as a variable option, then energy consumption and overheating as the main data and south façade tilt angle as the variable should have been chosen to reach optimization on the tilt angle. Thus, manual parametrisation was used as a substitute of automatic adjustment which is more time demanding. Each time a counterpart of the pilot unit with different façade inclination angle (see Figure 7-13) was modelled and simulations were run to conduct a sensitivity analysis of changing the south façade elevation. Data on pilot model and simulation setting are presented in the result of the pilot study (Section 7.3).

5.3.5 Implementing the proposed geometry to the case study

Results from the pilot unit simulations helped to narrow down the variables and choose a smaller parametric interval for the case study. Data analysis from the pilot study resulted in a smaller number of simulations on the reference building (Larch House) with a more complex geometry and thermal zones (see Figure 5-1). After replacing the south façade with the tilted walls all thermal properties of the affected zones were re-assigned and south facing windows also re-drawn based on the size of the windows as per case study PHPP file.

The proposed façade design based on the initial analysis was implemented to the actual case study for current and future London climate. Thermal analysis data, including overheating rate for selected facades, were carried out and an optimum (or near-optimum) façade inclination was defined. The suggested tilted façade was then analysed alongside the performance of some of the existing interventions i.e. overhangs and reducing window to wall ratio to compare their effectiveness in reducing overheating risk.

Manipulating the tilt of the south facing façade will clearly have other impacts on, for instance, winter heating demand, daylighting and natural ventilation air flows, and these parameters were also examined using the lighting and computational fluid dynamics CFD algorithms in DesignBuilder.

The air dynamics can be obtained by real scale measurement or by wind tunnel experiment. It also can be calculated by means of computational fluid dynamic (CFD). Although wind tunnel is a very accurate tool and it is easy to work with different shape models however the scarcity of such device makes it difficult to investigate numerous of building forms in a wind tunnel. CFD simulation has the same advantages for calculating pressure distribution and air flow pattern as a wind tunnel. However, the accuracy of such tool must still be enhanced in particular when working with complex geometry. The CFD package is widely used in industrial applications due to the reliable numerical stabilities and small computational expenses.

The study explored the consequence of the tilted façade on the air movement using a “calculated natural ventilation” analysis. The average indoor air velocity as an indicator of the physiological comfort for each alternative was calculated under different wind directions. The research also investigated the effect of different design combinations on daylighting. Daylight factors for the studied variants was calculated under an overcast sky. The values were then compared to the original case study.

5.4 Summary

Overall, this study presents a sensitivity analysis of building facade inclination as a function of shading for Passivhaus dwellings. The results of the simulations will test if the envelope shape affects the energy efficiency of the buildings and if it can, potentially, reduce probable serious overheating risks in future summers. The model was developed in DesignBuilder using EnergyPlus engine. It was validated against empirical data. The weather files used for simulations were created by PROMETHEUS team using the UKCP09 weather generator for current and future. In this study, the average values of future probabilistic scenarios were used rather than the best or worst case scenarios i.e. A1FI_50%_TRY for the 2030s, 2050s and 2080s. The initial pilot unit was conducted for a range of south façade inclinations. Then the results from the pilot unit led to investigating more realistic values on the case study to examine if potential improvements in reducing overheating rate were achieved. The proposed geometry was implemented to the case study and it was compared with existing passive interventions. A comparative analysis also investigated the consequences of the tilted façade on the heating demand, and natural ventilation and daylighting were also studied. In Chapter One (see Figure 1-5) the overarching structure of the research was depicted. Figure 5-5 also demonstrates schematically the structure of the methodology.

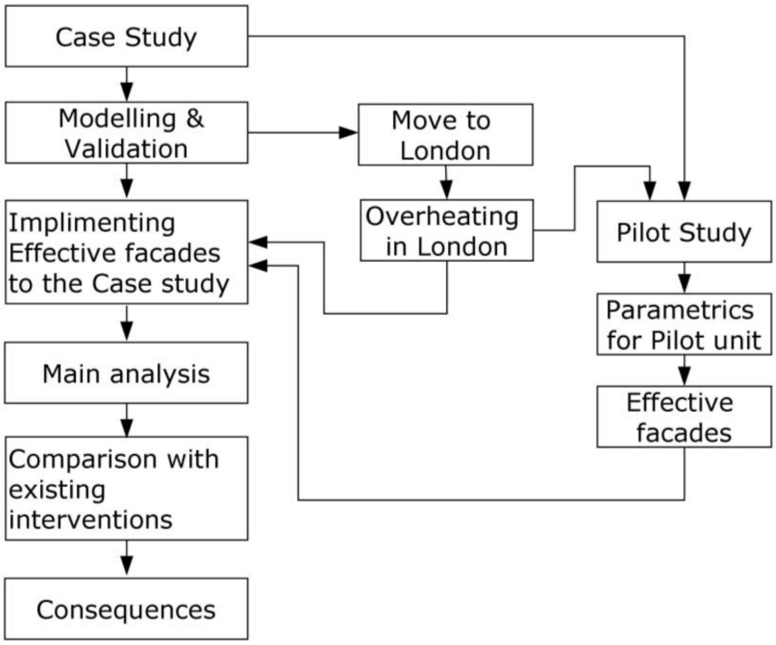


Figure 5-5 Methodology diagram

Chapter Six

6 Modelling and Validation

In this Chapter the case study (Larch House) was modelled, validated, and then moved (virtually) to London’s climate for further analysis in Chapter Seven. This chapter also comprised the software settings including construction material, HVAC template and user’s activity pattern.

6.1 Input parameters for simulations

6.1.1 Fabric

The software (DesignBuilder) supports importing 3D geometry files from various CAD software using BIM and gbXML format files. However, this may cause some problems with defining some of the fabrics. Therefore, 3D geometry was created in DesignBuilder to avoid potential errors in importing 3D model and integrating internal library to imported file. The model was drawn with almost the same dimensions as the existing house (as per AutoCAD file provided by bere:architects). The orientation of the house is along an east/west axis with a southern exposure and within a 7° deviation from south to west (the site orientation in DesignBuilder was set at 353°, with north-west being 315° and north arrow being 360°). In DesignBuilder north is used as the reference direction and all the deviation angles are measured from the North. Table 6-1 defines ɸ-values as the reference (as per software’s orientation detail) used in this study.

Table 6-1 Orientations and ϕ-values as per software settings

Orientation	ϕ
North (N)	0°-360°
Northeast (NE)	45°
East (E)	90°
Southeast (SE)	135°
South (S)	180°
Southwest (SW)	225°
West (W)	270°
Northwest (NW)	315°

The modelled house is a timber frame construction filled with heavily insulation materials with local timber cladding (Welsh larch timber). Construction materials used for the Larch House case study model and the pilot models are listed in Table 6-2. DesignBuilder requires a detailed input to define properties of construction layers, including the thermophysical properties of each layer. The summery of the materials property and calculated construction data for external walls are presented in Table 6-2 and Table 6-4. The full construction details of other materials are presented in Appendix A, Table A-1 to Table A-9.

Table 6-2 Construction materials and their physical properties used for Larch House

Element	Construction	U-value ($Wm^{-2}K$)	Thickness (mm)
Exterior walls	Plasterboard, wood fibre insulation, OSB, Knauf frame insulation, Panelvent and wood fibre insulation	0.095	467/525
ground floor slab	4 layer of FLOORMATE 500-A, concrete, screed and finish flooring	0.076	800
Flat roof	OSB and four layer of Knauf frame insulation	0.074	578
sloped roof	Timber truss, timber batten and slate tiles	0.33	175
In-between floor slab	Floor finish, chipboard, Ecojoist with loose fill insulation in between joists and plasterboard	0.17	271
Glazing	Triple solar glass with voids	0.86-0.76	48-54

Table 6-3 External wall's fabric data

	Larch House External Wall	
Source	DesignBuilder (Energy Plus)	
Category	Walls	
Definition method	Layers	
Simulation solution algorithm	Default*	
U-Value	0.095	
		Thickness (mm)
Number of layers	8	525
Outermost layer (Layer 1)	Welsh Larch timber cladding	20
Layer 2	Counter Battens	32
Layer 3	Pavatherm Plus insulation	100
Layer 4	DWD board	15
Layer 5	Knauf Thermal insulation (between studs)	225
Layer 6	OSB board	18
Layer 7	Steico Flex wood fibre insulation (between battens)	100
Innermost layer (Layer 8)	Plasterboard	15

*Refer to DesignBuilder user manual **(2015)**

Table 6-4 External wall's calculated constructions data

Calculated constructions data _ external wall	
Inner surface	
Convective heat transfer coefficient ($Wm^{-2}K$)	2.152
Radiative heat transfer coefficient ($Wm^{-2}K$)	5.540
Surface resistance (m^2KM^{-1})	0.130
Outer surface	
Convective heat transfer coefficient ($Wm^{-2}K$)	19.870
Radiative heat transfer coefficient ($Wm^{-2}K$)	5.130
Surface resistance (m^2KM^{-1})	0.040
No bridging	
U-value surface to surface ($Wm^{-2}K$)	0.091
R-value ($Wm^{-2}K$)	11.123
U-value ($Wm^{-2}K$)	0.095
With bridging (BS ENISO 6946)	
Thickness (m)	0.5250
Km Internal heat capacity ($KJm^{-2}K$)	23.9250

Calculated constructions data _ external wall	
Upper resistance limit (m^2KW^{-1})	11.123
Lower resistance limit (m^2KW^{-1})	11.123
U-value surface to surface ($Wm^{-2}K$)	0.091
R-value (m^2KW^{-1})	11.123
U-value ($Wm^{-2}K$)	0.095

The glazing area was calculated based on the original PHPP file of the case study presented in Appendix D (Larch House PHPP File, 2010). The "Windows" tab in the worksheet directory i.e. PHPP file of the case study (see Figure D-2) shows that nearly 55% of the south facade consisted of glazing, of which 68.5% was fixed and 18.5% could be opened. The remaining 13% of the glazing accounts for a glazed sliding door, which opens from the living room to the yard. The total windows area for south façade is 28 m^2, of which 67.5% is fixed. Figure 6-1 depicted and Table 6-5 summarises the amount and type of glazing used to model the case study, including fixed and operable windows.

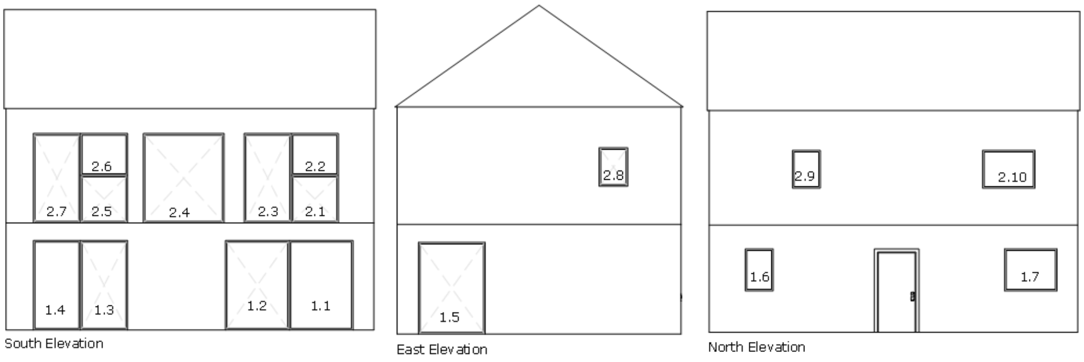


Figure 6-1 Glazing input: South (left), East (middle) and North (right) elevations

Table 6-5 Glazing input for the model

Window No	Position	Orientation	Type	Area (m^2) Inc. frame*	U-Value
1.1	G Floor	South	Fixed	3.6	0.73
1.2	G Floor	South	Operable**	3.6	0.73
1.3	G Floor	South	Fixed	2.7	0.75
1.4	G Floor	South	Operable	2.7	0.75
2.1	1st Floor	South	Fixed	1.3	0.79

Window No	**Position**	**Orientation**	**Type**	**Area (m^2) Inc. frame***	**U-Value**
2.2	1st Floor	South	Operable	1.4	0.78
2.3	1st Floor	South	Fixed	2.7	0.75
2.4	1st Floor	South	Fixed	4.6	0.72
2.5	1st Floor	South	Fixed	1.3	0.79
2.6	1st Floor	South	Operable	1.4	0.78
2.7	1st Floor	South	Fixed	2.7	0.75
1.5	G Floor	East	Fixed	3.7	0.75
2.8	1st Floor	East	Fixed	0.7	0.90
1.6	G Floor	North	Operable	0.7	0.89
1.7	G Floor	North	Operable	1.4	0.82
2.9	1st Floor	North	Operable	0.7	0.90
2.10	1st Floor	North	Operable	1.3	0.84

*Area of the glazing including the frame of the window
**Sliding door glazing

All windows have internal curtains and the occupancy schedule section will reflect on the usage of the internal shading. External blinds with high reflectivity slats were positioned outside of south facing windows to control shading, providing an 85% reduction factor. The blinds are operating based on the occupancy schedule, because the automatic system was deactivated upon the occupants' request (see Section 6.1.3). Window frames and partition materials were chosen from the software's built-in library. The chosen default options of the reveal and frame dimensions were very like those from the case study. However, these will not make a noticeable difference in the results.

6.1.2 HVAC

DesignBuilder provides both simple and detailed HVAC modelling capabilities. The simple HVAC definition method is normally used for early stage modelling and for modelling more involved in other aspects of building performance such as heat gain and losses from the building envelope (DesignBuilder User Manual, 2015). Detailed HVAC is normally used to design an optimum mechanical heating system and provide with a comprehensive analysis of an automated system. This option involved more work in setting up the parameters for each zone to calculate how efficiently the mechanical ventilation with heat recovery system works. This study used a simple HVAC model that operates using load calculation algorithms. In this model the heating/cooling capacity was set by heating/cooling set point temperatures and occupancy schedule and ventilation is set using air change per hour rate (ac/h) for each thermal zone. In this research the assembly of the components to create an HVAC system model did not take place because the scope of the study was not to analyse the performance of the HVAC system (i.e. MVHR). Accordingly, the heat recovery efficiency was not calculated and it was set according to the average of two-year monitoring data i.e. 76% (Technology Strategy Board, 2014).

Thus, the study chose the closest system to the MVHR system used in Larch house. This operation template was selected from the built-in HVAC library of the software. Like the MVHR system in the Larch House, it was a mechanical ventilation system with heat recovery using supply and extract terminals. This system works based on the extract and supply ducts (Figure 6-2). Exhaust air is removed from extract terminals (shown in red) and returns to the system. The air then is filtered and heated (recovery) to provide heating to the living spaces using supply terminals (shown in blue).

Windows were closed in wintertime and ventilation was operating only using MVHR system with a minimum 0.3 air changes per hour. However, in the summer natural ventilation was operating by opening the windows (cross ventilation). It should be noted that “scheduled natural ventilation” mode was used for all the simulations except those for the CFD analysis, where “calculated natural ventilation” mode was used (Chapter Eight, Section 8.2.1). The monitoring data (Technology Strategy Board, 2014) revealed a monthly MVHR ventilation rate of between 0.3-0.4 ach^{-1} (average of two years HVAC ventilation 0.31 ach^{-1}) with a low summer natural ventilation. In addition to mechanical ventilation, the summer natural ventilation change rate was defined for each zone by ACH value on a schedule operation (see Table 6-6). Nonetheless, air infiltration was defined by a constant ACH value independent of a schedule that was like Larch House, was set to 0.2 ach^{-1} @ n50.

The heating set point, which operates like a heating thermostat, was set at 20°C operative temperature. This defines the temperature in the space when heating is required to operate to ensure the minimum temperature of 20°C for Passivhaus in occupied periods. Similar to the Larch House, there is no mechanical cooling available in the HVAC system for summer time.

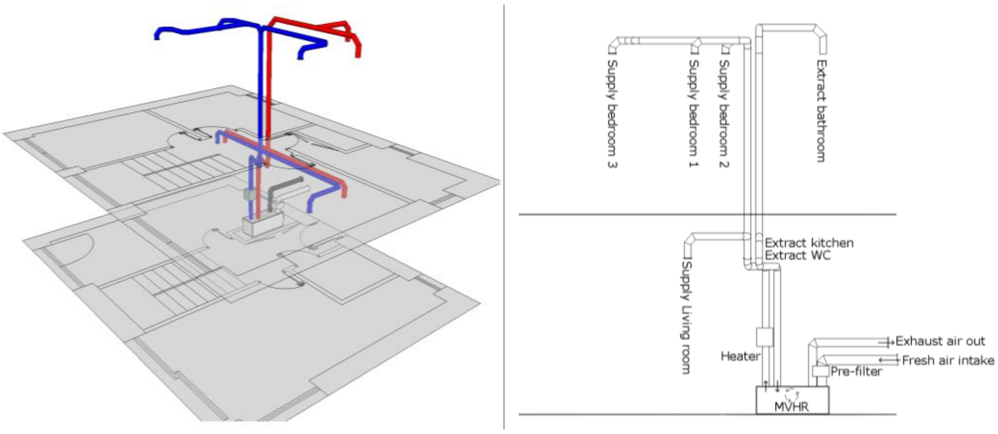


Figure 6-2 MVHR system scheme, adapted from Technology Strategy Board (2014)

To prevent opening the window on cold days in this period, especially in the shoulder months (current climate), the window opening was disabled in case heating was in operation. Also, to avoid transferring heat into the building for future weather data (in the case of excessive outdoor temperature), the temperature difference (Delta T) was set at 2°C. This meant that the ventilation was available if the outside air temperature was at least 2°C cooler than the zone indoor temperature. Windows were to be closed if the temperature outside was too warm, and then natural ventilation was automatically turned off.

6.1.3 Occupancy schedules

The output results from the thermal simulation in DesignBuilder (like other building thermal simulation tools) vary significantly depending upon changing the operation schedule, even for small changes. For instance, different behavioural pattern towards blind operation would give very different overheating rates, and consequently different thermal comfort, and energy use. To represent a realistic operation schedule, where both optimum solar heat gain and visual comfort are met, the research used several studies, including the work of (Haldi & Robinson, 2010; Sutter, et al., 2006).

Several projects found in the literature have studied the impact of the occupants' behaviour on building energy and environmental performance. They found a significant uncertainty in predicted energy performance due to residents' behaviour. This study will follow those models where the activities depend on different variables, including clustering the time, density of presence and comfort indicator. For instance, Schweiker, et al. (2011) used a stochastic model based on Multi-layered Artificial Neural Network (MANN) where the calculations depend on nine explanatory variables (see section 3.3.7).

In this study, different occupancy patterns were applied to explore the impact of occupant use and extent of the vulnerability. In particular, with automatic blind operation on the south façade disabled (see section 3.3.2) the blind operation schedule would be more difficult to replicate. Different occupancy schedules were introduced to the model and are presented in Table 6-6. Some of the blind operation schemes were chosen from a dropdown menu built in DesignBuilder. The operation schedules included a perfectly tuned operation of blinds to be shut when internal temperature was high in summer (DB.10) or summer solar radiation was excessive (DB.7). It also included a poorly managed arrangement (DB.6) and an arrangement where users operated the blinds to their best (DB.3). Because none of the built-in schedules in the DesignBuilder library were a good fit and, consequently, the results achieved were not satisfactory, the author adapted the schedules based on a compact schedule script in the DesignBuilder specified for the living spaces, where the fraction of the blind operation is higher during intense summer sunshine hours (DB.1 and DB.2). However, this does not mean that blinds were always closed during these periods i.e. intense solar radiation. These specific scripts for the blind operative schedules derived from a typical UK household and limited data about occupants lifestyle and working hours (Tenants' household, 2012). The bedroom is occupied (with different fractions) from 10:00 PM to 8:00 AM weekdays and 11:00 PM to 9:00 AM weekends. The Living room is occupied from 5:00 PM to 11:00 PM weekdays and 9:00 AM to 11:00 PM weekends. Operation of the blinds differed in different seasons.

A full Blind operation schedule script written by the author and used for the living room and bedroom can be found in Appendix B. With two parents and two children occupying the house, and the total treated floor area being 87 m^2, the occupancy density was set to 30 m^2/person (0.03 P/m^2). At the time monitoring took place children were very young so each were counted as 0.5 of a person. Internal heat gain from people and appliance was determined according to data from reliable guidelines (CIBSE Guide A, 2006; ASHRAE, 2013). Metabolic rate for a seated adult was set to 108 W/person and for sleeping adult and children was set respectively to 72 and 54 W per person. The appliance gain for the living room was assumed to be 150W and 100W for bedrooms at the time of occupancy.

Table 6-6 Case study model with various non-definitive values (occupant choice)

	Occupants' blind operational schedule	Lights and appliances	Window opening*
DB.3	Occupants use the blinds relatively to their best winter; mostly open / summer; mostly close	3900 kWh (high)	0.6 ach^{-1}
DB.4	Summer and winter; blinds always open	2400 kWh (Low)	0.7 ach^{-1}
DB.5	Summer and winter often open	3500 kWh (average)	0.7 ach^{-1}
DB.6	Winter; often close, summer; highly open	4420 kWh (high)	0.4 ach^{-1}
DB.7	Shading is active if radiation incident on the window exceeds 300 Wm^{-2}	3100 kWh (average)	0.8 ach^{-1}
DB.8	Blinds are shut if solar radiation incident on the window exceeds 250 Wm^{-2}	3210 kWh (average)	0.6 ach^{-1}
DB.9	Blinds are shut if solar radiation incident on the window exceeds 200 Wm^{-2}	3308 kWh (average)	0.7 ach^{-1}
DB.10	Blinds are shut if zone air temperature in the previous time step exceeds 24°C	3100 kWh (average)	0.7 ach^{-1}
DB.1	Operation based on a specific script written by author	4235 kWh (high)	0.4 ach^{-1}
DB.2	Operation based on a specific script written by author	2873 kWh (average)	0.9 ach^{-1}

* Average minimum natural ventilation in addition to MVHR ventilation

Monitoring performance of the house showed a significant difference in overheating rate from the predicted PHPP file. The high percentage of overheating difference was because residents did not effectively open the windows in summer. However, an occupancy schedule was modelled to reflect the monitoring data (DB.1) where occupant did not open the windows adequately in summer. Nevertheless, monitoring revealed that the reason behind this was that in summer the children were not allowing windows to be opened at night due to a fear of spiders. This was resolved by fitting insect mesh in the window and explaining the situation to the occupants (Tenants' household, 2012). Therefore, the impact of summer night purge cooling should be added into calculations by increasing the ventilation rate from the average two years monitoring value. Thus, a repeated simulation (DB.2) identical to DB.1 simulation but with a higher natural ventilation being modelled to represent the house after installing the insect mesh. Another performance gap which was known after the monitored outcome was the amount of electricity used.

Additional energy demand, compared to the predictions, occurred due to the high amount of cooking and electricity consumption from sockets (appliance use type). The typical (conventional) UK domestic electricity consumption is around 3300 kWh per annum. The Larch House PHPP file predicted an electricity consumption of 2209 kWh, whereas the actual monitored data revealed a value of 4495 kWh (see Table 6-7). This led to 158 kWhm^{-2} total energy consumption, which surpasses the annual energy demand from the Passivhaus standard of 120 kWh/m^2. It should be mentioned that the second set of simulations (DB.2) also improved on the energy use of appliances using total electricity of 2873 kWh and achieved the accepted Passivhaus standards of being below 120 kWh/m^2.

The space heating demand for two years of monitoring reflected very different weather conditions during the period. The average outdoor temperatures during the first and second year of monitoring were 7.9 and 9.8°C respectively. The PHPP weather file had an average of 9.4°C and the CIBSE weather file used for the simulations showed an annual average of 8°C for Ebbw Vale.

Table 6-7 Annual average electricity use from two years of Larch House monitoring

Measured (kWh)	Larch House monitoring value
Lights	245
Cooking	660
Sockets	3002
Total electricity (PV offset not included)	4495

The electricity used from the appliances also was normalised and reflected in DB.2. It is also acknowledged that from the monitoring performance it was also evident that occupants did not use blinds to their best and probably this should be also reflected in the calibration before assessing the building for overheating. However, this performance gap was not fixed because it directly affects the main objective of the study. Therefore, the same blind schedule from DB.1 was used for simulations DB.2.

To summarise the collaboration made to occupancy schedule, it should be clarified that both DB.1 and DB.2 have the same blind operation but with different window opening rate in summer – DB.2 has more window opening than DB.1. (Further discussion in section 6.2). The schedule close to the occupancy pattern of the case study with fine-tuning for the window opening was chosen as a benchmark of occupant behaviour in this study where building users react to the applications at the medium to high level of understanding but not the best case scenario. It should be noted that the occupancy schedule used for the simulations may vary from the occupant behaviour of Larch House. However, keeping the occupancy pattern constant throughout the study allowed a compatible comparison on the effect of façade alterations where all other variables after validations remained intact.

6.2 Model verification and validation

Validation is an essential part of the model development process. Computer simulation is the best practice to evaluate a building operational energy performance at the design stage and in the future conditions. However, as earlier pointed out (section 3.3.7) there are significant discrepancies between simulated results and real data measurement due to non-definitive parameters, such as occupant's behaviour, which are difficult to measure and commonly referred to as the "performance gap". This gap often occurs as the building users have more complex behaviours than it is expected. In some cases computer modelling can fill these performance gap by normalising the computer model with real data.

As previously stated (section 5.3.2) advanced dynamic simulation modelling software DesignBuilder (DB) was selected for the modelling in this research. DB is the most inclusive interface to EnergyPlus, which is the most advanced building modelling analyser. It has been subject to extensive validation programme (ENERGYPLUS, 2014).

It is recognised that well-stablished energy simulation software such as DesignBuilder provide a precise assessment of building performance especially when the calculations involve the physics of a building. However, two models with exactly same physical properties but different user specification have significant contradictions in their outcomes.

The replica of the case study house (Larch House) was modelled in DB (Figure 6-3) according to the specifications presented in the previous sections (6.1.1, and 6.1.2). Following the argument in section 6.1.3, different occupancy schedules were used initially and are described in Table 6-6. Current Ebbw Vale (Wales) weather data were used, which was obtained from epw files created by PROMETHEUS using UKCP09 weather generator (Eames, et al., 2011). Figure 6-4 shows the step by step modelling and validation took place in this study.

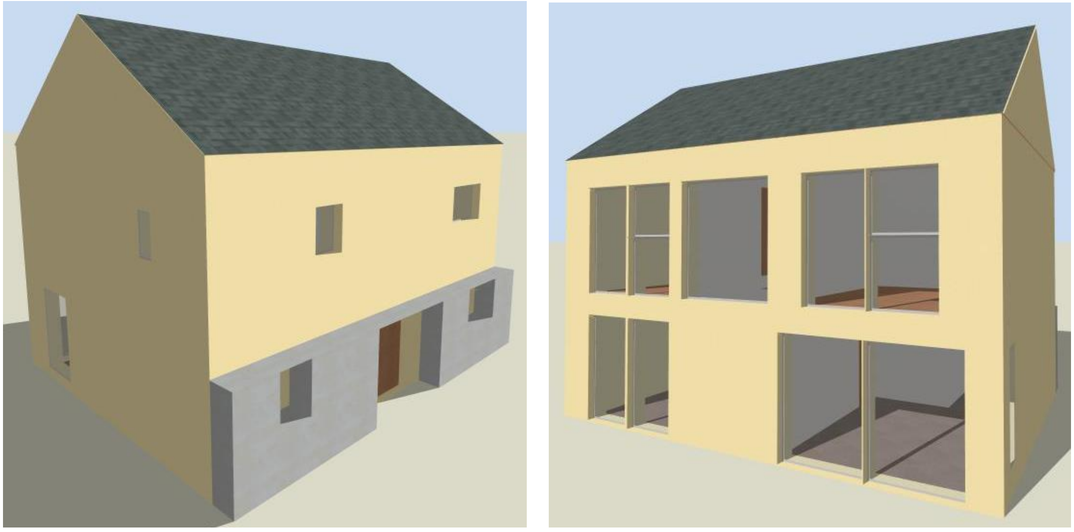


Figure 6-3 Case study model in DesignBuilder

The outcome results of the simulations of the Larch House model with different user-dependant variables showed that, although the occupant behaviour counts as one of the significant influence of the building performance, there is a small correlation between an individual variable (user dependant) and overheating (see Figure 6-5). The reason for this is that a combination of occupant behaviour i.e. blind schedule, window opening, appliances choice, etc. as a whole effects the building performance rather than one single behaviour. However, the operation of the blind and window opening had the most impact on overheating, especially the amount of solar gain received by windows showed the highest correlation to overheating amongst user dependant variables (Figure 6-6). Nevertheless, the correlation between indoor operative temperature and overheating for living room (Figure 6-7, left) with more glazing was higher than the bedroom (Figure 6-7, right).

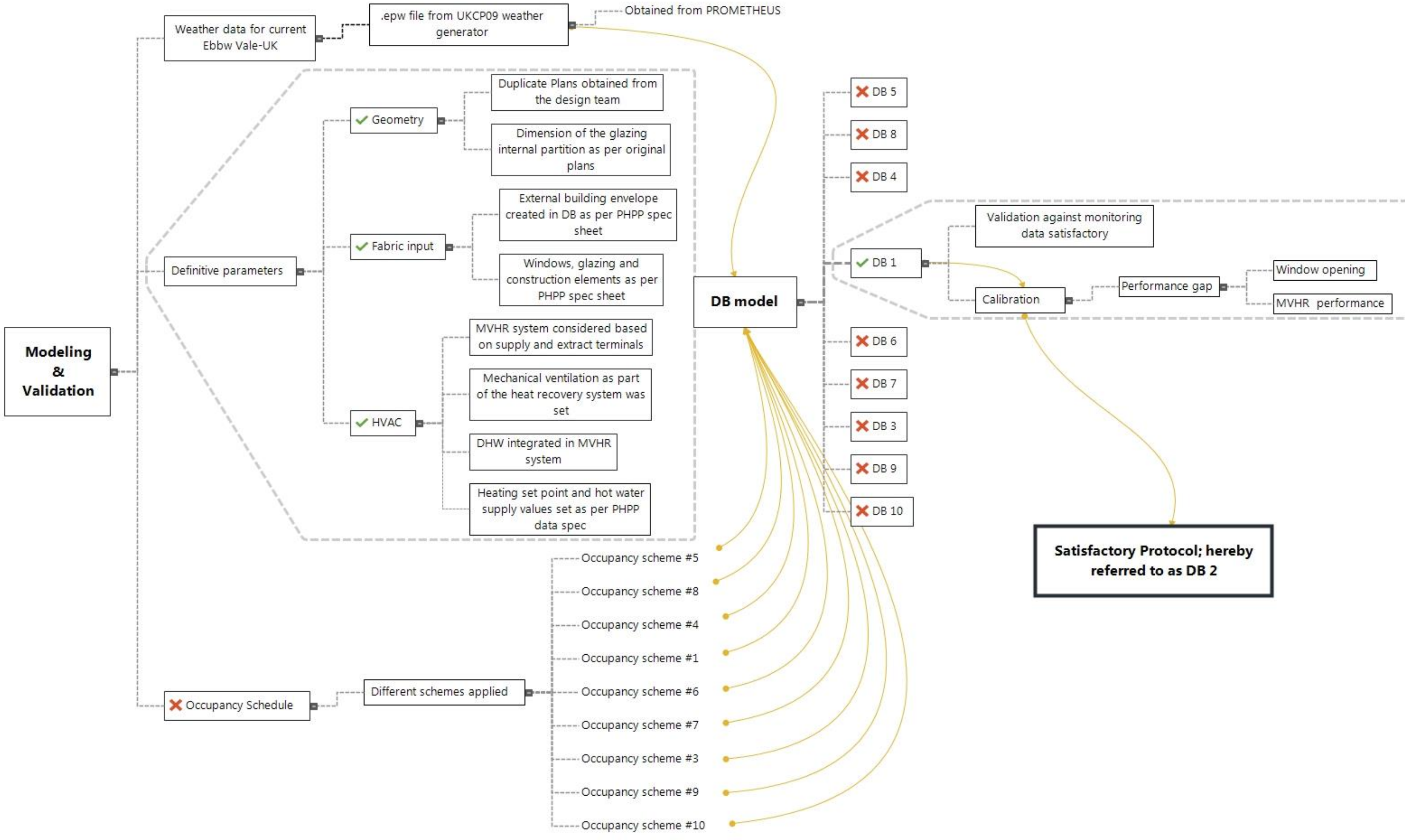


Figure 6-4 Steps of modeling and validation

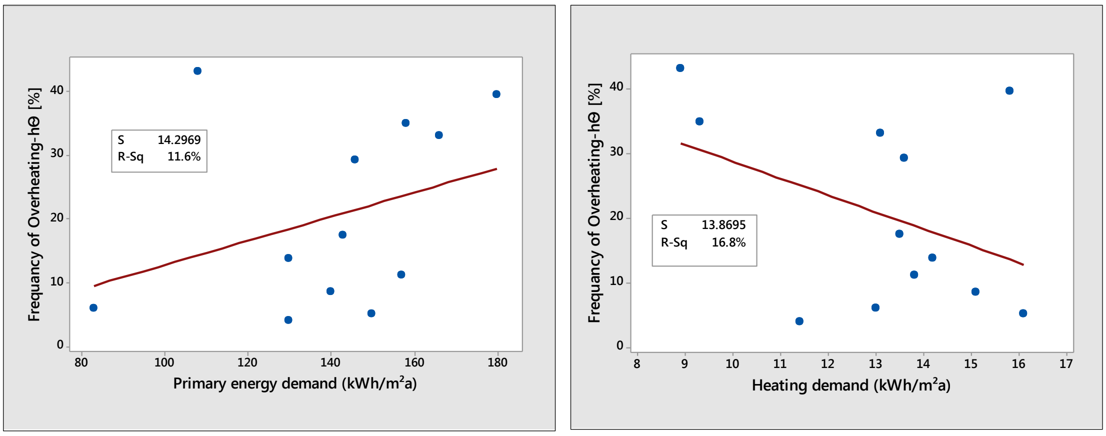


Figure 6-5 Correlation between overheating and energy use: primary energy demand (left), annual heating demand (right)

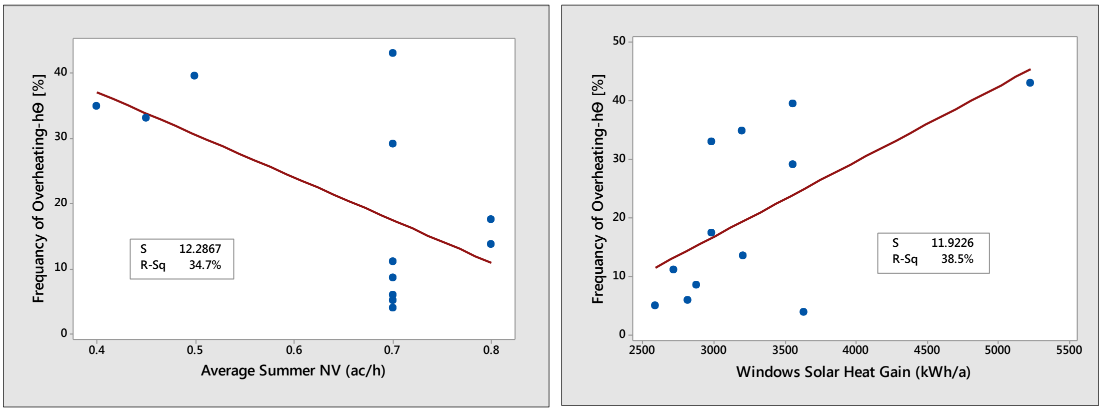


Figure 6-6 Correlation of overheating with natural ventilation (left) and solar gain through windows (right)

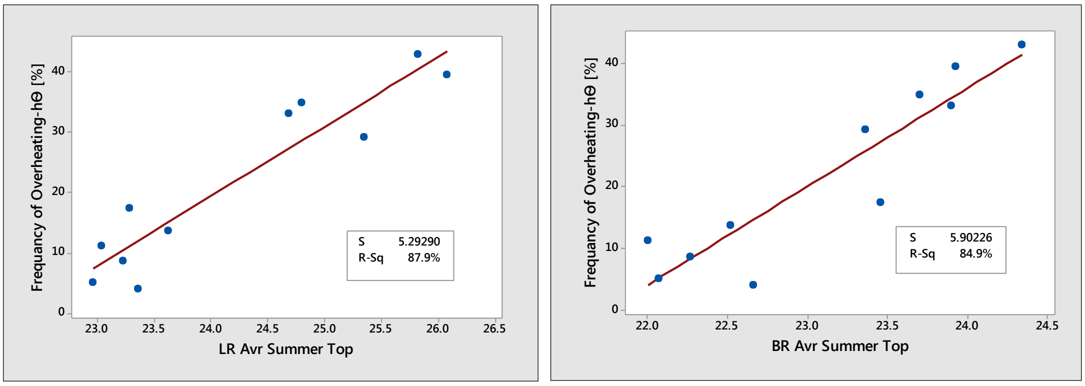


Figure 6-7 Correlation between overheating and average summer operative temperature: living room (left) and bedroom (right)

Data (Figure 6-8) obtained from the simulation of the house with different occupant schemes showed that, with roller blinds being open in summer and winter (DB.4), overheating hit the highest rate. The high solar gain from the windows meant the lowest annual heating demand was required for this case i.e. DB.4. However, by adjusting the blinds slightly and the same amount of window opening rate (DB.5) annual heating demand increased while the solar heat gain reduced. With blinds being open in summer (say for the view or daylight) and often closed in winter (DB.6) the house heating demand increased whereas the solar gain was exceeding the monitoring data in summer. Electricity consumption was also at a different level by different occupancy templates. DB.1 and DB.6 had the closest electricity use to the monitoring results. DB.1 and DB.3 offered a better alignment in terms of primary energy demand and solar gain received by the glazing for cases DB.7 and DB.1 was the closest to the PHPP spreadsheets. The solar heat gain through windows were not available for in the monitoring report.

Figure 6-9 shows winter and summer average operative temperatures for the living room and bedroom. DB.1, DB.4 and DB.5 experienced the closest summer internal temperature to the case study. It is interesting to note that although DB.4 had more solar gain received, DB.6 experienced a higher summer average temperature in the living room. The reasons perhaps, is that DB.6 had a lower cross ventilation rate in summer. However, in the bedroom with a single aspect ventilation, the average temperature is higher compared with the case DB.4.

An overall comparison of the models showed that the occupancy schedule had a significant impact on the outcome of the same model i.e. Larch House model. The model with occupancy schedule adapted from the Larch House occupant (DB.1) had the best alignment and achieved a satisfactory validation. The energy demand, electricity consumption, opening windows, and operation of blinds was fairly close to the data from the monitoring results (average 2 years of monitoring). However, the heating demand was slightly offset. This was mainly due to a mild winter in the second year of monitoring.

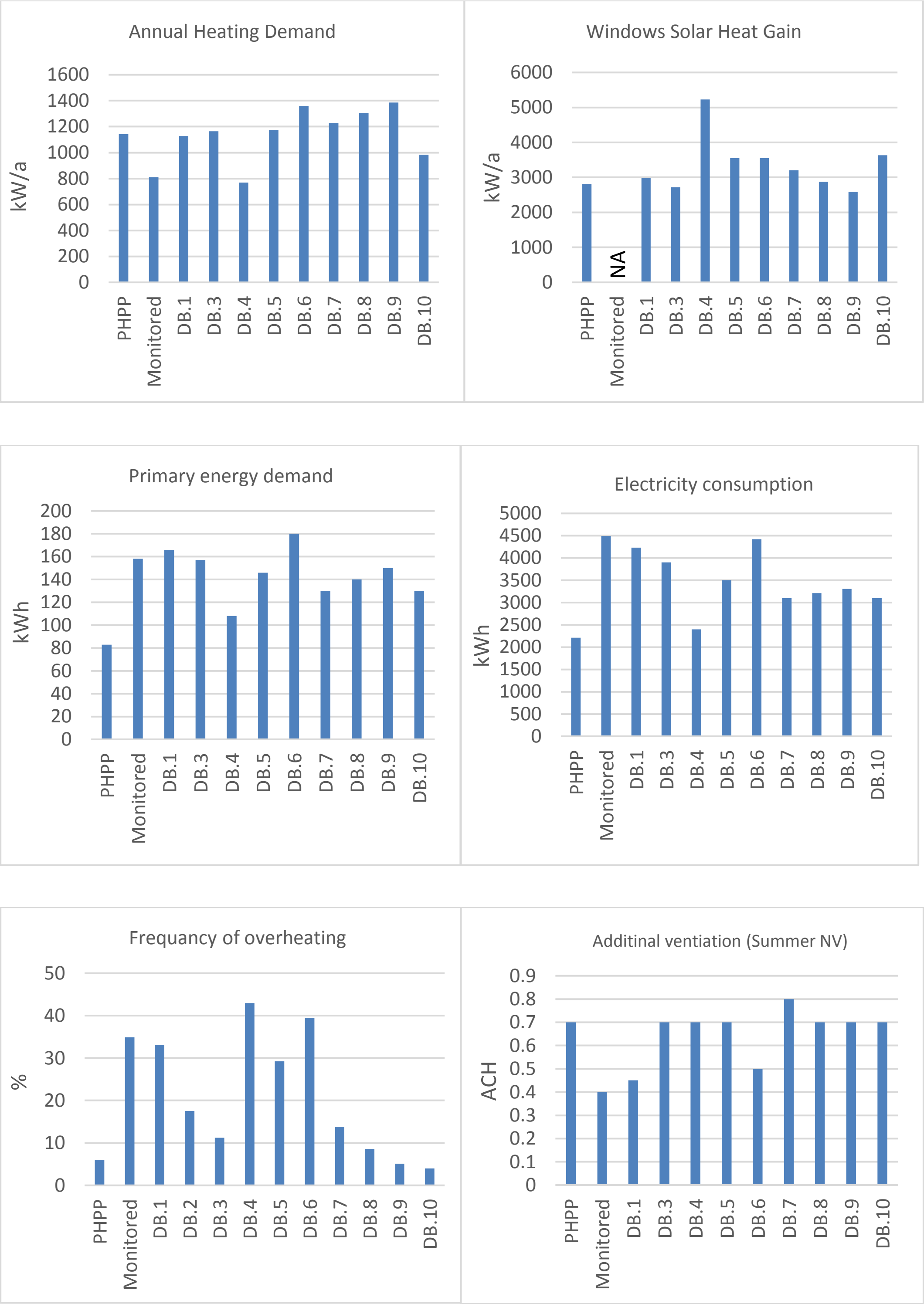


Figure 6-8 Comparison between different occupancy schemes in the house

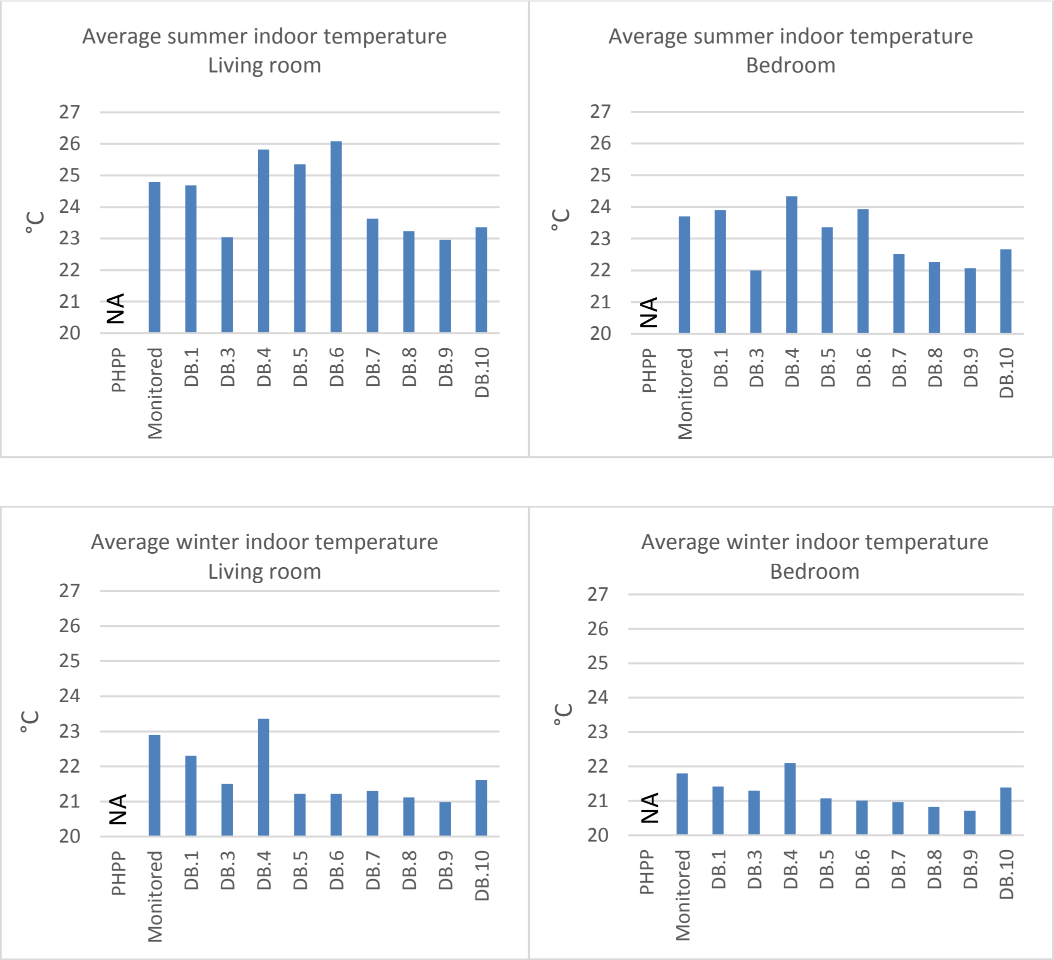


Figure 6-9 Average operative temperature in the living room and bedroom of different DesignBuilder models

Simulation DB.1 was validated according to the monitoring data and predicted Passivhaus Planning Package calculations. However, after installing insect mesh and a better usage of the MVHR boost function it was expected that the overheating rate of the first two years of monitoring would be reduced (Technology Strategy Board, 2014). Data from the monitoring after installing the insect mesh reported that the children were now keeping window open during the winter and spring as well (this claim was discharged in the simulation process in this study).

After validating the model “DB.1”, recurrence simulation of DB.1 with slight occupancy amendments (Table 6-6) was carried out to represent the current situation of the house after identifying the aforementioned problematic issues.

Data from Table 6-8 showed a small percentage difference for annual heating demand, primary energy use, airtightness, and annual CO_2 emission between the measures. The building evaluation used the average of two years monitoring data as the benchmark reference to assess the overall performance of the house. It is worth mentioning the comfort measures (overheating) refer to the living room and master bedroom (bedroom 1; Figure 5-1) as the reference. Overheating rates showed a significant fluctuation during the monitoring and validation process. Data from the monitoring performance showed that the house did experience an overheating frequency of over 34% in the main living space where internal temperature exceeded 25°C. Monitoring data exceeded the primary energy demand and the overheating calculated by PHPP, especially for the second year of monitoring. However, taking into account that the issues addressed were resolved, data presented for the DesignBuilder second simulation after validation (i.e. DB.2) revealed a 17.5% overheating rate, similar to the first year of monitoring data.

Table 6-8 Data comparison between PHPP, monitored data and DesignBuilder simulation results

Measures	PHPP file	Monitored Year 1	Monitored Year 2	Monitored Average	DB.1	DB.2
Annual heating demand (kWh/m^2)	13	13	5.6	9.3	9.1	13.5
Annual Primary Energy (kWh/m^2)	83	163	153	158	166	115
Airtightness (h^{-1} at 50 Pa)	0.2	0.198	0.198	0.198	0.2	0.2
Annual CO_2 emission (kg/m^2)*	20.1	32.9	31.1	32	34.2	26.2
Windows solar heat gain (kWh/a)	2816	NA	NA	NA	2986	2986
Living Room T>25°C, (%)	6	18.1	51.7	34.9	33.1	17.5
Living Room T>28°C, (%)	NA	0.9	0	0.5	5.8	1.2
Bedroom T>25°C, (%)	NA	8.3	26.1	17.2	15	8.1
Bedroom T>26°C, (%)	NA	4.3	12.5	8.4	6.9	1.9

* Disregard due to the amount offset by the PVs

A more detailed analysis of the monthly space heating showed a fairly close alignment between DesignBuilder model and the empirical data (Figure 6-10). The curves for all sets of data, except year 2 monitoring, sit closely in the graph. Heating demand was exceptionally low for the monitoring report of the second year due to a very mild winter (Figure 6-11). According to TSB report (Technology Strategy Board, 2014) *"space heating in Larch was notably reduced in year 2 due to the milder external temperature. However at the time of second winter of monitoring study, the occupants of the Larch House reported that the housing association had complied with their request for the solar override on the external blinds to be disconnected, giving manual control of the blinds to the occupants. For the first time this allowed the house to benefit from winter solar gains when the occupants were out at work, whereas previously the blinds automatically lowered to shade the building even in winter when the solar gains should be allowed to enter the building."*

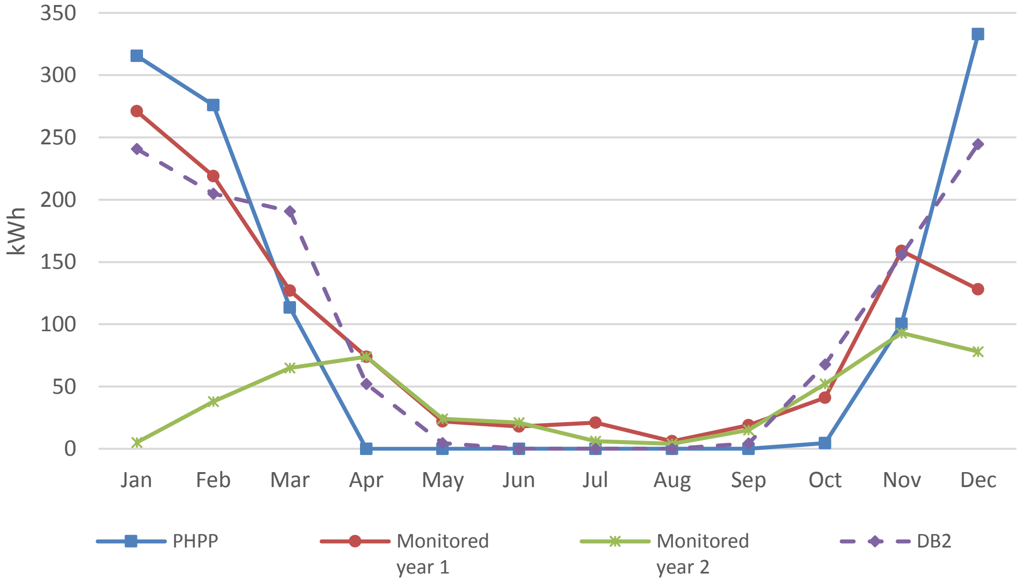


Figure 6-10 Monthly heating demand for PHPP, monitored data (year 1, and 2) and DesignBuilder simulation results (DB.2)

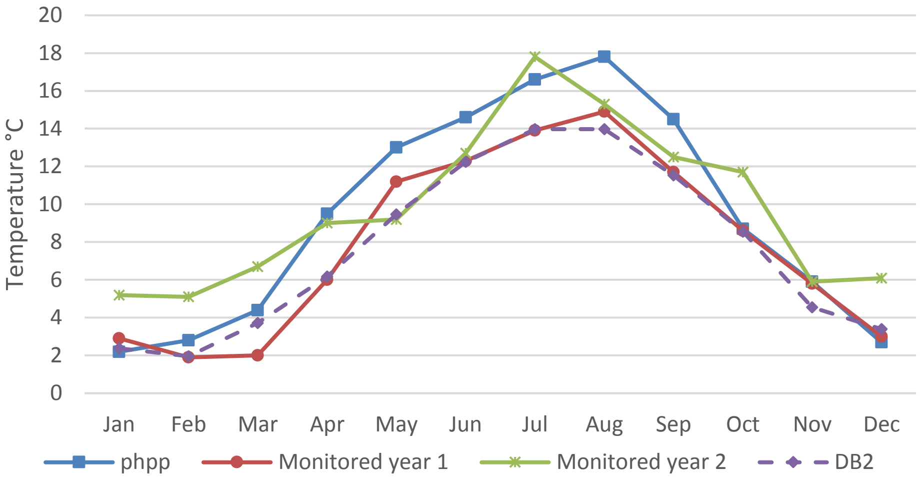


Figure 6-11 Ebbw vale monthly dry bulb temperature for PHPP, monitored data (year 1, and 2) and DesignBuilder simulation results (DB.2)

Figure 6-12 to Figure 6-15 plotted summer and winter temperature profiles for the monitoring result and the DesignBuilder model (DB.2). The profile showed that the indoor temperature for the DesignBuilder model was slightly cooler but had a fairly close alignment to the monitoring results.

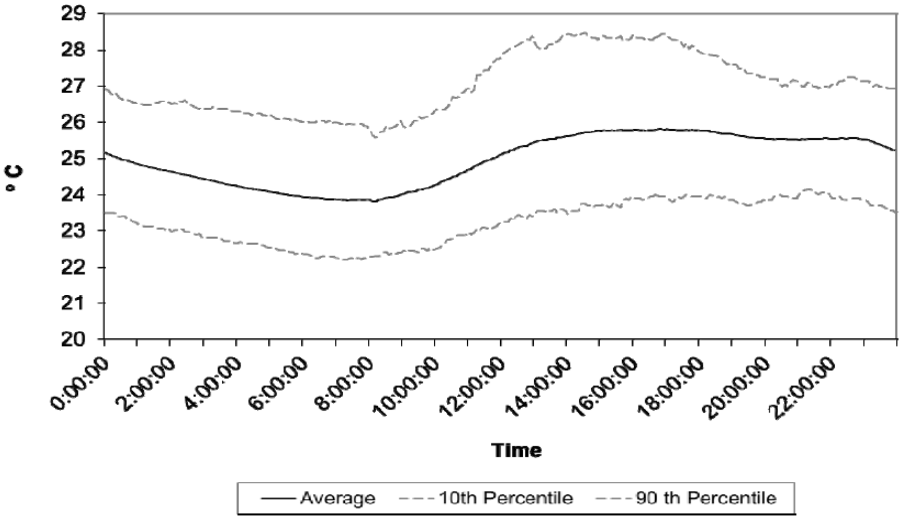


Figure 6-12 Summer temperature profile: Larch House monitoring (Technology Strategy Board, 2014)

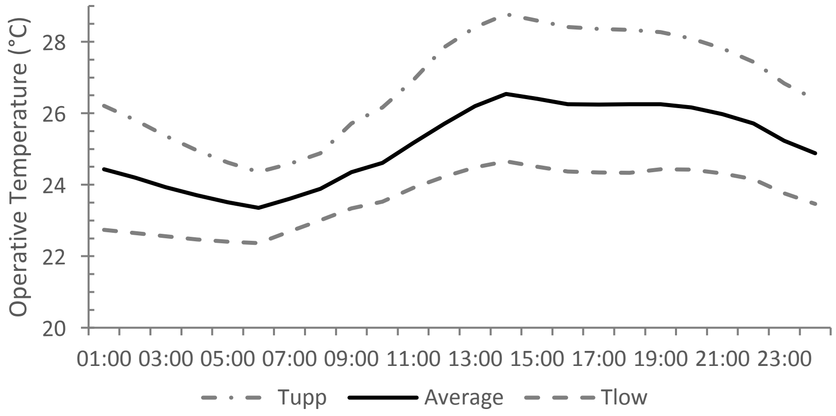


Figure 6-13 Summer temperature profile DB.2

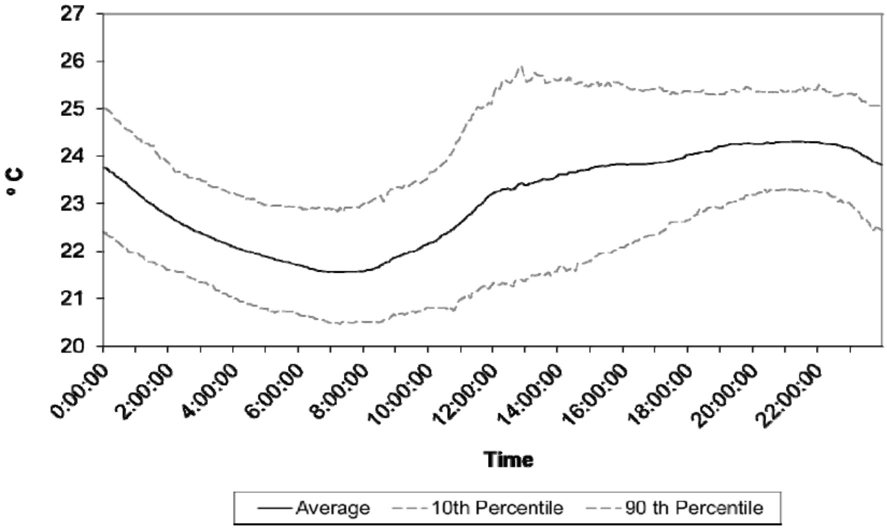


Figure 6-14 Winter temperature profile: Larch House monitoring (Technology Strategy Board, 2014)

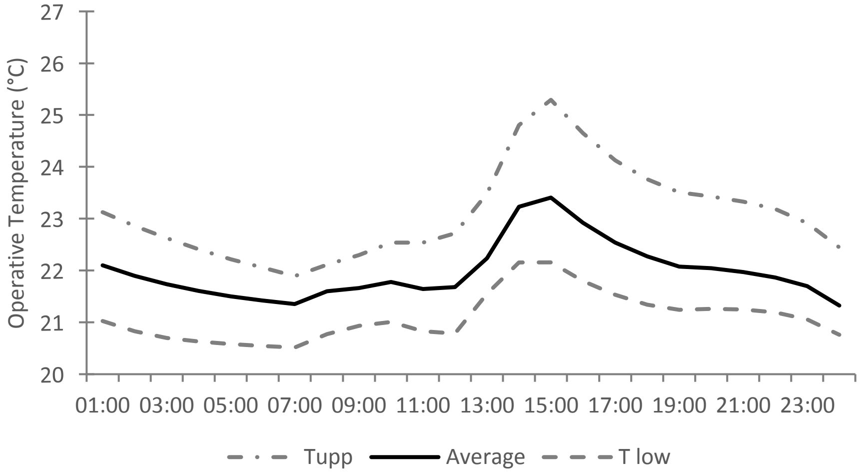


Figure 6-15 Winter temperature profile DB.2

It should be mentioned that, in addition to the Passivhaus requirements, Larch House had a photovoltaic PV system installed to meet Level 6 of the at-the-time applicable UK Code for Sustainable Homes, i.e. zero carbon emission. Thus, the net value of some measures presented in the table would vary. For instance, PHPP calculated 20.1kgm^{-2} carbon dioxide emissions for the building, with 12.8 kgm^{-2} CO_2 emissions being avoided due to the solar system.

On site energy generator such as PV panels and solar hot water collectors are not mandatory to achieve Passivhaus certificate (as long as Passivhaus criteria are met). As stated by Passivhaus Primer (McLeod, et al., 2014) "*Passivhaus does not allow energy use and the resultant emissions from a building to be 'offset' using on site generation of zero carbon electricity. Any such generation is specifically excluded from Passivhaus certification. The use of solar thermal systems to meet part of the domestic hot water heating demand is however allowed and expected.*" Therefore, in order to reduce the carbon footprint most of the Passivhaus employ PV systems to generate some of the electricity needed for the house. The Electricity generated by PV panels at the Larch House reduced 22.6 kgm^{-2} of the CO_2 emission, meaning 9.4 kgm^{-2} Net CO_2 emission for the House. Without the PV systems, the CO_2 emission of the house would have been 30 kgm^{-2}. In order to meet Level 6 UK Code for Sustainable Homes (zero carbon) all 30 kgm^{-2} of the CO_2 emission which is calculated based on the total energy consumption should have been avoided. However, to offset all the CO_2 emission a more advance PV system that generate 6 kW peak of electricity would be required. Therefore, the building did not achieve a truly net zero carbon emission.

Hence, this study gives the value of the building's total consumption rather that net value of the measures, i.e. this study disregarded the CO_2 emission avoided by the solar panels. In this way, the performance of the House can be assessed based on the building characteristics and not the power of the PV system.

The difference between the predicted and actual performance of low energy dwellings can be significant in some cases (Gill, et al., 2011; Ridley, et al., 2014). This is because of the unexpected occupant behaviour (Robinson & Haldi, 2011), different appliance uses, and different weather conditions. As might have been expected, the model did not achieve the absolute values of the monitoring data, but it was relatively close to the average monitoring data and PHPP calculations.

Because of comparing the Larch House monitored data with DesignBuilder predictions, and then fine-tuning the DesignBuilder parameters to reflect known conditions in the house, it was felt that a satisfactory protocol had been established for using DesignBuilder model in the next stage of this study's analysis of façade geometry impacts on overheating in London.

6.3 Moving the house to London climate

Modelling the closest possible replica of the building was the first step and was served for validation of the model against real-time data. It was concluded that the house experienced a relatively high percentage of overheating; however, after fine-tuning some of the known conditions a slight overheating was observed. In accordance with the research's main objective, the house was then moved (virtually) to London where overheating is a major concern for future weather conditions.

It should be remembered that Larch House in Ebbw Vale was chosen because it was the only Passivhaus designed to be certified to meet Code Level 6 zero carbon house in the UK at-the-time (although, it did not achieve a real zero carbon statement after the reports on the monitoring data.

It is acknowledged that perhaps for the London climate there would be a different sets of design consideration, however, the Idea was to see the thermal performance of a very airtight passive house with large south-facing glazing which was designed to meet Level 6 UK Code for Sustainable Homes in London climate.

Chapter Seven

7 Overheating Analysis and Implication of Proposed Geometry

7.1 Introduction

Several organisations and researchers (Zero Carbon Hub, 2010; Energy Saving Trust, 2005; Technology Strategy Board, 2014; Hacker, et al., 2008; GLA, 2006; Chow & Levermore, 2010; Gupta, et al., 2015; Lomas & Porritt, 2017) have highlighted that overheating is a concern for near future climates in the UK housing, especially in London. Previous studies found in the literature have considered that the risk of overheating in Passivhaus dwellings depends on context, user behaviour and envelope's thermal specification. Research has investigated the implementation of various interventions to prevent summer degree hours of cooling in the UK housing sector to maximise indoor comfort. Successful passive interventions for summer indoor comfort have been reviewed within the study and the most effective strategies have been highlighted. A review of the literature (section 3.3) showed that the most effective interventions for reducing overheating were strategies to reduce solar heat gains, dissipate the heat by natural ventilation, and external wall insulation. Passivhaus already employs an excellent high level of insulation. Therefore, a combination of shading and ventilation strategies are the measures to avoid discomfort during warm summer days. The most common shading strategies used in Passivhaus are roller blinds and overhangs. Geometric consideration also in some extends have been implemented to reduce solar incident during summer.

Some methodologies presented to assist design decisions regarding the envelope shape and energy performance of the building based on a direct link between early design stage and energy simulation. This study contributed to the further investigation of façade shape. This chapter will explore if shelf-shading facades can also be considered as effective shading strategies in Passivhaus.

It is worth mentioning that for this study operative temperature (T_{op}) is used to measure comfort. T_{op} represents the average air temperature and the room surface temperatures; it is considered as a better representative of comfort measure than the air temperature alone (CIBSE TM36, 2005). It should also be reminded that both Passivhaus criteria (for lower threshold of 25°C) and CIBSE Guide A (for higher threshold of 26/28°C) were used as the benchmark to assess the overheating i.e. the operative temperature of 25°C and 28°C (26°C for bedrooms) should not exceed more than 10 and 1% of occupied hours respectively (section 3.2.1). As mentioned earlier it is agreed that relative humidity is a major factor in assessing thermal comfort, especially for adaptive criteria. However, the selected criteria do not consider the relative humidity to measure overheating. Secondly, since this study focused on the reduction of unwanted solar gain to reduce temperature, the critical factor for assessing the thermal comfort was the indoor operative temperature – the shading strategy would not have much effect on the relative humidity. The adaptive relative humidity is also not the focus here because it has not been clearly published the link between comfort experience and humidity level (CIBSE TM36, 2005).

In the previous chapter, the Larch House case study in Ebbw Vale was modelled and validated. The modelled house was moved to London to assess the overheating risk of a super insulated Passivhaus dwelling (Code Level 6 for sustainability) for future London climate and investigate the implication of the self-shading façades.

7.2 Potential risks of overheating in London

This section will reflect on the potential risks of overheating in the Larch House (or identical to the Larch House) under current and future London climate. To investigate the future indoor environment of the house in London, some of the critical climatic data of the weather file used for this study were analysed. Then, the risk of overheating was estimated by measuring the fundamental thermal component i.e. indoor operative temperatures.

7.2.1 London current and future climate

There is compelling scientific evidence that the Earth's average surface temperature will increase by up to several degrees Celsius in this century (CIBSE TM36, 2005). This increase of temperature in the UK is expected to have major impacts on the indoor environment of buildings. The south east of England is predicted to be the most at-risk area for summer overheating in the UK (Jenkins, et al., 2009), and dwellings within Greater London are predicted to be at the highest risk. During the heat wave of 2003, the average temperature recorded in London was about 10°C higher than the surrounding rural area. Research revealed that 50% of the death tally during the 2003 heat wave was due to the exposure to heat in people's house (Zero Carbon Hub, 2015). This resulted in 2000 deaths in England and over 15,000 in France.

When designing to the specific climate conditions, critical weather data that have the most effect on the building loads are considered into design decision making. Architects are usually attentive to climatic variables that affect indoor comfort via heat transfer through building envelope and ventilation. These measures are dry-bulb temperature, solar irradiation, and wind direction and speed. The increase of the dry-bulb temperature is, by far, the most important criterion for designing under future conditions (CIBSE TM36, 2005). The temperature in a poorly designed house would exceed the outside temperature for much of the time during hot spells whereas a good design would keep the indoor temperature close to the average daily temperature or even lower.

As indicated previously (section 5.3.3) the summer months of June, July and August were mainly considered for the thermal discomfort analysis. Figure 7-1 shows the average monthly outdoor temperature in current and future London (CIBSE A1FI 50% TRY). July and August are the hottest months for all four time slices. It is clear that temperatures will rise over the whole 12-month cycle of the year in future. However, the increase in average dry bulb temperature in the summer time is double the temperature rise for winter.

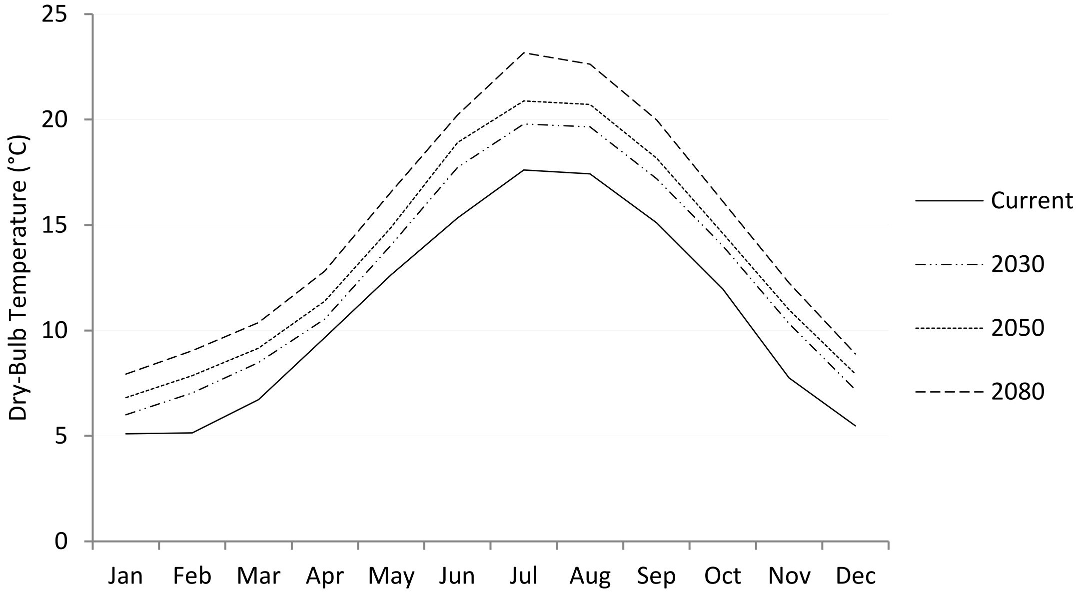


Figure 7-1 Average monthly dry-bulb external air temperature for current and future London climate

Because this study contributes to designing shading elements, solar irradiation also is of a significant impact on the design. Figure 7-2 predicts an increase in solar radiation for future London climates. However, it is not following a steady growth pattern like the air temperature, but shows that the amount of direct solar radiation is higher than the baseline of the current data. Details of main climatic factors for the current and future London weather data are presented in Appendix C.

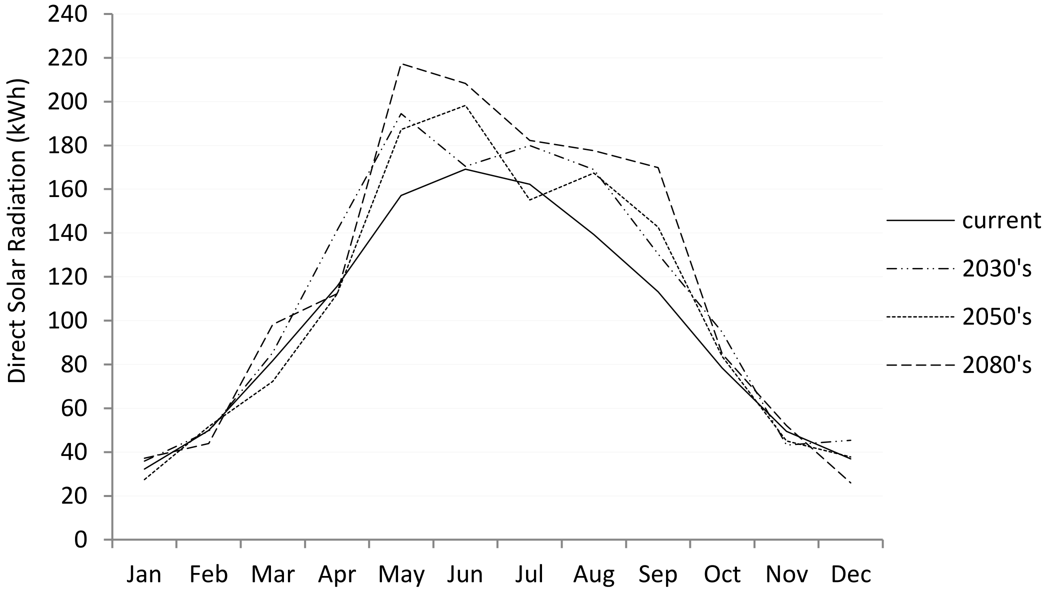


Figure 7-2 Site direct solar radiation rate for four climate periods

For the current London climate, the average outside dry-bulb Temperature (T_{db}) of July was 17.6°C, with the hottest day being 29th July with a peak temperature of 28.2°C at 17.00. The average T_{db} for the 2080's is close to the hottest day of current climate at 23.2°C, which indicates an increase of 5.6°C in average monthly temperature for the hottest month i.e. July (Table 7-1). The average hottest day also was very close to the hottest hour of current climate that was on 10th of July (Figure 7-3). However, the peak temperature of 31.9°C was estimated for another day (26th July). The data showed that the warmest day in the current summer would be clustered as a typical summer day in the 2080's. Temperatures of 2030's timeslice also showed a noticeable rise from the current data. Warmer summer days with higher solar radiation will contribute to an increase in the operative temperatures inside the buildings.

Hajat, et al. (2002) recorded that increased overheating problems occurred when the average daily temperature exceeded 19°C. The average external temperature for current summer climate exposes a slight potential of overheating risk. However, data from the 2030's and 2050's suggests medium to high concern over excessive indoor temperature. Nevertheless, the hourly and daily temperature during July 2080 estimated an average dry-bulb temperature of higher 19°C for every day. During this period, the average daily external temperature varied from 19.91 to 28.21°C. Solar power is also expected to increase in summers for coming years. Summer Design Week, gives a relatively high value of solar irradiation for all future time slices with the raise in solar radiation showing the highest at 2080's (see Figure 7-4 and Table 7-2). However, there are uncertainties on the amount of solar irradiation for future weather scenarios. The cloud cover factor has a significant impact on these data, which is one of the uncertainties in generating future weather data.

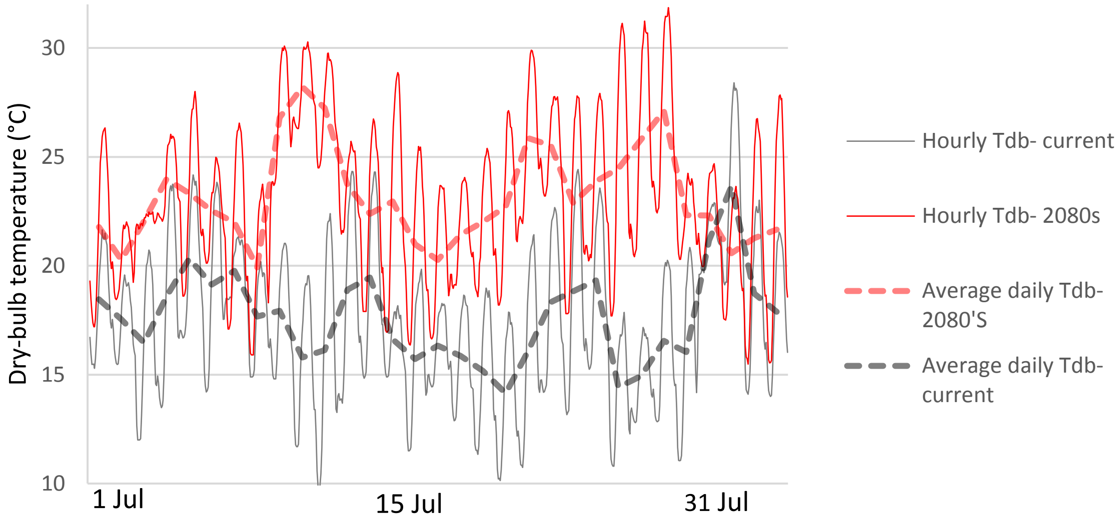


Figure 7-3 Hourly and average daily outdoor temperature for current and 2080’s hottest month (London)

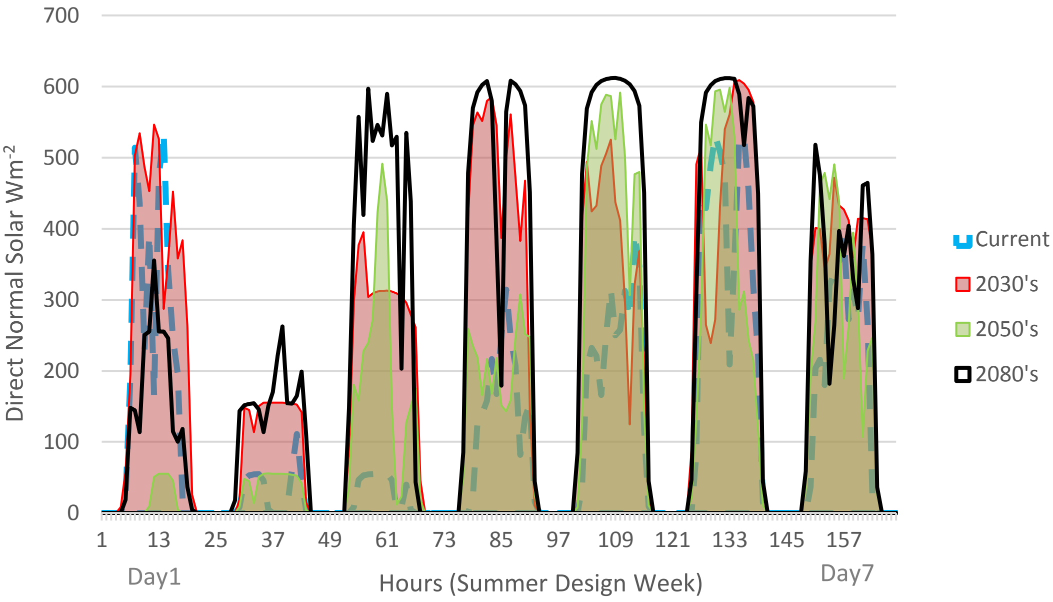


Figure 7-4 Solar irradiation during the period of Summer Design Week

Table 7-1 Average dry-bulb temperature for London current and future (High emission scenario at 50% probability TRY)

Average dry-bulb temperature London (Islington)	Current	2030s	2050s	2080s
Annual	10.83	12.67	13.52	15
All winter (Oct-Mar)	7.03	8.84	9.59	10.77
All summer (April-Sep)	14.63	16.49	17.49	19.23
Summer (Jun, Jul, Aug)	16.80	19.07	20.18	22.02
Hottest month (July)	17.61	19.79	20.88	23.17
Hottest day	23.64	24.01	26.54	28.21
Hottest hour	28.15	29.63	29.80	31.85

Table 7-2 Direct normal solar radiation for London current and future (High emission scenario at 50% probability TRY)

Direct normal Solar Radiation (kWm^{-2})	Current	2030s	2050s	2080s
Annual	867.549	981.412	936.888	1032.622
All winter (Oct-Mar)	239.737	258.883	231.12	250.059
All summer (April-Sep)	627.812	722.579	705.376	782.593
Summer (Jun, Jul, Aug)	346.171	382.236	485.336	417.690
Highest month	Jun 121.773	July 144.707	Jun 142.725	July 161.693

7.2.2 Larch House overheating rate in London current and future climate

A description of the Larch House case study in Ebbw Vale was presented in the case study selection section (section 5.3.1). Technical information including construction materials, HVAC system and occupancy schedule were addressed in section 6.1. The house was modelled and validated in Ebbw Vale against empirical data (Section 6.2).

In the following section, considering the house was moved to London (Figure 7-5), the potential overheating risk for current and future climates are analysed. Current and future climate projections used to assess overheating are listed in Table 7-3.

The Larch House energy performance was simulated in London using the settings presented above, and the same building specifications addressed in section 6.1.

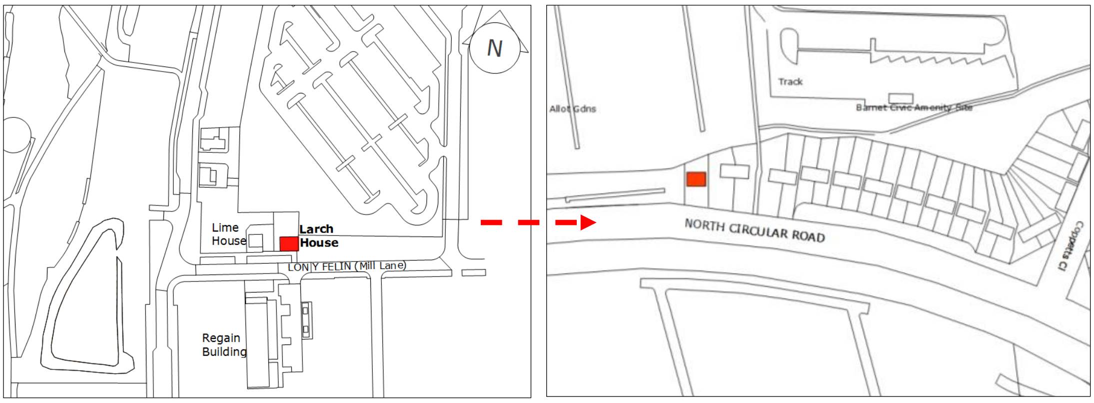


Figure 7-5 Larch House location plan in Ebbw Vale (right) and virtual location in London-Islington (left)

Table 7-3 Climate data for simulations

Timeslice	Climate Period	Emission scenario	Probability
Current climate	1961-1990	NA	NA
Climate projection I	2030's	High emissions	50%
Climate projection II	2050's	High emissions	50%
Climate projection III	2080's	High emissions	50%

Table 7-4 presents a breakdown of the measures, including the preliminary data required for the Passivhaus standard. Calculated data presented in Table 7-4, shows that the house's energy requirement is much lower in London, with a small supplementary annual heating demand. Consequently, annual energy demand was also reduced to below Passivhaus levels.

As discussed earlier (Section 6.2), the PV systems offset up to 22.6 kgm^{-2} of CO_2 emissions, and this would probably certify the house as a truly zero carbon Code Level 6 in London, which was not achieved in Ebbw Vale. However, the data presented determined that the house would experience a greater deal of overheating. The percentages of hours above the benchmark temperatures of Passivhaus standards (25°C) and CIBSE Guide A (28°C) were used as a measure of overheating and h_{ϑ} was given as the symbol. Cases that experienced $h_{\vartheta\ >25^{\circ}C} <10\%$ and/or $h_{\vartheta\ >28^{\circ}C} <1\%$ ($h_{\vartheta\ >26^{\circ}} <1\%$ for bedroom) were deemed to "pass" and cases that did not meet these criteria were deemed to "fail". The model has achieved Passivhaus standards in London climate (first three measures). However, overheating was estimated to be higher than Passivhaus recommendations in the current climate. Furthermore, to indicate the future performance of the house, the model was simulated under probabilistic climate projections for three future time slices. Table 7-5 shows the summary of overheating criteria for the future climates. It should be remembered that the metrics presented are for living room and master bedroom i.e. bedroom1 (see Figure 5-1). It also should be noted that all occupancy schedules, including window opening and blind operations, were kept the same as per validated model.

Table 7-4 Simulated measures for Larch House in London (current)

Measures	Simulated	Required	Remark
Annual heating demand (kWh/m^2)	8.2	<15	Pass
Annual Primary Energy (kWh/m^2)	109	<120	pass
Airtightness (h^{-1} at 50 Pa)	0.2	<0.6	pass
Living room overheating risk $h_{\vartheta>25^\circ}$	28.2%	<10%	fail
Living room overheating risk $h_{\vartheta>28^\circ}$	2.9%	<1%	fail
Bedroom overheating risk $h_{\vartheta>25^\circ}$	12.3%	<10%	fail
Bedroom overheating risk $h_{\vartheta>26^\circ}$	4.9%	<1%	fail
Annual CO_2 emission (kg /m^2)	22	NA	NA
Windows solar heat gain (kWh/a)	3252	NA	NA

Table 7-5 Summary of overheating criteria for future climates

	CIBSE Guide A /Passivhaus	h_ϑ	Occupied hours (%)	Remark
2030's	Living Room	$h_{\vartheta>25^\circ}$	43.3 > 10	fail
		$h_{\vartheta>28^\circ}$	11.2 > 1	fail
	Bedroom	$h_{\vartheta>25^\circ}$	21.6 > 10	fail
		$h_{\vartheta>26^\circ}$	15.2 > 1	fail
2050's	Living Room	$h_{\vartheta>25^\circ}$	48.1 > 10	fail
		$h_{\vartheta>28^\circ}$	16.3 > 1	fail
	Bedroom	$h_{\vartheta>25^\circ}$	27.7 > 10	fail
		$h_{\vartheta>26^\circ}$	21.3 > 1	fail
2080's	Living Room	$h_{\vartheta>25^\circ}$	58.1 > 10	fail
		$h_{\vartheta>28^\circ}$	28.2 > 1	fail
	Bedroom	$h_{\vartheta>25^\circ}$	38.3 > 10	fail
		$h_{\vartheta>26^\circ}$	31.2 > 1	fail

Average monthly operative temperatures are presented for the living room and the bedroom for current and future weather projections (Figure 7-6). Although the number of hours exceeding 25°C was greater for the living room, the average temperature was lower than the bedroom. This is because of the occupancy schedule difference between the living room and bedroom – for instance, bedroom temperature during noontime is high when not occupied and that is not included into the overheating assessment. According to the new CIBSE Guide A (2015), this is a significant disadvantage of the current method of calculating overheating CIBSE Guide A (2006) which was used in this study.

Overall, data showed the house experienced a slight overheating risk during July and August of the current climate. However, in the future, medium to high overheating rate was predicted. Despite a lower amount of solar gain by the exterior windows of the bedroom, the summer indoor temperature was higher than the living room. The average summer temperature in the living room and the main bedroom was 23.9 and 24.1°C respectively. The highest single hourly temperature recorded in the living room was 32.4°C at 11:00 on 23rd of July (see Figure 7-7). Peak hourly operative temperature in the bedroom was recorded on the same day at 14:00 with 31.4°C. On the other hand, the results in Figure 7-8 found almost no discomfort low operative temperature i.e. below 20°C for the entire year. The data showed the house is within the neutral comfort temperature i.e. 0 PMV. However, the discomfort experienced was only the warm indoor temperature (i.e. above 0.5-1 PMV).

Summer Typical Week (STW) represents a relatively warm week during the summer period but not the hottest week i.e. Summer Design Week (SDW). Data plotted in Figure 7-9 indicates the internal temperatures in the living room and bedroom during STW in July under current and future London climates. As the indication of the house performance in a warm summer period, the data showed living room would overheat for a minimum of two days in the STW. Another three days of the typical warm week, indoor temperature was higher than optimal comfort temperature but remained within the acceptable overheating criteria. The optimum operative temperature was fully achieved for two days during the summer typical week (in the living room). However, the bedroom will experience up to four days high operative temperature.

Understandably, the overheating will be lower in a relatively cooler week and higher for the hottest week.

Indoor temperature drifts in response to the changing outdoor temperature. However, this deviation occurred with a greater time lag and attenuation in the bedroom. This perhaps is due to the single-sided opening in the bedroom compared to the opposite-window cross-ventilation in the living room. Conversely, when the external temperature is high, and there is an intense solar radiation for two successive days living room experienced a higher temperature because of the greater amount of glazing. However, in the next day, the warm air was removed easier in the living room compared to than the bedroom (see Figure 7-7). Although it is evident that the temperature will rise over the coming decades, however, it does not mean temperature during every single day is higher for future weather data (see Figure 7-9).

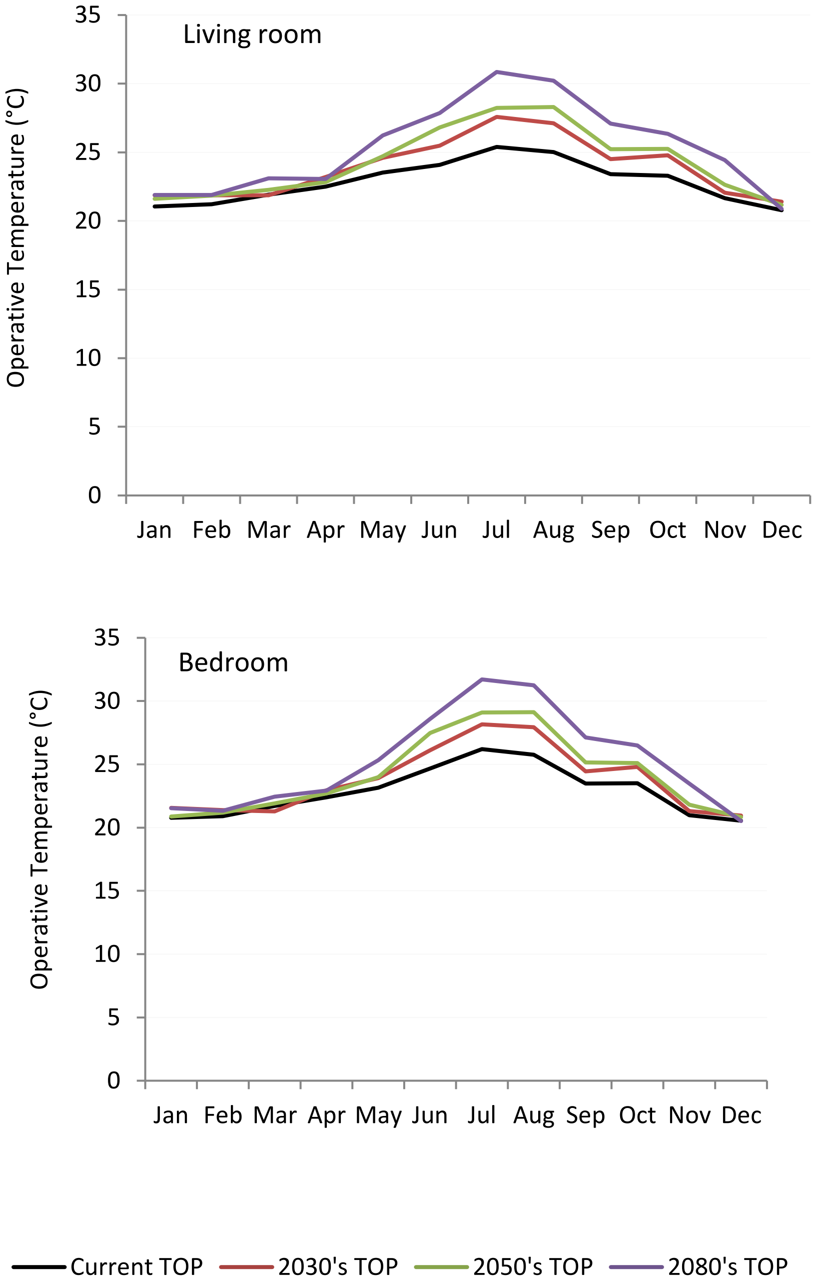


Figure 7-6 Monthly mean Operative Temperature (T_{op}) in the living room and bedroom of the Larch House in London

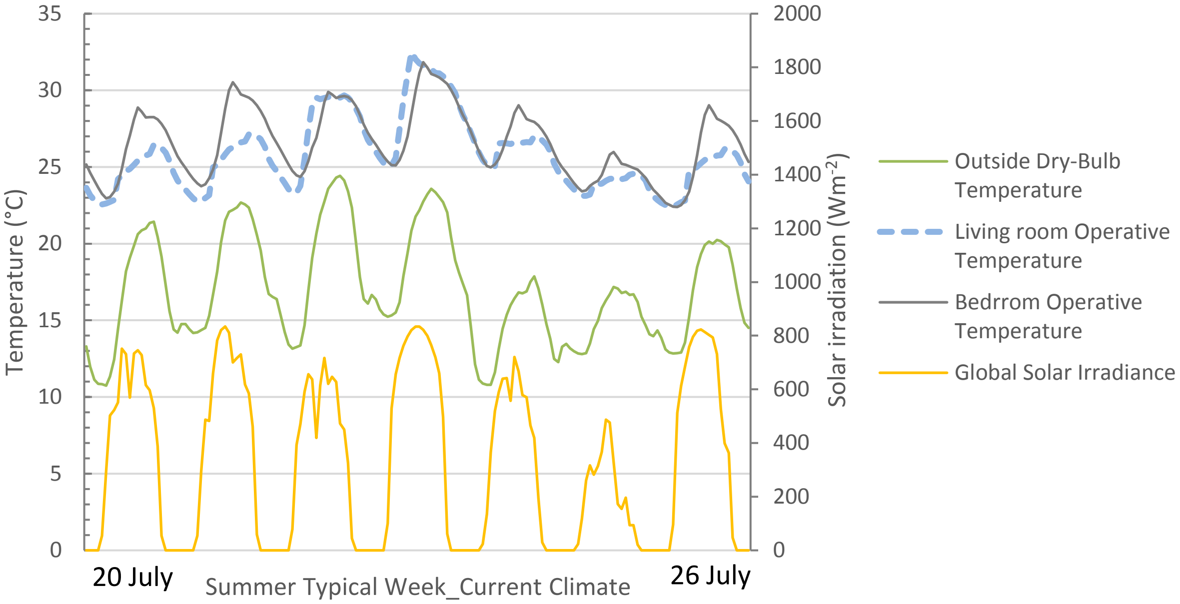


Figure 7-7 External temperature, solar irradiation and estimated internal temperatures

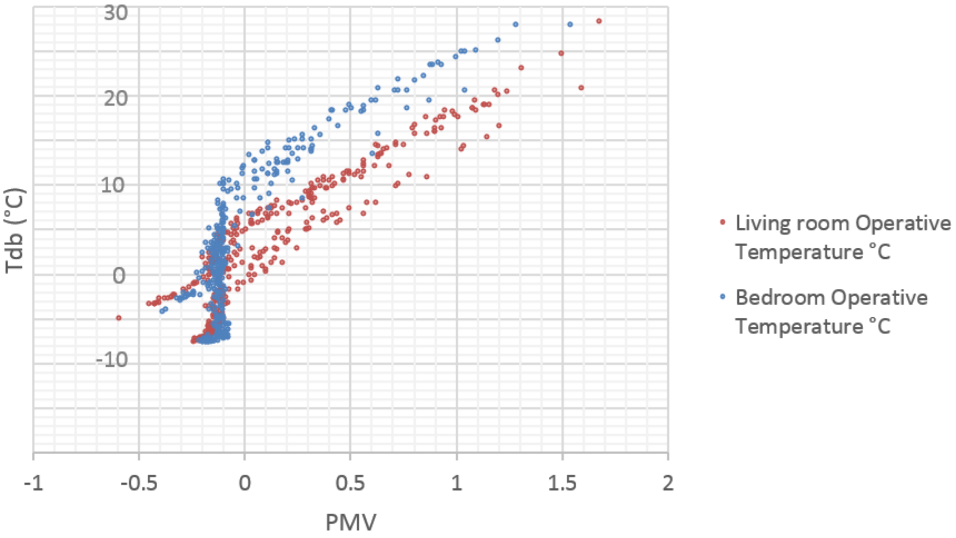


Figure 7-8 Outside dry-bulb temperature and corresponding Predicted Mean Vote during the year

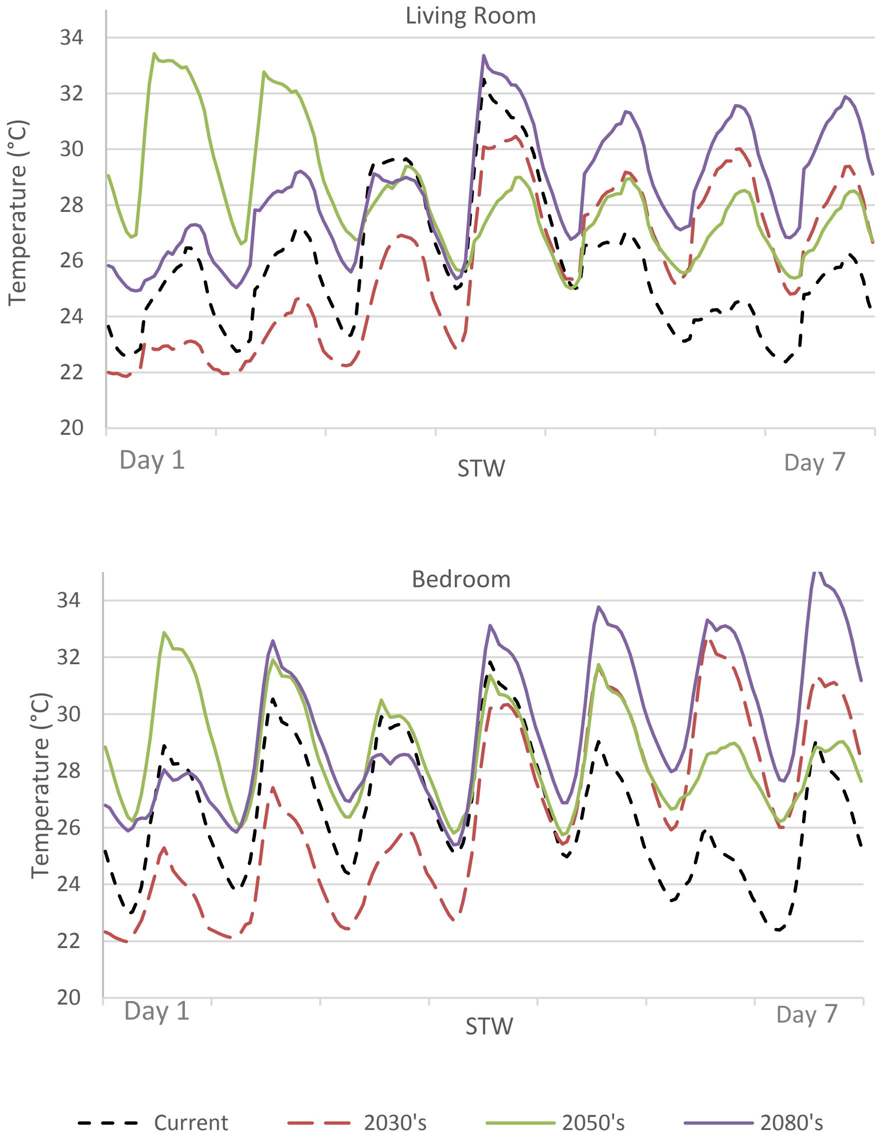


Figure 7-9 Operative temperature during a warm summer week

The research reviewed in the literature agreed that solar gain has a significant role in measuring overheating rate for a super insulated building. Given a vertical window with a 90% transmittance glass, it produces 1000 Wm^{-2} of heat, comparable to a portable space heater i.e. every one square meter of the window counts as a portable heater (Feist, 2012). The curves presented in Figure 7-10 demonstrates that overheating occurred when the excessive solar gain was allowed through the external windows and/or in the case of high external temperature. On the 22nd and 23rd overheating occurred due to the high heat gain through the windows and overheating was at high risk again when internal temperature hit the peak on 29th and the following day. Nevertheless, due to malfunctions in using shading to protect the windows some days e.g. 15th 23rd. 29th and 30th had high internal temperatures that caused discomfort for the next day. Therefore, high internal temperatures also happened during some days with relatively low levels of external temperature and solar radiation (because of the excessive overheating on the previous day e.g. 24th). Potential overheating was prevented on some days despite intense solar radiation e.g. 4th, 11th, 26th by reducing solar gains of the exterior windows i.e. effectively shading the windows.

It is evident that excessive solar radiation in summer was the main reason for overheating in the Passivhaus (Figure 7-10 and Figure 7-11). It was found that in the hottest month of the year, overheating was experienced for up to 12 days (current climate). During July 2080, almost every day's operative temperature in the living room experienced conditions above the current recommendations (Figure 7-11). It is observed that the high indoor operative temperatures are related to the high solar radiation levels.

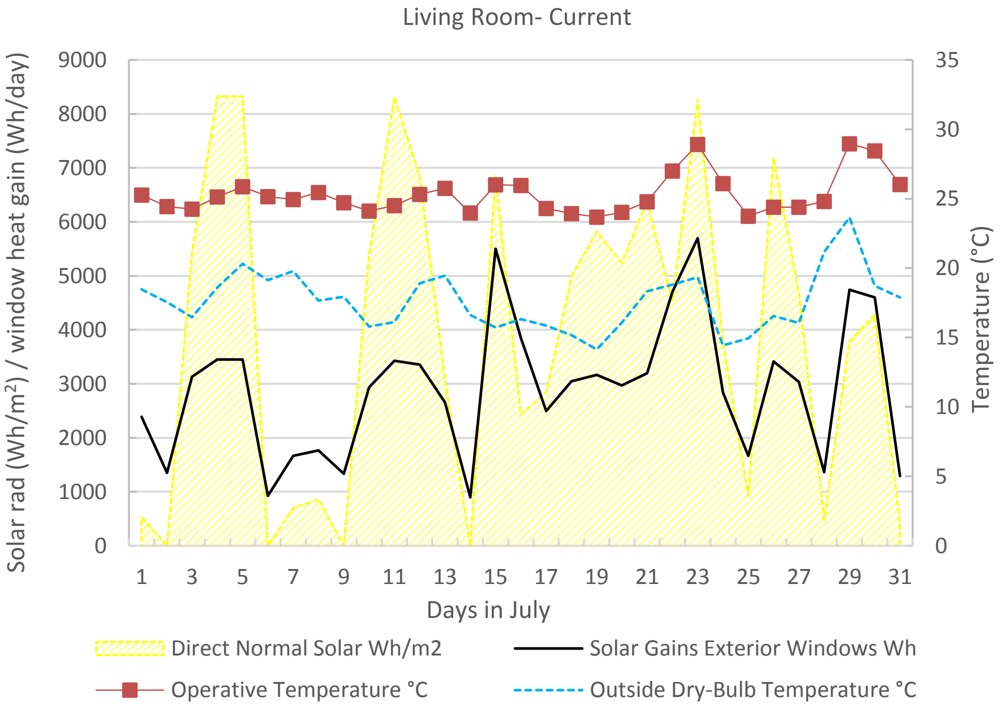


Figure 7-10 Internal and external temperatures, direct normal irradiation and external windows heat gain during July under current climatic data

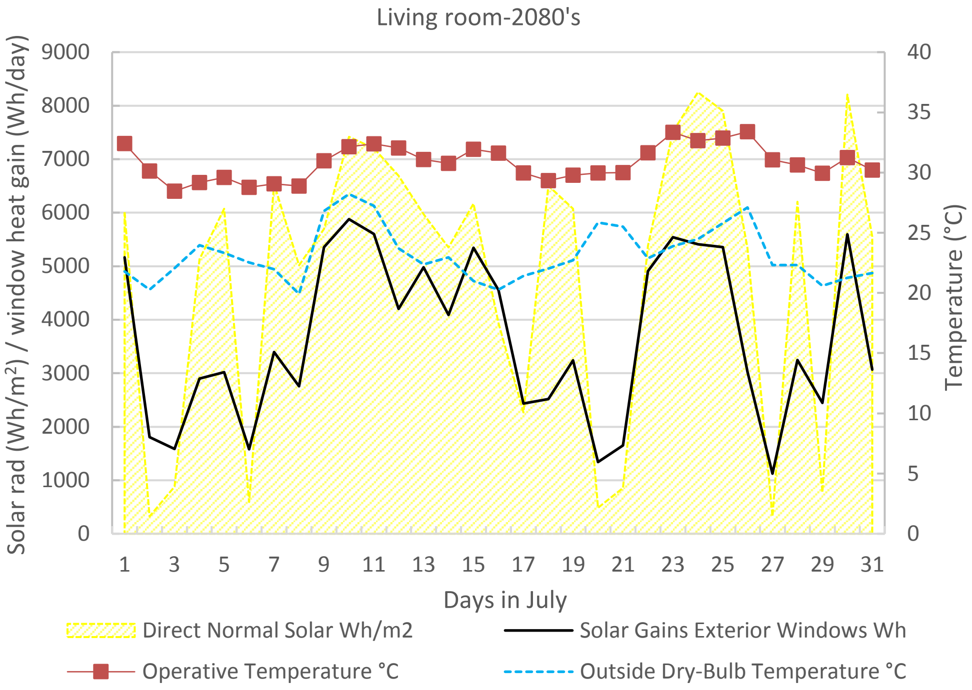


Figure 7-11 Internal and external temperatures, direct normal irradiation and external windows heat gain during July under 2080's climatic data

7.3 Simulations on alternative pilot unit

Results from the Larch House simulations in London revealed a medium risk of overheating for current and near future (i.e. 2030) weather data, with a growing concern over the decades to come, especially for the 2080's weather scenario. Throughout the literature, it was established that overheating could be eradicated or significantly reduced for a Passivhaus by two central dynamics; shading and ventilating.

In this study, a proposed façade i.e. self-shading façade was hypothesised to reduce excessive solar radiations during summer and increase occupant's thermal comfort. As discussed in the Methodology Chapter (Section 5.3.4), to evaluate the feasibility of the hypothesis a small-scale pilot study was conducted. The results from the pilot study also helped to choose a smaller number of inclination angles (i.e. reducing the sample size) prior to conducting the full-scale case study experiment.

7.3.1 Pilot study description

A hypothetical Passivhaus standard unit (Figure 7-12) in an urban exposure was developed to represent a Passivhaus structure with fabric specifications like the Larch House case study to generate the closest interpretable results (Table 7-6). The unit was nine metres long, seven metres wide and three metres high and was a stand-alone unit. Construction materials, building specifications HVAC system and occupancy schedule all were set like the case reference described in detail in section 6.1. The amount of glazing was calculated based on the Window-to-Wall Ratio (WWR) comprising 55%, 11%, 7% and 0% for the south, east, north and west facing facades respectively. Figure 7-12 depicts the amount of south glazing for the pilot unit, including fixed and opening windows (see also Figure 6-1 and Table 6-5). Like the case study, external roller blinds used for the shadings.

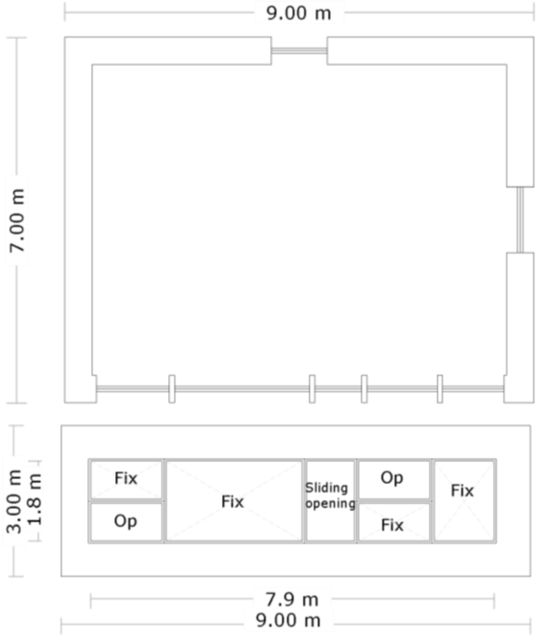


Figure 7-12 Pilot unit

Table 7-6 Fabrics used for the pilot unit

Element	*U*-Value (Wm^{-2}K)	Thickness (mm)
Exterior walls	0.095	467
Flat roof	0.074	578
Ground floor slab	0.076	800
Windows	0.860	Triple glazing 13 mm argon filled

The angle of inclination theta $(Tilt_{\Theta})$ as described by (Feist, 2012) represents the angle between the normal (perpendicular) to the window surface and the zenith. For instance, the inclination angle of a window on a vertical wall is 90° ($Tilt_{\Theta} = 90°$), while a window on a flat roof has a 0° angle of inclination ($Tilt_{\Theta} = 0°$). Figure 7-13 depicts side elevation of different façade inclinations used in the study. The tilt angle (Θ) of the south facade $(Tilt_{\Theta\,\mathrm{south}})$ was manipulated to test the effectiveness of the façade inclination at 5° intervals starting from $Tilt_{\Theta\,\mathrm{south}}$= 90°, i.e., a vertical façade, to 55° beyond the vertical i.e. $Tilt_{\Theta\,\mathrm{south}} = 145°$, as shown in Figure 7-13. Each elevation was then simulated to measure to what extent the south facing inclination will influence the future performance of a Passivhaus dwelling, in particular overheating rate for London climate. It is worth reminding that the south façade was only investigated because it is the most dynamic façade in any Passivhaus design.

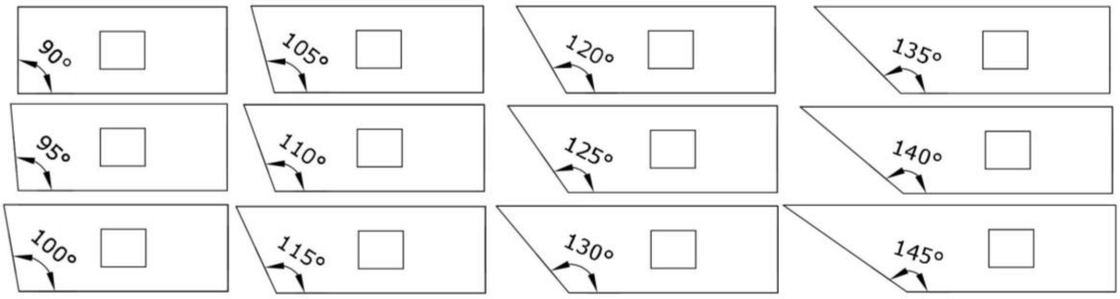


Figure 7-13 Side elevation of different façade inclinations

7.3.2 Pilot study's sensitivity analysis of different tilt façade

The pilot unit was simulated under four climatic scenarios. The unit was set up to characterise the indoor conditions of the case study. Monthly operative temperatures of the unit are shown in Figure 7-14, corresponding to the average monthly operative temperature for the living room and bedroom of the case study (see Figure 7-6). However, energy demand and overheating rate varied from the actual case study. This is because the scales of the models are different and the fact that the pilot unit consists of a single thermal zone.

However, to ensure the reliability of the data analysis, indoor temperature was compared with the modelled case study. Both results (Figure 7-6 and Figure 7-14) showed a similar trend for current and future climate conditions. The curves show a satisfactory performance of the Passivhaus structures in winter since the temperature never dropped below 20°C. The comfortable temperature in winter was achieved within the energy consumption limit of the Passivhaus standard i.e. 15 kWh/m^2. However, the temperature seems to rise over the comfort zone in summer time, in particular for July. For the current climate, operative temperatures inside the super insulated pilot unit displayed a slight overheating, which can be eliminated if the inside temperature dropped by an average of 1.4°C for the hottest period of July. However, future temperatures show an unsettled thermal comfort during summer, where the average operative temperature for the hottest month of the year in 2080 may rise to over 32°C if no extra cooling strategy is implemented.

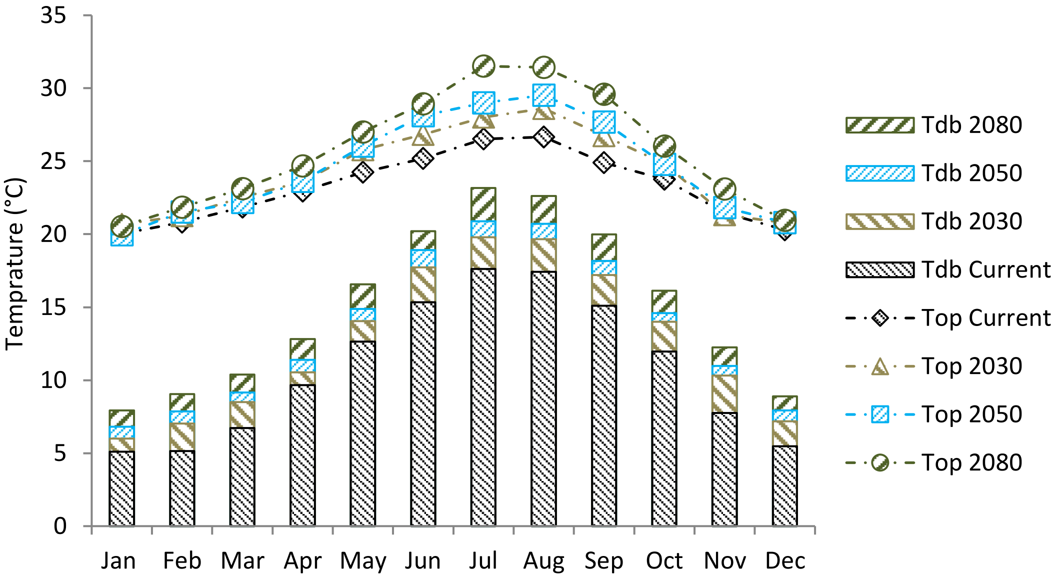


Figure 7-14 Pilot unit's operative temperature (Top) and London's average monthly dry-bulb temperature (Tdb) (current and future weather data)

At this stage of the research, the application of self-shading principle was undertaken to investigate if the Passivhaus pilot unit with different façade inclinations can provide a lower operative temperature in summer. Simulations were carried out for all facade inclinations (12 alternatives) shown earlier (Figure 7-13). This batch of data was available for four climatic scenarios under high emission 50% projection in London (i.e. total number of simulations; 12 x 4 = 48 sets of simulations).

The findings (Figure 7-15 - Figure 7-18) indicate that the operative temperature was reduced when the inclination façade was introduced to the unit. However, during the summer months, the gap between the values became more perceptible. For the current climate, the indoor temperature of the unit with the vertical facade dropped by a maximum of 2.1°C in July with respect to the steepest tested facade i.e. 145°, whereas the temperature reduction at the measured point for 1st January was just 0.4°C.

Insignificant margins between consecutive angles were measured above 120° and had little effects on the summer reduction of indoor temperature. The different between the vertical facade and the 95° angled facades was also smaller than those within the interval of 100° to 120°.

The alterations on the south facade resulted in a more pronounced variation under future climates (Figure 7-16 - Figure 7-18). The average operative temperature in July of 2080 fell by 3.6°C from the vertical facade to the steepest inclination tested (Figure 7-18). However, these variations remained very close during the heating period. It is worth mentioning that because the heating system was operating based on the set point of Passivhaus requirement i.e. 20°C, there will be a slight increase on the heating demand. These data demonstrated the perceptible impact of the self-shading facades on the overall outcome of thermal comfort in summer. However, the effect ceased after a certain point (above 120° inclined facade).

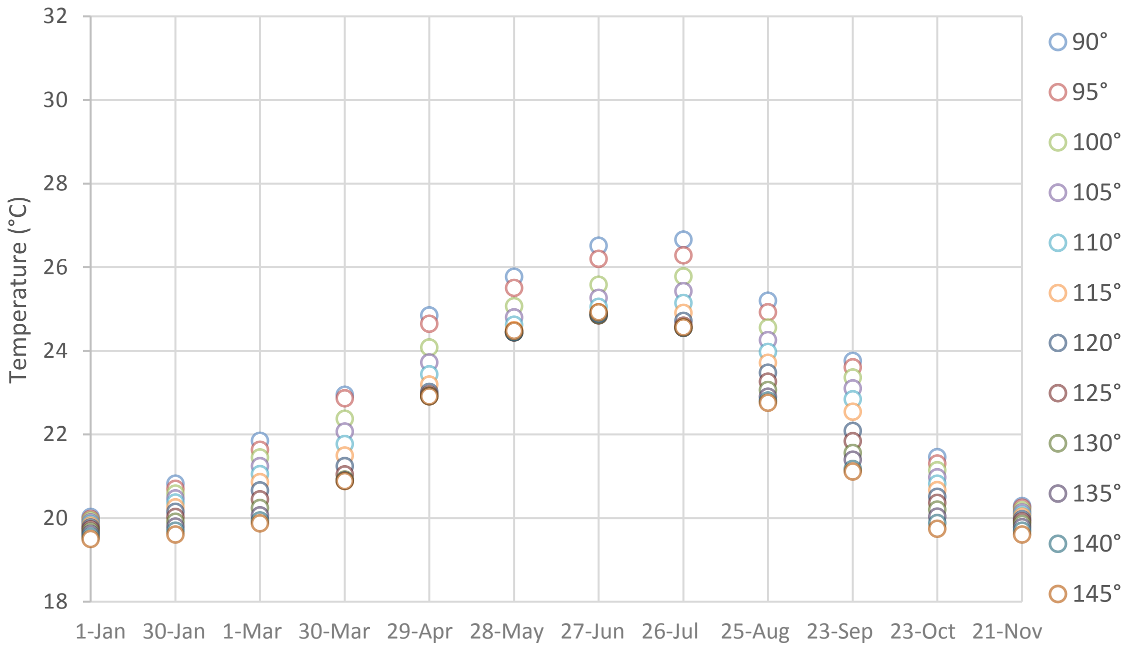


Figure 7-15 Monthly operative temperature for 12 façade alternatives under current London climate

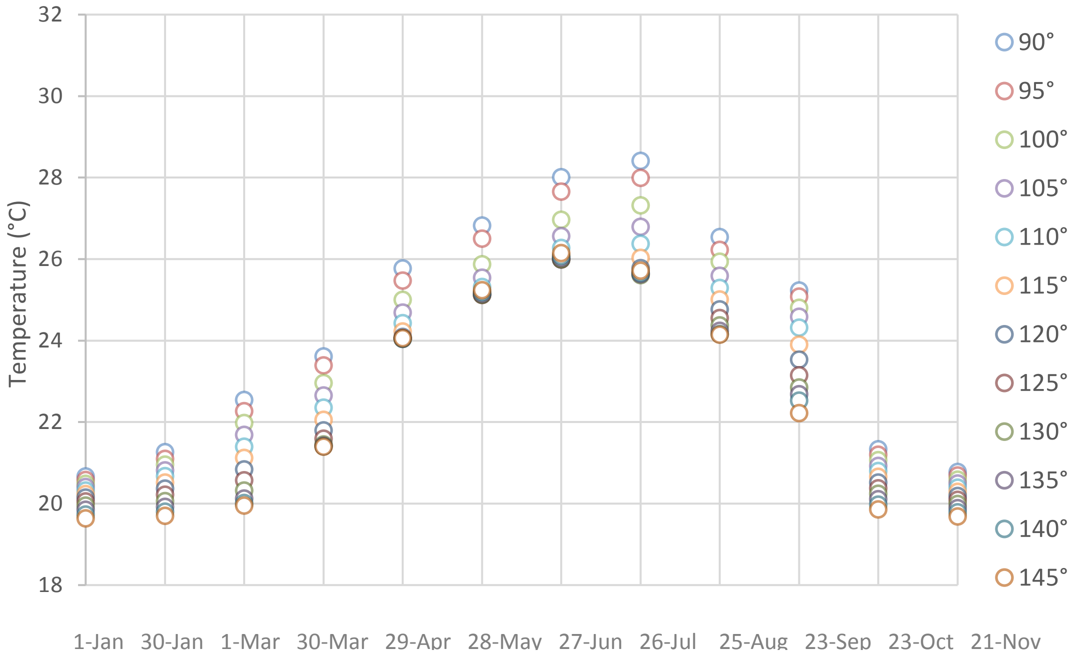


Figure 7-16 Monthly operative temperature for 12 façade alternatives under 2030's London climate

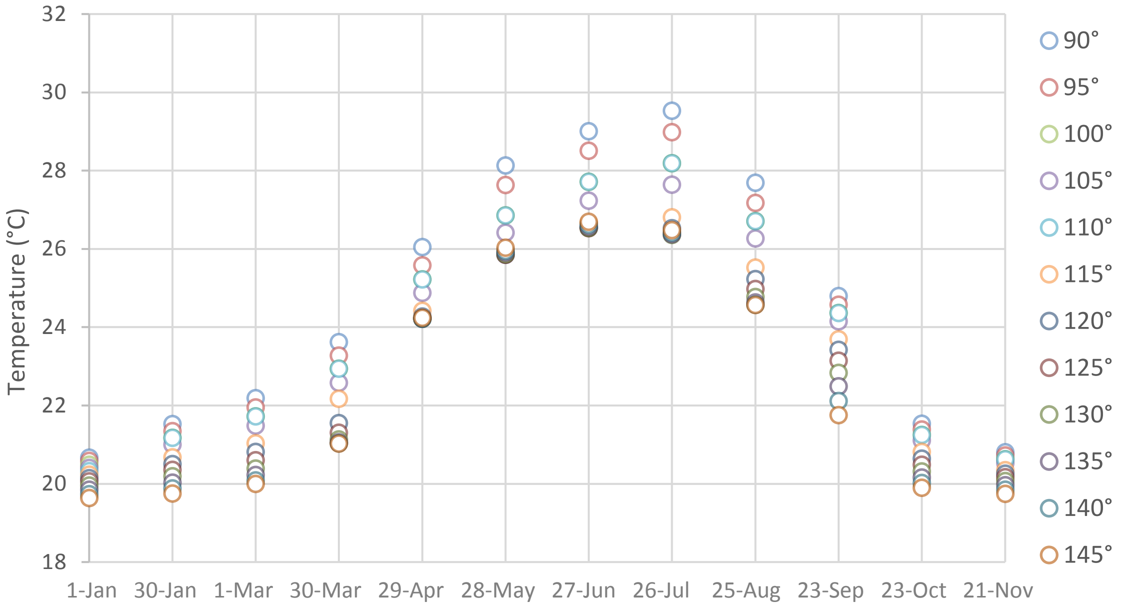


Figure 7-17 Monthly operative temperature for 12 façade alternatives under 2050's London climate

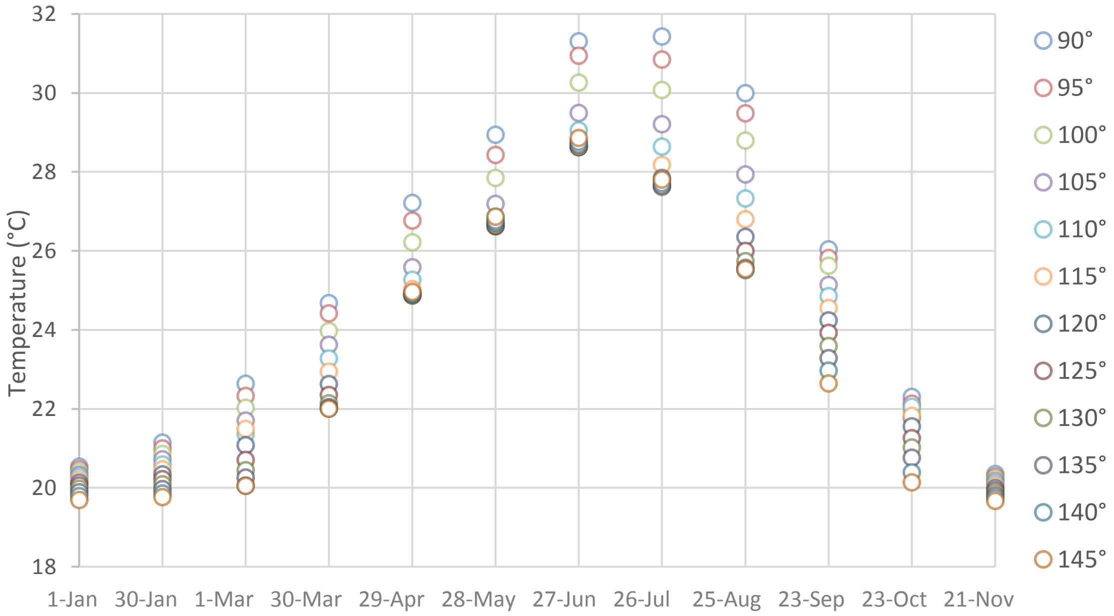


Figure 7-18 Monthly operative temperature for 12 façade alternatives under 2080's London climate

It is worth mentioning that the angle of 145° was found to be too steep and not practical in terms of interior design. Therefore, it was eliminated from the rest of the simulations.

Next, the study examined the impact of different façade geometries on the supplementary energy requirement (supplementary space heating and cooling) to provide the minimum indoor temperature of 20°C in winter and a maximum indoor temperature of 25°C in summer. In this case, the MVHR heating option remained "ON", based on a set point of 20°C. Natural ventilations in summer was operating, and the cooling option also was switched "ON" (only for the following analysis) to supply cool air when the temperature exceeds the cooling set point of 25°C i.e. comfort temperature. Figure 7-19 demonstrates the amount of energy, including heating and cooling, that the pilot unit would require to keep the temperature within the comfort interval of 20-25°C. It should be noted that the required supplementary cooling in summer was provided by an air-conditioning system running on electricity. The results (Figure 7-19) compared the space heating and cooling load for different south façade inclinations. As expected, for the heating demand there was an upward trend as the inclination angle increased.

The vertical bars in Figure 7-19 shows current and future data concerning the additional cooling load to insure the maximum set point temperature of 25°C during the summer. In contrast to the heating demand, the cooling load decreases as the inclination angle increased. However, the inclination stops having much effect when the angle reaches 120°. What is surprising is that when the angle increased from 130° to 140° the cooling demand marginally started to increase. This might be because the windows on that façade will then receive more reflected radiation from the ground. The software has a surface solar reflectance (albedo) that can be modified between 0 and 1. In this study the default value of 0.3 was modelled as this value represented a typical average albedo for grass and soil.

From Figure 7-19 there is a modest cooling demand for the current London climate, which can be eliminated by implementing an angled façade. The data show that the cooling demand will raise significantly by the second half of the century, and the self-shading strategy promises a substantial drop in cooling need for future London climates.

Considering active cooling is in operation, Figure 7-20 sums up the amount of energy used for both heating and active cooling. The increase in current energy demand is because of the electricity use for active cooling to keep the operative temperature below CIBSE warm threshold temperature of 25°C. The vertical façade has the lowest energy use in the current climate. However, for future climates the façade with 105°-110° inclination angle experiences the least heating and cooling load. Figure 7-21 gives an indication of the percentage of operative temperature above 28°C in the pilot unit. The graph compares the overheating rate of the different façade tilt. Overheating was completely eradicated by introducing a tilted façade of 110° in the current climate. For future climates, overheating was reduced as the angle reached 105° and significantly dropped by an angle of 120°. However, further inclinations had no more reduction in sensible cooling load and overheating rate. The method is assumed an effective way to improve thermal comfort in summer.

Although self-shading façades improved overheating rate, it added to the heating load of the building. The total amount of energy use for Heating and air-conditioning was higher for angled facades in the current climate. On the other hand, total space conditioning load was lower for tilted facades of up to 110° inclinations for future climates, especially for 2080's period. When the inclination angle was 115-degrees, the total load relapsed back to almost equal with the vertical façade for 2030's and 2050's scenarios. However, it was lower than the vertical façade under 2080's projection and higher under current climate (see Figure 7-20).

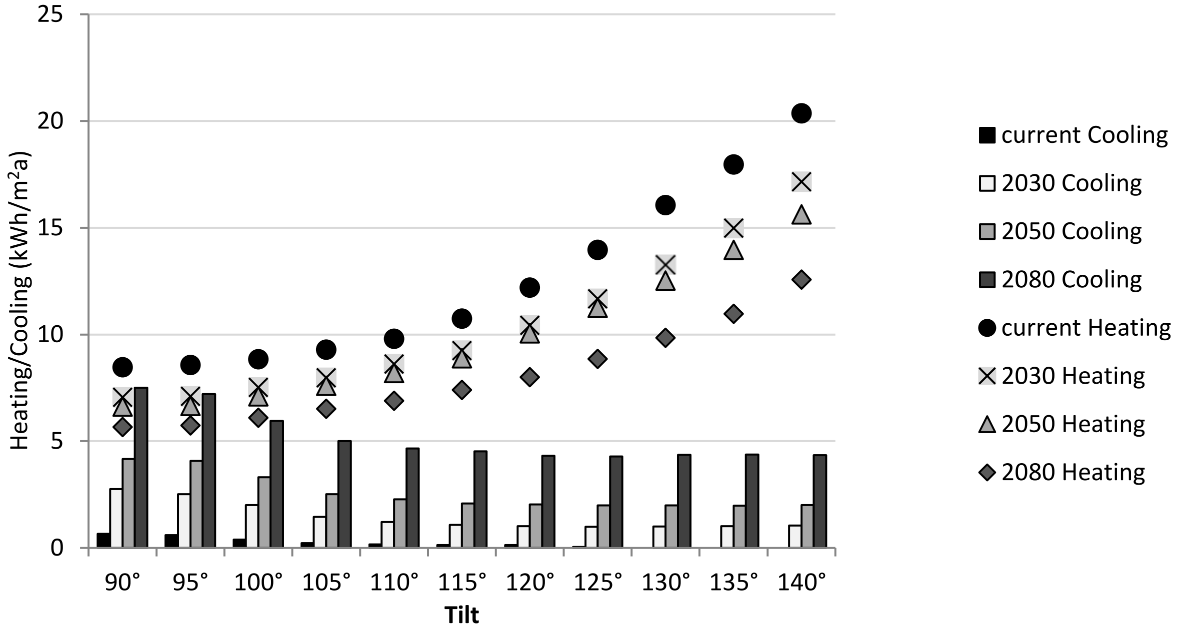


Figure 7-19 Annual energy demand of the pilot study unit for different façade geometries under four climate scenarios

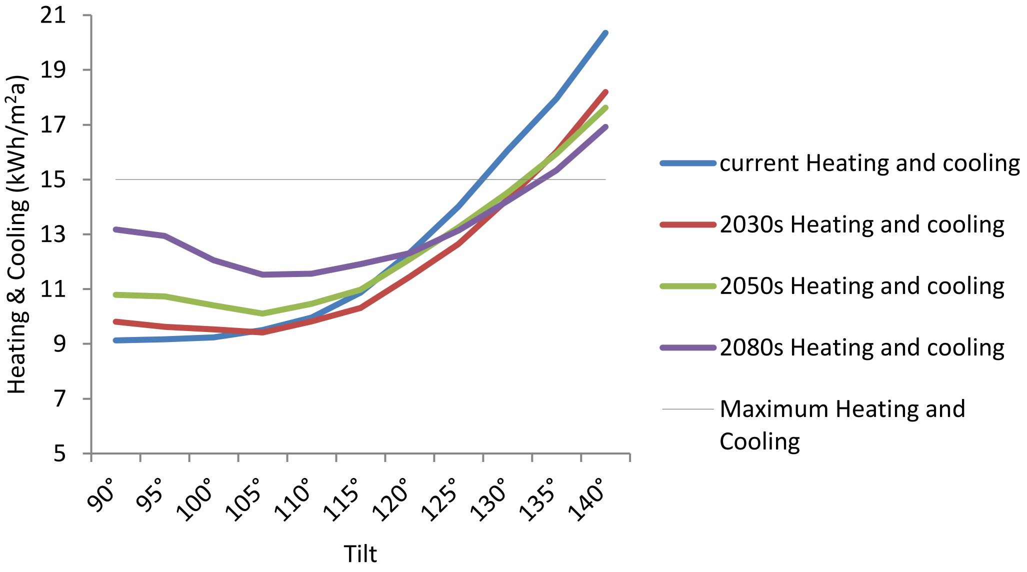


Figure 7-20 Annual heating and cooling demand to achieve 20-25 indoor temperature

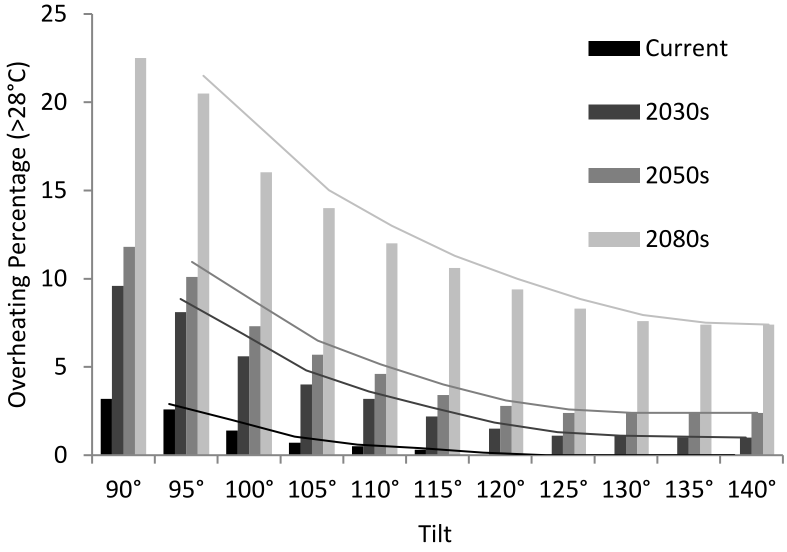


Figure 7-21 Overheating percentage (h_ϑ>28) and average reduction trend line

7.3.3 Conclusion on the pilot study result

The scenario approached by a constraint varying inclination established the inclination interval of 105°-120° as the favourable self-shading interval to reduce summer discomfort. Evidently, steeper tilt facades are more useful for future climates, and a slight angle would decrease much of the overheating for current weather. In the current climate, the temperature above 28°C will never occur by implementing a tilt façade of 120°. Although the facade of 105°-115° will have some spell of 28°C operative temperature, this will be within the overheating limit criteria. The tilted facades of 110° and 115° cut the overheating by half when compared with the vertical case, while the heating demand increases by a smaller margin for current climate and a much lower value under future projections. The reduction of sensible cooling and consequently overheating hours should not compromise the Passivhaus requirement for the heating demand. Although the space heating was increased because of the self-shading façades of the chosen interval i.e. $Tilt_{\Theta\,\mathrm{south}}$=105°-120°, it remained within the acceptable Passivhaus criteria. Therefore, eliminating the inclination angle of above 120°.

Figure 7-22 presented the effective tilt interval for the pilot unit i.e. $Tilt_{\Theta\,\mathrm{south}}$=105°-120°. Overheating was reduced dramatically; however, the increase in heating demand was not as dramatic as the overheating reduction. After a sharp drop in overheating rate, from the vertical to 105-degree tilt, the reduction of overheating decreased steadily for the steeper angles. In contrast, the increase is heating demand was small from the vertical to 105°. It rose marginally from 105 to 115°, however, the heating demand started to increase further from 115° to 120° hypothesizing $Tilt_{\theta\ \mathrm{south}}$ =110° and $Tilt_{\theta\ \mathrm{south}}$ =115° as the optimum (or near optimum) inclination angles to be implemented to the case study for further analysis (achieved by a constrained approach).

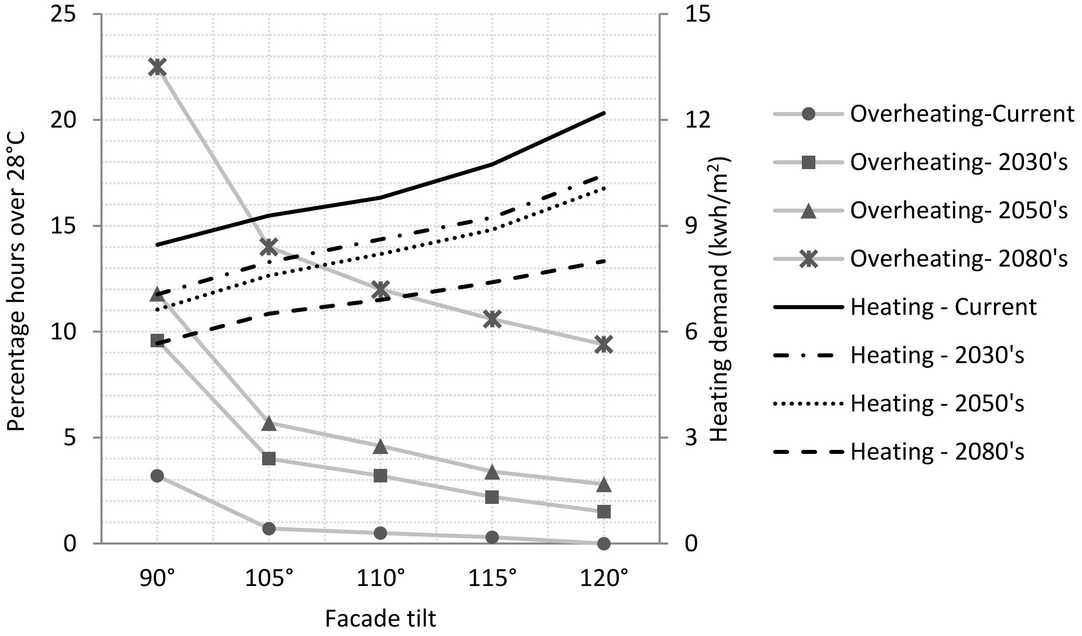


Figure 7-22 Overheating and heating comparison for the effective interval

7.4 Implementing optimum self-shading facades to the case study

Concerning the study's main objective, the data gathered in the pilot study suggest that the inclination angle of 110°-115° ($Tilt_{\theta south} = 110° - 115°$) is the most effective self-shading to be implemented to the case study in London. Thus, selected tilted walls replaced the original vertical wall (south elevation) of the house to self-shade the large southern glazing in summer (Figure 7-23). The following section analysed the impact that these shapes created on the thermal comfort of the house under current and future climates in London. The simulations were calculated for the living room and main bedroom. The structure of the modelling is shown in Figure 7-24, and Table 7-7 indicating the shading inputs for simulations on the selective inclination angle and the original vertical façade.

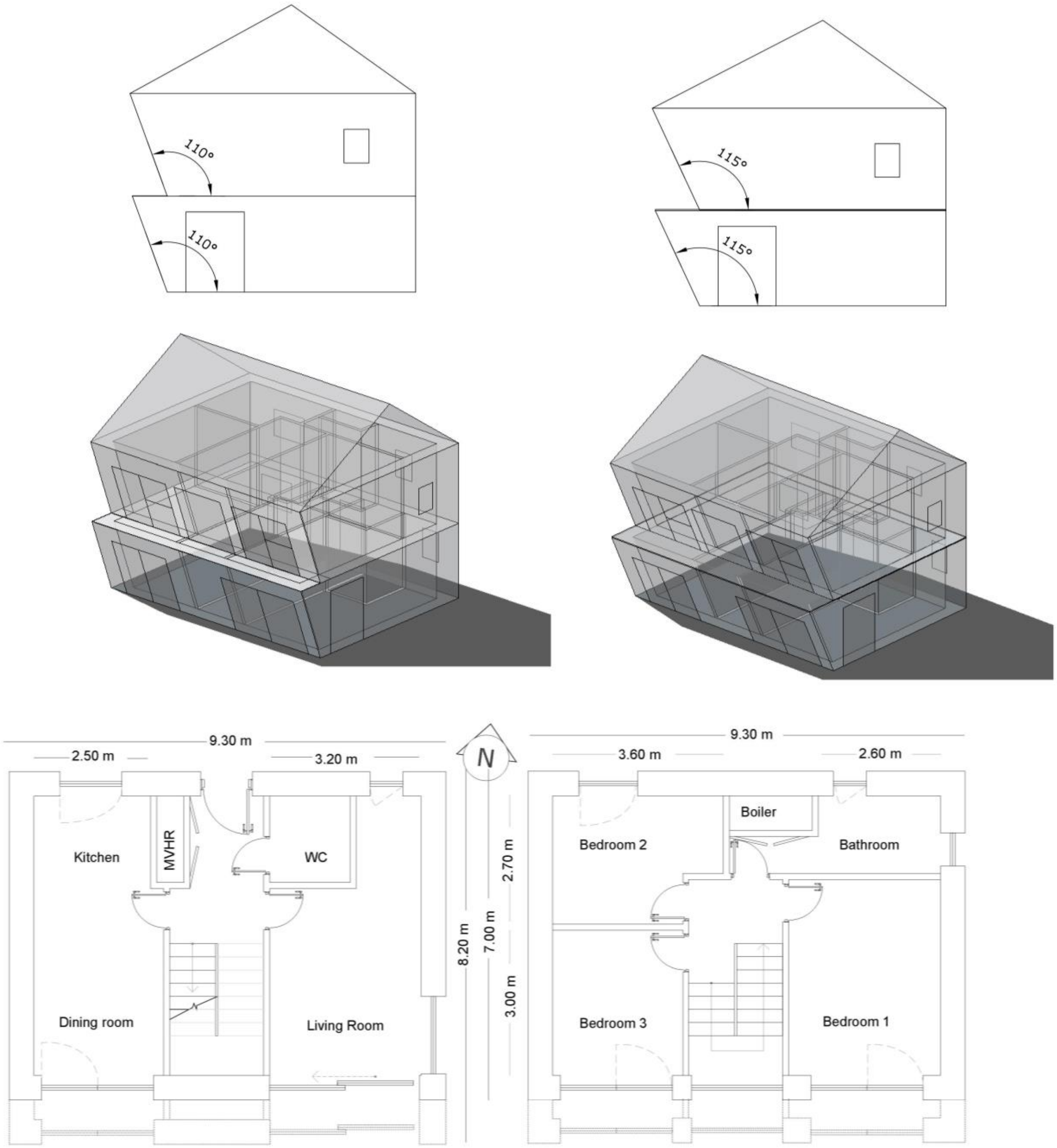


Figure 7-23 Plan, elevation and 3D image of the altered cases

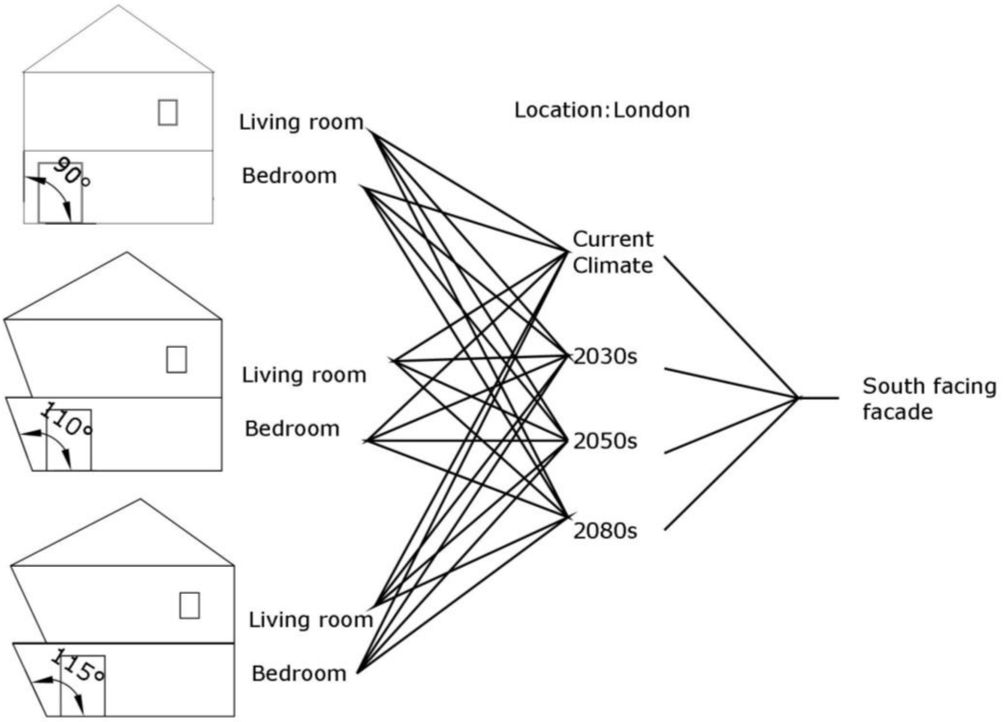


Figure 7-24 The structure for modelling overheating risk of the selected façade inclinations

Table 7-7 Shading input for modelling

South Façade Design	External Shading strategy for south facing glazing
Vertical facade	External roller blinds
110° inclined facade	Self-shading strategy
115° inclined facade	Self-shading strategy

7.4.1 Simulations on selective self-shading facades

This section will reflect on the result outcomes of the simulations for the proposed façades. It will investigate the effectiveness of the implemented strategy as a single intervention to reduce overheating risk. In this case, the case study model was simulated 12 times i.e. for three façade arrangements, and four climate periods. Operative temperatures were available for the living room and bedroom on each of 12 models creating 24 sets of data.

Current and future operative temperatures and corresponding heating demands of the vertical and proposed inclined facades were compared for the living room (Figure 7-25) and the main bedroom (Figure 7-26). The graphs indicate a significant reduction of average indoor temperature for the 115° tilted case compared with the vertical facade. The difference between the two suggested tilted façades was insignificant in the current climate. However, this variation becomes larger in future due to the elevated outdoor temperature and solar radiation.

Because of changing the façade angle, the average operative temperature dropped for both summer and winter periods. However, the impact on the current climate was small, while the mean temperature in July 2080's fell by up to 2.5°C in the living room. There was also a slight increase in heating load for tilted facades, which is greater in the current climate. Despite this increase, heating demand always remained within the Passivhaus limitation of 15 kWh per square metre while assuring the minimum indoor temperature of 20°C.

The house with the original (vertical) south façade in London current climate experienced 28% of the occupied hours over 25°C ($h_{\vartheta>25^{\circ}C}$) in the living room, and 12% in the bedroom. Overheating in the living room reduced to 15% and 12% using 110 and 115° self-shading façades respectively. The tilted façade of 115° eliminated the overheating in the bedroom and just exceeded 2% above the overheating limit in the living room. The reduction of the internal solar gain and consequently operative temperature was greater for the bedrooms (Figure 7-26). The average operative temperature in the bedroom was reduced up to 4°C by implementing a 115° inclined façades (this reduction was 2.5˚C for the living room). In the current climate, the improvement of the internal comfort temperature was estimated 1.9°C for the bedroom and 1.0˚C for the living room. The operative temperature in July reduced from average of 25.7°C to 23.8°C in the bedroom and 25.4°C to 24.4°C in the living room.

It is worth mentioning that, unlike the bedroom, which has glazing only on the south façade, the living room also has glazing on the other facades, which are protected only by internal blinds, and no additional shading strategy i.e. self-shading was implemented to those windows on east and north façade of the living room (see Figure 7-27).

Table 7-8 plotted overheating percentage for the living room and bedroom for both benchmark temperatures i.e. low or base benchmark of h_{ϑ}>25°C, and the high benchmark of h_{ϑ}>26/28°C. Under current climate, overheating in the living room (28.2% above 25°C and 2.9% above 28°C) exceeded almost three times more than the acceptable CIBSE criteria i.e. 10% and 1%. The bedroom's low benchmark criteria were not far from the optimum thermal comfort. However, the high benchmark significantly surpassed the optimum comfort criteria.

For the current climate, all the exceeded overheating rates except low benchmark criteria for the living room were dropped below maximum benchmark values when 110° tilted façade was introduced. The numbers continued to descent by using the steeper south façade i.e. 115° degree. This led to a slightly lower percentage of overheating that almost fully eradicated overheating risk solely by self-shading the south elevation.

In the 2030's climate conditions, the house experienced more than 40% and 20% of overheating frequency in the living room and bedroom respectively. In this case, a tilted façade of 115° decreased the overheating by more than 50%. Although overheating was increased under 2050's weather prediction, the rise was not as significant as the first interval i.e. from current climate to 2030's.

Summer operative temperatures above 25°C displayed a sharp increase under 2080's weather projection, making the overheating rate 58% and 38% for the living room and bedroom respectively. High benchmark temperature was at the peak of 28% and 31% for living room and bedroom respectively, which was reduced to 15% and 14% using self-shading facades (Table 7-8).

Assessing overheating based on the static criteria resulted in a very high level of overheating in the future climate simulations. Although overheating frequency was reduced by the shading strategy, it significantly exceeded the current overheating criteria suggesting a high risk of overheating for the future.

Table 7-8 also presents the growth in heating load occurring as a consequence of shading the envelope. The annual heating demand of 8.2 kWhm^{-2} that the house required to provide thermal comfort was increased by 1.1 kWhm^{-2} for a 110° tilt façade and went up further to 9.9 kWhm^{-2} because of implementing a 115° façade. However, this increase became smaller for the future scenarios. This is due to the elevated winter temperature in the future climate projections. The self-shading strategy resulted in just under 1.0 kWhm^{-2} increase in heating load for both 2030 and 2050’s. For 2080’s condition the added heating load of the tilted facades were insignificant (Table 7-8).

The change in façade angle led to a noticeable and effective reduction of the overheating rate and a comparatively small increase in heating demand. However, despite the increase in heat load, the space heating demand remained well below the Passivhaus requirements (i.e. under 15 kWh/m^2).

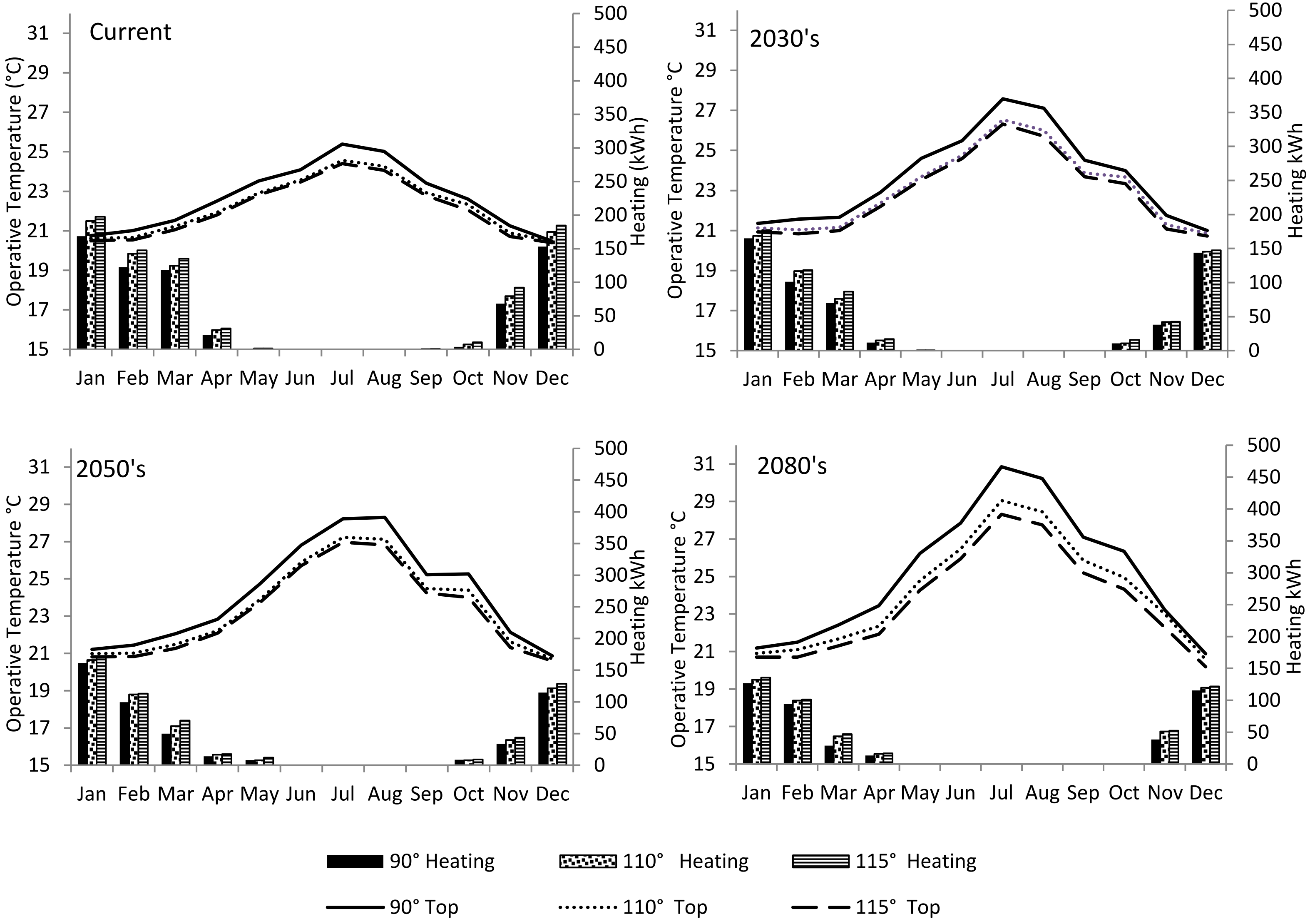


Figure 7-25 Heating demand and living room average monthly operative temperature for vertical and tilted façades

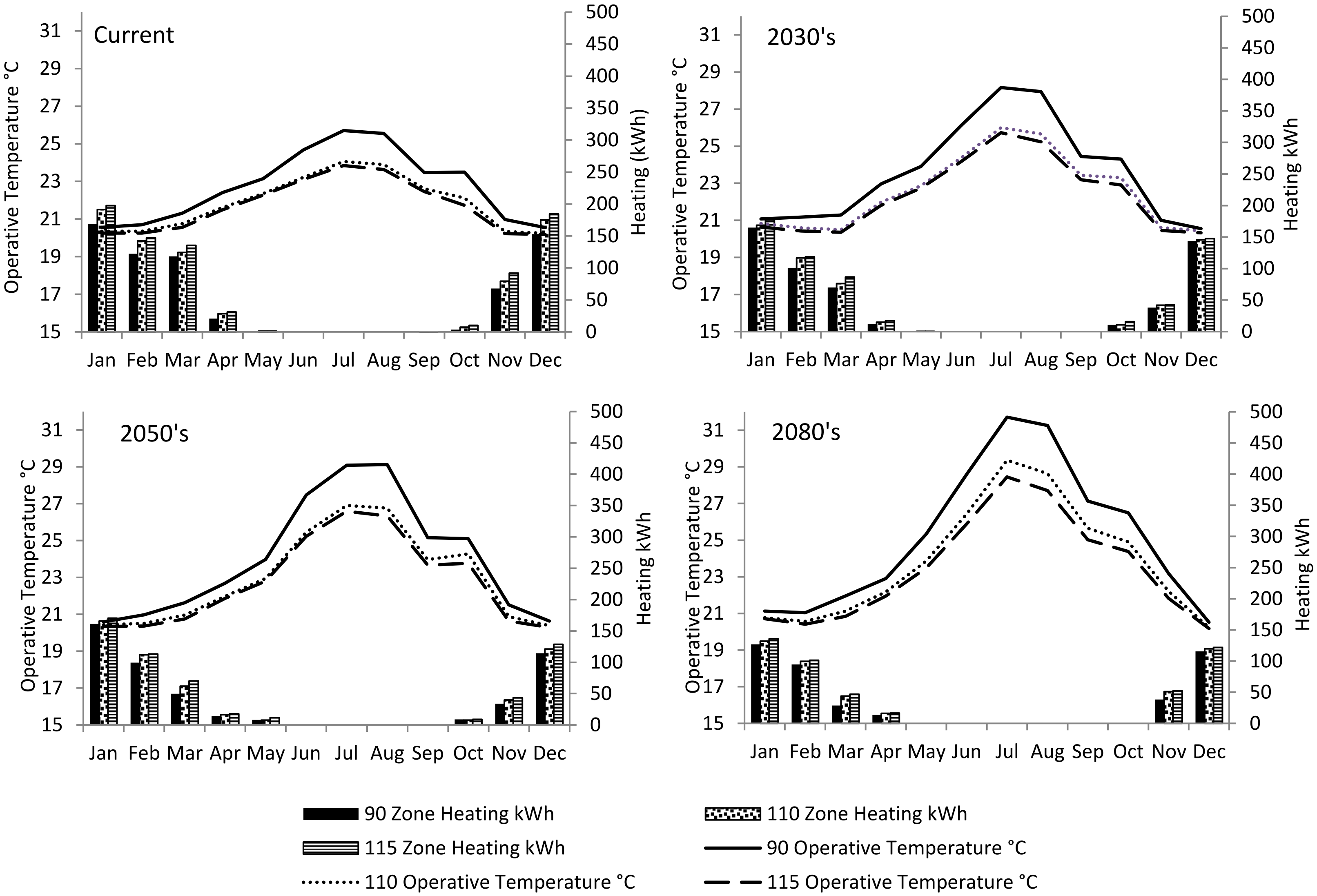
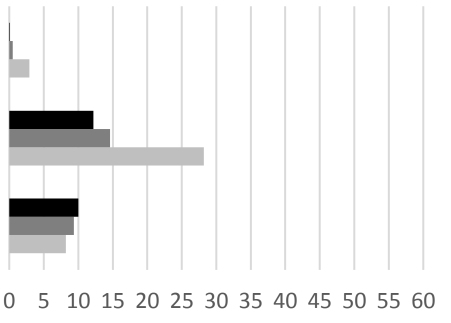
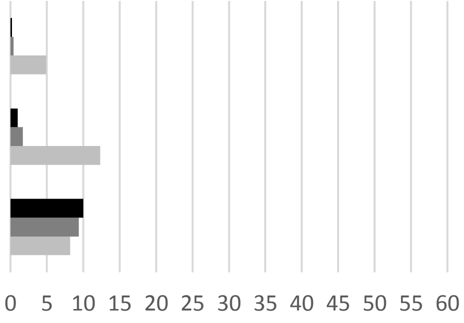
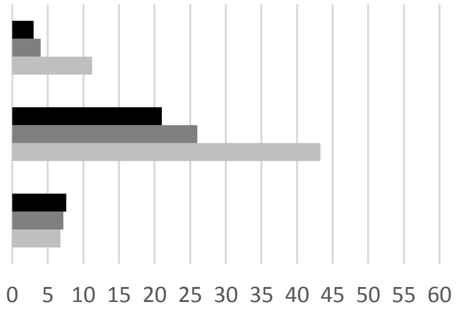
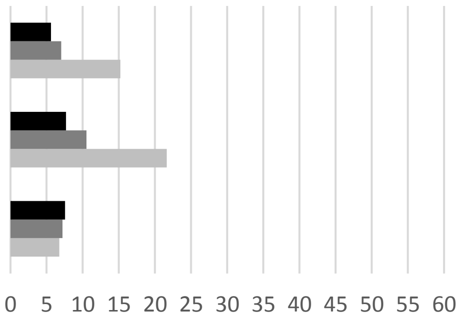
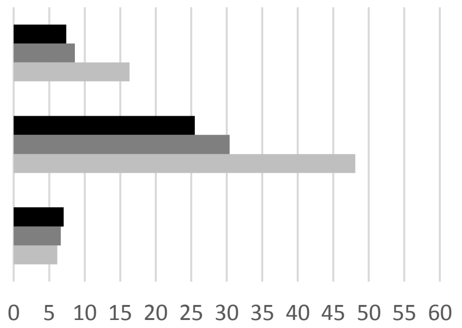
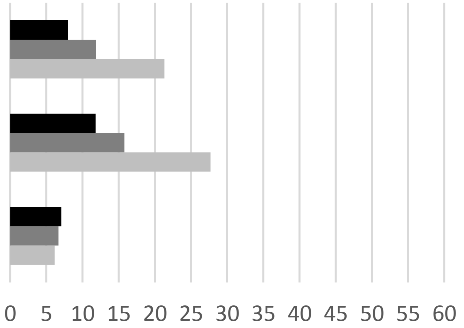
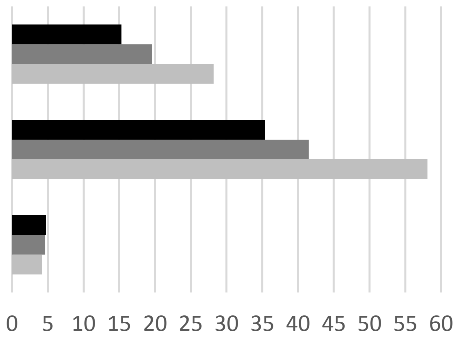
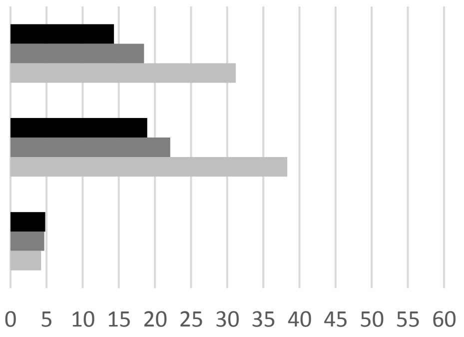


Figure 7-26 Heating demand and bedroom average monthly operative temperature for vertical and tilted façades

Table 7-8 Overheating percentage, current and future scenarios

	Living Room	Bedroom
Current Climate		
Overheating >28/26 % of occupied hours Overheating >25 % of occupied hours Annual Heating Kwh/m^2 ■ 115° ■ 110° ■ Vertical		
2030's		
Overheating >28/26 % of occupied hours Overheating >25 % of occupied hours Annual Heating Kwh/m^2 ■ 115° ■ 110° ■ Vertical		
2050s		
Overheating >28/26 % of occupied hours Overheating >25 % of occupied hours Annual Heating Kwh/m^2 ■ 115° ■ 110° ■ Vertical		
2080s		
Overheating >28/26 % of occupied hours Overheating >25 % of occupied hours Annual Heating Kwh/m^2 ■ 115° ■ 110° ■ Vertical		

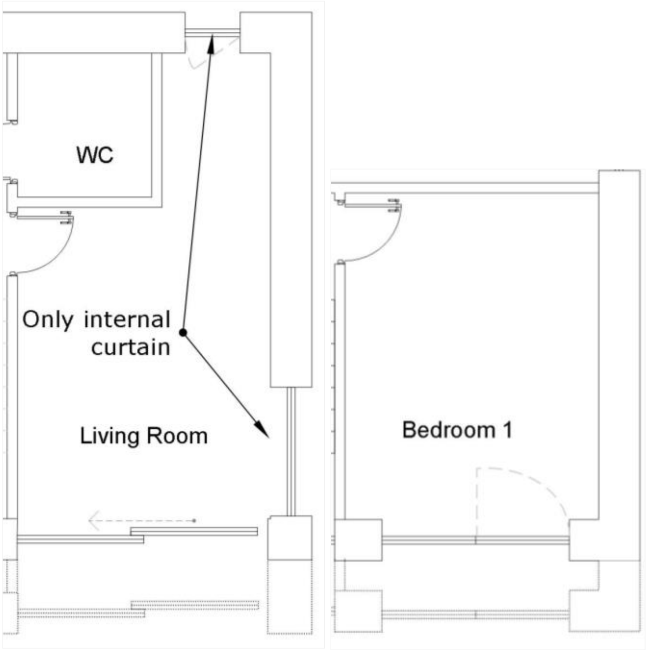


Figure 7-27 Glazing location shown for living room and bedroom

Although this study has focused on the risk of summer overheating, it is necessary to measure the impact that the proposed geometry will make on winter days. Weather data used in this study were analysed to select a typical day in both summer and winter of current and future climate to indicate an hourly performance of different facades in a given day. The chosen days are representative of summer and winter climates.

Figure 7-28 compares a daily breakdown of the indoor temperature fluctuations and transmitted solar radiation through the windows for three facade alternatives. During a cold day, there is a marginal variation in the indoor temperature when implementing the tilted façade for both current and future climates. It is shown that the solar gain transmitted into the room is reduced during midday and early afternoon when implementing the inclined façade (Figure 7-28a, and c). However, this reduction of solar gain is significant for a current warm summer day (Figure 7-28b) and it becomes very effective in reducing overheating under 2080's climate scenario (Figure 7-28d, Figure 7-29d). The reduction of excessive solar gain at 12:00 (peak operative temperature) was reduced by half (up to 600W) by the inclined south façade (Figure 7-28d). Considering that the super insulated structure can keep the heat in, the temperature remained high for the rest of the day. Then, an adequate amount of natural ventilation i.e. night purging is required to remove the excessive heat during the evening.

The calculation of solar transmission for the living room encompass all windows i.e. on the south, east and north elevations. The blind operating schedules remained the same throughout all simulations. Figure 7-29 shows the result of a similar simulation as above on the same days for the bedroom1 that has windows only on its south façade. The results show a more significant reduction of total solar transmission for the house with the tilted facade. Consequently, the reduction of indoor temperature in the bedroom was greater than for the living room. A possible reason was that all the glazing in the bedroom are affected by the shading created by the façade geometry whereas for the living room the transmitted solar for the east and north facing windows will be the same as the original case. The reduction of solar transmission was much higher during the midday hours. During the late hours of the afternoon the transmission of both vertical and tilted facades were similar due to the sun movement towards the west elevation of the building, where the building has no glazing (see Figure 7-30). The seasonal and hourly positions of the Sun change as the Earth rotates. In fact, the most impact the tilted façade will make is when the Sun is at a high incident and equator side (south facing). Another possible reason is that the fraction of the blind operation is higher in the living room than the bedroom during afternoon period (i.e. occupant presence is more and the living room blinds are predicted to be closed more in the afternoon- see Appendix B: “from Jun-through 25Aug; midday” fractions for weekends and weekdays)

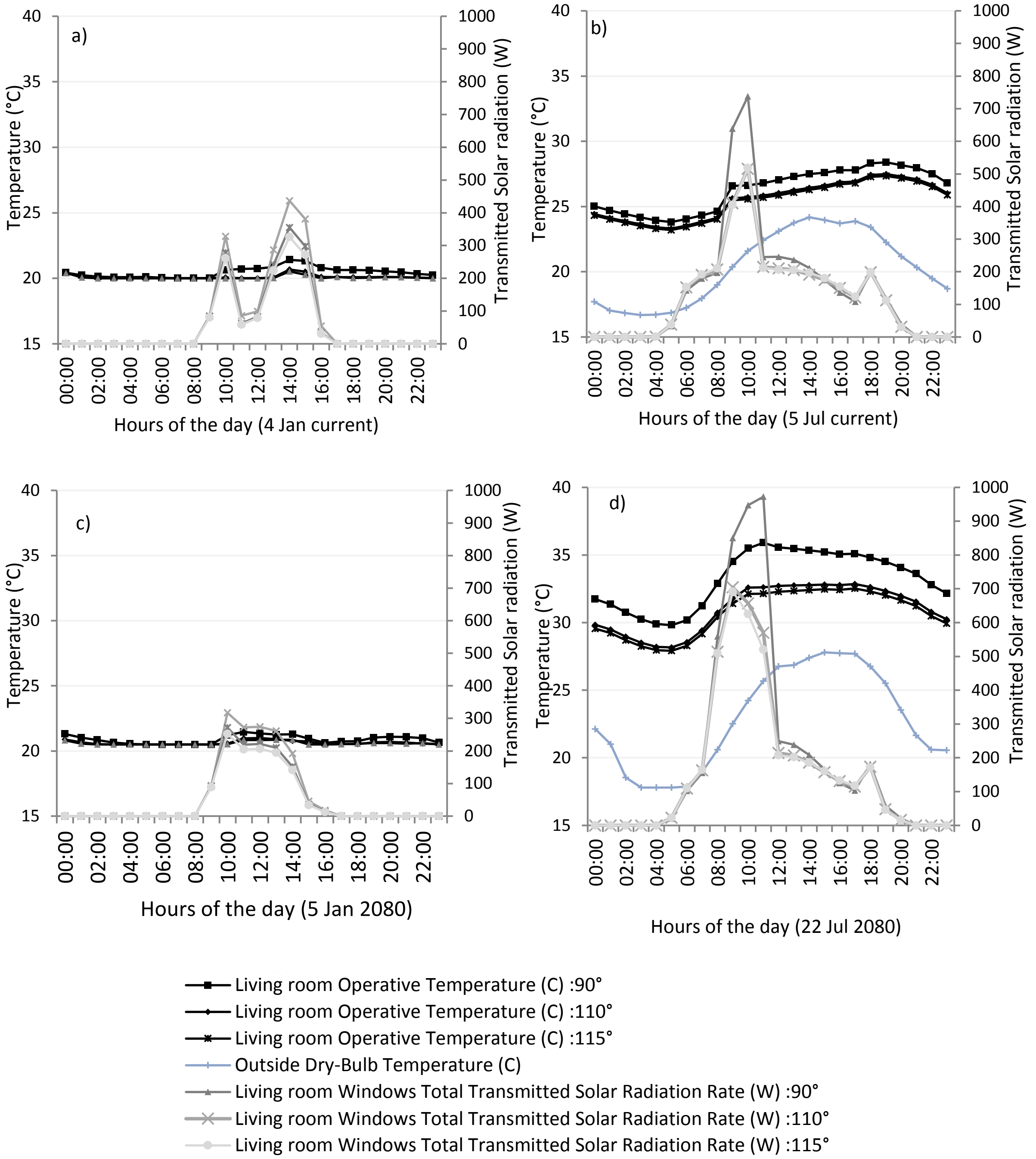


Figure 7-28 Winter and summer single day analysis in the living room: a) 4th January-current climate, b) 5th July-Current climate, c)5th January-2080, d)22nd July- 2080.

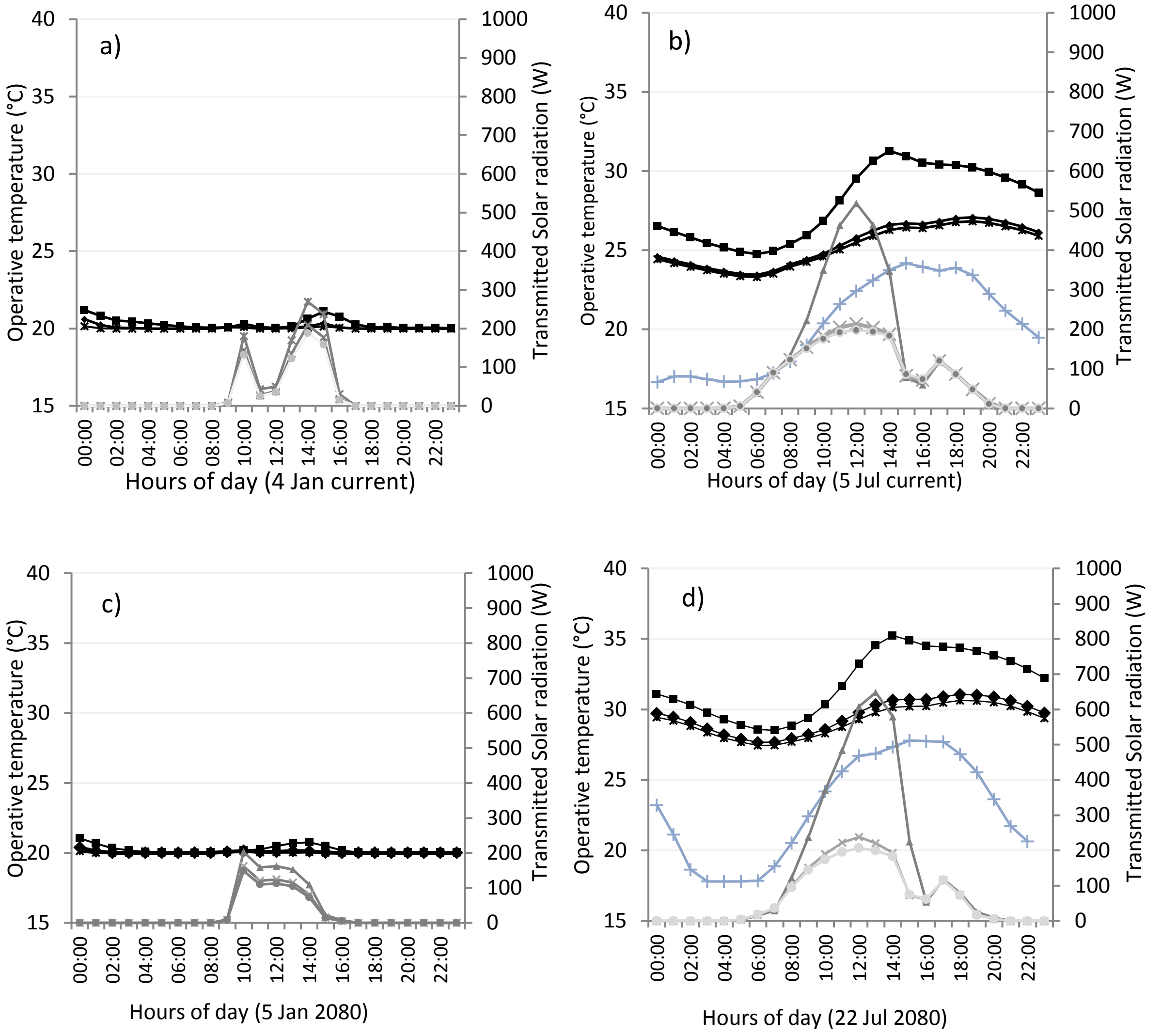
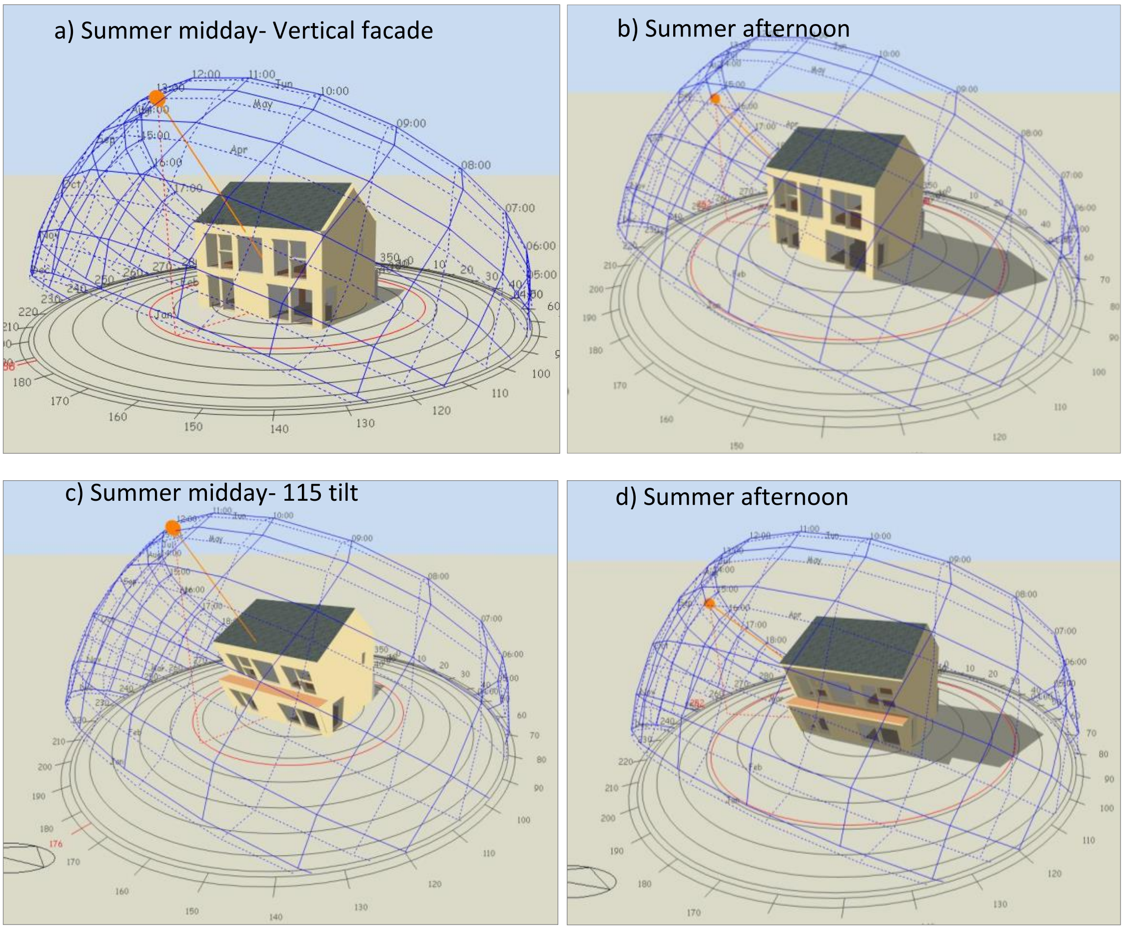


Figure 7-29 Winter and summer single day analysis in the bedroom: a) 4th January-current climate, b) 5th July-Current climate, c)5th January-2080, d)22nd July- 2080.

—■— Living room Operative Temperature (C) :90°
—◆— Living room Operative Temperature (C) :110°
—✱— Living room Operative Temperature (C) :115°
—+— Outside Dry-Bulb Temperature (C)
—▲— Living room Windows Total Transmitted Solar Radiation Rate (W) :90°
—✕— Living room Windows Total Transmitted Solar Radiation Rate (W) :110°
—●— Living room Windows Total Transmitted Solar Radiation Rate (W) :115°


a) Summer midday- Vertical facade

b) Summer afternoon

c) Summer midday- 115 tilt

d) Summer afternoon

Figure 7-30 Sun path during a summer day for vertical and tilted façade design

7.4.2 Integrated active cooling

The research has shown that a successful single passive intervention could remove overheating for current climate in the UK. It is also expected that clustered passive measures would be capable of mitigating overheating in the Passivhaus dwellings for projected pre-2050s climate scenarios. However, the results predicted that the passive measures to combat the overheating risk of the projected post-2050s climates might be insufficient in eradicating overheating. This result is in agreement with the study on the future performance of the housing stock (Gupta, et al., 2015) and office buildings (Chow & Levermore, 2010) in the UK that stated the need for mechanical cooling is becoming a necessity in many part of the UK.

Therefore, the study has developed the investigation to simulate the house with active cooling to produce a thermally comfortable indoor environment in the future summers. Within this context, the following section specifically investigated the energy demand for air conditioning unit (on electricity) to operate when the indoor temperature is at or above 25°C. Figure 7-31 plotted summer cooling load for the house with original and alternative tilted facades. Set points and other settings remained intact throughout the simulations. The only change is that the mechanical cooling system was switched "ON" as part of HVAC system at the set point temperature of 25°C.

Given the aforementioned scenario, the temperature of the living spaces will not exceed the maximum optimum comfortable temperature. It is worth mentioning that with the active cooling operating using the 25°C set point, the overheating will be 0%, surpassing the current overheating allowance i.e. 10% of $h_{\vartheta}>25$°C and 1% of $h_{\vartheta}>28/26$°C.

Chart (a) in Figure 7-31 shows that there is a small cooling load required for current climate, which was discharged by the proposed single intervention i.e. self-shading $Tilt_{\Theta south} = 110° - 115°$. The electricity needed to keep the living spaces below the set point temperature in the Passivhaus was about 3.6 kWhm^{-2} for 2030s summer months and 4.2 kWhm^{-2} for 2050s. However, these were reduced to 1.1 and 1.6 kWhm^{-2} using a 115° angled façade, suggesting an effective reduction in cooling load. Chart (d) reveals that even with the shading strategy (single intervention of $Tilt_{\Theta south} = 115°$) cooling is necessary for at least four months under 2080s climate period (representing potential condition from 2070-2099 high emission 50% scenario). Assuming the current optimum comfort temperature, the electricity required to fulfil the 25°C cooling set point temperature in summer will have surpassed the energy required for MVHR system to keep the house above the minimum indoor comfort temperature of 20°C. It is also worth mentioning that the mechanical heat recovery systems (MVHR) are very efficient in terms of energy consumption compared to conventional air conditioning units, which were used for supplementary cooling in the above analysis.

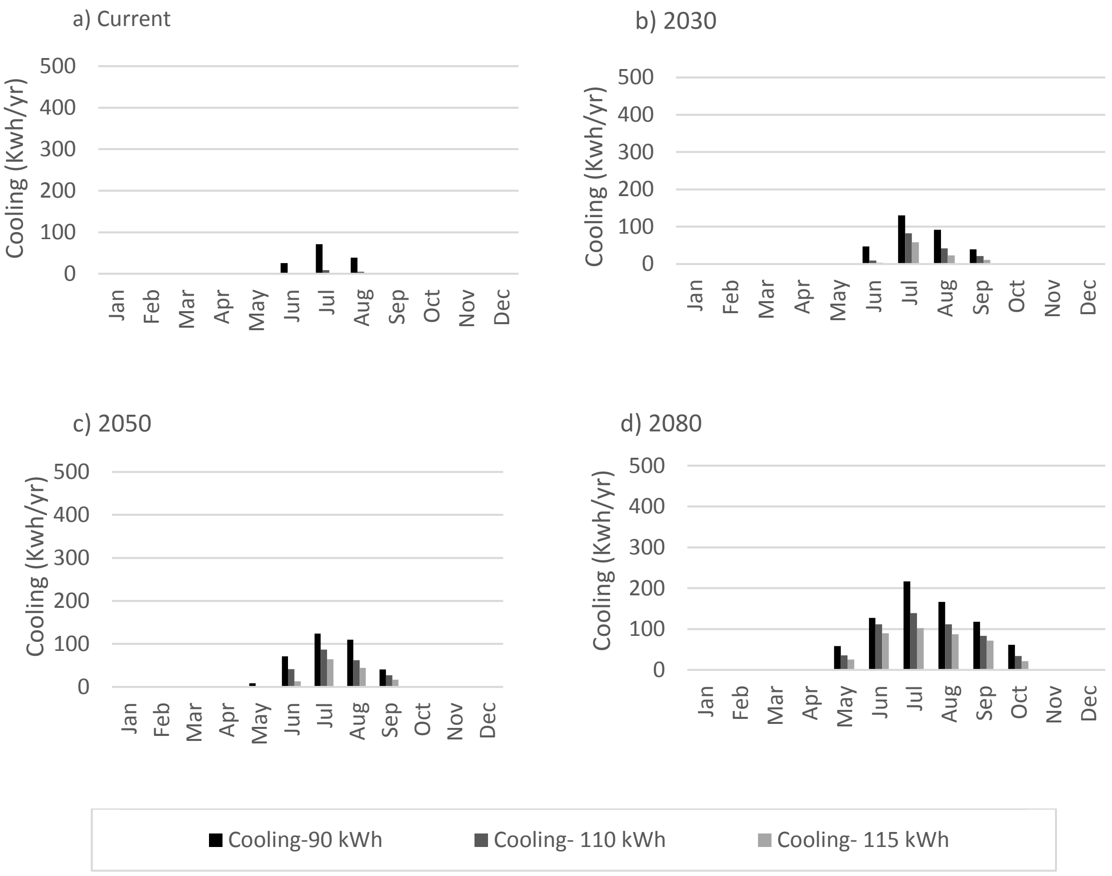


Figure 7-31 Supplementary cooling if active cooling is used

7.5 Comparing the suggested arrangement with common shading strategies

Modelling analysis of the house with inclined walls showed the potential of geometrical implications in reducing the overheating risk for the case study Passivhaus. In the previous section, south-facing tilted walls were compared with the original vertical wall with an external roller blind. In this section, the study compares the tilted walls with the most common interventions to reduced summer excessive solar gain.

As previously mentioned (see section 3.3.3) the second Passivhaus (Lime House located just next to the Larch House) which was part of the Welsh social housing prototype, was designed with a reduced window to wall ratio (20%). This was based on the lessons learned from the Larch House because of a few issues addressed by the design team. One reason was to reduce potential overheating risks. A study entitled *"The Passive House in Summer"* from the Passivhaus Institute regarded the use of overhangs as one of the effective shading strategies in the Passivhaus to reduce summer discomfort. Therefore, five alternatives of single interventions were compared to test the effectiveness of each single intervention towards enhancing summer thermal comfort. These design arrangements are listed in Table 7-9 and will be regarded as variants "I-V" throughout the study. This was mainly set to compare the self-shading facades against the most common existing solutions to reducing unwanted solar radiation in summer.

Table 7-9 List of the different design arrangements (variants)

Intervention	Description of the south facade	Key Legend
Variant I	Vertical wall with external roller blinds with 55% window to wall ratio (i.e. as per the original case study model)	vertical
Variant II	Tilted façade (110-degree) as a self-shading design strategy (proposed strategy) with 55% window to wall ratio	110°
Variant III	Tilted façade (115-degree) as a self-shading design strategy (proposed strategy) with 55% window to wall ratio	115°
Variant IV	Overhang (1.3 m) as a fixed shading device (as a conventional intervention) with 55% window to wall ratio	1.3 (oh)
Variant V	Reducing window to wall ratio from 55% to 26% as a function of minimizing heat gain in summer (as a conventional intervention)	26% WWR

As previously claimed (in Section 3.3.1) for UK latitudes, and based on the SAP calculation, overheating was reduced by 40% using an external overhang of around 1.3 metres. The Passivhaus summer study found that overhangs with a depth of 1.3 m reduced overheating below the 10% criteria and overhangs with a depth of 1.5m were found to almost eliminate overheating without significantly changing annual heating demand (for Germany's climate).

This study also used Ecotect calculation wizard algorithm to generate optimised overhang depth for future London climate. The same weather data which was used in the format of (.epw) for DesignBuilder were converted to (.WEA) for simulations in Ecotect. The shading design wizard was used to calculate the optimum overhang size for current and future London climate. Different results were obtained for the current and future weather scenarios varying from 1.0 to 1.4 metres to block the intensive solar beams in summer. Since the study focused on the future performance of the Passivhaus, 1.3 m was chosen as an optimum overhang (variant "IV") for analysis in this section.

The last variant of the window to wall ratio was chosen based on the data presented in Passivhaus Summer study. It is regarded indoor temperature will not exceed 25°C if the window size is 14% or less; however, this is in contrast with the idea of free heat gain from the sun in winter. Research showed an optimum window to wall ratio on the south façade is about 20-30%. Overheating events sharply raised with south facing glazing being more than 20% of the façade. However, overheating will remain within 10% of acceptably warm up to 30% window size. The automatic parametric design option in DesignBuilder also calculated an optimum of around 26% of window to wall ratio for the south façade. Therefore, the original 55% glazing area was reduced to 26% in order to form another common single intervention (variant “V”) for the comparative analysis.

The most indicative of data regarding the low energy building is the demonstration of heating and cooling demand. Today, Passivhaus has been proven the most advanced standards in terms of low-heating demand in the UK. However, a reduction of solar heat gains by any of presented variants (shadings or reducing WWR) will have an impact on the respective heating load.

Figure 7-32 and Figure 7-33 compare the overheating rate of all five variants and the knock-on effect that these design combinations have on heating demand. The reduction of overheating in the variant IV i.e. Overhang was like the 110° tilt facade. Variant V i.e. 26% WWR was close to the 115° tilt façade. However, the lowest overheating was calculated for the 115° façade (variant III). On the other hand, the heating demand increased comparatively greatly for both inclined facades. The heating demand for overhang was almost unchanged (a reduction of 0.2kWh/m^2). In contrast to variants II, III, and IV, the heating demand was reduced for variant V– the 26% WWR case, and was even lower than the original case. This means the lowest heating requirement and the second lowest overheating rate measured are for the variant V. Nonetheless, the heating demand for the 115° titled facade was the highest amongst the variants II-IV under current climate. The building with the overhang received greater solar gain in winter as the sun will be at a lower altitude angle. Therefore, it will pass below the obstruction created by the overhang. However, for the building with a tilted façade the window angle of incidence will always be shallower, resulting in a lower solar gain in winter (see Figure 7-34).

The relationship between the heating load and overheating risk was an inverse correlation for all the variants except variant V, where the heating load and overheating rate were both reduced from the original case. This proved to be the reason for designing the second house (Lime House) with the smaller window size (See section 3.3.3). However, there are disadvantages to this solution, which will have an impact on the psychological comfort, provision of daylighting and natural ventilation. These factors feature the “spirit lifting” mentioned by Heerwagen (2000) that promote positive emotional functioning in the interior environment and serve as a buffer to discomforts and stresses. A study in Canada also, showed residential buildings with large windows are popular amongst buyers despite the cold climate and are valued by prospective owners for their views (Ge, 2002).

The increase in heating demand was relatively greater for the 115-degree-tilted façade but it was not significant under future climates. However, the rise for the façade with overhangs was minor even in the current climate. Living room experienced a greater overheating when considering the lower benchmark criteria. Conversely, considering that the upper benchmark value for the bedroom is smaller (26°C Vs 28°C for living room), the bedroom had a more significant potential in overheating based on the upper benchmark temperature.

It is observed from the charts that the upper benchmark temperature frequency under a milder climate condition was reduced by a higher percentage when introducing the self-shading or other shading strategies. In another words, the frequency of high internal temperature i.e. 28°C during pre-2050’s climate was significantly reduced by shading strategies (by an average of 75% and up to 100%). However, the frequency of low benchmark temperature i.e. 25°C during post-2050’s climate was reduced by an average of 30% and up to 55%. The temperature occurrence above 28°C for variant III ($Tilt_{\theta south} = 115°$) was eliminated (100% reduction) in the current climate (Figure 7-32a). In addition, 57% reduction was estimated for the temperature frequency above 25°C (from 28.2 to 12). On the other hand, the heating demand for the same case was increased by 1.7 kWh/m^2, which is about a 20% increase from the original case. However, this number was much lower for 2080’s baseline. Variant IV had just a 5% increase in current heating demand, and variant V experienced a 4% decrease from the original case (Figure 7-32a, and Figure 7-33a). The highest percentage of increase in heating demand was experienced by implementing the 115° inclined wall (by 20% under current climate and 13% in the future).

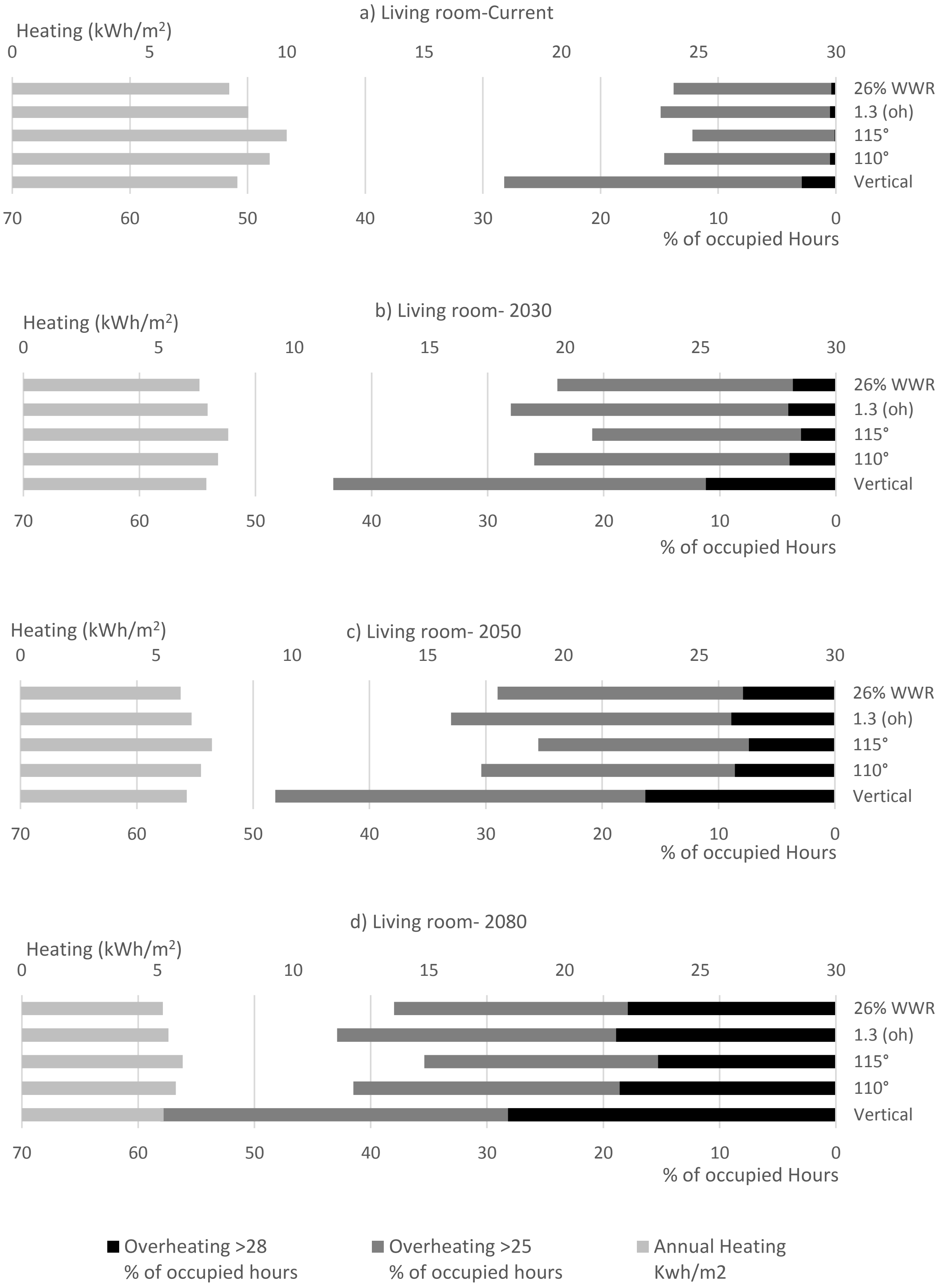


Figure 7-32 Annual total heating demand and percentage of living room operative temperature above 25°C and 28°C

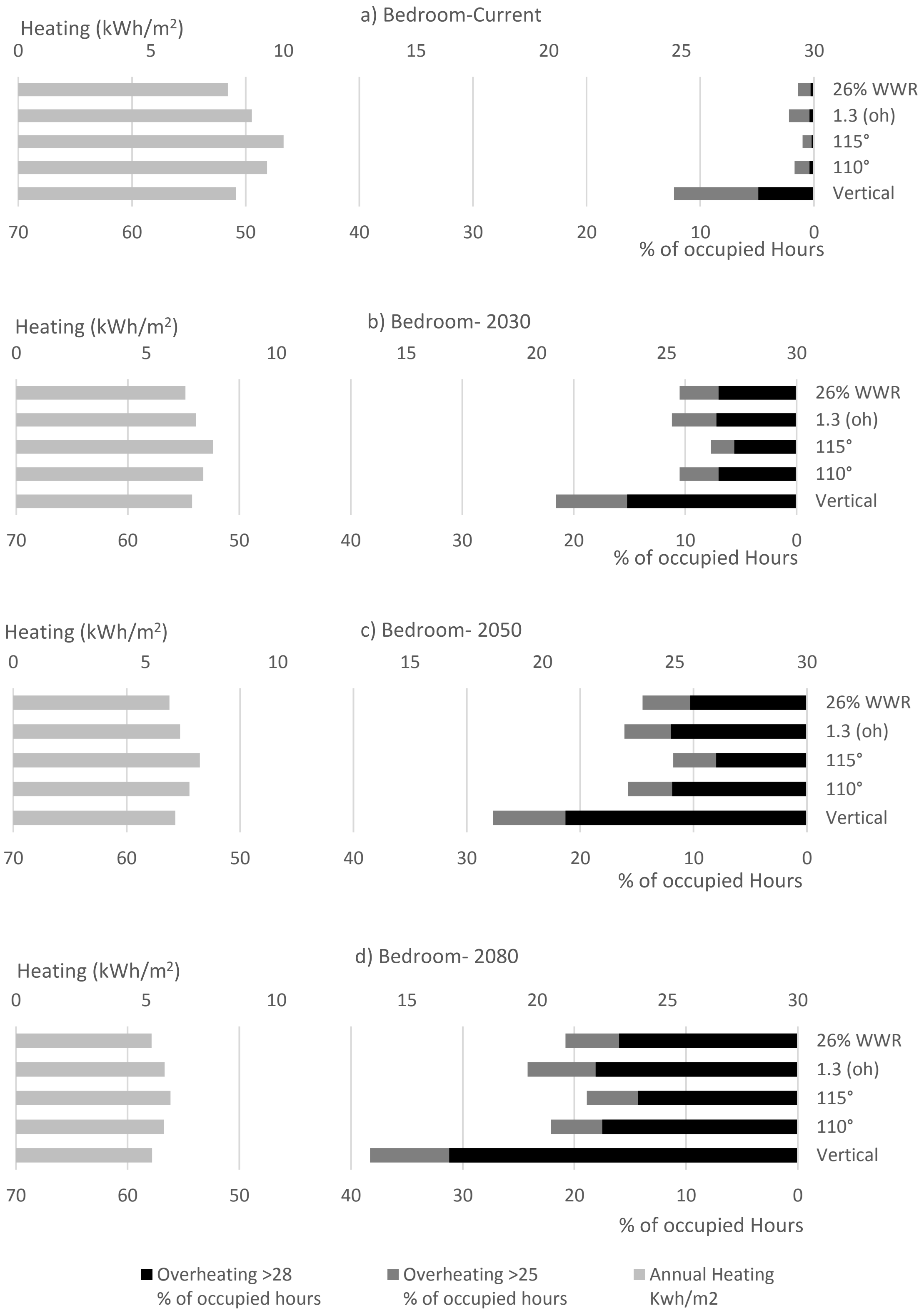


Figure 7-33 Annual heating demand and percentage of bedroom operative temperature above 25°C and 28°C

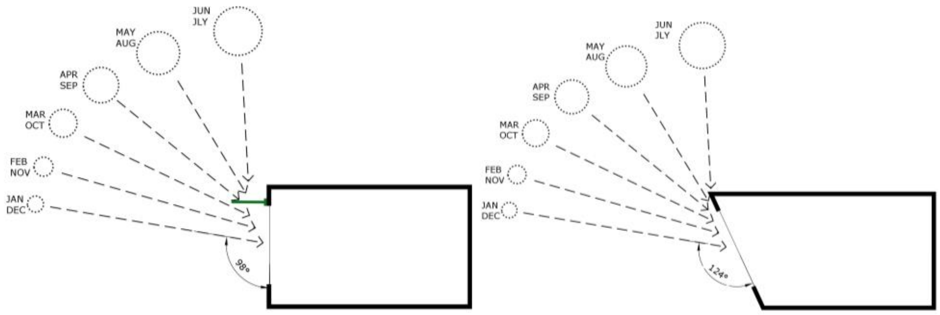


Figure 7-34 The Sun’s movement and incidence angle for different envelope designs

The size of the glazing does not only effect the heating gain but also the winter heat loss from the building. The ideal design for the building envelope is to improve heating gain during the cold months and reduce the intensive solar heat during the warm summer days. Large windows have been proven to provide significant amount of free solar energy. Although certified Passivhaus windows are very airtight, the U-value of the glazing (0.86 $Wm^{-2}K$) is almost ten times lower than the wall fabric (0.09 $Wm^{-2}K$). Figure 7-35 shows the heat balance of the average monthly heat loss and heat gain for the different cases. Variant “V” with reduced size windows has the lowest heat loss rate. It also has the lowest amount of heat gain during whole period of the year. Nevertheless, the heat loss is greater than the heat gains for most of the winter months under current climate (January, February, November and December). Although for the original case (variant “I”), the heat loss balance from the windows sometimes (mainly in December) was greater than the heat gains, but overall the original case (variant I) benefits from free solar gain, which offsets the heat loss and heating demand.

Also, it should be noted that the inclined glazing will be effected by Frensel’s equations and Brewster's Angle which is the angle of incidence at which light with a particular polarisation is transmitted through the glass. Frensel’s equations describes how the amount of reflected and transmitted light is different for the two different incident polarizations (refer to Lvovsky, 2013 for more detail).

For the projected 2080’s climate, the solar heat gains were dominant during the cold period, even for the cases with the self-shading and overhang (Figure 7-35b), suggesting large glazing with adequate shadings as a better design approach in future UK climate. Implementing any shading strategy would also reduce useful solar gain in winter. However, the greatest winter solar gain among the interventions (excluding the original case) was for the variant "IV" (overhang) which also had a significant reduction of heat gain in summer. Heat loss for the variants II, III, and IV was almost the same as the original case. Variant "II" with the 115° inclined façade had the second lowest solar gain (after variant V) during both summer and winter periods. The benefit from large glazing (variants I-IV) in winter was apparent under future climate (Figure 7-35b), although the risk of overheating was greater, especially for large glazing with no fixed shading strategy (variant I).

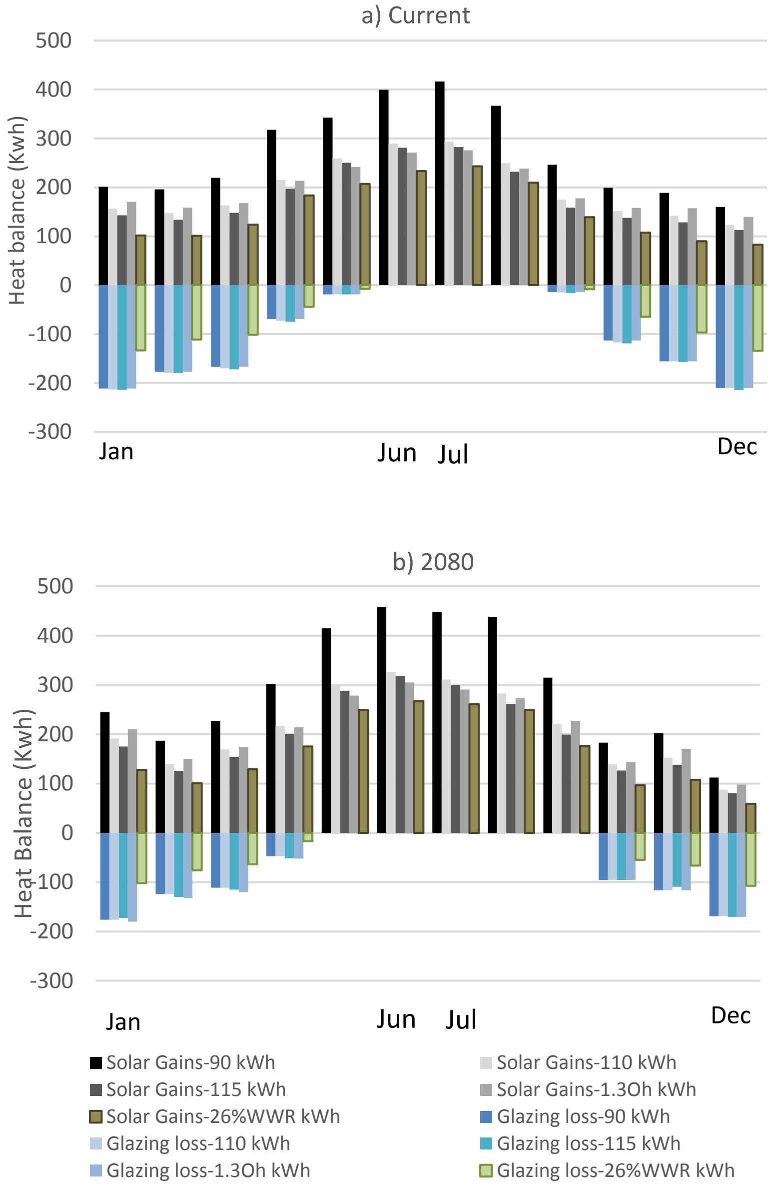


Figure 7-35 Average monthly heat gain and loss from the glazing

Previous results showed the effect of the shading strategies and the interventions to reduce solar gain on the alternative climate circumstances. They were simulated based on the data presented for the original case study i.e. the operation of the blinds and curtains according to the occupancy schedule presented in section 6.1.3. The following results (shown in Figure 7-36) analysed the effect of the alternative façade designs with blinds being disabled i.e. no internal and external blind/curtain. The assumption was that the external roller blinds had broken down and occupants were not present at home to operate internal shading (curtains). Therefore, the blinds are not in operation for all the windows in all the variants. All other settings remained the same.

Data previously presented in Figure 7-28 compared the original case with suggested tilted façades where the occupants were operating the blinds. This was presented for a representative of a typical warm summer day (not the hottest), and so this was also used to show data for all five variants while no blinds were in operation (Figure 7-36). This is, to measure the effect of the design regardless to the blind schedule operation. Results show that during early hours of the morning when the sun mainly hits the eastern façade of the building there is a small difference for solar gain between the variants. This is because the living room window on the east wall does not employ any changes from the original house. However, during noontime and early afternoon, there is a significant drop in solar heat gain for all alternative cases (variant II-V). This is when the angle of incidence is higher and the direction of the Sun's rays are more concentrated on the south elevation (see Figure 7-37). The intensity of the solar energy is higher and more concentrated when the angle of elevation is higher.

The amount of heat energy received from the Sun is a direct effect of the angle at which sunlight strikes on different location, time of the day, and season due to the Earth's orbit around the Sun and the Earth's rotation around its tilted axis. The higher the Sun angle the more intense is the solar energy and the more the sun going to set the more spreads out its energy. Therefore, it is important to control the solar gain during direct and concentrated sunlight i.e. noontime and early afternoon. Figure 7-36b presented the bedroom solar heat gain for different facade alternatives. The bedroom has a smaller amount of glazing and consequently smaller amount of solar gain. Windows are only located on the south façade that is why, the reduction in solar gain was mainly at the time when the sun is directly on the south façade (Figure 7-37b). According to the results, the reduction of solar gain also happens during the early morning and afternoon for the case with small windows i.e variant VI (when the sun direction is not at the south façade- there is no windows on the other facades of the bedroom except the south elevation). The reason is that less diffuse sky radiation is entering through a smaller glazing area whereas all other variants have large glazing (55%), and consequently they receive the same amount of defused solar radiation.

During the noontime, a stronger reduction happened for the self-shading façade of 115° as well as the second lowest average daily solar gain. The lowest mean daily solar gain was achieved for the variant V because of the constant reduction of both direct and defused solar radiation during the day. Conversely, during the noontime, variant V experienced a smaller reduction of solar gain amongst the interventions (variant II-V). Variant III and IV experienced a parallel and similar reduction of solar gain during a typical warm summer day in London, suggesting the tilted façade of 115-degree as a successful application to reduce excessive solar gain. However, variant IV and then variant III received the lowest solar gain during a typical winter day as presented in Figure 7-36c and d. The reduction in solar gain was relatively small during a typical cold winter day. The sudden reduction of solar gain during the winter day (Figure 7-36 c and d) was found to be due to the cloudy sky.

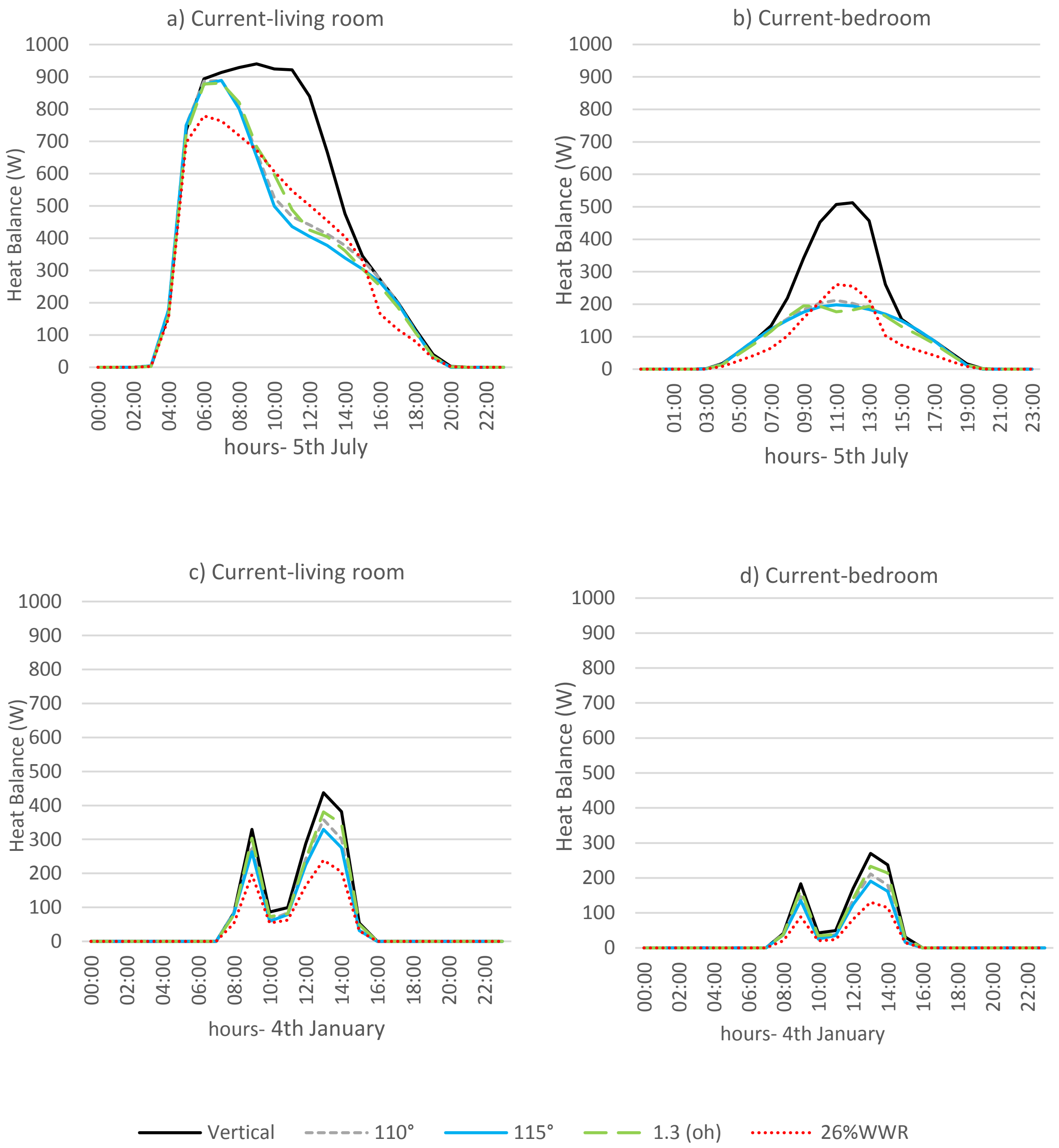
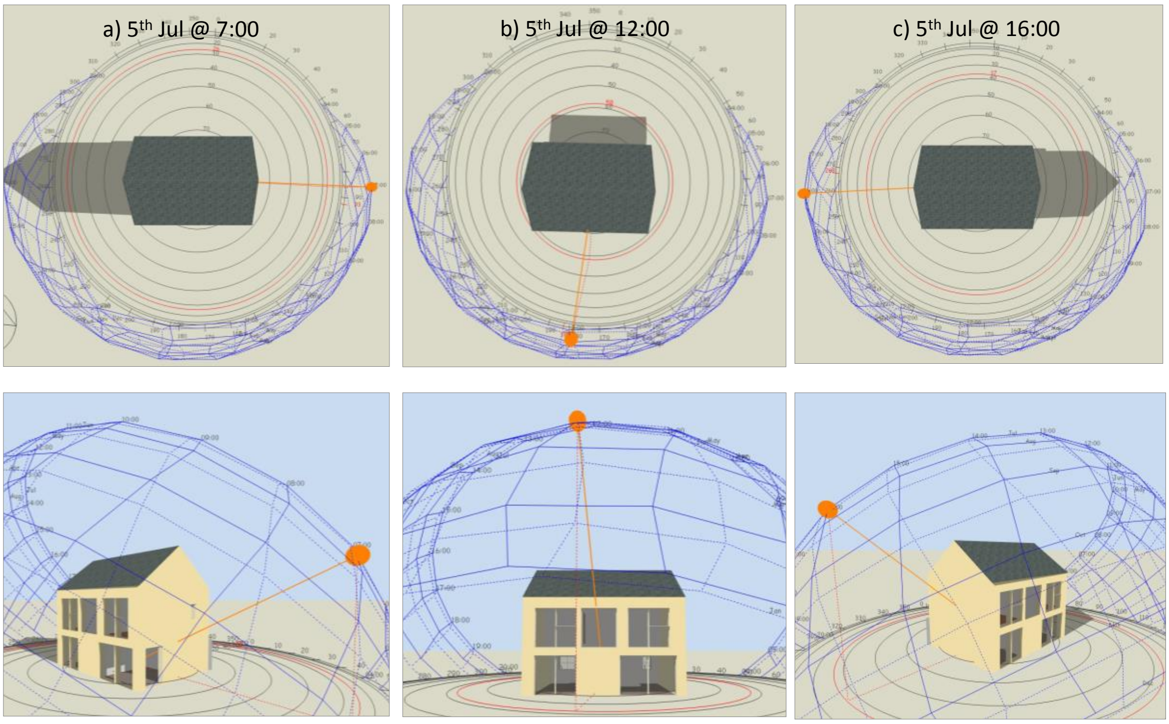


Figure 7-36 Solar gain exterior windows: living room and bedroom



a) 5th Jul @ 7:00

b) 5th Jul @ 12:00

c) 5th Jul @ 16:00

Figure 7-37 Sun path diagram 5th July at early morning, noon and afternoon time

7.5.1 Analysis of free running buildings

Previous analysis showed a daily investigation of the energy performance of the house. However, to investigate the behaviour of each alternative in a more detailed analysis and during a longer period, Summer Design week (SDW) and Winter Typical Week (WTW) were considered for estimating the thermal behaviour of each case.

DesignBuilder uses the location data and weather file set at site level to identify the ‘typical’ and ‘peak’ summer and winter weeks. Summer design week is a week identified by the weather data translator as being the hottest of the year. Summer typical week is a week identified by the weather data translator as being typical of the summer. Winter design week is a week identified by the weather data translator as being the coldest of the year and winter typical week is a week identified by the weather data translator as being typical of the winter.

For each given weather file a period of 7 consecutive days as described above can be selected for simulation calculation options which allows to simulate the given period. Summer typical week were used to test the building performance for the hottest week referred to as “summer design week” or for an average representative of summer months referred to as “summer typical week”.

SDW is representative of a relatively harsh climatic condition. WTW is representative of a typical week in winter. The reason for considering SDW was to reflect on the main objective of the study and obtain a robust design to ensure a comfortable condition in the summer worst-case scenarios under current condition. However, as mentioned previously, the conditions under current SDW are very like the STW under future climates. The WTW was used to estimate the consequences of the robust summer design on the typical winter condition. However, unlike summer conditions, WTW under the current condition is estimated to be similar to the future WTW.

Figure 7-39 presents data to investigate the performance of the house, in particular for different envelope shapes with and without heating or cooling devices i.e. free-running mode. The free-running mode during summer and wintertime and the respective operative temperatures shows, to what extent, the envelope design solely affects the internal conditions. Figure 7-39 represents the energy demand when mechanical heating and cooling devices were switched ON at the set point temperature of 20°C for winter and 25°C for the summer period. It calculates the amount of energy required for heating and cooling for different design alternatives during the design week to keep the indoor temperature within the comfort conditions for both winter and summer (i.e. min 20°C – max 25°C). The data show the geometrical form of the envelope would act as an effective climate optimiser for mild summer days (summer day 1, 5, and 7) and the compromise that these implications will have is more apparent for relatively moderate winter days (winter day 3 and 6). Mild summer days are relevant in the UK summer condition (current and pre-2050s climate) and winter mild days are less frequent.

Due to the super insulation of the Passivhaus, the free running temperature was between 11 to 15°C. A relatively small heating demand was required to provide optimal comfort condition. Indoor temperatures of the free-running winter design week were very similar for different alternatives. However, the temperatures on winter sunny days were different between the cases. Therefore, the compromise of the shadings was apparent on winter sunny days (WTW; day 3 and 6). On the other hand, the upper benchmark temperatures of 28°C and above were eliminated when implementing the 115° tilted façade (SDW; day 3 and 4). For both shading alternatives (variant III i.e. 115° and variant IV i.e. 1.3 oh), the operative temperature above 25°C reduced to an acceptable limit for most of the summer design week.

The cooling demand also was significantly reduced for the hottest days of the summer design week (day 3 and 4), but no cooling was required for the last 3 days (summer days 5, 6 and 7).

Figure 7-40 analyses the building envelope performance in the free running mode where no blinds were functioning. This was to calculate the effectiveness of the proposed shading geometry (self-shading) in blocking the solar gain in a free running Passivhaus and compare it with other shading strategies. The data showed the average monthly operative temperature and the amount of solar gain through windows for January and July of current and future climates. The temperature increase of different time slices followed the same trend as the increase in dry-bulb temperature (see also Figure 7-1). However, the graph showing the solar radiation through windows presented an unsteady change between the future climates (also see Figure 7-2). The increase in operative temperature during the winter month was relatively small between the variants. The case with small windows (26%WWR) received almost 50% less solar gain than the original case. Although the winter solar gain was also reduced for alternative design arrangements, variant “V” with overhang received the highest winter solar gain amongst the modified cases (variants II-V). The amount of summer solar radiation showed a sudden drop after introducing any of the different design alternatives. The data demonstrate the effective influence of the envelope design for summer comfort. Operative temperatures were reduced by up to 3.4°C solely due to the envelope design. The extent of the reduced solar gain between different design alternatives can be seen in Figure 7-41. The curves estimated the solar heat gain through the windows of the living room in a yearly cycle.

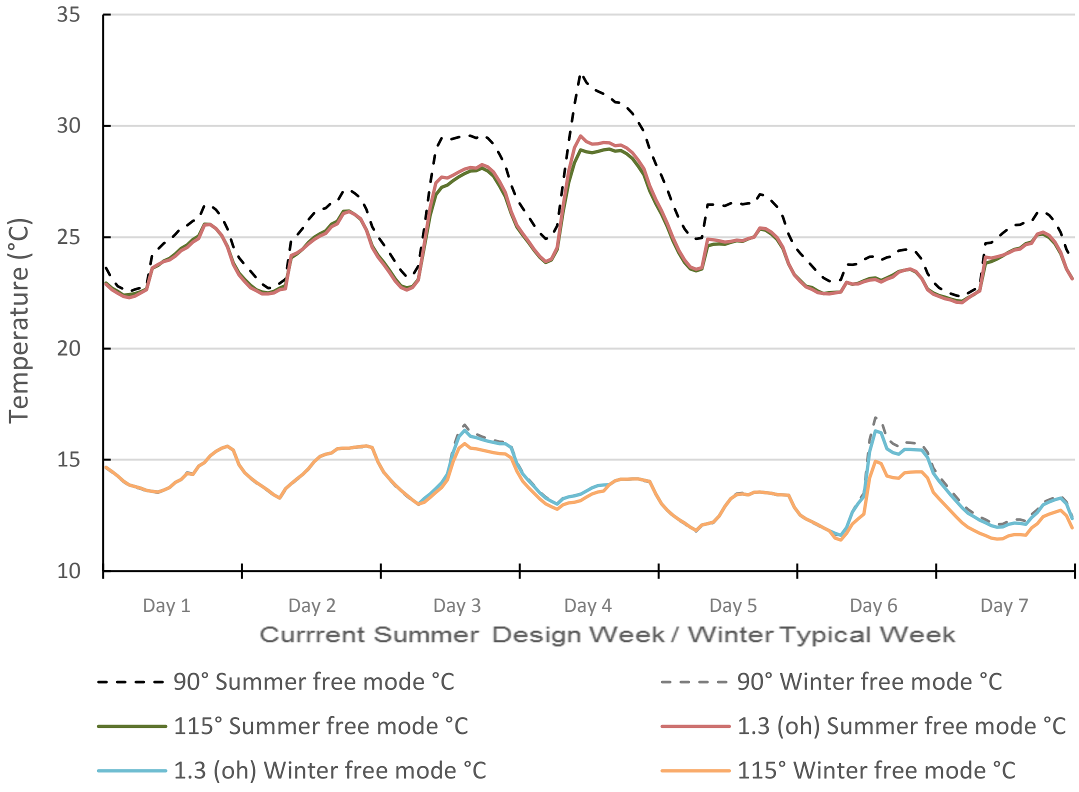


Figure 7-38 Summer and winter free running mode

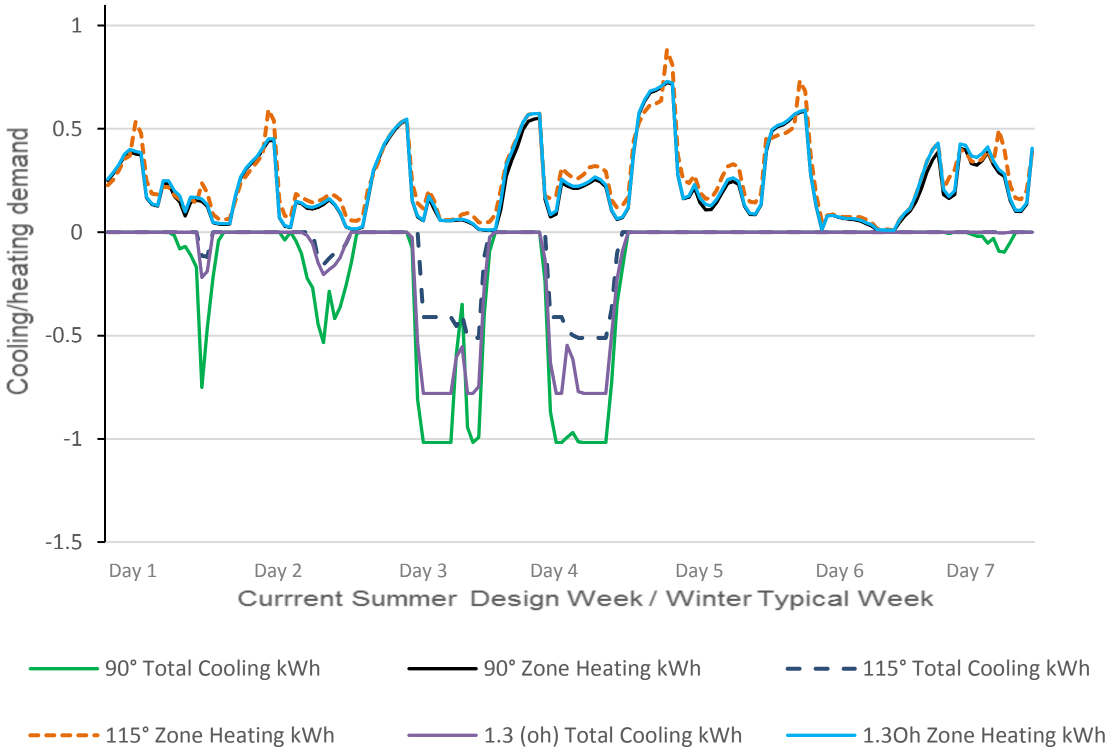


Figure 7-39 Heating and cooling demand

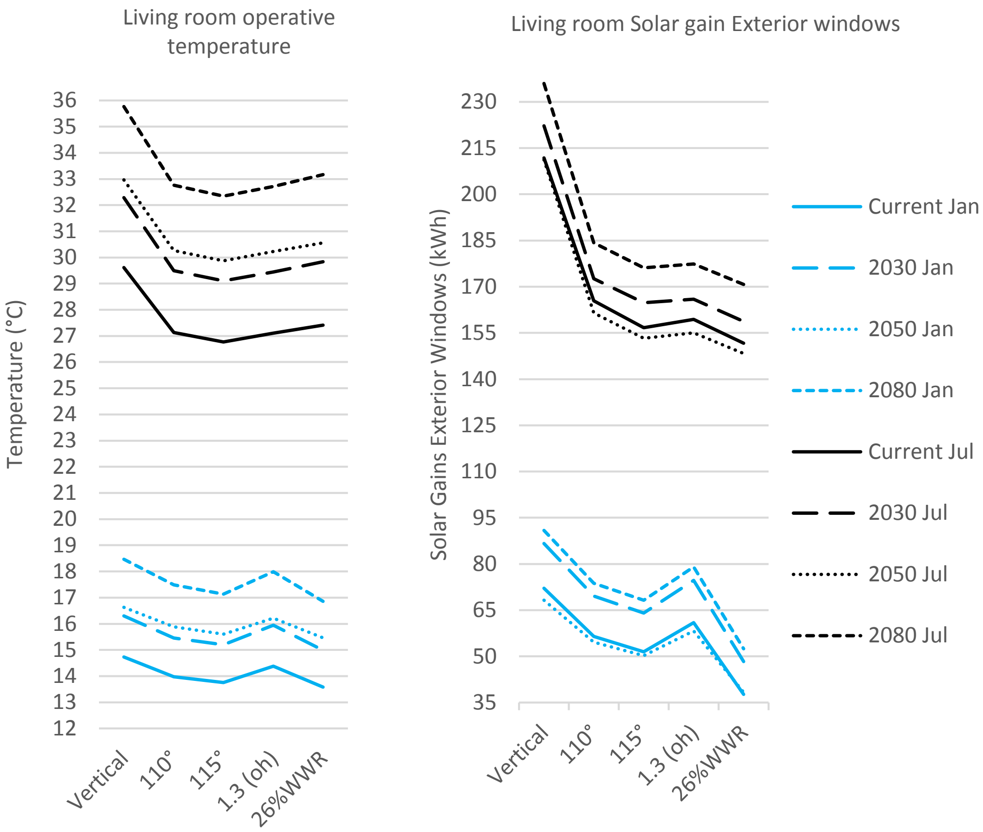


Figure 7-40 Temperature and solar gain for the living room- January and July free running mode without blinds

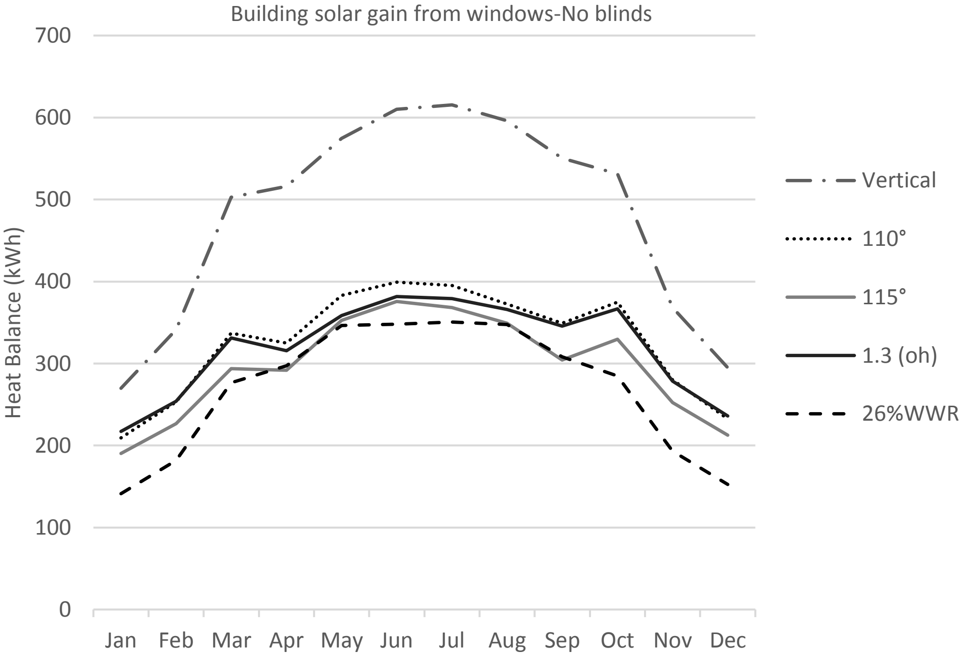


Figure 7-41 Average solar gain when blinds (internal and external) are not in operation

7.5.2 Adaptive thermal comfort analysis for the cases

The application of the static criteria determined that the Passivhaus case study (Larch House) in London experienced a significantly overheating risk under a warmer climate scenario. On the other hand, analyses using adaptive thermal comfort standards indicate rather different results. It has been argued in the literature that adaptive methods are more applicable for assessing indoor thermal comfort in future conditions. However, static criteria are used mainly for assessing model prediction and whole years of data. As mentioned earlier, the static criteria are also used for assessing single design intervention that has impact on indoor thermal behaviour, whereas adaptive methods consider all the individual measures assigned to different persons' comfort perception. Static criteria are useful for ranking the occurrence of elevated room temperatures but they cannot clearly indicate whether the measured temperature is acceptable or not in different circumstances. In contrast, adaptive thermal comfort methods are used for assessing buildings in use and can define if the indoor temperature is acceptable or not for occupants with different temperature tolerance and behaviour. Contrary to the previous sections, where the research focused on the static CIBSE criteria, the following section predicts the future comfort according to the ASHRAE's adaptive thermal comfort using the methodology presented in Section 3.2.2 (see Equation 3-1; $t_{oc} = 18.9 + 0.225\ \mathrm{t_{out}}$). The adaptive model indicated that the indoor temperatures falling outside the CIBSE Guide A and Passivhaus criteria may). Since the adaptive thermal comforts stretch to a slightly warmer acceptable conditions following the increase of the outdoor temperature, the house was just out of the comfort zone at 2030's (Figure 7-42b). The house as per the original south-façade arrangment would experience a significant overheating risk even under adaptive criteria after 2050's climate condition (Figure 7-42d). However, the reduction of the solar heat gain which is created by the tilted façade kept both the living room and bedroom within the ASHRAE upper limit (80%) adaptive comfort criteria for current and 2030's climate condition (Figure 7-42a and b). The bedroom in the tilted building remained withing the 80% of the ASHRAE adaptive criteria for all time lines except for the 2080's.There was a very small increase in the frequency of the high temperatures outside the comfort zone for the 2050's (Figure 7-42c); however, the suggested passive intervention ($Tilt_{\theta south} = 115°$) could not keep the building inside the comfort zone for post-2050s climates.

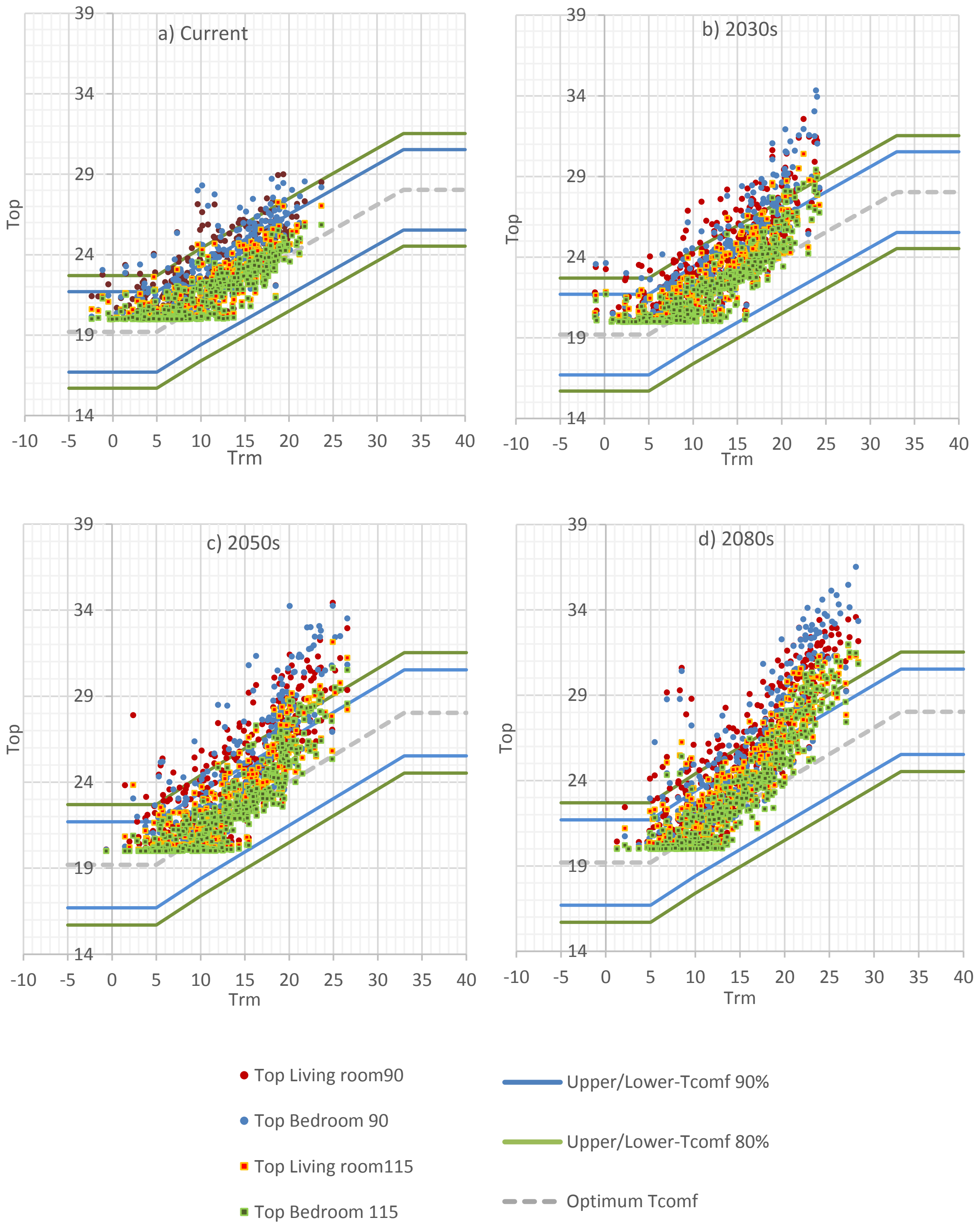


Figure 7-42 Adaptive comfort after ASHRAE

7.6 Overheating analysis under medium emission scenarios

Up to now the study used high emission 50% probability to investigate overheating in a super insulated Passivhaus in London. In this section the proposed geometry will be tested under medium scenario central emission 50 percentile (A1B 50%) and 10% probability level where summer temperature is very unlikely to be less than (A1B 10%).

Simulation results in the previous chapter showed that the proposed self-shading façade ($Tilt_{\Theta south} = 115°$) was capable to eliminate overheating for current climate and reduce overheating under high emission future weather projections. Future overheating rate was at a very high risk before implementing the tilted façade and it remained at a high level even for self-shading façade for 2080's weather projection. However, the proposed façade tested for future proofing under medium weather projections indicate a medium risk under 50% probability and a low risk of overheating for 10% probability level (Figure 7-43). This means that the proposed self-shading geometry could almost eliminate the higher threshold overheating for a super insulated Passivhaus under an optimistic future weather scenarios in London. However, it should be noted that 10% probability level is very unlikely to happen.

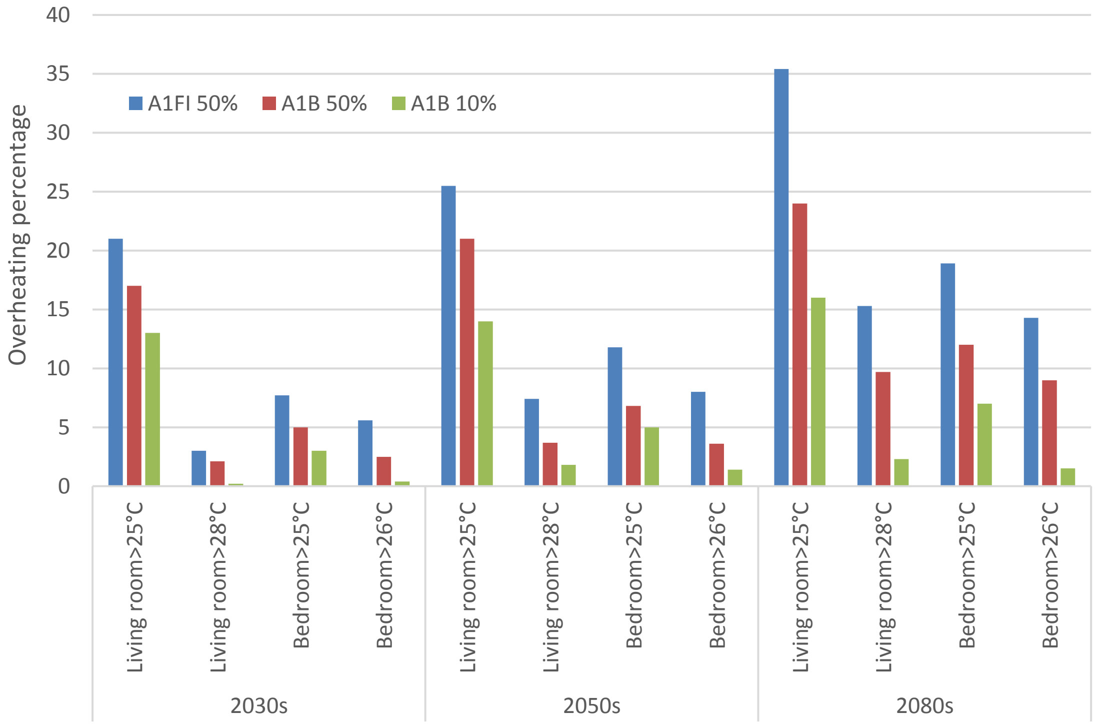


Figure 7-43 Overheating under different weather scenarios for the proposed self-shading façade (115°)

7.7 Conclusion of results

The main results of the research were presented in this chapter. The key outcomes of the results are emphasised in the list below. The highlighted points refer to overheating according to the static criteria; Passivhaus standard and CIBSE Guide A 2006, unless otherwise stated.

- CIBSE High emission 50% projected climate change scenarios in London showed a significant increase in summer temperature especially for 2080's.
- Overheating in the Passivhaus case study (Larch House) was significant when it was moved to London. The house (or a similar house) would experience a critical overheating risk under future conditions. The House as per existing arrangements would require active cooling after 2050's climate scenarios.
- After implementing the tilted façade ($Tilt_{\Theta south} = 115°$), overheating for current London climate was entirely removed. The house with the south tilting facade experienced medium overheating before 2050's. Overheating was significant for post-2050's weather scenarios.
- When comparing the self-shading façade with the overhang shading approach, it was found that, like the fixed shading device, the proposed shading method effectively reduced overheating in summer. However, the building with overhangs benefited from a greater solar gain in winter. Consequently, the building with tilted facade required greater heating demand.
- Reducing window to wall ratio from 55% to 26% experienced the lowest energy demand to provide comfort in both summer and winter.
- The lowest overheating rates were calculated for the 115° tilted façade and 26% WWR respectively.
- The lowest heating demands were calculated for 26% WWR and 1.3m overhang respectively.
- CIBSE Guide A and Passivhaus method may ultimately lead to an "exaggerated need" for cooling. Therefore, sensible cooling units will surpass the heating demand in a super insulated Passivhaus under high emission scenarios.
- The energy requirement for cooling was calculated based on the normal A.C systems whereas, the heating demand was calculated using a very efficient system i.e. MVHR.

- When implimenting the adaptive criteria, the comfort zone allowed a slightly warmer indoor conditiones compared with the static criteria of CIBSE and Passivhaus.
- Findings have shown that assessing overheating using adaptive criteria indicated a significantly lower overheating frequency for the case study alternatives which would have otherwise been at a critically high overheating under Passivhaus and CIBSE static criteria for assessing overheating.
- Due to longevity of residential buildings future-proof buildings is of a great concern. Choices made today in new-built homes will have long lasting effect.
- Considering the summer thermal performance of a building, super insulated buildings i.e. Passivhaus are probably more effective in hot summer conditions and less effective in mild summers where active cooling is not required.
- Passive measures examined in this study will not be sufficient to mitigate the overheating risk for 2080's climate.
- Tilted south façade effectively reduced overheating risk however, geometrical implications will not solely be able to eradicate overheating risk for post-2050's climate. Further passive strategies are required to provide summer comfort. However, by the end of the century it will be a great challenge to mitigate overheating in Passivhaus dwellings using solely passive measures for climate changes under high emission future weather scenarios.
- Future overheating rate was at a very high level of risk for the house with original façade design. The overheating was at a medium level for the proposed façade ($Tilt_{\theta south} = 115°$) under a high emission scenario, and it was at a low risk under a medium emission scenario however, it could not be fully eradicated solely by proposed facade.

Chapter Eight

8 Other Consequence of a Tilted Façade

8.1 Introduction

Chapter Seven considered the potential impact of the proposed self-shading facades in terms of summer solar heat gain and consequently the elevated thermal comfort for a London Passivhaus case. This chapter will reflect on the consequences that these geometries will make on some other aspects of the building performance – specifically, natural ventilation and daylighting.

In the first section of this chapter, CFD analysis was conducted to examine the impact of the study's hypothesis– the proposed inclined façade on the airflow patterns and natural ventilation inside the building. This section presents the key results of the parametric study to investigate the air movement in the living room affected by the tilted façade. The fluid dynamic analysis was conducted using the CFD algorithm built in to DesignBuilder software to investigate the case study model and its alternative designs. Air velocities obtained from DesignBuilder were adopted as the significant parameter to investigate the air velocity that natural ventilation created and consequently thermal comfort that is affected by an increase or decrease in physiological cooling.

In the second section of this chapter, daylighting simulations were conducted to compare the consequence of the different design interventions (within the scope of this study) on daylighting illuminance inside the rooms. Daylighting simulations available in DesignBuilder software allowed the ready analysis of the house models to calculate daylight factors and illuminance data. Daylight contour plots were available to show daylight availability and the distribution of light across the floorplan. A summary output of the average daylight factor and uniformity data for the living room and main bedroom were addressed for four design variants, including the original design of the house (variant I), tilted façade of 115° (variant III), the building with 1.3m overhang (variant IV) and with the reduced window to wall ratio approach (variant V).

8.2 Natural ventilation and CFD analysis

The main strategy to maintain thermal comfort during summer is to: 1) prevent overheating that occurs primarily due to incident solar radiation entering the space, and 2) dissipate excess heat using natural ventilation.

Understanding the airflow patterns and pressure distributions on building envelope is essential for evaluation of wind-induced natural ventilation and thermal comfort. Natural ventilation is achieved by airflow through the building envelope, which can be either unintentional (i.e. flow of outdoor air through cracks and holes in the structure) and or intentional (i.e. through doors and window openings). Passivhaus tends to minimize infiltration. As a result, unintentional inflow is almost negligible in a Passivhaus. This helps to reduce the heating load dramatically.

The amount of natural ventilation air entering through an opening depends on factors such as wind speed and direction, the size and position of openings. The shape of the building also can affect natural ventilation (Santamouris & Asimakopoulos, 2013). It is believed (Arens & Williams, 1977) that *"The shape of the building and its orientation to the wind strongly influence the wind velocities and flow characteristics in its vicinity"*. Even the small-scale architectural details, such as mullions and window frames, affects airflow pattern and lead to different turbulent mixing (Arens & Williams, 1977).

Wind direction and speed have a major impact on pressure distributions (Pw) on the building envelope. They influence the amount of airflow inside the building by creating high and low pressures on the building envelope. On the windward side of the building the pressure zone is subjected to positive pressures while the leeward side experiences negative pressures. The building side facades can be either in positive or negative pressure zone depending on their form, fractures, inclination and the wind incidence. External air is driven through an opening from the zone with the high pressure (windward) and leaves from the zone where the pressure is lower (Figure 8-1). Therefore, a greater positive pressure by the inlet zone and a greater negative pressure by the outlet zone produce a stronger airflow rate in the building. The stronger negative pressure by the outlet produces a higher suction zone to extract the air. The greater the pressure difference ($\Delta\rho$) between windward and leeward side, the greater is the indoor airflow rate.

What makes natural ventilation to increase thermal comfort is in fact, the internal air velocity (Vin) which produces the occupants' psychological cooling effect (see 3.3.5). According to Equation 8-1 (Szokolay, 2008), airflow (Q) through an opening is based on the velocity (v) and opening area (A).

$$Q = vA$$

Equation 8-1

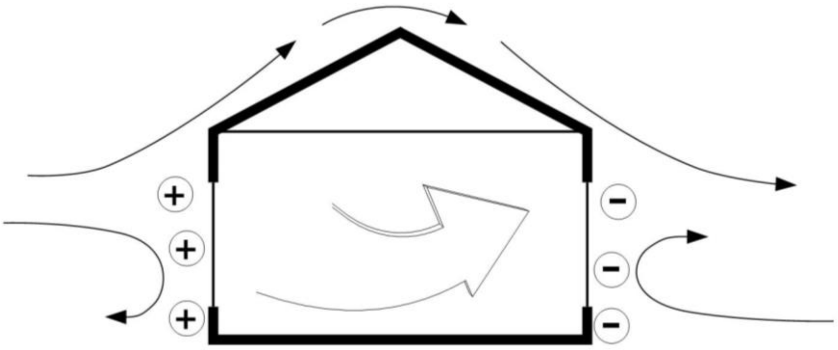


Figure 8-1 Wind pressure on the building façade

Overheating in most Passivhaus cases is associated with the lack of natural ventilation in the UK dwellings. The unexpected overheating from the first monitoring data of the Larch House (also first simulations DB.1) was mainly because of the infrequent windows opening. The overheating was later reduced by opening windows for the night purge ventilation (DB.2).

As mentioned before, physiological comfort occurs when occupants feel air movement across their body, which will make them feel comfortable. Not only comfortable temperature but also adequate air velocity is required in the occupied space to provide thermal comfort for occupants. Therefore, it is important to assess whether the proposed inclined façade would compromise the airflow within the building.

8.2.1 The case study CFD analysis when implementing different façade designs

There are two general approaches to natural ventilation modelling in DesignBuilder, including "Scheduled Natural Ventilation" (SNV) and "Calculated Natural Ventilation" (CNV) (DesignBuilder User Manual, 2015). The SNV approach defines an air exchange rate for each zone by a constant ACH value for a given schedule and it is generally used to make a simple and reasonable estimate of the natural ventilation rates. On the other hand, CNV calculates the natural ventilation based on window opening and dimensions, buoyancy and wind driven pressure differences etc.

In the previous chapters (6 and 7) natural ventilation was simulated based on the scheduled approach for summer (SNV) and for winter there was no natural ventilation operating through the window opening and just mechanical ventilation was operating. However, this chapter used CNV to calculate the fluid dynamic. This will increase the complexity of the model and increases the simulation time. CFD analysis in EnergyPlus uses a K-epsilon (k-ε) turbulence model, which is one of the most widely tested turbulence models.

The case study model and the alternative designs which were already used as a comparative study in the Chapter Seven, were used for the CFD simulations and will be referred to in the figures as a) The original Larch House model, b) The house with a 115° tilted south wall, c) The house with a 1.3m overhang on the southern windows and, d) The house with a reduced window to wall ratio– 26%WWR.

The CFD analysis took place in an urban district using London current climate. Wind direction was set in terms of wind incident angle ($\mathrm{Wind\ INC}_{\theta}$) to the main façade windows i.e. south façade. Three wind directions (θ =0°, θ =90°, θ=180°) were tested to assess the impact of the different façade arrangements (Figure 8-2). The external wind speed was set at U=5m/s, representing the average maximum wind velocity during summer period. The calculation procedure for CFD analysis in EnergyPlus-DesignBuilder was set to converge the solution for a snapshot in time. Therefore, the result derived from the CFD analysis represents a specific time of the particular day in the year using the weather data uploaded to the weather folder of the software. The same weather file was used for all simulations with different wind direction. All other site data i.e. wind speed, atmospheric pressure, temperature etc. remained the same.

CFD calculations in DesignBuilder use a non-uniform rectilinear Cartesian grid. Grid lines are parallel to the major axis and main wall and windows. Different grid spacing can be modelled e.g. 0.5 m (coarse regions), 0.3 m (normal regions), 0.1 m (fine regions) or 0.05 (very fine regions). Very small grid spacing can lead to a very long calculation times and excessive computer memory. For that reason, and also because the core of the activity in this research was not CFD analysis, the grid spacing was set to 0.2 m with the merge tolerance of 0.03m grid. The results of the CFD simulations were taken at 1500 iterations or a converged solution. The CFD simulation settings for this study are also presented in Table 8-1.

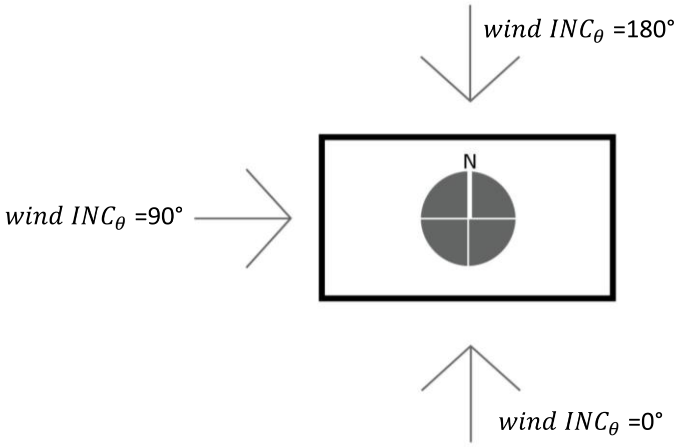


Figure 8-2 Tested wind directions

Table 8-1 Input parameters and settings used for CFD analysis

Fixed parameter	input
Location	London current climate-urban district
Wind speed	5 m/s
Window aperture opening	Openable part of the windows fully open
Converged result	Converged or Iteration at 1500
Wind incidence ($wind\ INC_\theta$)	0°, 90° and 180°
Grid spacing	Non-uniform grid line type with 0.2m grid spacing and grid line merge tolerance of 0.03 m.

There are different approaches to investigating the effect of natural ventilation on occupants' thermal comfort. Two main approaches include calculation of the i) average indoor air velocity ($V_{in.av}$) and ii) indoor operative (T_{op}) and compensated temperature (T_{comp}). The compensated temperature can be estimated due to the elevated air velocity and potential physiological cooling effect developed by Szokolay (2008) (see Section 2.3.2). In this study, the average air velocity ($V_{in.av}$) inside the living room and bedroom of each design alternative were obtained. The living room has openings on both sides of the room and the bedroom is a single aspect ventilated room. Figure 8-3, showed the floor plan of the tested zones.

Figure 8-3 Living room plan and notation of the investigated representative rooms; a) original case study, b) tilted façade, c) overhang, and d) 26% WWR

Predicted average air velocities inside the rooms were achieved by internal CFD. The results showed different air movements and velocities for different façade designs. Furthermore, the study conducted external CFD analysis to explore the possible explanation on the results achieved from the internal CFD analysis.

8.2.2 Internal CFD analysis

Figure 8-4 to Figure 8-9 present a comparison of the air velocity results inside the living rooms for three wind incident angles. The data are available for the occupied level i.e. 0.75m off the floor (Z-axis slice; Figure 8-4, Figure 8-5 and Figure 8-6) and cross section plane from the inlet to the outlet opening (X-axis slice; Figure 8-7, Figure 8-8 and Figure 8-9). These data indicate to what extent indoor air velocity is effected by introducing different façade combinations. The openable part of the windows was fully open at the time of the internal CFD calculation. It is clear from the data that the highest velocity occurred at the inlet and outlet especially around the smaller opening on the north façade before gradually dropped with the distance from the inlet and increased again at the point of the exit. The air velocity was particularly greater when the northern opening (window 2) was the inlet and the bigger window on the south façade (window 1) was the outlet i.e. wind $\mathrm{INC}_{\theta} = 180°$ (Figure 8-5).

Figure 8-4 shows the resultant average air velocity distribution at the occupied level of the case study (a), and alternative designs (b-d) with the wind direction being at 0° incidence i.e. perpendicular to the south façade window, which was effected by the facade modifications. The greatest air velocity was calculated for the original case study model (a) and the lowest was calculated for the tilted facade (b). However, it should be mentioned that for this analysis the external roller blinds for the original case (a) that were designed to mitigate overheating were omitted –which would have dramatically reduced natural ventilation. The house with the overhang (c) led to a minor reduction of average air velocity, but variant IV with smaller windows (d) experienced a reduced average air velocity inside the room.

Figure 8-5 shows the simulated air distribution at the occupied level (Z slice) for the alternative cases under wind incidence angle of 180°. A greater airflow compared to the normal incidence angle (Figure 8-4) was found for all cases. Furthermore, the greatest average air velocity was calculated for the tilted building ($V_{in.av}$=0.35 ms^{-1} at occupied level). Maximum air velocity also elevated at the point of inlet opening ($V_{in.max}$=1.9 ms^{-1}). This is also due to the concentrated air entering the building through a smaller opening and because of the large outlet. Variant “V” with smaller percentage windows had the lowest average velocity at occupied level (Figure 8-5d).

In the case of wind direction at a 90° angle of incidence ($Wind\ \mathrm{INC}_{\theta} = 90°$), expectedly, the average wind velocity drops dramatically for most cases. Similarly, variants I, IV and V (Figure 8-6a, c, and d) had a very low average velocity at occupied level. However, for the tilted façade (variant III) the average wind velocity was surprisingly high (Figure 8-6b).

Average air velocities were also calculated on the cross-section plane (X-axis slice) from inlet to outlet for the three aforementioned wind directions (Figure 8-7 to Figure 8-9). The results showed a similar ratio in average velocity as was calculated previously for the occupied level (Z-axis slice). Similarly, the living room of the reference case had a greater air velocity at 0° wind incidence angle (Figure 8-7a) compared to the tilted building which experienced the lowest air velocity (Figure 8-7b). However, the average air velocity was greater for the inclined wall at $Wind\ \mathrm{INC}_{\theta} = 180°$ (Figure 8-8b) and $Wind\ \mathrm{INC}_{\theta} = 90°$ (Figure 8-9b). The internal CFD showed a noticeable reduction of air velocity at 90-degrees wind incident angle.

However, the tilted façade had a surprisingly greater air velocity amongst all four variants. The 26% WWR received the lowest total average velocity amongst the cases.

These results on the internal CFD analysis demonstrate that the average air velocities in the living rooms varied across the different locations, contrasting the average air velocity from the mean value. Much higher air velocities were recorded across the inlet to outlet as they are opposite each other in the room. The other side of the room is where the toilet partitions (left-hand side) obstruct the air movement; there was a considerably lower air velocity (minimum $V_{in.av}$ of 0.05 ms^{1}). A relatively higher velocity was found when the wind blew from the rear elevation i.e. $Wind\ \mathrm{INC}_{\theta} = 180°$. A different airflow regimes were found around the tilted south wall, with velocity vectors moving downwards and upwards around the outlet creating a greater turbulence (Figure 8-8b).

The most interesting result was the improvement of the natural ventilation for the building with an inclined façade ($Tilt_{\Theta south} = 115°$) at 90° wind incident angle (westerly wind-$Wind\ \mathrm{INC}_{\theta} = 90°$). A possible explanation for this is that the inclined façade increases the air flow speed by squeezing the air (Bernoulli's effect) and this create two different flow regimes where higher wind speed around the tilted wall caused a stronger negative pressure by the outlet. Velocity plots in Figure 8-6b and Figure 8-9b indicate elevated air speed entering the living room. This was later analysed using external CFD calculation to find a reliable explanation.

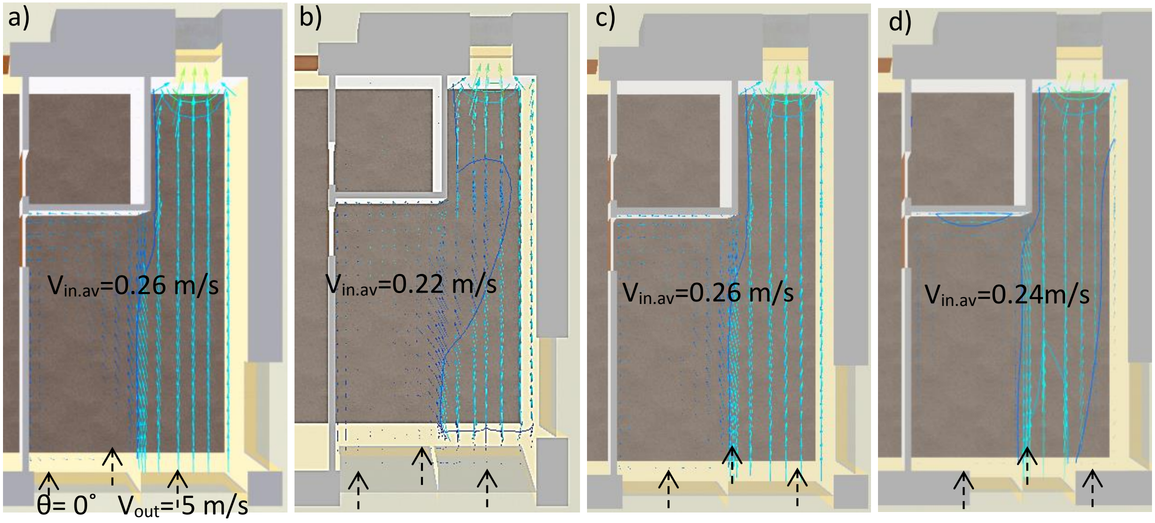


Figure 8-4 Living room air velocity at occupied level under θ= 0˚ for variants I, III, IV and V (a-d)

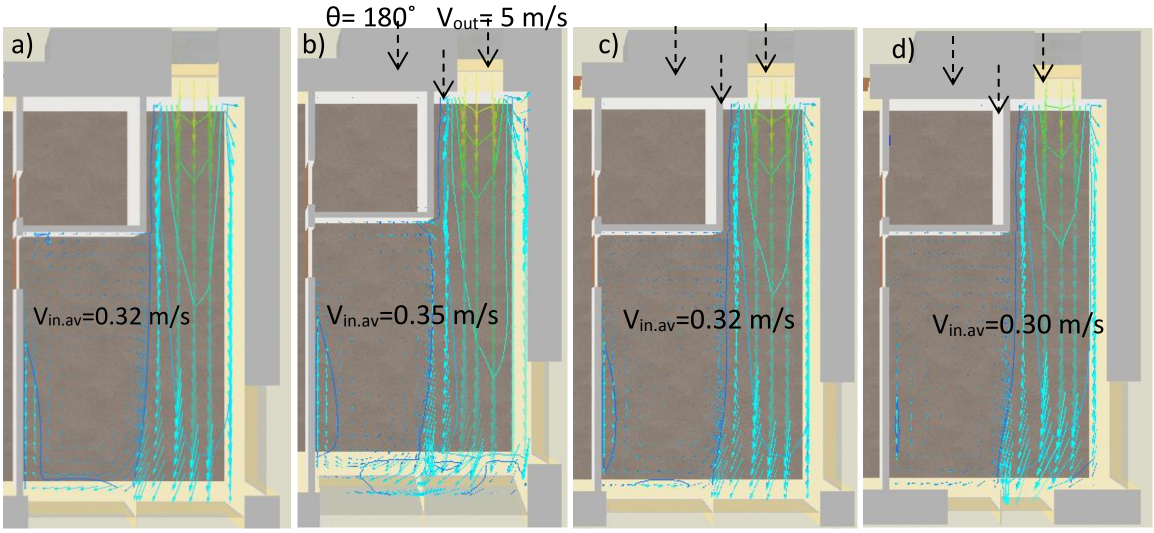


Figure 8-5 Living room air velocity at occupied level under θ= 180˚ for variants I, III, IV and V (a-d)

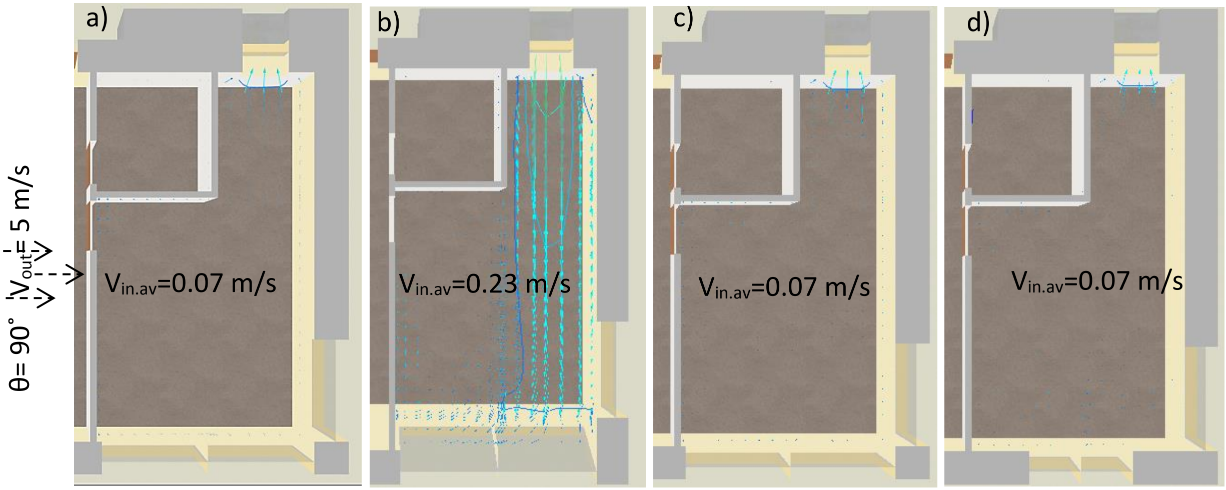


Figure 8-6 Living room air velocity at occupied level under θ= 90˚ for variants I, III, IV and V (a-d)

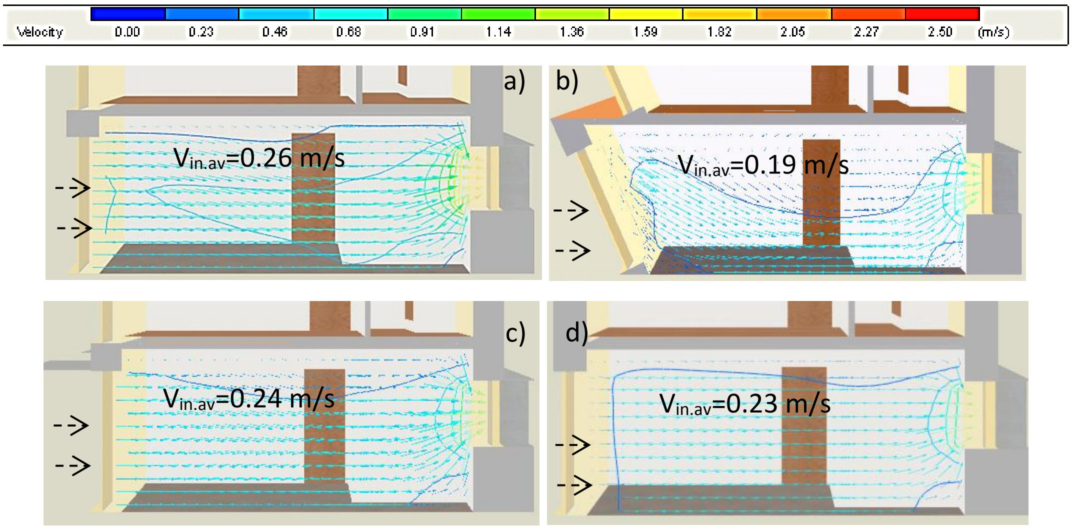


Figure 8-7 Cross section of living room air velocity plot under θ= 0˚ for variants I, III, IV and V (a-d)

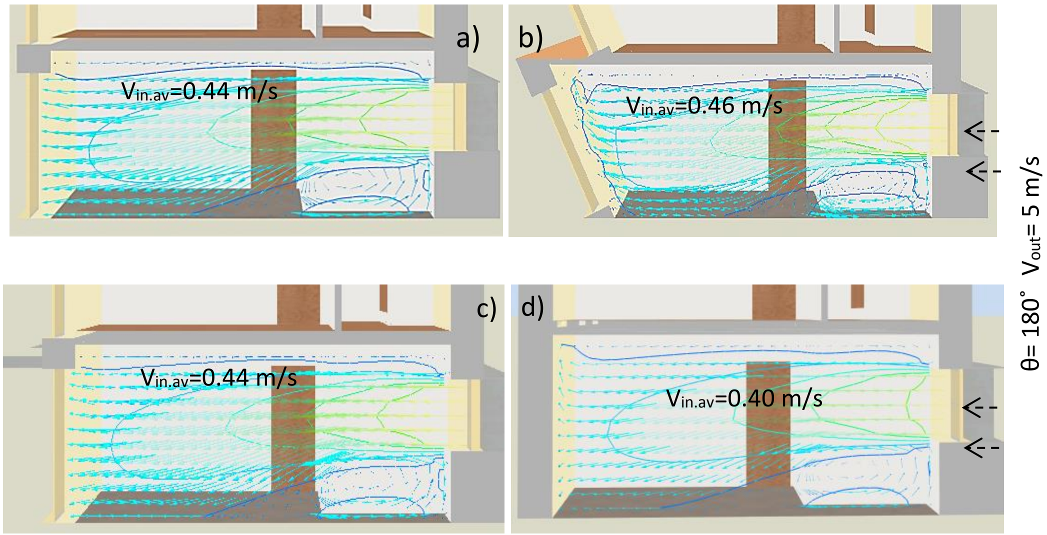


Figure 8-8 Cross section of living room air velocity plot under θ= 180˚ for variants I, III, IV and V (a-d)

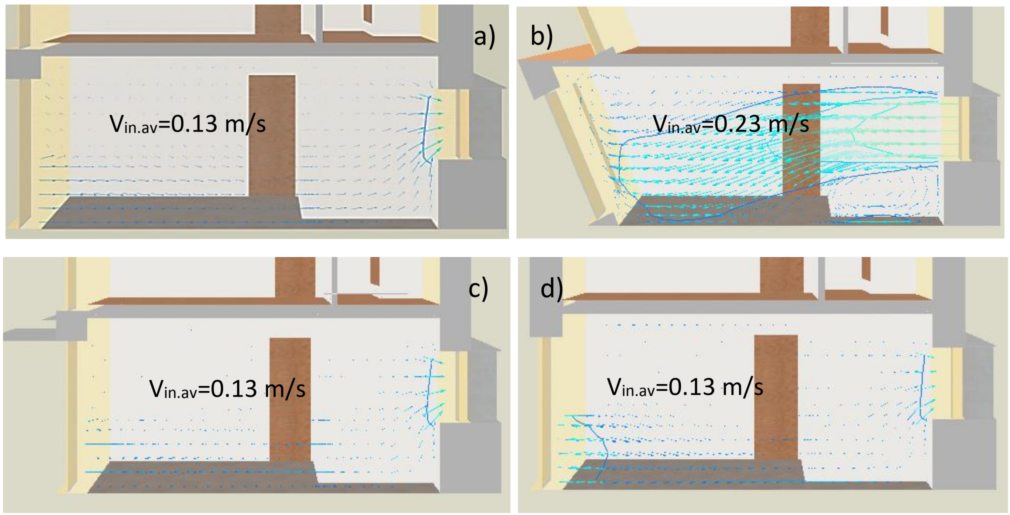


Figure 8-9 Cross section of living room air velocity plot under θ= 90˚ for variants I, III, IV and V (a-d)

8.2.3 External CFD analysis

External CFD simulations (Figure 8-10 to Figure 8-15) were carried out for all the wind directions tested to measure the internal CFD. The results showed different pressure distribution on the alternative façade designs. The contrast in pressure distribution on the south façade was apparent for the tilted building. There was a small deviation for the building with the overhang, and similar pressure distribution contours were found for the case study and its identical form with the smaller window to wall ratio.

The pressure distribution coefficient (Cp) on and around the building envelope is influenced by various factors, including wind velocity and direction, the envelope design, and neighbouring topography. Wind pressure distributions over a building surface are not uniform, and vary for different points of the façade surface. Therefore, it is hard to give an exact pressure coefficient value for specific point on the façade (Prajongsan, 2014) especially for an angled façade, but it can be predicted in a wind tunnel or approximated by using computational fluid dynamic (CFD) simulation.

External CFD plots for all three wind incidence angles resulted in a generally expected pressure contours where the windward has a positive pressure, and leeward and lee sidewalls all have negative pressures (Figure 8-11, Figure 8-13 and Figure 8-15). The pressure distribution contours on the horizontal walls were almost constant and similar values were found on the facade surface. However, the pressure on the tilted wall experienced a divided pressure contours, creating pressure differences (Δρ) on the same façade (Figure 8-10b, Figure 8-12b and Figure 8-14b).

The reduced internal air velocity previously established for the tilted case at $Wind\ \mathrm{INC}_{\theta} = 0°$ (Figure 8-7b) was found to be due to a lower positive air pressure at the inlet opening (Figure 8-10b and Figure 8-11b). This led to a smaller pressure difference (Δρ) between the inlet and outlet and consequently a lower air movement within the room.

In the previous section, the internal CFD plots for the westerly wind ($Wind\ \mathrm{INC}_{\theta} = 90°$) revealed an unexpected increase in air velocity within the room (see Figure 8-6b and Figure 8-9b). The external CFD analysis revealed the negative pressure around the lee side tilted wall has an area of stronger negative pressure at the top and bottom of the openings (Figure

8-12b). This might be creating an area of a void to allow a greater force of drag. Because a stronger negative pressure formed on the front elevation, the wind enters from the opposite window at the rear of the building (Figure 8-12b, Figure 8-13b, and Figure 8-9b). Contrarily, all other cases have similar pressure distributions on the both lee sides, so that the wind enters from the front window which is bigger in size (a, b, and c in Figure 8-12, and Figure 8-9).

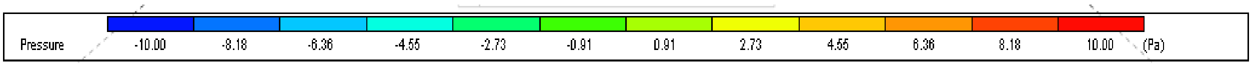
Overall, CFD analysis showed that pressure on the proposed façade decreased when the wind angle of incidence was 0° (i.e. wind is facing the tilt façade opening). This led to a lower airflow through the building. However, the air volume entering the building was enhanced when the wind angle of incidence was set to 90° (wind facing the side elevation) or 180° (wind facing the rear elevation). For these two later cases, a stronger negative pressure on the outlet was experienced, leading to a greater pressure-differences between the inlet and outlet. This caused a stronger suction force from the outlet opening and consequently an elevated air velocity inside the building. When air velocity increases, this helps to reduce a room's high operative temperature. Szokolay (2000) estimated the cooling effect of elevated air velocity using the following formula:

$$dT = 6V_e - 1.6\,(V_e)^2$$

Equation 8-2

Where dT is the cooling effect, Ve is the effective ventilation calculated as $Ve = V - 0.2m/s$, and V is the air velocity at the body surface for up to 2 m/s. For the wind direction of $\theta = 180°$ the area of low air pressure on the leeward tilted window would possibly strengthen the suction force at the outlet. There is also a divided area of negative pressure at the outlet that would possibly increase Δρ. Internal CFD analysis of the $Wind\,\mathrm{INC}_{\theta} = 180°$ shows a different airflow pattern at the point of exit (outlet) compared to the other cases. These would led to an increased air velocity within the room.

The effect of the inner topology of the building on the air change rate was not considered in this analysis however, research (Nikas, et al., 2010; Nikolopoulos, et al., 2012) found that internal geometry does not have a pronounced effect on the overall air change rate but can be an important factor in terms of air refreshing for different zones of a room.



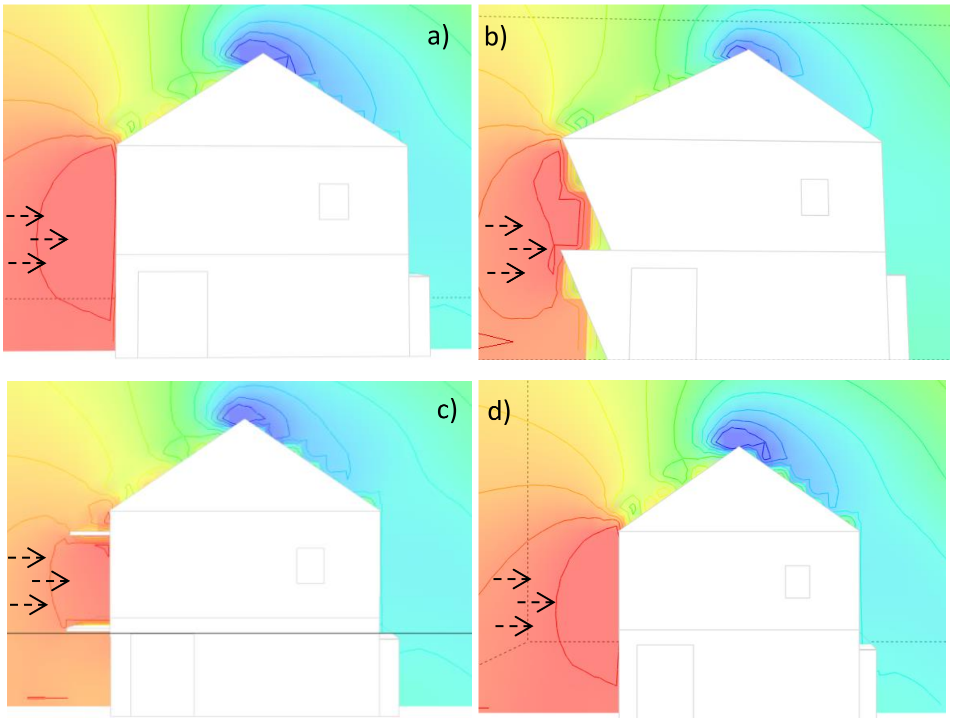


Figure 8-10 X-slice pressure distribution contour θ= 0˚ for variants I, III, IV and V (a-d)

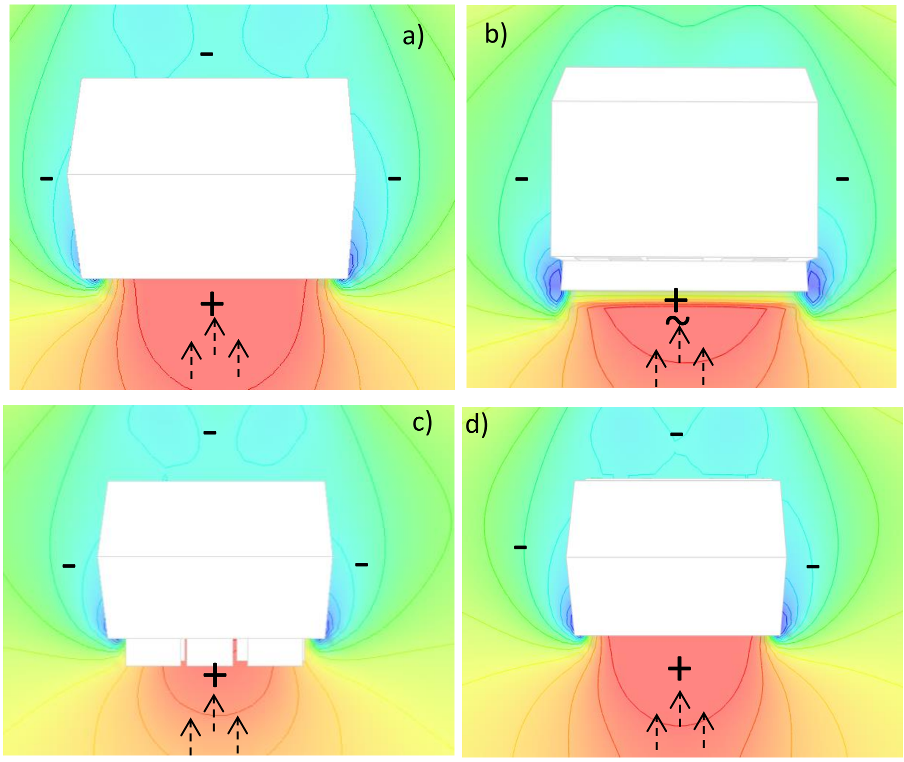
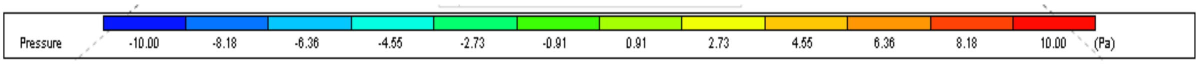


Figure 8-11 Z-slice pressure distribution contour θ= 0˚ for variants I, III, IV and V (a-d)



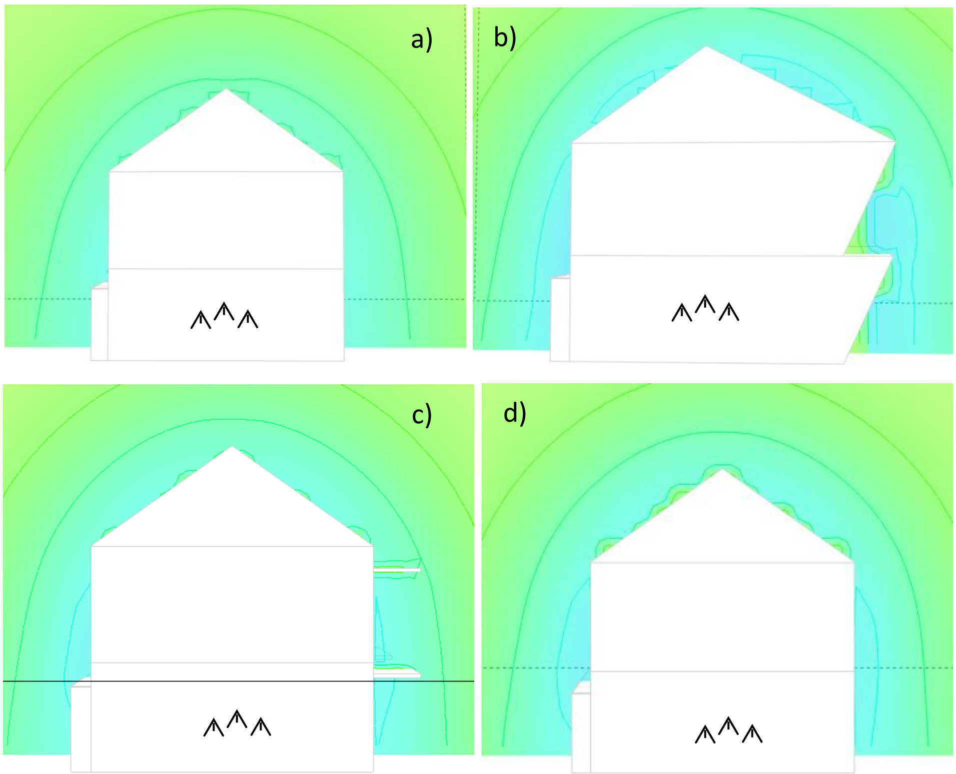


Figure 8-12 X-slice pressure distribution contour θ= 90˚ for variants I, III, IV and V (a-d)

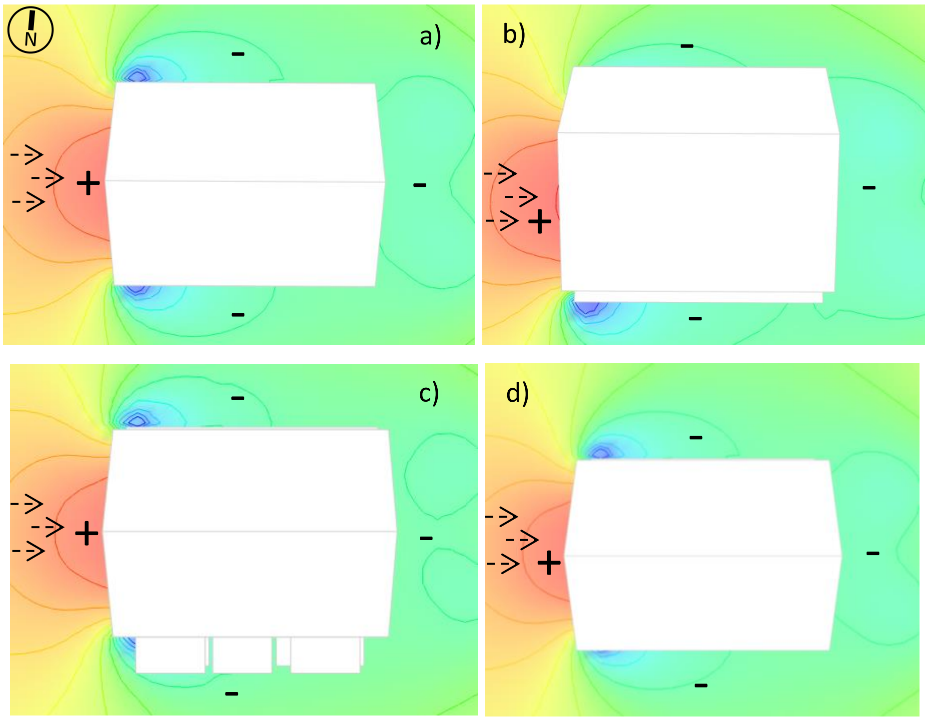
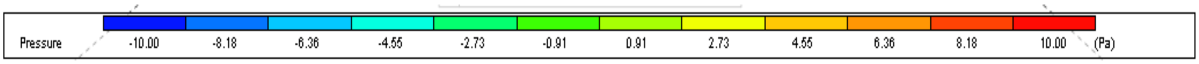


Figure 8-13 Z-slice pressure distribution contour θ= 90˚ for variants I, III, IV and V (a-d)



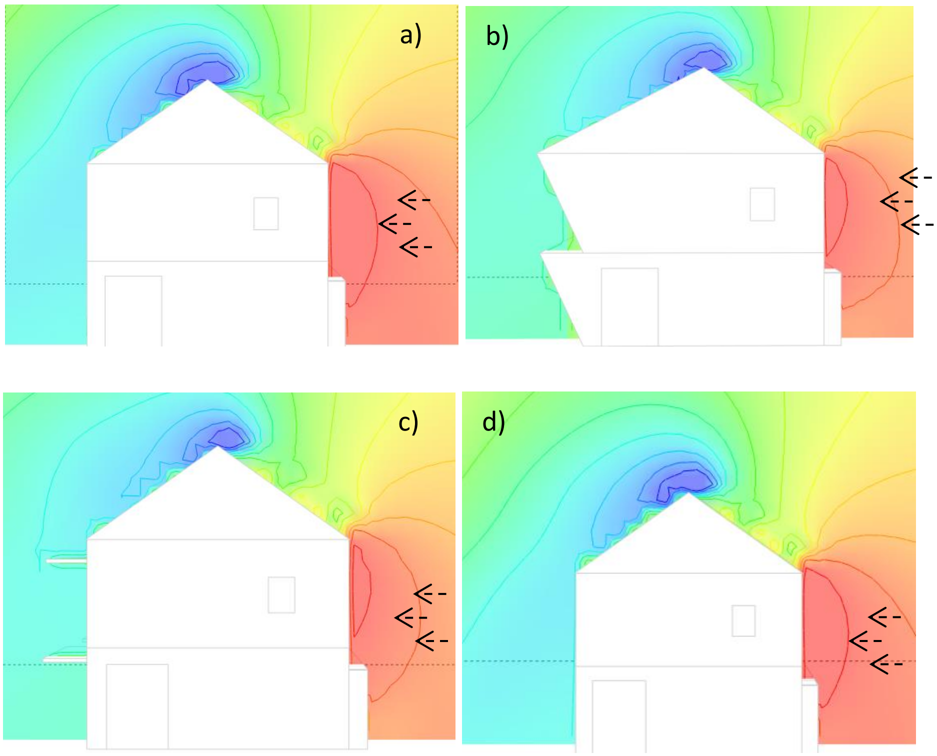


Figure 8-14 X-slice pressure distribution contour θ= 180˚ for variants I, III, IV and V (a-d)

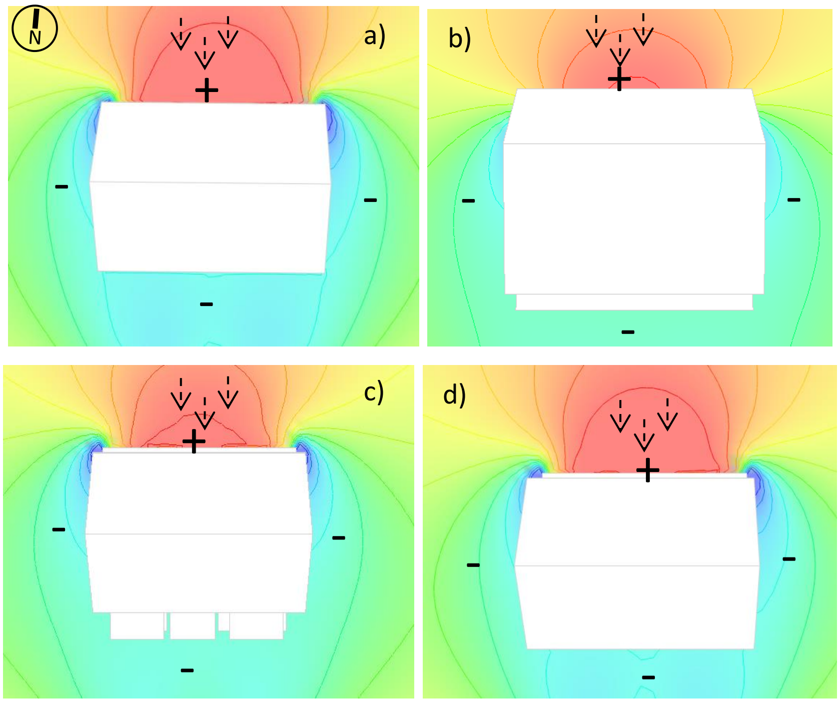


Figure 8-15 Z-slice pressure distribution contour θ= 180˚ for variants I, III, IV and V (a-d)

8.3 Daylighting

In recent decades, research has underlined the importance of indoor environment lighting quality. The quality of daylighting has become one of the leading concerns in the architectural design process. Providing interiors with adequate daylight can effectively reduce the electricity use of artificial lighting and providing interiors with adequate solar gain can effectively lower the energy consumption by reducing heating demand. On the other hand, with an increased level of solar illuminance, discomfort glare may appear and with excessive solar gain, overheating may occur. In the previous chapters this study presented the tilted façade as a potential alternative intervention to the common shading device strategies. In the first part of this chapter, the consequence that this shape created on airflow pattern was examined. This section set out to investigate the consequence of the south facade inclination on the natural lighting performance and to probe if the possible benefit of glare reduction can be achieved using this form.

8.3.1 Comfort illuminance criteria

According to British Standard BS8206-2 (2008) the recommended minimum average daylight factor is 1.5% for the living room and 1% for the bedroom. Different standards require different values; some of these standards define the adequate minimum average daylight factor as 2% and the maximum of 5% for the dwellings. This means that under a 10,000 lux standard overcast sky the average illuminance inside the room should be around 200 lux. This value is lower for a bedroom, where a 100 lux average illuminance is acceptable. Maintained illuminance in the bedroom should be around 100 Lux and for the living room depending on the activity it is required to achieve an illuminance of up to 300 lux (50-300 lux) across the area (CIBSE Guide A , 2015). Higher illuminance levels, especially above 500 lux, are not recommended for dwellings. In terms of brightness, the highest recommended luminance for the interior is typically 500 cd/m^2 for in the centre of the visual field, and 2000 cd/m^2 for the outside the normal visual field (IESNA, 2000).

A higher daylight level in interiors does not always correspond to a positive luminance range and may lead to discomfort glare. Although an acceptable average daylight factor sometimes is achieved because of an unbalanced distribution of light, this unbalanced distribution of light may lead to occupants closing their blinds or curtains and using artificial lighting while outside is quite bright and sunny. Piccolo and Simone (2009) stated that the glare disturbance is often reduced at the expense of reduction of daylighting so that artificial lighting needs to be used despite the available external light.

Interventions to balance both energy efficient control of solar radiation and interior visual comfort have been addressed in detail throughout the study. Shading strategies can have both positive and negative impacts on the overall lighting performance of the dwellings. The use of external blinds, shutters and internal curtains also could result in the loss of the view or increase the use of artificial lighting.

There are many interventions for increasing the daylighting quality and refinement of the luminance distribution across the internal space. Piccolo and Simone (2009) studied electrochromic (EC) glazing to increase daylighting and reduce indoor visual discomfort caused by glare from windows. They concluded that the EC glazing could be very effective in reducing discomfort glare without increasing the need for artificial lighting and unlike external blinds preserving an unobstructed view of the outside. Gugliermetti and Bisegna (2006) investigated the illuminance in the buildings with vertical facade fins and overhangs. Carbonari, et al. (2001) used automatic control of external shading devices and studied the optimum orientation of the building to elevate daylighting quality in office buildings. Research concluded that external shading devices have represented a simple solution to optimize energy savings with thermal comfort and a reliable way to prevent glare (Chauvel, et al., 1982; Dubois, 2003).

8.3.2 Daylighting simulation

Daylighting analyses on the alternative south façade arrangements (variant I, III, IV, and V) were calculated using the Radiance simulation engine in DesignBuilder. It provides a detailed multi-zone physics-based calculation of illumination levels on the working planes of the building. Radiance is a raytracing computational method to calculate the distribution of the illuminance in the working plane. The model data passed to Radiance include the visible reflectance of the surfaces, site ground reflectance, window glazing transmittance and detailed geometry including local and component block shading devices. However, shading due to movable internal shading devices such as blinds, are not included in Radiance daylight calculations.

It should be remembered that the results are taken for the London location. Although the original location of the case study is in south Wales (Ebbw Vale), a location known for typically having cloudy and overcast weather condition. A standard design overcast sky in the UK gives a horizontal illuminance of 5000 lux, while a sunny clear sky (CIE) ranges from 20,000-50,000 lux. As this study's main objective was not to analyse the daylighting performance of the house, simulations were taken only for a sky model of overcast with a horizontal illuminance of 10,000 lux as the representative of sky model.

There are different credit assessments for daylighting level. The main aim of these credit assessments is to identify designs that provide adequate levels of daylighting for occupants and encourage designers to employ required conditions to meet certain criteria. For instance, BREEAM Health and Wellbeing Credit HEA1 require the following:

i. At least 80% of net lettable floor area in occupied spaces should be adequately daylit. The average daylight factor should be at least 2% at the working plane height of 0.7m under a uniform CIE overcast design sky.
ii. A uniformity ratio of at least 0.4 or a minimum point daylight factor of 0.8%.

To pass LEED; NC 2.2 Credit EQ 8.1, it requires at least 75% of net lettable area in occupied spaces to be adequately daylit, having illuminance over the minimum threshold value.

This study investigated how the Sun angle of incidence would change by introducing a tilt façade and what would be the extent of the consequence of this form on daylighting levels (Figure 8.16). Illuminance map plots also showed if possible benefits of this form could be achieved to reduce discomfort glare.

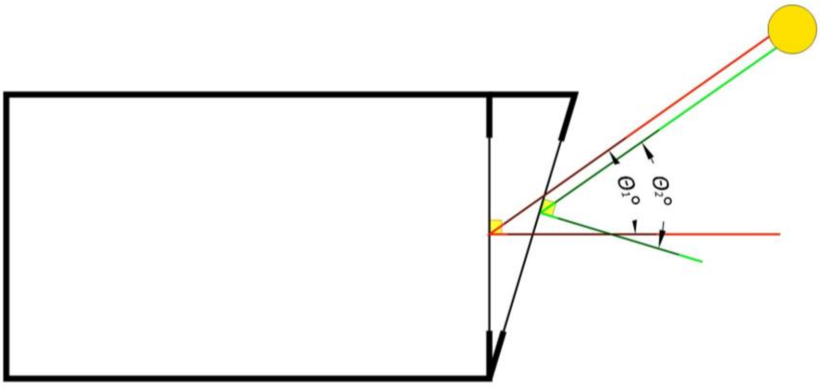


Figure 8-16 The sun angle of incidence on a horizontal and tilted surface

Data presented here compared the daylight factor percentage under an overcast sky with 10,000 lux for the four design arrangements. Daylight factor (DF) is the ratio between indoor illuminance and outdoor illuminance and is calculated under the CIE overcast sky condition using Equation 8-3 where Ei is indoor illuminance and Ee is the outdoor illuminance (Baker & Steemers, 2013).

$$DF = 100 \times \frac{Ei}{Ee}$$

Equation 8-3

Figure 8-17 plotted the illuminance map and daylight factor level for the ground floor and first floor of the original case study when the external blinds are fully open (Figure 8-17a), the proposed tilted façade (Figure 8-17b), overhang (Figure 8-17c), and reduced window to wall ratio (Figure 8-17d). Expectedly, the original case experienced the highest daylight factor due to the large windows and no permanent shading strategy. However, this case also received the highest glare due to the excessive daylight factor near the glazing. Although the original case study model appeared to have a very bright and adequate illuminance level, a daylight factor higher than 5% (too bright) was received for a relatively large area of the room affected by large glazing (Figure 8-17a). When implementing the shading interventions i.e. tilted façade and overhang, it is clear that the excessive illuminance of greater than 500 lux in the room was reduced effectively but this resulted to a lower average daylighting value. The excessive illuminance and daylight factor in these cases are within the 0.5 metre of the window, which is acceptable.

The living room for all four cases received adequate daylighting values, but only the bedroom of the original building (variant I) was adequately lit and all other variants (III, IV and V) received inadequate daylighting in the bedrooms. The consequence of the reduced daylighting due to shading strategies did not rise a concern over the daylighting level in the Livingroom. This reduction even may fine-tune the illumination within the room and better balance the light distribution. However, the tilted façade had an undesirable effect on the daylighting level in the south facing bedrooms (Figure 8-17b2).

Further calculation on the living room and main bedroom were conducted using a margin of 0.5 metre around the zone boundaries, which is recommended by CIBSE and LEED calculations. It means the illuminance values by 0.5m off the walls and windows are not included in the average daylight factor of the space. This will help to avoid the misleading illuminance data close to walls and windows.

The living room illuminance data (Figure 8-18 and Table 8-2) showed that a substantial percentage of the floorplan in the living room received the minimal optimum daylight factor (i.e. 2%) with an average daylight factor of 4.15%. A very small area of the room experienced a DF of less than 1%. However, a maximum illuminance was recorded at 1641 Lux for the original case, which would cause discomfort glare. The maximum illuminance was reduced to about 1000 lux near the glazing for the tilted façade.

Table 8-2 and Table 8-3 show that the original case study had the highest requirements of minimum daylight factor and illuminance. The second highest values were estimated for the building with 1.3m overhang. Tilted façade had relatively lower measures especially in the bedroom. The case with smaller windows received the lowest measures in uniformity ratio (the ratio between minimal illuminance over the area weighted average illuminance), minimum daylight factor and minimum illuminance. However, the lowest average daylight factor received by the self-shading geometry. This is because variant IV with no shading and 26% WWR had received a high daylight illuminance around the glazing and resulted in a greater average daylight factor.

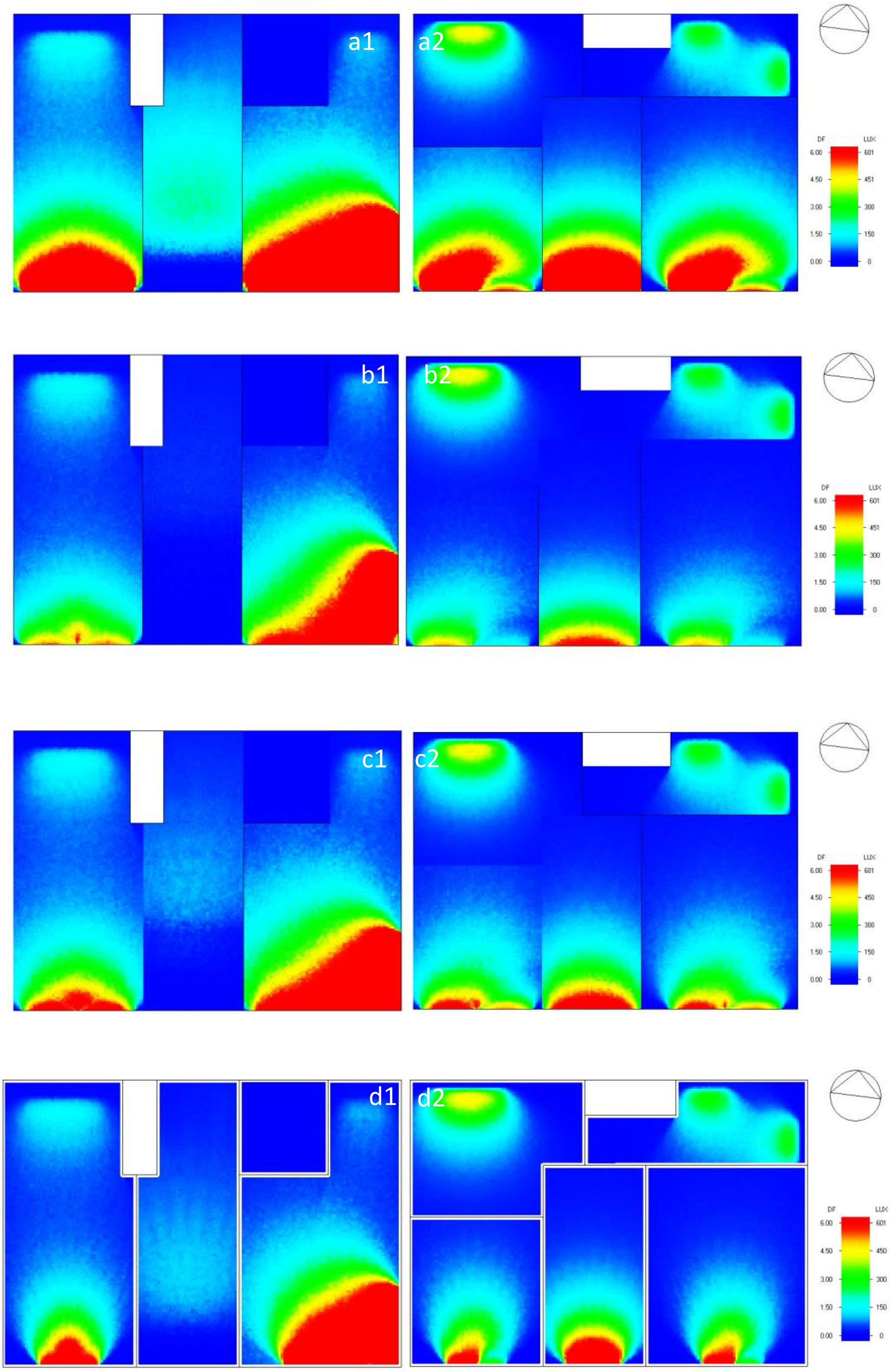


Figure 8-17 Illuminance and daylight factor level for ground floor and first; a) original case – a1 G floor and a2 1st floor, b) tilted facade, c) overhang and d) 26% WWR

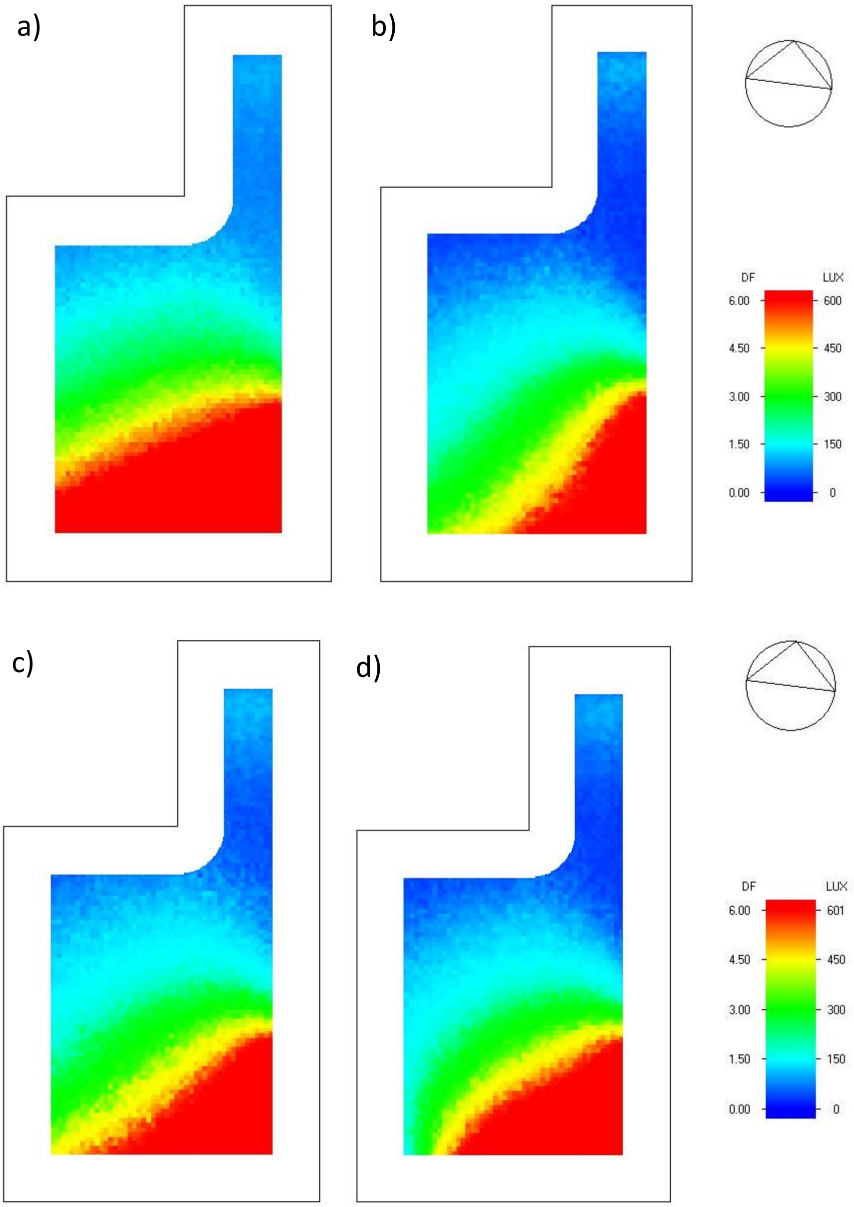


Figure 8-18 Living room daylight factor for variants I, III, IV and V (a-d)

Table 8-2 Living room daylighting measures for different variants

Living room	Floor Area above Threshold (%)	Average Daylight Factor (%)	Minimum Daylight Factor (%)	Uniformity ratio (Min / Avg)	Min Illuminance	Max Illuminance
90°	61.04	4.15	0.67	0.16	66.81	1641.06
115°	46.71	2.58	0.4	0.15	39.53	1052.61
1.3 (oh)	49.57	2.88	0.46	0.16	45.83	1236.14
26%WWR	46.15	2.81	0.37	0.13	36.61	1052.75

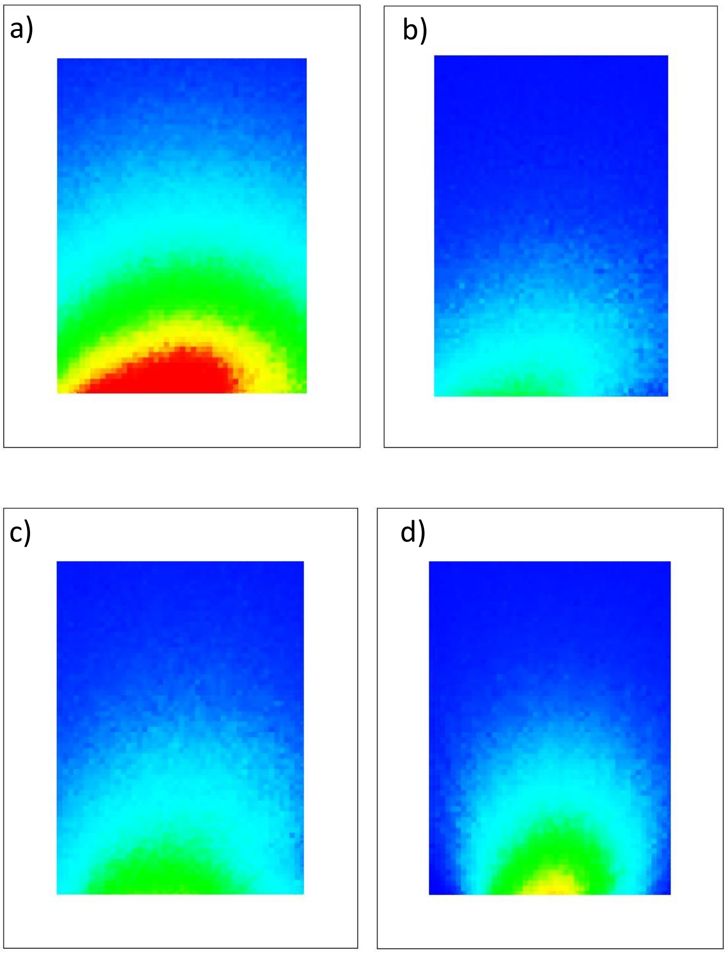


Figure 8-19 Bedroom daylight factor for variants I, III, IV and V (a-d)

Table 8-3 Bedroom daylighting measures for different variants

Bedroom	Floor Area above Threshold (%)	Average Daylight Factor (%)	Minimum Daylight Factor (%)	Uniformity ratio (Min / Avg)	Min Illuminance	Max Illuminance
90°	38.26	2.05	0.35	0.17	35.1	787.91
115°	2.11	0.67	0.1	0.15	10.25	269.38
1.3 (oh)	9.44	0.97	0.15	0.16	15.16	354.81
26%WWR	10.7	0.9	0.01	0.01	0.94	493.97

8.4 Summary and conclusion

Data presented in Chapter Eight revealed the consequences of the proposed tilted façade strategy on natural ventilation and daylighting.

Internal CFD results showed that, when the inclined wall faced the wind, there appeared to be a lower volume of airflow rate entering through the space. This was then approved by external CFD, where the results showed a reduction in pressure distribution on the external surface of the tilted façade. In contrast, for wind incident angle of 90°, and when the tilted façade was on the leeward side ($Wind\ \mathrm{INC}_{\theta} = 180°$), ventilation rates increased noticeably. In this case, external CFD calculated a stronger negative pressure on the exterior of the tilted façade where the openings forced an extra amount of airflow extracted from the building.

Daylighting analysis showed that for the tilted façade the reduction of the illuminance inside the rooms was noticeable. However, other design interventions for reducing overheating also resulted in reduced illuminances inside the building. The daylight reduction was more noticeable for the bedroom and the living room's average daylight factor remained within a satisfactory value. The bedroom average daylight-factor was reduced to just below 1% for the building with overhangs, which is rather acceptable for a bedroom, but the tilted façade resulted in a considerably lower illuminance. On the other hand, the tilted façade was beneficial at controlling the direct sunlight penetration at low angles in the living room which can bring disability glare affects and high luminance spots on the work-plane surface.

Chapter Nine

9 Discussion and Conclusions

9.1 Introduction

In the last two chapters the results of the study were presented. In this chapter, a summary of the results are presented and discussed. The limitations of this study are addressed and recommendations for future works are suggested.

9.2 Discussion

This thesis investigated the applicability of the Passivhaus standards in the UK future climate context by studying four inter-related agendas: i) UK government target for limiting CO_2 emissions; ii) climate change scenarios; iii) assessing the uncertainty of the Passivhaus overheating risks; iv) investigating the geometrical implications for new build UK Passivhaus dwellings to reduce overheating.

The thesis has argued that the rapid transition to super insulated Passivhaus or any advanced energy performance standards should proceed with specific context and application testing. The thesis also has argued against the misconception that environmental design strategies are mostly engineering-based rather architectural and aesthetic. The research attempted to incorporate the form of the building as a shading strategy for Passivhaus dwellings. The geometrical implementation of the design, which is architectural in nature and has both aesthetic and environmental benefits, were assessed.

The study presented successful applications towards resolving overheating issues, which have been implemented in the passive house designs. Both user-dependent and non-user-dependent interventions were reviewed. However, non-user dependent interventions, such as overhangs and reduced window to wall ratio were focused on, in this study. The Larch

House case study used a user-dependent approach i.e. external shading blinds to control the solar access in summer.

The result of this research incorporated three environmental assessments that the proposed geometry created. These included 1) Thermal comfort in terms of indoor air temperature, 2) CFD analyses of natural ventilation and 3) daylighting assessment.

9.2.1 Conclusions of the thermal analysis

Overheating in residential buildings during the summer mainly occurred due to combinations of high solar radiation levels, warm outdoor air temperatures and a lack of air movement. According to the precedent studies addressed in the literature, overhangs and fixed shading devices are probably the most common type of shading strategies. Many existing passive houses use external roller blinds to tackle overheating and glare. External roller blinds are successful in reducing overheating if they are used to their best advantage. However, research has shown that shading devices inside the building cannot be considered as a useful intervention towards the reduction of overheating because the solar heat gain has already entered the building. External insulation was one of the most effective interventions for reducing overheating, especially for warmer climates where outside temperatures are higher than comfort levels. Thermal mass is one of the most effective interventions in reducing overheating when coupled with nocturnal ventilation. Internal insulation was not effective regarding overheating reduction. In terms of superinsulation, there are still disagreements among researchers. Previous studies, however, agreed on the beneficial contributions of the solar shading and natural ventilation in preventing the overheating.

The problematic interaction between the occupants and the solar overheating control systems was a stimulus for this study's investigation of an alternative novel, non-user dependent intervention rather than the more conventional approaches such as overhangs and thermal mass. An alternative to overhangs is to create a self-shading geometry to make use of a building's envelope to act as a shading device for itself. This research was an attempt in adjusting the building's geometry to consider an alternative to overhangs. A tilted façade replaced the vertical south façade of an existing Passivhaus (Larch House) to create a self-shading geometry. The self-shading form was assessed to investigate the applicability that this form created. A sensitivity analysis of internal temperatures and discomfort degree hours was conducted for a single univariate input i.e. south-façade geometric alteration. The internal operative temperature was measured for the living room (where the occupants spend most of their time while present and awake), and the main bedroom (as thermal comfort is very important during sleep) for the existing vertical façade and proposed tilted façades. The sensitivity analysis of the parametric variables helped to discover whether, and in what conditions, the façade inclination angle becomes beneficial concerning the total energy performance in both summer and winter.

According to the results presented in Chapter Seven, applying a tilted wall with an inclination angle in the range $Tilt_{\Theta south} = 110° - 115°$ is constructive to reduce the potential of overheating for current and, especially, future climates in London. There is a significant reduction in operative temperatures in summer when using a self-shading façade whereas the operative temperature will not significantly drop in winter. On the other hand, data analysis on the pilot unit revealed that the implementation of a steeper façade would block the required solar gain in winter.

The concurrent increase in heating demand will be slight, although noticeable. CIBSE future weather data show an increase in average dry bulb temperature even in winter months, and extreme weather events in winter are also predicted to be more frequent. Passivhaus provides most of its heating demand from the heat recovery system, i.e. heat given off by appliances and occupants, and solar gains. This means the Passivhaus heating demand is almost zero for most of the days. However, to achieve comfort temperature a small amount of supplementary heating is required (up to 15 kWh/m^{2}year is acceptable). In the case of maintaining the minimum of 20°C temperature, the self-shading approach would lead to an increase in the peak heating load in a very cold spell.

The UK will remain a heat dominant climate, even in future climate scenarios. However, in this study summer time discomfort, especially in July, was focused on because the most cooling was required in July under both current and future climate conditions. Nevertheless, overheating also occurred in the shouldering months. In this study, overheating referred to the temperature exceeding 25°C for more than 10% and 28°C (26°C) more than 1% of occupied hours. This is to achieve an Ideal indoor condition in summer. The percentage representing the overheating scale is calculated based on the ratio of the hours of above 25°C to the total number of hours in which the room is occupied.

The results of the sensitivity analysis underlined the importance of envelope geometry. Table 9-1 and Table 9-2 summarise the percentage of the hours the tested rooms experienced high indoor temperatures. Green numbers represent the “pass” criteria according to Passivhaus and CIBSE Guide A criteria and red numbers represent the “fail” criteria. Blue numbers also show the fail criteria; however, it is very close to the optimum value, which can achieve the “pass” criteria with a slight adjustment e.g. slight increase in natural ventilation. Bold greens emphasise the ideal case and bold reds show very high risks of overheating that requires additional effective passive interventions or perhaps active cooling to remove overheating.

A self-shading façade of $Tilt_{\theta south} = 115°$ was established as the optimum inclination angle, mainly because of the reduction of overheating for future climate scenarios. The established proposed façade was then compared with the most conventional approaches in Passive design i.e. reducing the window to wall ratio and overhangs. Table 9-2 summarised the result of the overheating percentage for the alternative façade arrangements. The building with the original south façade arrangement experienced overheating in current London climate and was found to be critically at risk of summer overheating under future climate scenarios. However, all three altered interventions were successful in reducing overheating in the current climate. However, the lowest overheating achieved for the proposed geometry. The reduced window to wall ratio also was a successful application in reducing overheating. However, the overhang of 1.3m was the better choice in receiving solar gain in winter. The self-shading intervention would be an effective shading device for the Passivhaus especially in a warming climate. However further interventions are required to eliminate the overheating in a super insulated Passivhaus under high emission future weather scenarios.

Table 9-1 Summary of the results on overheating percentage

Climate	Space	Vertical variant I	110° tilt variant II	115° tilt variant III
Current	Living room>25°C	28.2%	14.6%	12.2%
	Living room>28°C	2.9%	0.5%	**0.1%**
	Bedroom>25°C	12.3%	**1.7%**	**1%**
	Bedroom>26°C	4.9%	**0.4%**	**0.2%**
2030s	Living room>25°C	**43.3%**	26%	21%
	Living room>28°C	11.2%	4%	3%
	Bedroom>25°C	21.6%	10.5%	7.7%
	Bedroom>26°C	**15.2%**	7%	5.6%
2050s	Living room>25°C	**48.1%**	30.4%	25.5%
	Living room>28°C	**16.3%**	8.6%	7.4%
	Bedroom>25°C	27.7%	15.8%	11.8%
	Bedroom>26°C	**21.3%**	11.9%	8%
2080s	Living room>25°C	**58.1%**	**41.5%**	**35.4%**
	Living room>28°C	**28.2%**	**17.6%**	15.3%
	Bedroom>25°C	**38.3%**	**22.1%**	**18.9%**
	Bedroom>26°C	**31.2%**	**18.5%**	14.3%

Table 9-2 Summary of the comparative study of the proposed and most common interventions

Climate	Space	Vertical variant I	115° tilt variant III	1.3m overhang variant IV	26% WWR variant V
Current	Living room>25°C	28.2%	12.2%	14.9%	13.8%
	Living room>28°C	2.9%	**0.1%**	**0.5%**	**0.4%**
	Bedroom>25°C	12.3%	**1%**	**2.2%**	**1.4%**
	Bedroom>26°C	4.9%	**0.2%**	**0.4%**	**0.2%**
2030s	Living room>25°C	**43.3%**	21%	28%	24%
	Living room>28°C	11.2%	3%	4.1%	3.7%
	Bedroom>25°C	21.6%	7.7%	11.2%	10.5%
	Bedroom>26°C	**15.2%**	5.6%	7.2%	7%
2050s	Living room>25°C	**48.1%**	25.5%	**33%**	29%
	Living room>28°C	**16.3%**	7.4%	8.9%	7.9%
	Bedroom>25°C	27.7%	11.8%	16.1%	14.5%
	Bedroom>26°C	**21.3%**	8%	12%	10.3%
2080s	Living room>25°C	**58.1%**	**35.4%**	**42.9%**	**38%**
	Living room>28°C	**28.2%**	15.3%	**18.9%**	**17.9%**
	Bedroom>25°C	**38.3%**	**18.9%**	24.2%	20.8%
	Bedroom>26°C	**31.2%**	14.3%	**18.1%**	**16%**

9.2.2 Natural ventilation behaviours

The precedent research found that the different forms of the building component- for instance roof or window reveal could affect the air movement in and around the building. It is stated that the effect of geometrical alterations on heat loss was substantially higher for a low-rise building.

The aim of the CFD analysis in this study was to test if the from that self-shading facade created would increase or decrease indoor air velocities. This will have a direct effect on physiological cooling and comfort during summer. Initially, this agenda was not included in the main objective of this study. However, because of the ability of the DesignBuilder software to carry out CFD analysis the models were used to calculated air velocity and average air volume entering the rooms. The CFD calculations took place in the existing building and three alternative cases; i.e. (1) tilted façade of 115°, (2) overhang of 1.3 m and (3) window to wall ratio of 26%. The varied parameters were the direction of the wind and the façade arrangements. The summarised findings in Table 9-3 shows that the building with an overhang had almost the same air flow volume as the original case study, however for the south-facing tilted façade and the reduced windows size the overall flow rate was different from the original case.

Table 9-3 Summary of the results on the CFD analysis

Wind direction	**115° tilted façade variant III**	**1.3m overhang variant IV**	**Window to wall ratio of 26% Variant V**
$\mathbf{wind\ INC}_{\boldsymbol{\theta}} = \mathbf{0}°$	Reduced	No sensible changes	Slightly reduced
$\mathbf{wind\ INC}_{\boldsymbol{\theta}} = \mathbf{90}°$	Increased	No sensible changes	No sensible changes
$\mathbf{wind\ INC}_{\boldsymbol{\theta}} = \mathbf{180}°$	Slightly Increased	No sensible changes	Reduced

9.2.3 Conclusion on the daylight assessments

Another consequence of the tilted façade established in this study related to daylighting. During the first phase of a design, it can be very beneficial to supply architects with an instruction manual for the selection of geometrical and dimensional characteristics of the shading devices. This will help to develop a more efficient control of solar radiation and glare while satisfying requirements of illuminance and daylighting.

The results of the daylight analysis showed a notable reduction in daylighting levels inside the house with a tilted façade. However, some of the reduction were positive in terms of reducing discomfort glare. The living room was not conspicuously affected by the introduction of the shading interventions. However, a negative reduction of daylighting was measured for the bedroom. Table 9-4 gives an overall indication of the daylighting results when implementing the three different design strategies tested in the study.

Table 9-4 Summary of the results on the daylighting analysis

Daylight factor	**115° tilted façade variant III**	**1.3m overhang variant IV**	**Window to wall ratio of 26% variant V**
Living room	Minor reduction	Minor reduction	Minor reduction
Bedroom	Major reduction	Minor reduction	Medium reduction

Although the proposed geometry led to a reduced natural daylight, however, using high albedo surfaces could be a valid approach to increase the daylight for the proposed geometry while benefiting from glare reduction and improving visual comfort (Figure 9-1).

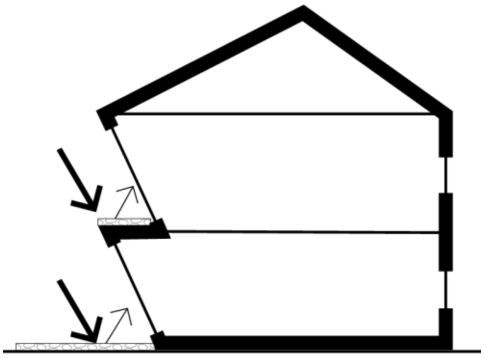


Figure 9-1 Using high albedo surface to improve daylighting

9.3 Limitations of this study and suggestions for future works

This study focused on the south façade shading to reduce excessive solar gain through large south-facing glazing in Passivhaus. East and west façades of the Passivhaus are recommended to have the minimum glazing because of the low solar altitude in the evening enabling deep penetration of incident solar radiation onto the facade. Tilting the façade (steeper than 115°)

would consequently change the angle of solar incidence and reduce the direct radiation gain. It would be interesting to see if a tilted facade could help architects to use these facades to allocate windows for these east and west orientations. This will also help to increase the natural ventilation for rooms with a single sided opening to have openings in adjacent walls.

It is acknowledged that this study was perhaps too narrowly focused on a single alteration of geometry (i.e. tilt façade) and very restrictive for the other geometrical implications. However, the result of this study make a novel contribution to the knowledge of Passivhaus envelope design.

When a global optimization method is not available, often the best way to navigate the design options is to use parametric analysis. When considering several variables, the number of outputs can be extremely large (for instance the inclination angle for all four facades at 1° increment angles). A platform (jEPlus) compatible with EnergyPlus was developed at De Montfort University (Zhang, 2011) to perform complex parametric analyses on multiple parameters. jEPlus was established to run simulation cluster jobs (batch file) and arrive at the optimal solution. At the time of this research the first version of the software was available and it was in the process of being tested and validated. The later version of the software offers a more accurate batch analysis, which can find an optimum solution within a broader set of variables.

One of the limitations of the software used in this study was the fact that parametric simulation option in DesignBuilder did not have the geometrical variation to be able test the geometric implications for the building envelope with more diverse shape alterations. At the time, other well-stablished parametric design software, like Grasshopper and Galapagos (Rhino Plug-ins), were not compatible with the DesignBuilder/EnergyPlus, which was the main simulation tool in this study. The process of form selection in future works can be improved by using evolutionary parametric tools to enable simultaneously switch between the energy calculation and graphical visualization during the design process. Some of the current platforms in building information modelling, such as Design Performance Viewer (DPV), have this ability. Although, they have their limitations but could be used for future studies.

9.3.1 Geography

The relationship between the proposed alterations in form and energy performance was revealed. Following this relationship, there is the link between the form and the climate of the region. It is widely accepted that, contrary to contemporary design, vernacular architecture had a climate responsive approach. In recent decades, there has been more attention paid to designing climate-responsive new builds. One of the obvious building characteristics of different climates can be seen when travelling from a region with a dry climate to a region with a high annual rain fall – the inclination of the roof becomes steeper. The tilted facade as a shading device perhaps becomes steeper in a hotter climate or has a smaller inclination for a region with milder summers. The impact of geography and climate can be studied in the future works to investigate if there is any benefit from the proposed geometry in different regions. The same hypothesis can be conducted for other parts of the UK to demonstrate if a tilted façade would be beneficial for a colder climate where the climate change impact is relatively smaller than for London. The results may include the complete removal of overheating even for high emission scenario 2080's or may increase the heating demand by an unacceptable trade-off.

9.3.2 Cost

It is often argued that the potential cost increase associated with energy efficient strategies to meet certain criteria could have a negative impact on their wider application. The Passivhaus standards already require an apparent cost difference from conventional buildings. The suggested façade geometry may add to constriction costs, although this form creates an extra space on the first floor which can be used as a balcony (Figure 9-2). However, the overall cost of the building will most likely increase when compared with a vertical wall or overhang to shade the glazing. Nevertheless, the cost of interventions will vary significantly. There is not a clear fix price source to provide information that covers all of the studied interventions. However, a report from the Energy Saving Trust (The Energy Saving Trust, 2009) estimated the cost of some interventions. Envelope insulation is by far the highest cost amongst the interventions. Triple windows and external shutters, internal blinds, and fixed shading devices were the medium costly interventions. Night ventilation was among the cheapest interventions to tackle overheating in the UK. However, this will require a window security upgrade. Future works can investigate the price applicability of the self-shading facades to reach a more comprehensive conclusion.

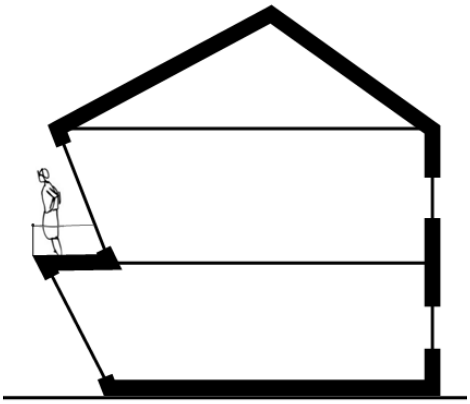


Figure 9-2 Balcony created by the proposed geometry without increasing the building footprint

9.4 Conclusion

The heating demand for the UK housing stock has been partially but successfully resolved by introducing low energy criteria such as the Passivhaus standard. Passivhaus dwellings have been successful in reducing the heating demand by up to 85% compared to conventional houses. However, the only concern for super insulated dwellings is the summer-time overheating discomfort, especially for a warming summer climate in London. Elevated temperature due to climate change could be resolved with air-conditioning, but this will simply increase electricity and consequently greenhouse gas emissions and hinder attempts towards low-carbon future. Research has been trying to achieve thermal comfort by solely using passive interventions. Successful passive interventions towards reducing overheating risks were acknowledged within the context of this study, and it was concluded that among shading strategies overhangs were the most effective intervention.

The research argued that most Passivhaus design strategies are engineering-based concepts and do not exert a perceptible architectural influence on the design of the building. Although architects and engineers perform many parallel functions, there are obvious differences when it comes to designing the building form. The form of the building is not generally an area of interest among building physicists who have been involved in intensive research over many years on reducing energy use in buildings. In the few decades architects have begun to engage more in this debate. Reducing energy demand by manipulating, say, façade shape has not been of interest among researchers involved with energy efficiency to achieve thermal comfort in buildings. They would rather use a simple overhang, computerised roller blind or reflective façade.

This study tried to integrate a form-based shading strategy into the Passivhaus concept. The research focused on the impact of building geometry on the energy performance of a Passivhaus dwelling in the UK under alternative future weather projections. A particular focus was the optimum inclination of a south facade to make use of geometry to self-protect the building and mitigate the possible overheating risks in the very airtight UK dwellings. Self-shading geometries were proposed to alternate overhang devices. Overall, the study found that a self-shading strategy of 115° tilted south façade ($Tilt_{\theta south} = 115°$) seemed to be constructive in alleviating overheating risk in London (Figure 9-3). It was found that when using this form the comfort hours during hot summer days were extended. The proposed geometry could not entirely eradicate the overheating. However, by combining with enhanced ventilation, the overheating risk can be eliminated or significantly reduced.

Parameters that have the most pronounced effect on the energy performance of the Passivhaus have been established mainly by Passivhaus Institute and other researchers. This research, though, proposed criteria to quantify the impact of the developing solutions.

This research was a step in contributing to ***“Form Follows Energy”*** concept for Passivhaus design. It can become a useful source of inspiration to architects to derive an *“architectural solution”* to a given *“building physics”* problem.

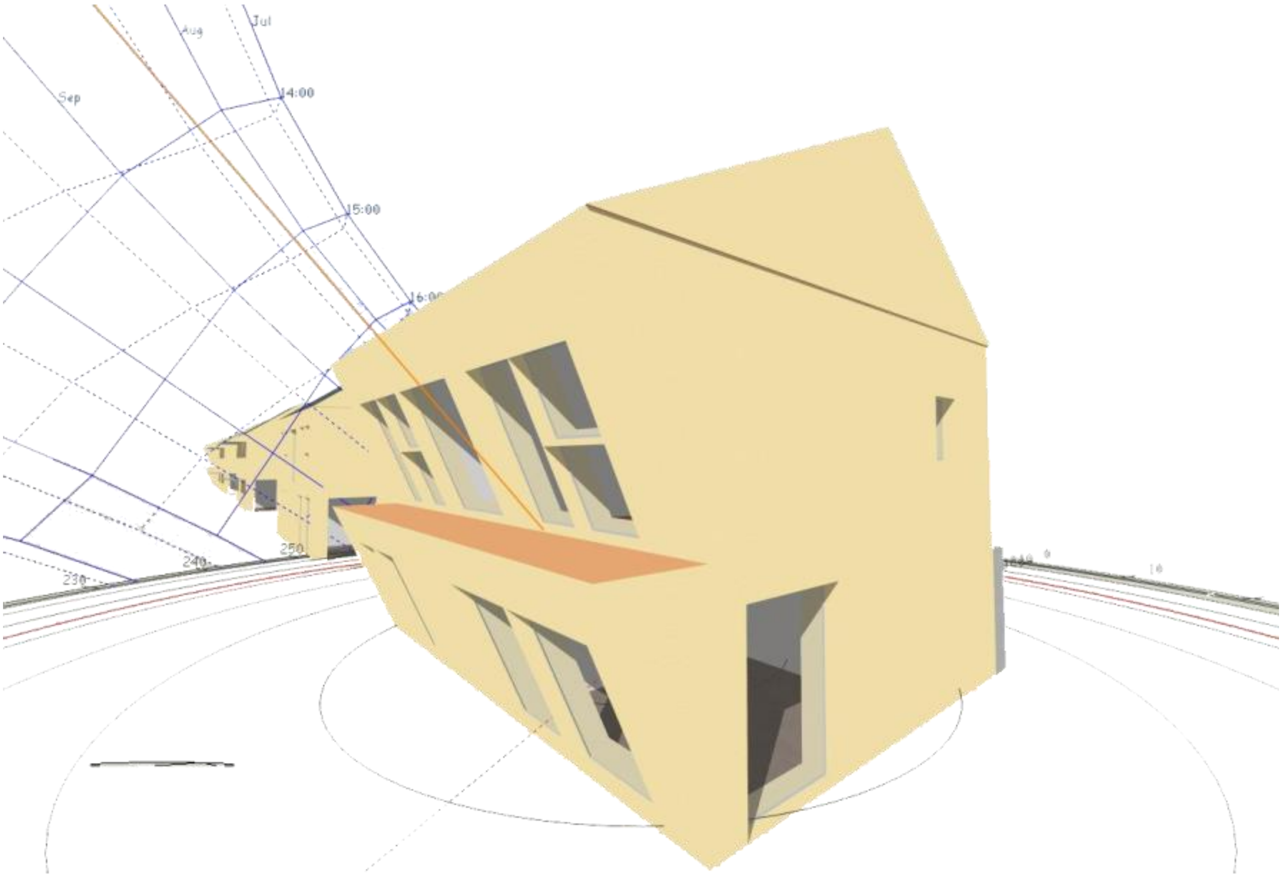


Figure 9-3 Proposed façade design for Larch House

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Appendix A: Data input in DesignBuilder/Energy Plus

Table A-1 Ground floor's fabric data

Name	**Larch House ground floor**	
Source	DesignBuilder	
Category	Floors (ground)	
Definition method	Layers	
Simulation solution algorithm	Default*	
U-Value	**0.076**	
		Thickness (mm)
Number of layers	8	800
Outermost layer (Layer 1)	Formaldehyde foam	25
Layer 2	FLOORMATE 500-A (insulation)	120
Layer 3	FLOORMATE 500-A (insulation)	120
Layer 4	FLOORMATE 500-A (insulation)	120
Layer 5	FLOORMATE 500-A (insulation)	120
Layer 6	Concrete	200
Layer 7	Floor screed	60
Innermost layer (Layer 8)	Timber flooring	15

*Refer to DesignBuilder user manual **(2015)**

Table A-2 Calculated constructions data for ground floor

Calculated constructions data _ floor (ground)	
Inner surface	
Convective heat transfer coefficient ($Wm^{-2}K$)	0.342
Radiative heat transfer coefficient ($Wm^{-2}K$)	5.540
Surface resistance (m^2KM^{-1})	0.170
Outer surface	
Convective heat transfer coefficient ($Wm^{-2}K$)	19.870
Radiative heat transfer coefficient ($Wm^{-2}K$)	5.130
Surface resistance (m^2KM^{-1})	0.040

Calculated constructions data _ floor (ground)	
No Bridging	
U-value surface to surface ($Wm^{-2}K$)	0.077
R-value ($Wm^{-2}K$)	13.188
U-value ($Wm^{-2}K$)	0.076
With Bridging (BS ENISO 6946)	
Thickness (m)	0.780
Km internal heat capacity ($KJm^{-2}K$)	81.38
Upper resistance limit (m^2KW^{-1})	13.188
Lower resistance limit (m^2KW^{-1})	13.188
U-value surface to surface ($Wm^{-2}K$)	0.077
R-value (m^2KW^{-1})	13.188
U-value ($Wm^{-2}K$)	0.076

Table A-3 Flat roof's fabric data

Name	**Larch House flat roof**	
Source	DesignBuilder	
Category	Roofs	
Definition method	Layers	
Simulation solution algorithm	Default*	
U-Value	**0.074**	
		Thickness (mm)
Number of layers	7	578 (693 discrepancy)
Outermost layer (Layer 1)	Knauf Thermal insulation (between studs)	140
Layer 2	Knauf Thermal insulation (between studs)	140
Layer 3	Knauf Thermal insulation (between studs)	140
Layer 4	FLOORMATE 500-A (Knauf Thermal insulation (between studs)	140
Layer 5	OSB board	18
Layer 6	Formaldehyde foam	100
Innermost layer (Layer 7)	Plasterboard	15

*Refer to DesignBuilder user manual **(2015)**

Table A-4 Calculated constructions data for internal flat roof

Calculated constructions data _ flat roof (ceiling above first floor)	
Inner surface	
Convective heat transfer coefficient (Wm^{-2}K)	4.460
Radiative heat transfer coefficient (Wm^{-2}K)	5.540
Surface resistance (m^{2}KM^{-1})	0.100
Outer surface	
Convective heat transfer coefficient (Wm^{-2}K)	19.870
Radiative heat transfer coefficient (Wm^{-2}K)	5.130
Surface resistance (m^{2}KM^{-1})	0.040
No bridging	
U-value surface to surface (Wm^{-2}K)	0.075
R-value (m^{2}K/W)	13.424
U-value (Wm^{-2}K)	0.074
With bridging (BS ENISO 6946)	
Thickness (m)	0.693
Km internal heat capacity (KJm^{-2}K)	13.719
Upper resistance limit (m^{2}K W^{-1})	13.424
Lower resistance limit (m^{2}K W^{-1})	13.424
U-value surface to surface (Wm^{-2}K)	0.075
R-value (m^{2}KW^{-1})	13.424
U-value (Wm^{-2}K)	0.074

Table A-5 Pitched roof's fabric data

Name	**Larch House pitched roof**	
Source	DesignBuilder	
Category	Roofs	
Definition method	Layers	
Simulation solution algorithm	Default*	
U-Value	**0.33**	
		Thickness (mm)
Number of layers	3	175
Outermost layer (Layer 1)	Redland Cambrian reconstituted slate tiles	10
Layer 2	Timber batten Veltitech Underlay	25
Innermost layer (Layer 3)	Timber Truss	140

*Refer to DesignBuilder user manual **(2015)**

Table A-6 Calculated constructions data for pitched roof

Calculated constructions data _ pitched roof	
Inner surface	
Convective heat transfer coefficient (Wm^{-2}K)	4.460
Radiative heat transfer coefficient (Wm^{-2}K)	5.540
Surface resistance (m^{2}KM^{-1})	0.100
Outer surface	
Convective heat transfer coefficient (Wm^{-2}K)	19.870
Radiative heat transfer coefficient (Wm^{-2}K)	5.130
Surface resistance (m^{2}KM^{-1})	0.040
No bridging	
U-value surface to surface (Wm^{-2}K)	0.346
R-value (m^{2}KW^{-1})	3.028
U-value (Wm^{-2}K)	0.33
With bridging (BS ENISO 6946)	
Thickness (m)	0.400
Km internal heat capacity (KJm^{-2}K)	41.436
Upper resistance limit (m^{2}KW^{-1})	3.028
Lower resistance limit (m^{2}KW^{-1})	3.028
U-value surface to surface (Wm^{-2}K)	0.346
R-value (m^{2}KW^{-1})	3.028
U-value (Wm^{-2}K)	0.33

Table A-7 Internal ceiling's fabric data

Name	**Larch House internal ceiling (above ground floor)**	
Source	DesignBuilder	
Category	Slabs	
Definition method	Layers	
Simulation solution algorithm	Default*	
U-Value	**0.176**	
		Thickness (mm)
Number of layers	4	256
Built-up from above (Layer 1)	Floor finish (first floor)	15
Layer 2	Chipboard	22
Layer 3	Ecojoist with loose fill insulation in between joists	219

Name	**Larch House internal ceiling (above ground floor)**	
Innermost layer (Layer 4)	Plasterboard and skin (ground floor ceiling)	15

*Refer to DesignBuilder user manual **(2015)**

Table A-8 Calculated constructions data for slab

Calculated constructions data _ internal ceiling/floor	
Inner surface	
Convective heat transfer coefficient (Wm^{-2}K)	4.460
Radiative heat transfer coefficient (Wm^{-2}K)	5.540
Surface resistance (m^{2}KM^{-1})	0.100
Outer surface	
Convective heat transfer coefficient (Wm^{-2}K)	0.342
Radiative heat transfer coefficient (Wm^{-2}K)	5.450
Surface resistance (m^{2}KM^{-1})	0.170
No bridging	
U-value surface to surface (Wm^{-2}K)	0.184
R-value (m^{2}KW^{-1})	5.561
U-value (Wm^{-2}K)	0.176
With bridging (BS ENISO 6946)	
Thickness (m)	0.256
Km internal heat capacity (KJm^{-2}K)	21.128
Upper resistance limit (m^{2}KW^{-1})	5.691
Lower resistance limit (m^{2}KW^{-1})	5.691
U-value surface to surface (Wm^{-2}K)	0.184
R-value (m^{2}KW^{-1})	5.691
U-value (Wm^{-2}K)	0.176

Table A-9 Calculated glazing data

Calculated glazing data _ Larch House triple glazing (equivalent to Passivhaus certified windows)	
Total solar transmission (SHGC)	0.474
Direct solar transmission	0.358
Light transmission	0.661
U-value (ISO 10292/EN 673) (Wm^{-2}K)	0.776
U-value (ISO 15099/NFRC) (Wm^{-2}K)	**0.780**

Appendix B: Operation schedule script for using window shading device

a) Living room

```
Compact Schedule
Larch House_Blind
Fraction,
Through: 20 Jan,
For: Weekdays SummerDesignDay WinterDesignDay,
Until: 06:30, 1,
Until: 09:00, 0,
Until: 17:00, 0,
Until: 19:00, 0.5,
Until: 24:00, 1,
For: Weekends,
Until: 08:00, 1,
Until: 09:00, 0,
Until: 17:00, 0,
Until: 24:00, 1,
For: Holidays AllOtherDays,
Until: 24:00, 1,
Through: 15 Feb,
For: Weekdays SummerDesignDay WinterDesignDay,
Until: 06:30, 1,
Until: 09:00, 0,
Until: 12:00, 0.25,
Until: 17:00, 0,
Until: 19:00, 0.5,
Until: 24:00, 1,
For: Weekends,
Until: 08:00, 1,
Until: 09:00, 0,
Until: 12:00, 0.25,
Until: 19:00, 0,
Until: 24:00, 1,
For: Holidays AllOtherDays,
Until: 24:00, 1,
Through: 28 Feb,
For: Weekdays SummerDesignDay WinterDesignDay,
Until: 06:30, 1,
Until: 09:00, 0,
Until: 12:00, 0.5,
Until: 17:00, 0,
Until: 19:00, 0.5,
Until: 24:00, 1,
For: Weekends,
```

```
Until: 08:00, 1,
Until: 12:00, 0.5,
Until: 14:00, 0,
Until: 19:00, 0.5,
Until: 24:00, 1,
For: Holidays AllOtherDays,
Until: 24:00, 1,
Through: 31 Mar,
For: Weekdays SummerDesignDay WinterDesignDay,
Until: 06:30, 1,
Until: 09:00, 0,
Until: 17:00, 0.25,
Until: 19:00, 0.5,
Until: 24:00, 1,
For: Weekends,
Until: 08:00, 1,
Until: 10:00, 0,
Until: 17:00, 0.25,
Until: 19:00, 0.5,
Until: 24:00, 1,
For: Holidays AllOtherDays,
Until: 24:00, 1,
Through: 31 May,
For: Weekdays SummerDesignDay WinterDesignDay,
Until: 06:30, 1,
Until: 09:00, 0,
Until: 18:00, 0.5,
Until: 20:00, 0,
Until: 24:00, 1,
For: Weekends,
Until: 08:00, 1,
Until: 09:00, 0.25,
Until: 16:00, 0,
Until: 19:00, 0.5,
Until: 24:00, 1,
For: Holidays AllOtherDays,
Until: 24:00, 1,
Through: 25 Aug,
For: Weekdays SummerDesignDay WinterDesignDay,
Until: 06:30, 1,
Until: 09:00, 0.5,
Until: 10:00, 0,
Until: 18:00, 0.75,
Until: 21:00, 0,
Until: 24:00, 1,
For: Weekends,
Until: 08:00, 1,
```

```
Until: 12:00, 0,
Until: 18:00, 0.75,
Until: 21:00, 0,
Until: 24:00, 1,
For: Holidays AllOtherDays,
Until: 24:00, 1,
Through: 31 Oct,
For: Weekdays SummerDesignDay WinterDesignDay,
Until: 06:30, 1,
Until: 09:00, 0.25,
Until: 17:00, 0.5,
Until: 20:00, 0,
Until: 24:00, 1,
For: Weekends,
Until: 08:00, 1,
Until: 11:00, 0,
Until: 19:00, 0.5,
Until: 24:00, 1,
For: Holidays AllOtherDays,
Until: 24:00, 1,
Through: 31 Dec,
For: Weekdays SummerDesignDay WinterDesignDay,
Until: 06:30, 1,
Until: 09:00, 0,
Until: 12:00, 0.5,
Until: 17:00, 0,
Until: 19:00, 0.5,
Until: 24:00, 1,
For: Weekends,
Until: 08:00, 1,
Until: 09:00, 0,
Until: 12:00, 0.5,
Until: 17:00, 0,
Until: 19:00, 0.5,
Until: 24:00, 1,
For: Holidays AllOtherDays,
Until: 24:00, 1;
```

b) Bedroom

```
Schedule:Compact,
Larch House_Blind_Opr,
Fraction,
Through: 20 Jan,
For: Weekdays SummerDesignDay WinterDesignDay,
Until: 06:30, 1,
Until: 09:00, 0.25,
Until: 17:00, 0,
```

```
Until: 19:00, 0.5,
Until: 24:00, 1,
For: Weekends,
Until: 08:00, 1,
Until: 09:00, 0,
Until: 12:00, 0,
Until: 15:00, 0.5,
Until: 17:00, 0,
Until: 24:00, 1,
For: Holidays AllOtherDays,
Until: 24:00, 1,
Through: 15 Feb,
For: Weekdays SummerDesignDay WinterDesignDay,
Until: 06:30, 1,
Until: 09:00, 0,
Until: 12:00, 0,
Until: 17:00, 0.5,
Until: 19:00, 0.25,
Until: 24:00, 1,
For: Weekends,
Until: 08:00, 1,
Until: 09:00, 0,
Until: 12:00, 0.5,
Until: 17:00, 0,
Until: 19:00, 0.25,
Until: 24:00, 1,
For: Holidays AllOtherDays,
Until: 24:00, 1,
Through: 28 Feb,
For: Weekdays SummerDesignDay WinterDesignDay,
Until: 06:30, 1,
Until: 09:00, 0.25,
Until: 12:00, 0.5,
Until: 17:00, 0,
Until: 19:00, 0.5,
Until: 24:00, 1,
For: Weekends,
Until: 08:00, 1,
Until: 12:00, 0.5,
Until: 14:00, 0,
Until: 19:00, 0.5,
Until: 24:00, 1,
For: Holidays AllOtherDays,
Until: 24:00, 1,
Through: 31 Mar,
For: Weekdays SummerDesignDay WinterDesignDay,
Until: 06:30, 1,
```

```
Until: 09:00, 0,
Until: 17:00, 0.25,
Until: 19:00, 0.5,
Until: 24:00, 1,
For: Weekends,
Until: 08:00, 1,
Until: 09:00, 0.5,
Until: 14:00, 0,
Until: 17:00, 0.25,
Until: 19:00, 0.5,
Until: 24:00, 1,
For: Holidays AllOtherDays,
Until: 24:00, 1,
Through: 31 May,
For: Weekdays SummerDesignDay WinterDesignDay,
Until: 06:30, 1,
Until: 12:00, 0,
Until: 17:00, 0.5,
Until: 20:00, 0,
Until: 24:00, 1,
For: Weekends,
Until: 08:00, 1,
Until: 09:00, 0.25,
Until: 15:00, 0,
Until: 17:00, 0.5,
Until: 19:00, 0,
Until: 24:00, 1,
For: Holidays AllOtherDays,
Until: 24:00, 1,
Through: 25 Aug,
For: Weekdays SummerDesignDay WinterDesignDay,
Until: 06:30, 1,
Until: 09:00, 0,
Until: 15:00, 0,
Until: 17:00, 0.5,
Until: 21:00, 0,
Until: 24:00, 1,
For: Weekends,
Until: 08:00, 1,
Until: 15:00, 0,
Until: 17:00, 0.5,
Until: 21:00, 0,
Until: 24:00, 1,
For: Holidays AllOtherDays,
Until: 24:00, 1,
Through: 31 Oct,
For: Weekdays SummerDesignDay WinterDesignDay,
```

```
Until: 06:30, 1,
Until: 09:00, 0,
Until: 17:00, 0.25,
Until: 20:00, 0,
Until: 24:00, 1,
For: Weekends,
Until: 08:00, 1,
Until: 14:00, 0,
Until: 19:00, 0.5,
Until: 24:00, 1,
For: Holidays AllOtherDays,
Until: 24:00, 1,
Through: 31 Dec,
For: Weekdays SummerDesignDay WinterDesignDay,
Until: 06:30, 1,
Until: 09:00, 0.25,
Until: 12:00, 0.5,
Until: 17:00, 0,
Until: 19:00, 0.5,
Until: 24:00, 1,
For: Weekends,
Until: 08:00, 1,
Until: 09:00, 0.5,
Until: 12:00, 0.5,
Until: 17:00, 0,
Until: 19:00, 0.5,
Until: 24:00, 1,
For: Holidays AllOtherDays,
```

Appendix C: London current and future weather data

Table C-1 London current weather data

Current	Outside Dry-Bulb Temperature (°C)	Outside Dew-Point Temperature (°C)	Direct Normal Solar (kWh)	Diffuse Horizontal Solar (kWh)	Wind Speed (m/s)	Wind Direction (°)	Atmospheric Pressure (pa)	Solar Altitude (°)	Solar Azimuth (°)
Jan	5.10	2.49	32.23	18.92	5.11	197.15	101115.10	-18.22	178.88
Feb	5.14	2.62	49.86	32.63	4.74	196.75	101908.80	-11.40	177.72
Mar	6.72	3.33	81.75	55.54	5.05	201.76	101606.60	-1.77	178.96
Apr	9.66	6.11	115.70	80.93	4.87	207.20	101053.20	8.43	181.07
May	12.64	8.50	157.12	107.96	4.51	196.13	100776.40	16.40	182.00
Jun	15.33	11.43	169.13	121.36	3.96	227.35	102054.20	20.14	181.10
Jul	17.61	14.26	162.26	112.65	4.03	211.63	101630.00	18.59	179.79
Aug	17.42	13.55	139.35	97.48	4.13	210.17	101616.80	12.15	180.14
Sep	15.10	11.90	113.11	66.23	4.08	211.82	101325.70	2.72	182.31
Oct	11.96	9.40	78.41	45.04	4.25	211.94	101337.60	-7.51	184.53
Nov	7.75	4.79	49.49	24.75	4.89	199.34	101556.50	-15.97	184.76
Dec	5.48	3.49	36.90	15.62	4.93	208.80	100952.00	-20.11	182.30

Table C-2 London 2030's weather data

2030	Outside Dry-Bulb Temperature (°C)	Outside Dew-Point Temperature (°C)	Direct Normal Solar (kWh)	Diffuse Horizontal Solar (kWh)	Wind Speed (m/s)	Wind Direction (°)	Atmospheric Pressure (pa)	Solar Altitude (°)	Solar Azimuth (°)
Jan	6.00	3.11	35.87	19.84	4.89	177.85	101102.40	-18.22	178.88
Feb	7.04	4.50	49.43	32.75	4.32	193.60	101616.40	-11.40	177.72
Mar	8.49	5.03	85.46	52.79	5.29	199.42	101836.70	-1.77	178.96
Apr	10.54	6.90	141.26	88.28	4.74	194.79	101477.10	8.43	181.07
May	14.05	8.84	194.50	106.44	4.27	204.63	101068.90	16.40	182.00
Jun	17.73	12.26	170.45	123.57	4.01	197.43	101821.50	20.14	181.10
Jul	19.79	15.06	179.90	114.69	3.97	202.31	101488.60	18.59	179.79
Aug	19.65	15.24	168.91	93.48	4.20	224.68	101598.90	12.15	180.14
Sep	17.20	14.40	130.45	69.61	4.32	195.20	100955.20	2.72	182.31
Oct	14.01	11.33	94.73	41.87	4.25	202.47	100908.50	-7.51	184.53
Nov	10.33	8.31	43.20	25.21	4.75	221.49	101025.30	-15.97	184.76
Dec	7.19	4.58	45.38	17.50	4.88	194.88	101566.90	-20.11	182.30

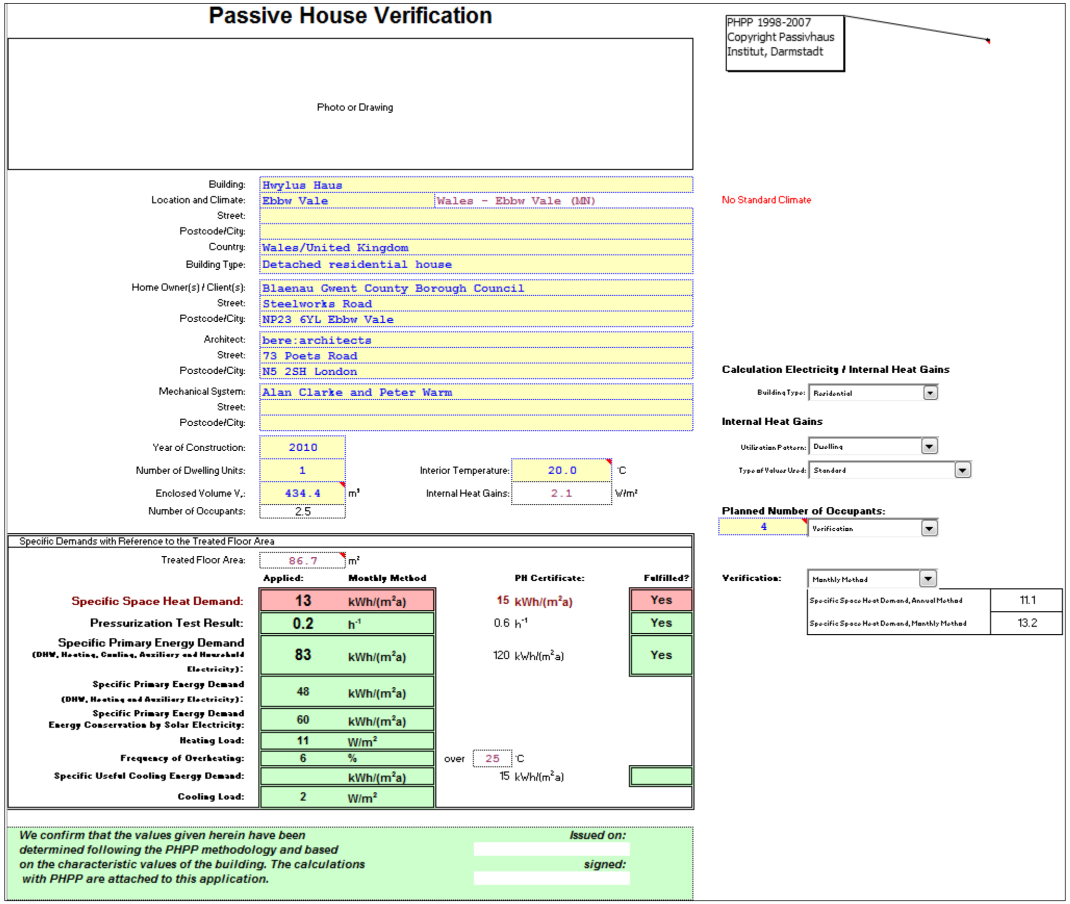
Table C-3 London 2050's weather data

2050	Outside Dry-Bulb Temperature (°C)	Outside Dew-Point Temperature (°C)	Direct Normal Solar (kWh)	Diffuse Horizontal Solar (kWh)	Wind Speed (m/s)	Wind Direction (°)	Atmospheric Pressure (pa)	Solar Altitude (°)	Solar Azimuth (°)
Jan	6.81	4.38	27.42	18.16	5.13	209.00	100850.50	-18.22	178.88
Feb	7.85	4.63	51.59	32.15	5.07	192.79	101561.90	-11.40	177.72
Mar	9.16	5.86	72.29	56.92	5.68	185.91	101296.30	-1.77	178.96
Apr	11.39	7.54	112.15	84.31	4.72	206.01	101915.90	8.43	181.07
May	14.88	10.84	187.22	111.11	4.22	188.94	101875.80	16.40	182.00
Jun	18.91	14.78	198.23	126.99	4.30	224.64	101612.70	20.14	181.10
Jul	20.89	16.37	155.06	117.93	4.20	217.07	101463.00	18.59	179.79
Aug	20.71	16.01	167.40	96.41	4.32	198.06	101441.80	12.15	180.14
Sep	18.17	15.06	142.64	69.72	3.82	207.25	101234.90	2.72	182.31
Oct	14.60	11.63	83.61	43.71	4.46	213.60	101096.50	-7.51	184.53
Nov	10.98	8.82	45.03	25.03	4.62	209.25	101161.70	-15.97	184.76
Dec	7.94	5.84	37.69	16.23	5.11	191.02	101931.40	-20.11	182.30

Table C-4 London 2080's weather data

2080	Outside Dry-Bulb Temperature (°C)	Outside Dew-Point Temperature (°C)	Direct Normal Solar (kWh)	Diffuse Horizontal Solar (kWh)	Wind Speed (m/s)	Wind Direction (°)	Atmospheric Pressure (pa)	Solar Altitude (°)	Solar Azimuth (°)
Jan	7.93	5.44	37.10	18.05	4.93	191.48	100862.40	-18.22	178.88
Feb	9.04	6.17	43.88	33.95	4.83	206.16	102062.00	-11.40	177.72
Mar	10.38	6.63	98.28	55.81	4.84	190.55	101700.50	-1.77	178.96
Apr	12.81	7.74	112.29	86.67	4.73	206.19	100606.90	8.43	181.07
May	16.57	12.96	217.33	104.04	4.00	198.43	102029.00	16.40	182.00
Jun	20.21	16.58	208.26	126.61	4.20	221.89	101690.40	20.14	181.10
Jul	23.17	16.59	182.28	116.08	3.88	204.28	101939.40	18.59	179.79
Aug	22.63	16.57	177.59	95.24	4.33	203.34	102010.10	12.15	180.14
Sep	19.98	15.07	169.90	70.37	4.05	189.22	101173.50	2.72	182.31
Oct	16.13	13.55	84.80	43.50	4.60	191.08	101051.40	-7.51	184.53
Nov	12.26	10.15	52.04	25.28	4.77	197.13	100941.30	-15.97	184.76
Dec	8.88	7.19	25.92	15.21	5.55	210.15	101372.40	-20.11	182.30

Appendix D: Example of spec sheets from the original PHPP file



Passive House Verification

PHPP 1998-2007
Copyright Passivhaus
Institut, Darmstadt

Photo or Drawing

Building: Hwylus Haus
Location and Climate: Ebbw Vale | Wales - Ebbw Vale (MN)
Street:
Postcode/City:
Country: Wales/United Kingdom
Building Type: Detached residential house

No Standard Climate

Home Owner(s) / Client(s): Blaenau Gwent County Borough Council
Street: Steelworks Road
Postcode/City: NP23 6YL Ebbw Vale

Architect: bere:architects
Street: 73 Poets Road
Postcode/City: N5 2SH London

Mechanical System: Alan Clarke and Peter Warm
Street:
Postcode/City:

Year of Construction: 2010
Number of Dwelling Units: 1
Enclosed Volume V_V: 434.4 m³
Number of Occupants: 2.5

Interior Temperature: 20.0 °C
Internal Heat Gains: 2.1 W/m²

Calculation Electricity / Internal Heat Gains

Building Type: Residential

Internal Heat Gains

Utilization Pattern: Dwelling
Type of Values Used: Standard

Planned Number of Occupants:
4 | Verification

Specific Demands with Reference to the Treated Floor Area

Treated Floor Area: 86.7 m²

	Applied:	Monthly Method	PH Certificate:	Fulfilled?
Specific Space Heat Demand:	13	kWh/(m²a)	15 kWh/(m²a)	Yes
Pressurization Test Result:	0.2	h⁻¹	0.6 h⁻¹	Yes
Specific Primary Energy Demand (DHW, Heating, Cooling, Auxiliary and Household Electricity):	83	kWh/(m²a)	120 kWh/(m²a)	Yes
Specific Primary Energy Demand (DHW, Heating and Auxiliary Electricity):	48	kWh/(m²a)		
Specific Primary Energy Demand Energy Conservation by Solar Electricity:	60	kWh/(m²a)		
Heating Load:	11	W/m²		
Frequency of Overheating:	6	%	over 25 °C	
Specific Useful Cooling Energy Demand:		kWh/(m²a)	15 kWh/(m²a)	
Cooling Load:	2	W/m²		

Verification: Monthly Method

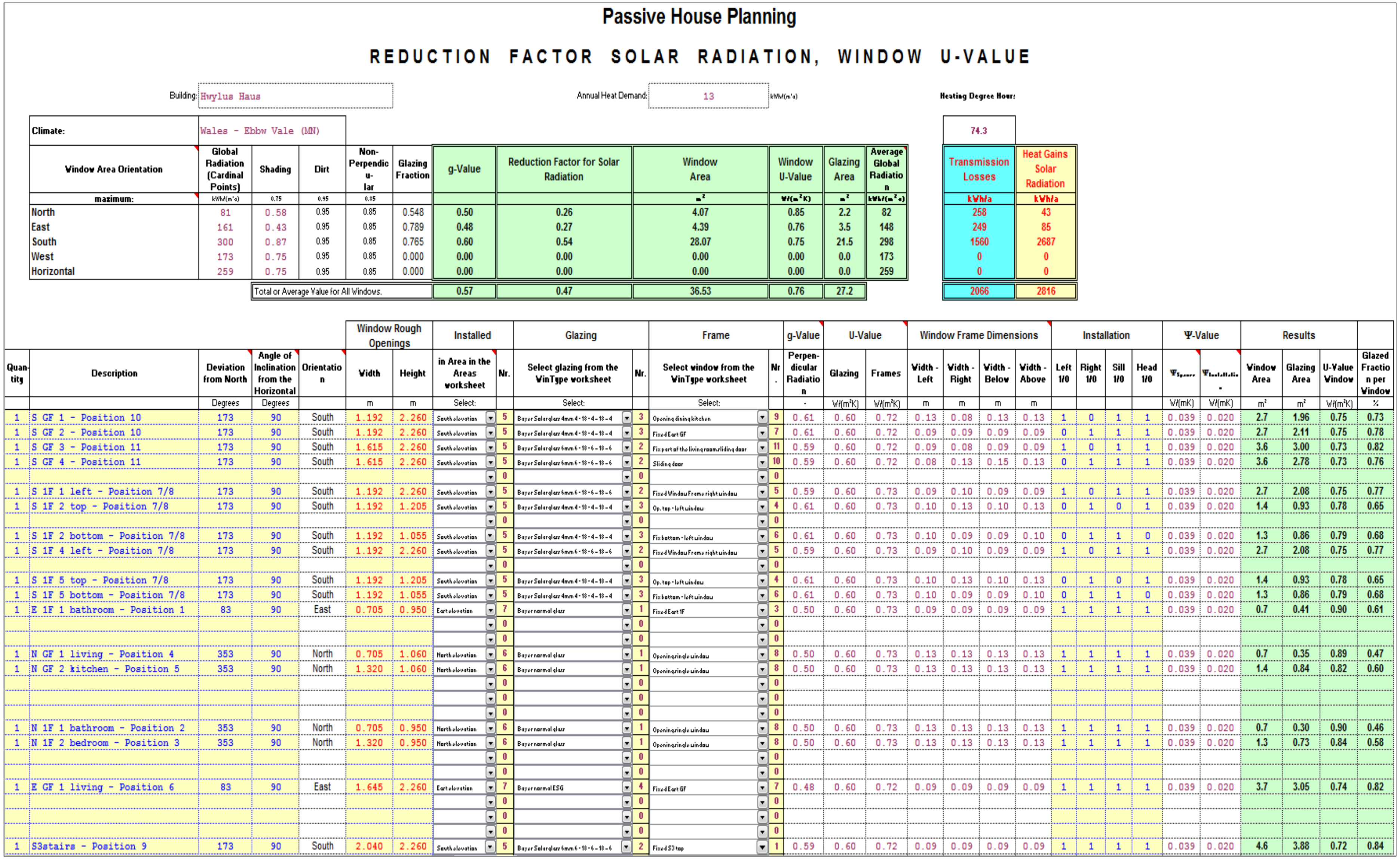
Specific Space Heat Demand, Annual Method	11.1
Specific Space Heat Demand, Monthly Method	13.2

We confirm that the values given herein have been determined following the PHPP methodology and based on the characteristic values of the building. The calculations with PHPP are attached to this application.

Issued on:

signed:

Figure D-1 Original PHPP "verification" page for the Larch House case study



Passive House Planning

REDUCTION FACTOR SOLAR RADIATION, WINDOW U-VALUE

Building: Hwylus Haus

Annual Heat Demand: 13 kWh/(m²a)

Heating Degree Hours: 74.3

Climate: Wales - Ebbw Vale (MN)

Window Area Orientation	Global Radiation (Cardinal Points)	Shading	Dirt	Non-Perpendicular	Glazing Fraction	g-Value	Reduction Factor for Solar Radiation	Window Area	Window U-Value	Glazing Area	Average Global Radiation	Transmission Losses	Heat Gains Solar Radiation
maximum:	kWh/(m²a)	0.75	0.95	0.85				m²	W/(m²K)	m²	kWh/(m²a)	kWh/a	kWh/a
North	81	0.58	0.95	0.85	0.548	0.50	0.26	4.07	0.85	2.2	82	258	43
East	161	0.43	0.95	0.85	0.789	0.48	0.27	4.39	0.76	3.5	148	249	85
South	300	0.87	0.95	0.85	0.765	0.60	0.54	28.07	0.75	21.5	298	1560	2687
West	173	0.75	0.95	0.85	0.000	0.00	0.00	0.00	0.00	0.0	173	0	0
Horizontal	259	0.75	0.95	0.85	0.000	0.00	0.00	0.00	0.00	0.0	259	0	0
	Total or Average Value for All Windows.					0.57	0.47	36.53	0.76	27.2		2066	2816

					Window Rough Openings		Installed		Glazing		Frame		g-Value	U-Value		Window Frame Dimensions				Installation				Ψ-Value		Results			
Quantity	Description	Deviation from North	Angle of Inclination from the Horizontal	Orientation	Width	Height	in Area in the Areas worksheet	Nr.	Select glazing from the WinType worksheet	Nr.	Select window from the WinType worksheet	Nr.	Perpendicular Radiation	Glazing	Frames	Width - Left	Width - Right	Width - Below	Width - Above	Left 1/0	Right 1/0	Sill 1/0	Head 1/0	Ψ_{Spacer}	$\Psi_{Installation}$	Window Area	Glazing Area	U-Value Window	Glazed Fraction per Window
		Degrees	Degrees		m	m	Select:		Select:		Select:		-	W/(m²K)	W/(m²K)	m	m	m	m					W/(mK)	W/(mK)	m²	m²	W/(m²K)	%
1	S GF 1 - Position 10	173	90	South	1.192	2.260	South elevation	5	Bayer Solarglass 4mm 4-18-4-18-4	3	Opening dining kitchen	9	0.61	0.60	0.72	0.13	0.08	0.13	0.13	1	0	1	1	0.039	0.020	2.7	1.96	0.75	0.73
1	S GF 2 - Position 10	173	90	South	1.192	2.260	South elevation	5	Bayer Solarglass 4mm 4-18-4-18-4	3	Fixed East GF	7	0.61	0.60	0.72	0.09	0.09	0.09	0.09	0	1	1	1	0.039	0.020	2.7	2.11	0.75	0.78
1	S GF 3 - Position 11	173	90	South	1.615	2.260	South elevation	5	Bayer Solarglass 6mm 6-18-6-18-6	2	Fix part of the living room sliding door	11	0.59	0.60	0.72	0.09	0.08	0.09	0.09	1	0	1	1	0.039	0.020	3.6	3.00	0.73	0.82
1	S GF 4 - Position 11	173	90	South	1.615	2.260	South elevation	5	Bayer Solarglass 6mm 6-18-6-18-6	2	Sliding door	10	0.59	0.60	0.72	0.08	0.13	0.15	0.13	0	1	1	1	0.039	0.020	3.6	2.78	0.73	0.76
								0		0		0																	
1	S 1F 1 left - Position 7/8	173	90	South	1.192	2.260	South elevation	5	Bayer Solarglass 6mm 6-18-6-18-6	2	Fixed Window Frame right window	5	0.59	0.60	0.73	0.09	0.10	0.09	0.09	1	0	1	1	0.039	0.020	2.7	2.08	0.75	0.77
1	S 1F 2 top - Position 7/8	173	90	South	1.192	1.205	South elevation	5	Bayer Solarglass 4mm 4-18-4-18-4	3	Op. top - left window	4	0.61	0.60	0.73	0.10	0.13	0.10	0.13	0	1	0	1	0.039	0.020	1.4	0.93	0.78	0.65
								0		0		0																	
1	S 1F 2 bottom - Position 7/8	173	90	South	1.192	1.055	South elevation	5	Bayer Solarglass 4mm 4-18-4-18-4	3	Fix bottom - left window	6	0.61	0.60	0.73	0.10	0.09	0.09	0.10	0	1	1	0	0.039	0.020	1.3	0.86	0.79	0.68
1	S 1F 4 left - Position 7/8	173	90	South	1.192	2.260	South elevation	5	Bayer Solarglass 6mm 6-18-6-18-6	2	Fixed Window Frame right window	5	0.59	0.60	0.73	0.09	0.10	0.09	0.09	1	0	1	1	0.039	0.020	2.7	2.08	0.75	0.77
								0		0		0																	
1	S 1F 5 top - Position 7/8	173	90	South	1.192	1.205	South elevation	5	Bayer Solarglass 4mm 4-18-4-18-4	3	Op. top - left window	4	0.61	0.60	0.73	0.10	0.13	0.10	0.13	0	1	0	1	0.039	0.020	1.4	0.93	0.78	0.65
1	S 1F 5 bottom - Position 7/8	173	90	South	1.192	1.055	South elevation	5	Bayer Solarglass 4mm 4-18-4-18-4	3	Fix bottom - left window	6	0.61	0.60	0.73	0.10	0.09	0.09	0.10	0	1	1	0	0.039	0.020	1.3	0.86	0.79	0.68
1	E 1F 1 bathroom - Position 1	83	90	East	0.705	0.950	East elevation	7	Bayer normal glass	1	Fixed East 1F	3	0.50	0.60	0.73	0.09	0.09	0.09	0.09	1	1	1	1	0.039	0.020	0.7	0.41	0.90	0.61
								0		0		0																	
								0		0		0																	
1	N GF 1 living - Position 4	353	90	North	0.705	1.060	North elevation	6	Bayer normal glass	1	Opening single window	8	0.50	0.60	0.73	0.13	0.13	0.13	0.13	1	1	1	1	0.039	0.020	0.7	0.35	0.89	0.47
1	N GF 2 kitchen - Position 5	353	90	North	1.320	1.060	North elevation	6	Bayer normal glass	1	Opening single window	8	0.50	0.60	0.73	0.13	0.13	0.13	0.13	1	1	1	1	0.039	0.020	1.4	0.84	0.82	0.60
								0		0		0																	
								0		0		0																	
								0		0		0																	
1	N 1F 1 bathroom - Position 2	353	90	North	0.705	0.950	North elevation	6	Bayer normal glass	1	Opening single window	8	0.50	0.60	0.73	0.13	0.13	0.13	0.13	1	1	1	1	0.039	0.020	0.7	0.30	0.90	0.46
1	N 1F 2 bedroom - Position 3	353	90	North	1.320	0.950	North elevation	6	Bayer normal glass	1	Opening single window	8	0.50	0.60	0.73	0.13	0.13	0.13	0.13	1	1	1	1	0.039	0.020	1.3	0.73	0.84	0.58
								0		0		0																	
								0		0		0																	
1	E GF 1 living - Position 6	83	90	East	1.645	2.260	East elevation	7	Bayer normal ESG	4	Fixed East GF	7	0.48	0.60	0.72	0.09	0.09	0.09	0.09	1	1	1	1	0.039	0.020	3.7	3.05	0.74	0.82
								0		0		0																	
								0		0		0																	
								0		0		0																	
1	S3stairs - Position 9	173	90	South	2.040	2.260	South elevation	5	Bayer Solarglass 6mm 6-18-6-18-6	2	Fixed S3 top	1	0.59	0.60	0.72	0.09	0.09	0.09	0.09	1	1	1	1	0.039	0.020	4.6	3.88	0.72	0.84

Figure D-2 Original PHPP “windows” page for the Larch House case study

Appendix E: Publications from this study

The following papers have been published according to the results of this study:

Lavafpour, Y. & Sharples, S. (2016), The Potential of Inclined Walls to Reduce Overheating Risk: A Passivhaus Case Study for UK Current and Future Climates; PLEA 2016 Los Angeles, USA; PLEA 32 (2) 1269-1274. (Full text available)

Lavafpour, Y. & Sharples, S. (2015). Summer thermal comfort and self-shading geometries in Passivhaus dwellings: A pilot study using future UK climates. Buildings, 5(3), 964-984. (Full text available)

Lavafpour, Y. & Sharples, S. (2015). Using Tilted Facade to Reduce Thermal Discomfort in a UK Passivhaus Dwelling for a Warming Climate, Energy Procedia 78 (2015) 2232 – 2237.(Full text available at http://www.sciencedirect.com/science/article/pii/S1876610215020731)

Lavafpour, Y. & Sharples, S. (2014), Impact of the Envelope Geometry on Cooling Demand in Very Airtight UK Dwellings under Current and Future Weather Projections, Elsevier Energy Procedia 62, 421-430 . (Full text available at http://www.sciencedirect.com/science/article/pii/S1876610214034353)

Buildings **2015**, *5*, 964-984; doi:10.3390/buildings5030964

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Article

Summer Thermal Comfort and Self-Shading Geometries in Passivhaus Dwellings: A Pilot Study Using Future UK Climates

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Abstract: This study uses numerical thermal simulation to investigate the potential use of building geometry to eliminate or reduce current and future thermal discomfort overheating risk in UK Passivhaus dwellings. The study focused on the optimum inclination of a south façade to make use of the building shape to self-protect itself. Dynamic simulation modelling software was used to test a range of different inclined façades with regards to their effectiveness in reducing overheating risk. The research found that implementing a tilted façade could completely eliminate the risk of overheating for current UK climates, but with some consequences for natural ventilation and daylighting. Future overheating was significantly reduced by the tilted façade. However, geometric considerations could not eradicate completely the risk of thermal discomfort overheating, particularly by the 2080s.

Keywords: geometry; passivhaus; overheating; climate change

1. Introduction

It has become increasingly evident that buildings contribute significantly to the serious environmental problems of the planet, especially in terms of the fossil fuel energy used to service the built environment. Consequently, in recent decades greater attention has been paid to reducing energy consumption in buildings. EU countries have adapted their building regulations to produce new buildings with nearly-zero energy consumption by 2020. One example of the low energy standards was introduced in Germany by Passivhaus Institute. In the UK a zero carbon new buildings target was announced by the UK government in December 2006 and a national target was set to reduce 80% of CO_2 emission below 1990 level by 2050 [1]. A number of energy efficient strategies have been employed in the UK housing sector to reduce energy consumption for heating demand, including the growing implementation of the Passivhaus standard. For the last few decades thermal insulation has been the most dominant and frequently used intervention for a range of building types in the UK. Much of the focus on the new build and refurbishment in the UK has concentrated on thermal comfort during the winter and on the reduction of space heating demand. However, as suggested by UK Climate Projections from the Meteorological Office [2] the increase in extreme weather events, such as heat waves, calls for the study of overheating risks in the summer period as well.

Although the majority of energy efficient standards have been successful in terms of reducing heating demand, several low-energy buildings have experienced problems with overheating, especially in summer time. Most of the interventions on reducing overheating have focused on users living in these buildings adapting to a specific behaviour to obtain thermal comfort, such as efficient operation of shading blinds or the use of a mechanical ventilation with heat recovery (MVHR) system to enhance ventilation. However, some other interventions have focused on the design of the building envelope to obtain thermal comfort in warm spells of a year. One of the stimuli for the current research was the possibility of using the building's geometry to be able to passively and consistently obtain thermal comfort via robustness of the building design. The research argues that self-shading geometric design of the building envelope can possibly recover some of the gap in the overall building performance that is created by occupants using overheating controls either incorrectly or not at all.

1.1. The Passivhaus Standard and Literature Review

The main concern of the Passivhaus Standard is to substantially reduce the requirements for space heating by introducing a "*fabric first*" approach to the design criteria, *i.e.*, applying high levels of insulation and airtightness to the thermal envelope. To obtain Passivhaus certification a building needs to meet a few main criteria [3]:

- Maximum specific space heat demand no more than 15 kWh/m^2 of floor area;
- Overall energy demand (including space heating and cooling) no more than 120 kWh/m^2;
- Airtightness no more than 0.6 h^{-1} at 50 Pa;
- For thermal comfort air temperatures in the living areas must not exceed 25 °C for more than 10% of the hours in a given year.

There is also a maximum cooling demand for climates where active cooling is needed. However, this is for climates where the external air temperature does not drop low enough to create a benefit from night time purge ventilation cooling. Therefore, for residual buildings the Passivhaus standard allows an annual cooling energy of 15 kWh/m^2 to be used [4].

For Passivhaus, the *U*-values of the building's solid envelope and glazing should be no more than 0.15 and 0.80 W/m^{2}K, respectively. Passivhaus dwellings benefits from large areas of south-facing glazing to capture passive solar gain. The Passivhaus Primer [5] states "*In order to benefit from the useful solar gains a Passivhaus requires the glazing to be optimised on the south façade with reduced glazing on the (other) façade(s)*". Solar gains make up a significant component of the free heat gains available to a Passivhaus during the heating season and large windows themselves become radiators for the room to offset some of the energy required for heating [6]. In addition, large windows provide good daylight levels and pleasant views for occupants. However, large areas of south-facing glazing, coupled with very high levels of thermal insulation and air tightness and the potentially elevated summer temperatures of future UK climates, means that the risk of summer overheating needs to be taken into consideration for future developments of Passivhaus dwellings.

Passivhaus designs should employ "*professional planning*", such as relevant orientation, shading and ventilation, to overcome a summer overheating risk [4]. There are a number of design approaches to mitigating the risk of overheating in dwellings, such as shading devices, reflective surfaces and thermal mass, that have received a good deal of research attention. For instance, Orme, Palmer and Irving [7] concluded that night time purging was the most effective single intervention to reduce overheating. Tillson *et al.* [8] showed that using a combination of window shutters or overhangs and ventilation can greatly reduce overheating. Mavrogianni *et al.* [9] investigated the effectiveness of thermal mass and insulation in reducing overheating. Piccolo and Simone [10] used reflective electrochromic glazing to minimize the solar heat gain and Robinson and Haldi [11,12] and Bennet *et al.* [13] focused on behavioural interventions to reduce overheating.

The present study has investigated the less examined arrangement by which dwellings have geometric forms that make the south-facing façades self-shading. This paper examines the potential benefits of using different self-shading façade geometries to reduce thermal discomfort in Passivhaus standard dwellings for current and future UK climate scenarios.

1.2. Future Climate, UK Passivhaus Dwellings and Overheating Risk

The probable impact of climate change over the coming decades demands two main responses: (i) mitigation of carbon emissions; and (ii) adaptation of buildings to be comfortable in the future climate [14] Adapting to the negative impact of climate change is becoming as important as mitigating the climate change itself [15]. The Intergovernmental Panel on Climate Change (IPCC) [16] stated that, even in the most optimistic projection, the Earth will experience at least 1.8 °C global average surface warming by the end of the 21st century. A warmer summer time is estimated to effect energy use patterns and comfort conditions in UK dwellings.

It has been argued that highly insulated and very airtight homes are more prone to overheating than older traditional housing [17–19]. Probabilistic climate change data from UK Climate Change Projections (UKCP09) [20] suggest that the UK will experience hotter and more extreme summers in the coming decades and the risk of buildings overheating may become very significant in future climate scenarios.

1.3. Definition of Thermal Discomfort (Overheating)

The definition of the term overheating is defined differently by different groups and it remains an area of uncertainty. The Housing Health and Safety Rating System from the Housing Act 2004 [21] stated "*a healthy indoor temperature is around 21 °C. As temperatures rise, thermal stress increases, initially triggering the body's defence mechanisms such as sweating. High temperatures can increase cardiovascular strain and trauma, and where 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*".

As stated in Section 1.1, for the UK climate a Passivhaus is permitted to use 15 kWh/m^2 year to provide space heating to obtain thermal comfort. However, with the potential growth in summer temperature in places like London active cooling may become inevitable to maintain the temperature around 25 °C. Bearing in mind that space heating may decrease because of less severe winters, future criteria may suggest that the limit of 15 kWh/m^2 applies for space conditioning including both heating and cooling demand to keep future Passivhaus within the 20–25 °C optimal temperature for a whole year. CIBSE Guide A [22] defines summer comfort air temperatures for living rooms and bedrooms in UK dwellings as being when indoor temperature are around 23 °C to 25 °C. The Guide noted that the quality of sleep begins to deteriorate if indoor bedroom air temperatures much exceed 24 °C. To avoid the risk of overheating CIBSE Guide A states that temperature should not exceed 25 °C for more than 10% of total occupied hours for living spaces. Inside temperature also should not exceed 26 °C for bedrooms and 28 °C for living rooms for more than 1% of total occupied hours. However, one shortcoming of these so called static criteria is that there is no specific limitation for the severity of overheating-for instance, 1 h at 28.1 °C and 1 h at 32 °C is considered as 1 h above 28 °C with the same level of overheating discomfort. Another concern over static criteria is that they do not include individual adaptation to changing temperatures. Adaptive thermal comfort was developed based on the hypothesis that people in different climate zones prefer different indoor temperatures [23]. The performance of a Passivhaus design is assessed using the Passive House Planning Package (PHPP), which is a set of over 30 linked Excel spreadsheets. In the PHPP spreadsheets overheating hours are calculated for the occupied period when in the living areas temperatures exceed 25 °C. The kitchen is excluded because of the probability of miscalculation of overheating when catering equipment is being operating during occupied periods. Passivhaus tries to keep inside temperatures within the interval of 20 to 25 °C during whole cycle of the year. There is a limit of 10% occupied hours having temperatures above 25 °C. For some other criteria a temperature excess of over 25 °C for up to 5% of the year is allowed [24].

In reality individuals will adapt to changing climate, therefore, adaptive methods may be more applicable for assessing future indoor thermal comfort. However, static criteria are used mainly for assessing model prediction and whole years of data [9]. Static criteria are also useful to focus and measure one specific parameter or a single design intervention and its impact on indoor thermal behaviour and to give a general prediction on the future possibilities. Whereas adaptive methods take into account all the individual measures assigned to different persons' comfort perception, static criteria are useful for ranking the occurrence of elevated room temperatures but it cannot clearly indicate whether the measured temperature is acceptable or not. People may adapt to the higher temperature (acclimatization) or people may expect higher levels of comfort and a cooler summer temperature as a result of increasing disposable income and higher life quality expectations. For this study the CIBSE Guide A static criteria were used for assessing thermal comfort for alternative climate scenarios. The occupant window opening patterns and the amount of natural ventilation was kept constant for current and future climate conditions in order to make a valid comparison between the façade alternatives. However, it is well understood that occupants will change their behaviour as outside temperatures change and adaptive criteria needs to be analysed for assessing overheating risk for future warming climates. However, using constant, *i.e.*, static criteria helped to make a fair comparison to study the impact of a single design factor, *i.e.*, façade geometry.

1.4. Aims and Objectives

This study set out to investigate the effectiveness of building geometry as an environmental design criterion. The first objective was to evaluate the impact of future weather data on the Passivhaus structures in order to estimate future overheating risk and rate. The second objective was to introduce self-shading façades as one the adaptation strategies for reducing overheating in homes.

2. Methodology

The main method used for this study was computer simulation modelling as a substitute for direct measurement and experimentation. Software reliability and the accuracy of the model were tested against an available real data series. An existing Passivhaus dwelling with available thermal analysis and monitoring data was considered as a reference case to validate the software. Thus, a pilot unit was modelled using the specifications of the reference case. A sensitivity analysis approach on the pilot model was then adopted to assess geometric alterations to the Passivhaus south facade. Eight preliminary steps were taken to examine the impact of the tilted south façade on Passivhaus performance and comfort:

i. Selection of an existing Passivhaus dwelling in the UK
ii. Modelling and validation of the dwelling's performance
iii. Conducting an initial pilot study
iv. Selecting weather data for simulation
v. Defining the risk of overheating
vi. Selecting the effective façade geometry (tilt angle)
vii. Implementing the effective design to current and future weather conditions
viii. Assessing the impact of the introduced geometry to future performance of the Passivhaus

2.1. Reference Case

An existing nearly zero carbon UK Passivhaus dwelling, Larch House in Ebbw Vale, Wales (Figure 1) with a typical cube-shape and large south-facing glazing (55% glazing of the façade area) was chosen as the reference case. It achieved an outstanding draught-free construction with an air tightness result of 0.2 air changes per hour (ac/h) at 50 Pascal indoor-outdoor pressure difference. The building uses external roller blinds to prevent summer overheating. It should be noted that the blinds have been assumed to be operated by the occupants in the summer time.

Occupant Behaviour

Occupant behaviour, such as operating windows and blinds, can have an influential impact on the energy performance of a house [17,25,26]. Findings from the monitored performance of the first London Passivhaus dwelling (Camden Passivhaus) [27] reported that occupants did not intend to change their window opening and blind operation use in future from the monitored data, which suggested that temperatures were above the CIBSE thermal comfort criteria in several periods. It has also been observed that the occupants of Larch House do not use the blinds to their best advantage [28]. Large glazing areas could lead to overheating in summer if internal/external blinds are not operated optimally. In the majority of Passivhaus dwellings, including Larch House, shading is controlled by internal or external blinds, which require occupant attention and understanding. Robinson and Haldi [11,12] showed how occupants' behaviours in terms of controlling windows and blinds can make a difference to the frequency of overheating.

Figure 1. Larch House in Ebbw Vale.

2.2. Modelling and Validation

The building was modelled using the dynamic thermal simulation package DesignBuilder (integrated EnergyPlus engine) version 3.4 [29]. DesignBuilder has been validated by reliable energy calculation standards, *i.e.*, EN ISO 13790 Standards [30], ASHRAE [31], and EnergyPlus validation testing results [32] that verified the robustness of the software. However, to ensure confidence in the results of the DesignBuilder model, it was necessary to compare the simulation data with the values provided by the designers. Bere Architects used the steady state Passive House Planning Package (PHPP) for simulation of the house. The predicted results from the PHPP file were used to validate the model. Monitoring data from the Technology Strategy Board [17] were also used for verifying the simulation data and mark out unexpected occupant's behaviour.

Post occupancy monitoring and evaluation of a building helps to compare the actual and predicted performance and to observe if any significant "performance gap" has been experienced. What is significant about monitoring compared to modelling is that unexpected occupant behaviour can be identified. Differences between the predicted and actual performance of low energy dwellings can be significant in some cases [33]. A comparison of the monitored and modelled data for Larch House (see Table 1) showed a small percentage difference for annual heating demand and air tightness. However, monitored data highly exceeded the total energy demand calculated by PHPP. Additional energy demand to the predictions occurred due to the higher amount of cooking and electricity consumption from sockets (appliance consumption type). The typical (conventional) UK domestic electricity consumption is around 3300 kWh per annum; for Larch House PHPP predicted an electricity consumption of 2209 kWh, whereas the actual monitored data revealed a value of 4495 kWh (see Table 2).

Table 1. Data comparison between PHPP, monitored data and DesignBuilder simulation results.

Measures	**PHPP**	**Monitored data**	**DB.1**	**DB.2**
Annual heating demand (kWh/m^{2}year)	13	9.3	9.1	13.5
Total Energy requirement including heating (kWh/m^{2}year)	83	189	166	96
Airtightness (h^{-1} at 50 Pa)	0.2	0.198	0.2	0.2
Annual CO_2 emission (kg CO_2/m^{2}year)	20.1	35.6	34.2	26.2
Frequency of overheating $T > 25$ °C, (%)	6%	34.9%	33.1%	17.5%

Table 2. Annual average electricity use from two years of Larch House monitoring.

Measured (kWh)	**Larch House**
Lights	245
Cooking	660
Sockets	3002
Total electricity (PV offset not included)	**4495**

Data from the monitoring also showed that the house did experience an overheating frequency (internal temperature exceeded 25 °C) for over 34% of total occupied hours in the main living space. This high percentage of overheating was mainly because occupants did not open the windows in summer. The monitoring revealed that in summer the children did not want windows to be open at night due to a fear of spiders. Although this could be resolved by fitting insect mesh in the window, the impact of summer night purge cooling should be incorporated into calculations by increasing the ventilation rate from the monitoring value. There was a small difference between the DesignBuilder model (herby referred to as DB.1) and the monitoring data but a much bigger difference with the results from the PHPP prediction. After the above mentioned unexpected occupants' behaviour was resolved and explained to the occupants, a second set of simulations (herby referred to as DB.2), with adequate natural ventilation and typical electricity use, were conducted. This will help to avoid exaggerated overheating in future climate analyses (after installing insect mesh the house continues to be monitored and it is expected that the overheating rate of the first two years of monitoring will be reduced [34]). In addition to the Passivhaus requirements, Larch House has a photovoltaic PV system installed to meet Level 6 of the at-the-time applicable UK Code for Sustainable Homes, *i.e.*, zero carbon emission. PHPP calculated 20.1 kg/m^2 CO_2 emissions for the building, with 12.8 kg/m^2 CO_2 emissions being avoided due to the solar system. However, the building did not achieve a truly net zero carbon emission and required a PV system of approximately 6 kW peak to meet zero carbon emissions. This study gives the value of the building's total consumption rather that net value of the measures, *i.e.*, this study ignored the CO_2 emission avoided due to the solar panels and electricity usage offset by the solar system. In this way the consumption of the dwelling can be assessed based on the building characteristics and not the power of the PV system.

As a result of comparing the Larch House monitored data with DesignBuilder predictions, and then fine tuning the DesignBuilder parameters to reflect known conditions in the house, it was felt that a satisfactory protocol had been established for using DesignBuilder in the next stage of this study's analysis of façade geometry impacts on overheating.

2.3. Pilot Study

To the best knowledge of the authors, the impact of a tilted façade has not been studied in terms of thermal comfort and energy use for a Passivhaus design. In order to gain a better initial understanding of the environmental parameters and the impact of the external inclination geometry, the preliminary pilot study modelled a simple single thermal zone in the form of a box shape replica of a house. The pilot study was, in fact, conducted to examine the effectiveness of the software in response to changing the façade inclination.

A hypothetical Passivhaus standard unit in a suburban exposure was developed to represent a typical Passivhaus dwelling (Figure 2). The unit was nine metres long, seven metres wide and three metres high and was a stand-alone unit. Construction materials, building specifications and occupancy schedule were set to be similar to the Larch House case study. The inclination angle θ of the south facade was manipulated to test the effectiveness of the façade inclination at 5° intervals starting from $\theta = 90°$, *i.e.*, a vertical façade, to 140°, *i.e.*, 50° beyond the vertical, as shown in Figure 3. The input data such as *U*-values, HVAC system, schedule pattern, and glazing area were chosen based on the original Larch House PHPP file [35] to generate the closest interpretable results. Table 3 indicates the building fabric thermal characteristics used for the model. The amount of glazing was based on window-to-wall ratio (WWR) and was applied to the pilot study model to represent 53%, 11%, 7% and 0% for south, east, north and west facing facades respectively. Figure 2 also depicts the amount of south glazing, including fixed and opening windows. Similar to the case study, external roller blinds were provided to try and prevent summer overheating.

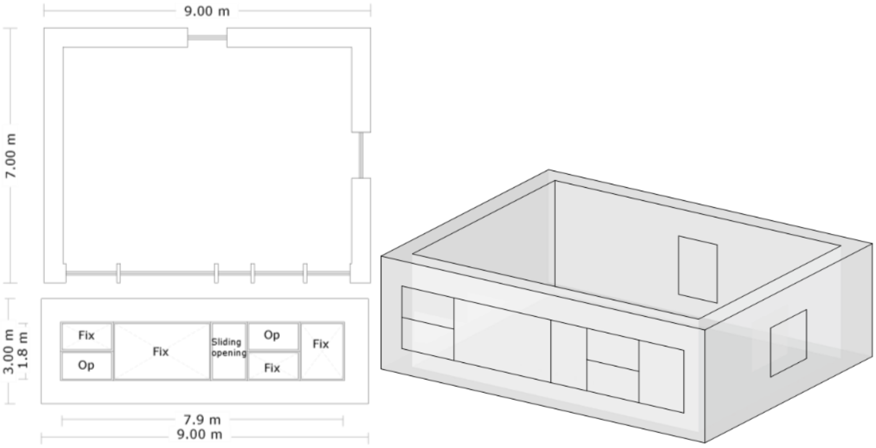

Figure 2. Pilot unit.

Table 3. *U*-Values used in the pilot study model.

Element	*U*-Value (W/m^{2}K)	Thickness (mm)
Exterior walls	0.095	467
Flat roof	0.074	578
Ground floor slab	0.076	800
Windows	0.860	Triple glazing 13 mm argon-filled

The HVAC operation template for the thermal simulation was set to mechanical ventilation with heat recovery system (MVHR). It must be noted that, similar to the existing reference case, the heat recovery system and heating supply were ON for winter time as the Passivhaus provides most of its heating demand from the heat recovery system, *i.e.*, heat given off by appliances, occupants and solar gain. However, in order to maintain a minimum indoor air temperature of 20 °C on the coldest days a small amount of supplementary heating is required, which is provided in the form of a post-air heating unit in the MVHR system. Any additional heating is acceptable up to 15 kWh/m^{2}year [5]. For the summer period natural ventilation was set to be operating, while the cooling supply was OFF since there is no mechanical cooling device used in the reference Passivhaus case. The blind operation schedule was set to simulate a typical use where occupants operate the blind based on the UK weekdays, weekends and holidays. This was chosen from a compact schedule script in the DesignBuilder library specified for living areas, where the fraction of the blind operation is higher during intensive summer sunshine hours. However, this does not mean that blinds were always closed during these periods. Natural ventilation was assumed to be operating in summer by opening the windows (cross ventilation). The air change rate for summer was 0.8 ach. In winter windows were closed and mechanical ventilation with a minimum 0.3 ach was operating. Heating and cooling set points were 20 and 25 °C respectively and the efficiency of heat recovery was set to 87% η_{HR}.

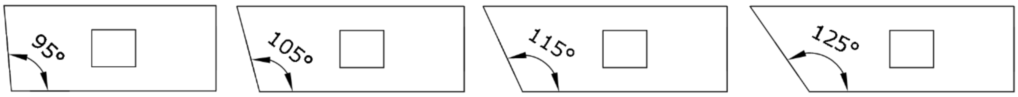

Figure 3. Side elevation of different façade inclinations.

2.4. Weather Data for Simulation

The most recent future climate change predictions for the UK were provided by UK Climate Projections in 2009 (UKCP09). The probabilistic weather data presented in UKCP2009 were not in a format that could be readily used by building modelling software. Consequently, a study entitled PROMETHEUS, based at Exeter University, developed techniques for creating future weather files using UKCP09 data but in software-friendly formats, such as in Energy Plus format (.epw) [20]. These hourly weather data files were available for medium and high emission scenarios with different percentile probabilities for both Test Reference Year (TRY) and Design Summer Year (DSY) weather data, where DSY tends to give warmer summer days and TRY is more representative of the whole year. The majority of the studies to date have used medium or high emission future weather data with the central estimate (50%), while some used the worst case scenario of high emission 90% probability, where the changes are very unlikely to be greater than the given value. Gupta and Gregg [19] argued that the most robust design for future climate should be resilient to a worst case scenario. On the other hand, some argue [17,28] that considering extreme worst case scenarios for building design is very costly and unnecessary because it is very unlikely to happen. For the modelling in this paper an average pessimistic scenario of high emission 50 percentile probability was chosen rather than the low, medium or worst case scenario. It must be borne in mind that this study tried to obtain an indication of what may happen and not to find absolute real values. Obviously, the current Ebbw Vale climate was used to validate the Larch House modelling case study exercise described previously. However, for assessing overheating risk the DesignBuilder modelling used weather files relating to future scenarios in London because London is projected to experience the greatest future external air temperature rises in the UK as a result of both climate change and urban heat island impacts [36].

3. Results and Discussion

3.1. Overheating Risk for the Pilot Study Unit in Current and Future Climates in London

Figure 4 gives current and future data concerning the consequence of predicted future temperatures on the thermal comfort inside the pilot unit with the typical vertical south façade. The bar chart depicts average monthly outside dry-bulb temperature over a year for current and future climates London. The data illustrate the predictions of possible future temperatures in London under high emission 50 percentile tested reference year (A1Fi 50%_TRY) for 2030, 2050 and 2080. The horizontal band across Figure 4 shows the range of comfort temperatures.

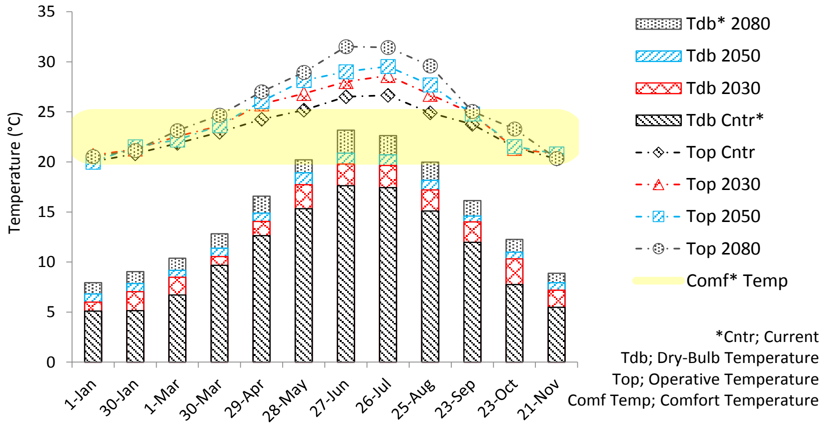

Figure 4. Monthly outdoor dry bulb air and average indoor operative temperature (°C) in the pilot study unit for current and future weather conditions (London).

It is clear from Figure 4 that temperatures will raise over the whole 12 month cycle of the year in future. However, the increases are more significant for the summer time, especially in June and July. The increase in average dry bulb air temperature in summer time is double the temperature rise for winter. The highest average dry bulb temperature for the current CIBSE file London climate is around 17.5 °C, while the value for 2080 shows a dramatic increase to over 23 °C. This will clearly cause an increase in operative temperatures inside the building. The curves in Figure 4 represent the indication of possible future overheating risk for London which needs to be taken into consideration at the early design stage. The mean value for indoor operative temperature never dropped below 20 °C whilst space heating demand was kept within the limit of the Passivhaus standards for current and future climate. This showed the robust performance of the Passivhaus structure for the heating period. However, the temperatures increase to just over the comfort zone in June and July for current weather data. For the current climate the indoor temperature of the super insulated pilot unit is close to an average of 26 °C in July. However, the future temperatures show a trend of thermal discomfort during summer, where inside temperatures for the hottest month of the year in 2080 may rise up to 31 °C if no additional adaptation strategies (apart from blinds) were implemented in the Passivhaus design. It should be noted that the window opening pattern and the amount of natural ventilation were kept constant for current and future climate conditions in order to make a valid comparison between the façade alternatives. However, it is accepted that occupants will change their behaviour as outside temperatures change and interiors become more uncomfortable.

3.2. Effect for the Pilot Study Unit of the Inclined Façade on Heating and Cooling Demand

Next, the study examined the impact that different façade geometries would have on the energy required (supplementary heating and cooling) to provide the minimum indoor temperature of 20 °C in winter and a maximum indoor temperature of 25 °C in summer. The MVHR heating option remained ON, based on a set point of 20 °C. Natural ventilation was operating and the cooling option was switched ON in order to supply cool air when the temperature rose above the cooling set point of 25 °C. Figure 5 demonstrates the amount of energy, including heating and cooling, that the pilot unit required to keep the temperature within the interval of 20–25 °C for the London climate under current and future weather conditions. It should be noted that the required supplementary cooling in summer was provided by an air-conditioning system running on electricity.

Results from the pilot study analysis (see Figure 5) showed that the façade inclination angle had a noticeable impact on both annual cooling and heating demand for the Passivhaus pilot unit in London for current and future weather scenarios. The curves compare the heating load for different south façade inclinations. As expected, for the heating demand there was an upward trend as the inclination angle grew. For all climate periods a steeper upward trend was observed when the inclination angle went beyond 115°. The reason for that is, perhaps, that there is some overshadowing during the winter.

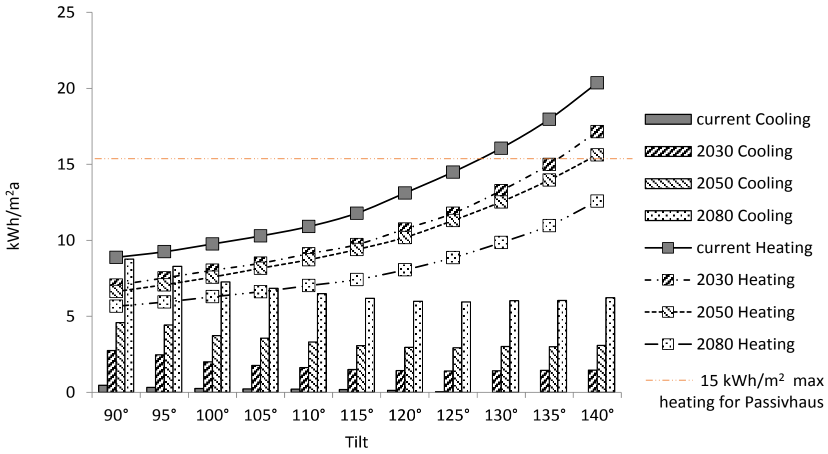

Figure 5. Annual energy demand of the pilot study unit for different façade geometries under four climate scenarios.

The vertical bars in Figure 5 show current and future data concerning the additional cooling load energy to maintain the maximum set point temperature of 25 °C during the summer. In contrast to the heating demand, the cooling load decreases as the inclination angle increases away from the vertical. However, the inclination stops having much effect when the angle reaches 120°. What is surprising is that when the angle increases from 130° to 140° the cooling demand starts to rise marginally. This might be because the windows on that façade will then receive more reflected radiation from the ground. The software has a surface solar reflectance (albedo) that can be modified between 0 and 1. In this study the default value of 0.3 was modelled as this value represents a typical average albedo for grass and soil.

It can be seen that there is a modest cooling demand for the current London climate, which can be eliminated by implementing an angled façade (details of corresponding indoor temperature can be found later in Figure 8a). It is clear from the data that the cooling demand will raise significantly by the second half of the century, when the self-shading strategy promises a substantial drop in overheating risk for future climates in London. However, a data analysis of all aspects of energy consumption is required to determine the design of the envelope shape that provides solar access in winter while acting as a self-shading facade in the summer.

The pilot study unit was also tested in a free-running mode, when both cooling and heating were unavailable for simulations. January and July were chosen as being representative of cold and hot months. Figure 6 shows the average operative temperature within the unit for January and July. It is observed that applying the 115° inclined angle produced an average of 0.5 °C lower indoor temperature in January while the temperature dropped by an average of 2 °C in July.

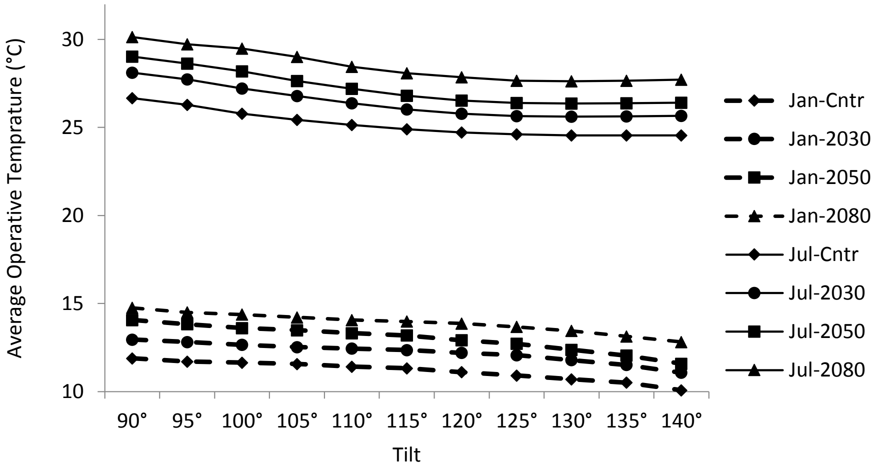

Figure 6. Average indoor operative temperatures for free-running Passivhaus pilot unit in January and July.

3.3. Overheating Frequency for the Pilot Study Unit

As mentioned above this study adopted the CIBSE Guide A static criteria on overheating (*i.e.*, temperatures exceeding 25 °C for more than 10% and 28 °C for more than 1% of total occupied hours) to assess the frequency of overheating in the pilot study unit. Figure 7 shows annual overheating rates for the four climate periods based on the number of hours at which the interior air temperature exceeded 28 °C. Applying an inclined facade should be precisely calculated to avoid over shading. The curves in Figure 5 showed that, upon implementing a tilted façade, the heating demand increased as a consequence of reduced direct solar radiation gain. According to the data, applying a tilted wall could be beneficial in reducing the potential overheating for current and future climates. Figures 5–7 suggest that in order to eliminate current overheating and reduce future overheating without greatly compromising the space heating demand then a reasonable inclination angle for the façade would be around 115°.

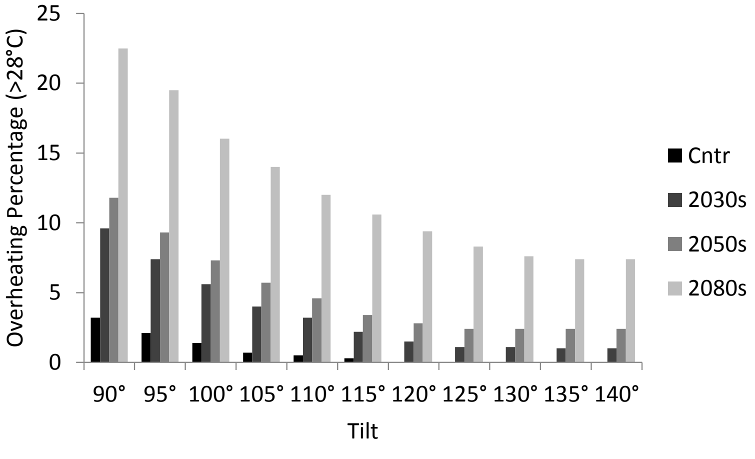

Figure 7. Frequency of overheating in the pilot study unit percentage of occupied hours the indoor operative temperatures exceeds 28 °C.

3.4. Implementing for the Pilot Study Unit the Effective Façade Geometry to Current and Future Conditions

Following on from the data analysis on the pilot study, the vertical south façade of the pilot study unit was replaced by a tilted façade with a 115° inclination. The simulations were carried out using the London future weather files. As the modelled data showed, there was a significant drop in summer operative temperature when using a 115° tilted wall, whereas the operative temperature did not significantly drop in winter. The implementation of a steeper façade, on the other hand, will block the required solar gain in winter while an angle around 115° will guarantee solar heat in winter and obstruct the high solar irradiation on hot summer days. Figures 8 and 9 indicate the annual monthly mean operative temperatures for heating (Figure 8) and cooling (Figure 9) demand when comparing the vertical (ϴ = 90°) and the suggested tilted façade (ϴ = 115°). The line graphs indicate operative temperature of the pilot unit with vertical and tilted south façades for current and future climate predictions. The bar charts indicate the amount of heating and cooling needed to provide comfortable temperature, *i.e.*, indoor temperatures between 20 and 25 °C. As mentioned earlier, Passivhaus, due to its super insulation, is capable of maintaining an internal temperature of 20 °C. The heat recovery system also operates by utilizing the heat given off by appliances, occupants and solar gain. However, a small amount of supplementary heating was required during the coldest period of the year (Figure 8). With the vertical glazed façade in the south elevation the pilot study unit experienced a marginal summer overheating rate under current climate conditions. Therefore, to ensure a comfortable indoor environment, the unit required a small proportion of supplementary cooling. This need was eliminated by implementing the tilted façade of 115° (Figure 9a). For the climate periods of the 2030s and 2050s the building experienced over 9% and 11% overheating respectively, exceeding significantly the 1% benchmark limit. This was reduced by the self-shading façade to just over 2% and 3% for the 2030s and 2050s climate periods respectively (Figure 9b,c). By the end of the century overheating is expected to occur in shoulder seasons, when high indoor temperatures could be seen from May up to September in the 2080s. Supplementary cooling for the Passivhaus pilot study unit with a vertical, highly glazed façade leapt to the point where the electricity consumption for summer cooling just surpassed the energy demand for space heating. Introducing an angled façade, however, cut the amount of supplementary cooling by up to 50% (Figure 9d), whereas the energy consumption for heating climbed only marginally, ensuring it did not exceed the maximum energy demand requirement of the Passivhaus standards. Overall, the current climate overheating risk of 3.2% was eliminated to below the benchmark number of 1%. For future weather projections the overheating rate was significantly reduced by the angled façade. However, the angled facade did not completely eliminate the potential overheating risk, especially for the climate of the 2080s.

4. Effect of the Inclined Façade on Daylighting

While shading strategies are among the tools to reduce overheating and glare discomfort, they can form as an obstacle to prevent good daylighting. The optimal design of any shading system requires an adequate trade-off between visual and thermal comfort. Much has been written about optimizing the functionality of external shading devices from different viewpoint [37–39], but none of them analyzed the impact of the façade inclination on the indoor illuminance for a relatively small house. This study was not focused on the daylighting performance of a Passivhaus. However, it is interesting to understand the consequence of the façade inclination and so a simplified numerical analysis was undertaken to show the effect inclination has on overall daylighting illuminance. The DesignBuilder package includes the advanced lighting simulation software Radiance, which provides the detailed calculation of illuminance data, including average daylight factor for each zone. Due to the large number of variables a relatively simple daylighting analysis on the pilot unit with different façade alternatives was examined. The results were generated based on BREEAM credit HEA1 with CIE overcast day (10,000 Lux). The maximum grid size and complexity of the chosen template type will significantly affect the time taken for the calculations. Therefore, a template type of "Good" with no interpolation (refer to [40]) with the default grid size was chosen. Since the pilot study was not divided into different zones by internal partitions the results may vary noticeably compared with actual cases. However, this analysis was not trying to obtain the accurate values of illuminance in the unit but attempting to understand the significance of inclination on daylighting illuminance. Figure 10 reveals the consequence of a tilted façade on the average daylight factor in a zone. Using a tilted façade of 115° will reduce the daylight factor by approximately 44% considering the current London climate. It may also increase the need for artificial lighting. It is worth mentioning that some of the decrease might be of benefit for visual comfort by blocking some of the direct glare. In addition, other, more traditional shading strategies are also likely to decrease daylighting levels.

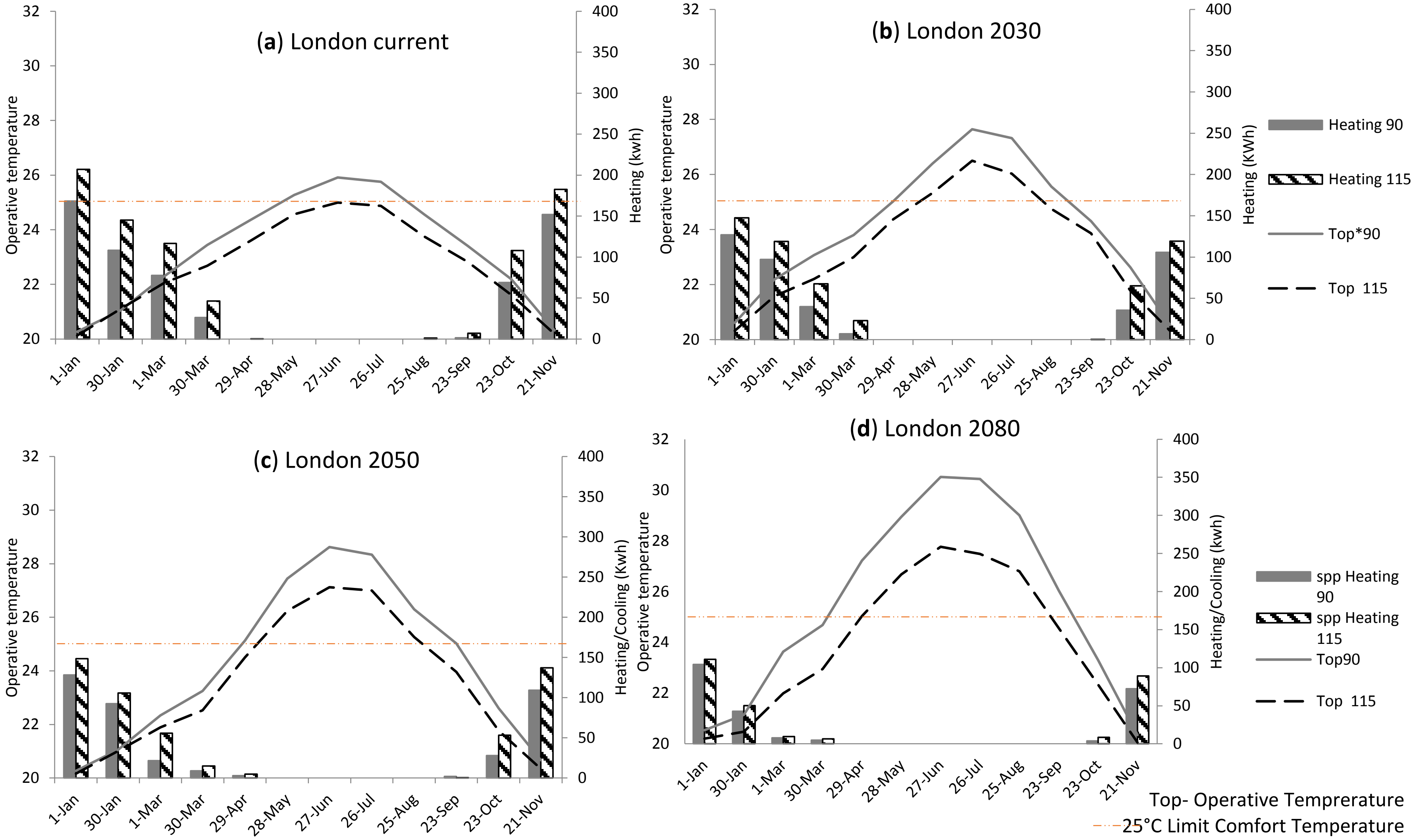

Figure 8. Indoor temperature and monthly supplementary heating required for the unit with vertical and tilt facade under four climatic periods.

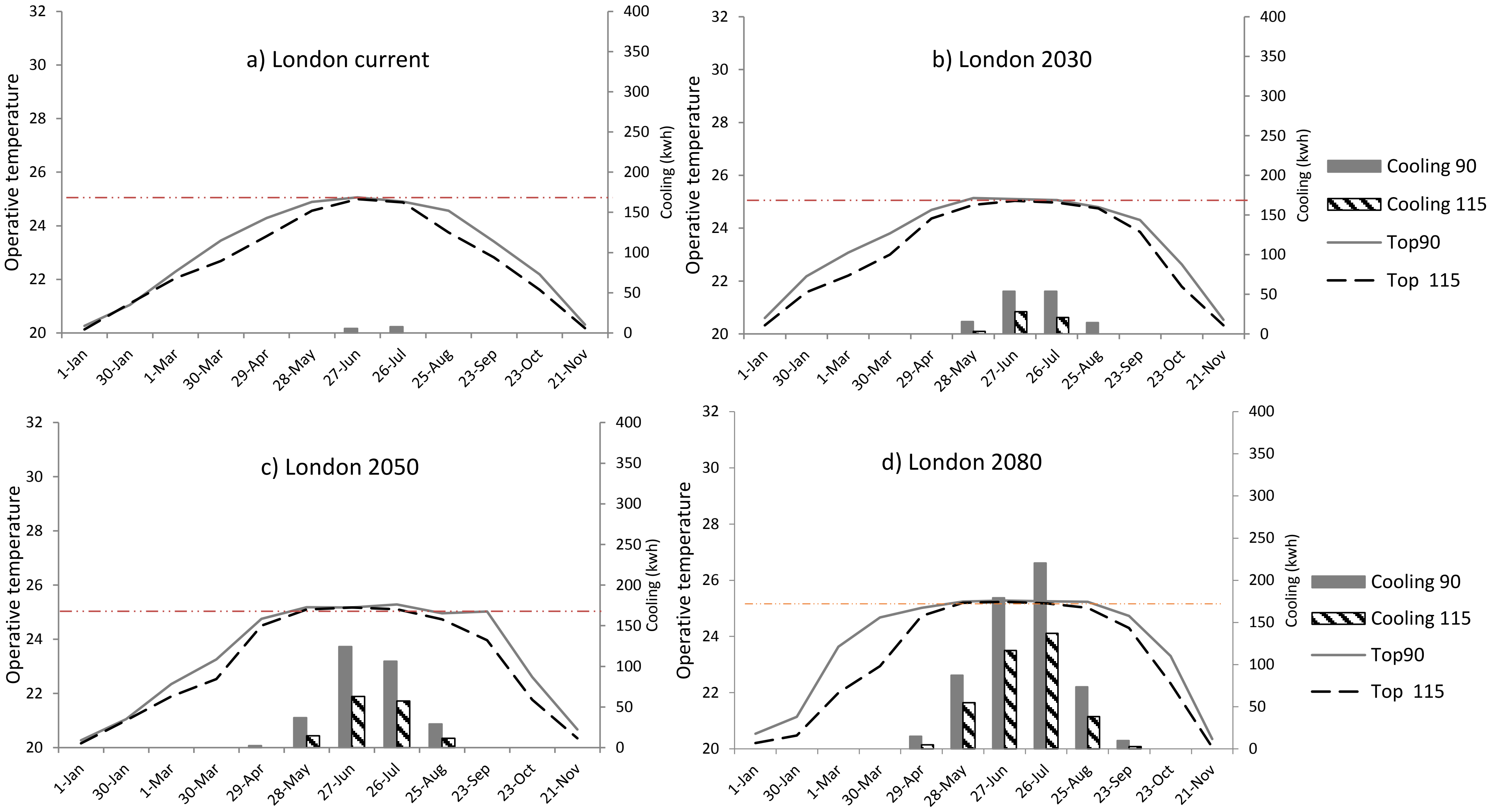

Figure 9. Monthly cooling required for the unit with vertical and tilted facade under four climatic periods.

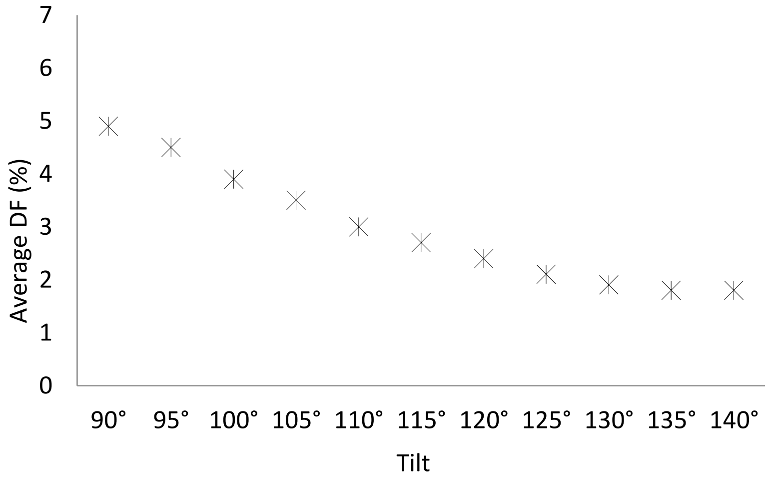

Figure 10. Average daylight factor in the whole unit with different façade inclinations.

5. Discussion and Future Studies

This is clear that when building a house with an angled facade there are some consequences in terms of structure, ventilation, daylighting and overall cost of the building. However any intervention will have a particular consequence on these issues. The cost of interventions will vary significantly. There is not a clear fixed price source to provide information that covers all the studied interventions. However, a report from Energy Saving Trust [41] estimated the cost of some intervention. Envelope insulation is by far the highest cost among the interventions. Triple windows and external shutters, internal blinds and fixed shading devise were the medium cost options. Night ventilation was among the cheapest interventions to tackle overheating in the UK. However, this will require the window security upgrade [42].

When the façade inclination increases the total surface area increases. This will increase the surface area exposed to outdoor temperature and consequently increase the heat loss. On the other hand the volume of the interior expands but the land cover will remain the same as a vertical façade and the extra overhang space can be used as a balcony for the upper floor without increasing the footprint of the property.

The effect of self-shading facade on the wind flow pattern around and inside the building also will vary from the vertical wall or having other shading devices such as overhang. This will be studied in a separate paper to provide detailed information about the fluid dynamics of the air movement and the amount of natural ventilation will be investigated respectively. Although the impact of the tilt facade on daylighting was briefly mentioned, a detailed analysis on the illuminance levels for different facade inclinations and also other shading devices will be conducted in a separate paper. Another issue which is worth investigating is the geography. Assuming a tilted wall in London could minimize overheating for future climates, but not eradicate totally the overheating, it would be interesting to know if the same façade tilt angle could completely remove overheating in future climates or if a steep angle would increase heating demand in a cooler climate at a different location and latitude.

6. Conclusions

The study has investigated the overheating risk in a UK Passivhaus and examined a novel way to reduce that risk for future climate scenarios. The study tested the high medium scenario (still not the worst case scenario), and the risk of overheating appeared to be significant. Some good examples of adaptive innervations were reviewed within the literature of the study and a proposed strategy was tested to define whether this can be counted as a successful intervention towards reducing the negative impact of the warming climate.

Some shading strategies addressed in the literature have limitations-for instance, occupants may not use blinds in the optimum way, thus reducing their effectiveness in combating overheating. This paper presented dynamic thermal simulations on a pilot study Passivhaus detached house unit. The study summarised how one factor could be considered in design stage to be best adapted to reduce future negative impacts of climate change and withstand current requirements. It was concluded that geometric considerations would help to improve the resilience of the London domestic stock to a warming climate and reduce reliance on the potential installation of air conditioning systems. It was found that a self-shading strategy via a 115° tilted south façade in London could eliminate the current climate overheating risk and mitigate greatly the future overheating risk. However, it was found that further interventions, like enhancing natural ventilation, will be necessary to minimize discomfort thermal condition within a Passivhaus dwelling. However, the proposed method tries to demote the overheating risk from high to medium or slight risk. Further energy efficiency programmes need to include adaptation if the adverse effects of summer overheating are to be avoided in the future. The results tend to emphasize the effectiveness of a good shading strategy in adapting dwellings to higher summer temperatures. Although London was chosen for the detailed analysis, the proposed approach could be applied to other locations to test how latitude and climate impact on the preferred façade tilt angle.

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Author Contributions

The paper investigated on the question; is there a relationship between the architectural form, energy usage and overheating risk in Passivhaus dwellings? The study used a tilted façade as a shading device to avoid summer overheating risk. It was found that inclined façade could potentially act as a fixed shading device and reduce overheating.

Conflicts of Interest

The authors declare no conflict of interest.

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The Potential of Inclined Walls to Reduce Overheating Risk:
A Passivhaus Case Study for UK Current and Future Climates

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ABSTRACT: This study used probabilistic climate change scenarios from the UK Climate Change Projections to determine the future overheating risk in an existing Passivhaus dwelling under a high emission 50 percentile scenario in London. Dynamic thermal simulation modelling software (DesignBuilder) was used to examine the impact of various inclinations of the south façade of the Passivhaus dwelling to make use of the self-shading that this form created. A sensitivity analysis of internal temperatures and thermal comfort conditions in the dwelling as a function of building facade inclination and prevailing climatic conditions was undertaken. The research found that implementing an optimum angle tilted façade would moderate indoor temperature variation between day and night in summer and could potentially act as an effective shading device while still be practical for collecting solar gain in winter. The proposed inclined façade could completely eliminate the risk of overheating for current climates; however, it was found that the tilted facade solely would not be fully capable of eradicating the risk of thermal discomfort overheating, particularly for UK climate scenarios of the 2080s.

Keywords: inclined façade, shading, summer overheating, climate change

INTRODUCTION

In recent decades thermal insulation has been the most frequently used intervention for developing low energy dwellings. Much of the focus on new build and refurbishment in the UK to date has concentrated on thermal comfort during the winter and on the reduction of space heating since space heating is the largest energy use for the housing stock. Highly insulated buildings with a high level of airtightness and energy recovery systems have been successful in minimising heating demand in the UK housing sector. One of the most successful and fastest growing standards, both in the UK and European housing sector is the German Passivhaus standard, which reduce significantly the demand space heating. However, as suggested by building physics researchers (Gupta & Gregg, 2012) and UK climate projections from the Metrological Office (Murphy, et al., 2010), the increase in extreme weather events, such as heatwaves, means that studies of overheating risks and the cooling energy demand must now also be considered, especially the vulnerability of domestic buildings to summer overheating.

According to the UK's Zero Carbon Hub (Dengel & Swainson, 2012) there is a growing concern in the UK that super insulated, very airtight homes, such as those developed in accordance with Passivhaus principles, might be vulnerable to the risk of summer overheating in future climates. There are a number of well-established passive cooling adaptation measures, such as solar shading, thermal insulation, thermal mass and ventilation, which have received a great deal of research attention and have been already implemented into the housing sector to reduce summer discomfort. The research presented here used a less examined passive approach to reduce overheating based on the potential implementation of the envelope shape as an environmental design strategy which is architectural in nature, and so has both aesthetic and environmental consequences.

PASSIVHAUS CASE STUDY

Passivhaus buildings are constructed using a heavily insulated exterior envelope with large glazed openings to the south (in the northern hemisphere) for maximizing spring, fall and winter solar gain. To obtain Passivhaus certification a building needs to meet a few main criteria (Feist, 2012), which include: (i) maximum specific space heat demand of 15 kWh/m^2 per year to provide a minimum indoor air temperature of 20°C in winter; (ii) total specific primary energy demand of no more than 120 kWh/m^2 per year; (iii) thermal bridge free and an airtightness of maximum 0.6 air changes per hour (ac/h) at 50 Pascal indoor-outdoor pressure difference. Furthermore, in order to provide a comfortable indoor air temperature in summer, living areas must not exceed 25°C for more than 10 % of the occupied hours in a given year.

The case study used in this paper was Larch House in Ebbw Vale, UK. It was the first zero carbon Passivhaus dwelling in the UK (McLeod, et al., 2013). Its design was based on the strategy of maximizing the benefit of solar heat gains (Ridley, et al., 2014). It uses an average of 9.3 kWh/m^2 energy for heating and achieved an air tightness result of 0.2 ac/h at 50 Pascal. Larch House has a large glazing area on the south elevation with a window-to-wall ratio of 55% (see Fig. 1), with occupants controlling the shading using external blinds. The house comprises a south-facing living room on the ground floor with windows on the east side and at the rear (north). There is a kitchen on the north side of the house and a south-facing dining room. There are three bedrooms on the first floor. The main bedroom (Bedroom 1) is located on the south façade, bedroom 2 at the rear of the building and bedroom 3 is south-facing on the west side (see Fig. 2).

Figure 1: The south facade of Larch House

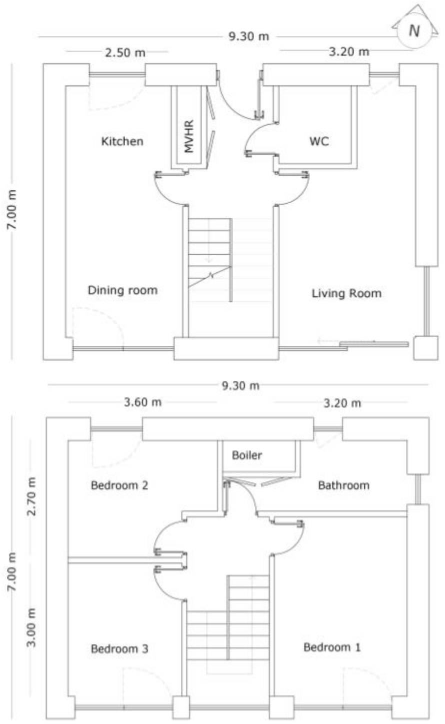

Figure 2: Ground (top) and 1st floor (bottom) plans

Passive interventions for reducing overheating are mostly user dependent and include operations such as blinds and window openings. Other passive overheating control options, such as thermal mass and overhangs, are non-user dependent. User-dependent approaches to passive solar control may not properly function due to the occupants not interacting with them as planned. For instance (Haldi & Robinson, 2009) found that occupants adjusted blinds more often on arrival [and departure] than during their presence in a room. Occupants also operated blinds to create privacy and alter view rather than solely for thermal comfort.

One reason for choosing Larch House as a case study for this research was the complaints of overheating that arose during monitoring of the house. Computerised shading devices had been provided, but studies in the house revealed that user preferences often contradicted automated shading control actions and occupants preferred to control the blinds manually or over-ride the automatic system. For the Larch House case study the automatic functioning of the external blinds was disabled at the tenants' request. The malfunction of the blinds use and window openings in the Larch House case study is believed to be the main reason for overheating problems during summer months (Technology Strategy Board, 2014).

The problematic interaction between the Larch House occupants and the solar overheating control systems was a stimulus for this study's investigation of an alternative non-user dependent intervention rather than the more conventional approaches such as overhangs and thermal mass. The idea was to test if altering the geometric form of Larch House (by tilting the south facade to give self-shading) might be capable of passively protecting the house from excessive solar gain in summer, both for current and future climate scenarios.

SUMMER THERMAL COMFORT

Guide A from the Chartered Institution of Building Service Engineers (CIBSE Guide A, 2007) is widely used to assess thermal summer comfort in the UK domestic sector (Lomas & Kane, 2013). The Guide suggests two threshold air temperatures to define a warm, uncomfortable indoor environment i.e. a lower temperature threshold that defines the moment occupants will start to feel warm (25°C), and a higher threshold temperature predicting the moment occupants will start to feel hot (28°C for living rooms and 26°C for bedrooms). In order to achieve thermal comfort temperatures should not exceed 25°C for living areas for more than 10% of total occupied hours and/or should not exceed 28°C for living rooms and 26°C for bedrooms more than 1% of total occupied hours.

METHODOLOGY

The research presented here expands on previous pilot study work by the authors (Author, 2015). In that study a comparison of monitored data from Larch House with predictions from the dynamic thermal simulation software DesignBuilder (a user-friendly version of EnergyPlus) established the validity of using DesignBuilder to model the energy performance of Larch House. The study parametrically tested a simple rectangular, single storey dwelling for London summer weather in order to test the effectiveness of inclining the south-facing façade outwards at 5° increments, starting from 90° (vertical façade) to 140° (50° beyond the vertical). It was found that an inclination angle of 110° to115° was effective for the London climate to shade the building in summer without greatly compromising the heating demand in winter. It is worth mentioning that pilot study dwelling had the same 55% window-to-wall ratio in the south façade as Larch House.

In this paper the proposed tilted facades suggested from the pilot study were applied to the architecturally more complicated (and more realistic) Larch House in order to investigate their effectiveness in reducing overheating risk. For this study Larch House was relocated to London, which provides a more challenging climate in terms of overheating risk, both for current and future climates. The aim was to examine whether the self-shading facades could act as an alternative design to overhangs and achieve summer thermal comfort. Thermal analysis data including indoor operative temperatures, transmitted solar radiation through the windows, and overheating rates for selected facades were calculated and an optimum (or near-optimum) façade inclination was defined. The current and future climate projections used for the overheating assessments are listed in Table 1, with the weather data being generated using techniques developed from a project called PROMETHEUS (PROMETHEUS, n.d.) which used UK Climate Projections weather inputs (UKCP09).

Table 1:Weather data used for simulations

Projection	Period	Emission	Probability
Current	1961-1990	NA	NA
Projection I	2030s	High	50%
Projection II	2050s	High	50%
Projection III	2080s	High	50%

RESULTS - LARCH HOUSE OVERHEATING RATE IN LONDON CURRENT AND FUTURE CLIMATES

Data representing a 50 percentile high emission scenario Test Reference Year (TRY) for 2030, 2050 and 2080 showed that future outdoor air temperatures will rise over the whole twelve month cycle of the year in the future (Fig. 3). The magnitude of the increase in average summer time dry bulb air temperatures is double the temperature rise for winter. July and August are the hottest months for all four time periods. Average monthly operative temperatures calculated by DesignBuilder are presented for the Larch House living room under current and future weather projections (Fig. 3). It is predicted that the house will experience a slight overheating risk during July and August for the current climate. However, in the future a much higher overheating risk is predicted. The summer average temperature in the living room and main bedroom were 23.9 and 24.1°C respectively. The highest single hourly temperature was in the living room (32.4°C) at 11:00 on 23rd July. The peak hourly operative temperature in the bedroom was calculated on the same day at 14:00 to be 31.4°C.

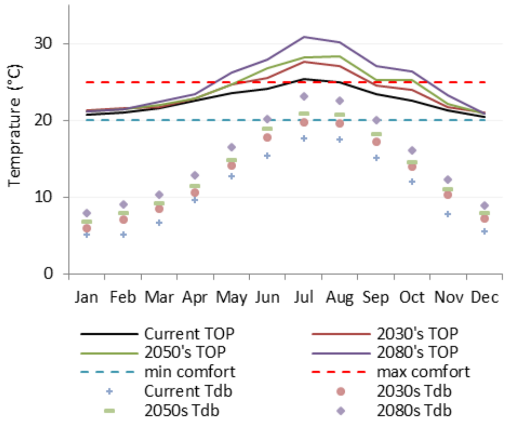

Figure 3: Monthly average outdoor dry-bulb (Tdb) and monthly indoor operative temperature (Top) in the living room of Larch House.

IMPLEMENTATION OF TILTED FAÇADES

The vertical south-facing wall of the London Larch House was replaced with inclined walls to investigate the impact on overheating. Inclination angles of 110° and 115° were adopted to analyse the impact that these shapes created on thermal comfort in summer under current and future climates in London. The simulations were calculated for living room and main bedroom. Operative temperatures were simulated 24 times i.e. three south façades, two rooms and four climates.

Current and 2080s data in the living room are shown in Fig. 4 as representations of all 24 simulations. The curves compare operative temperatures of the vertical and inclined facades. Corresponding heating demands for the alternative designs are also shown.

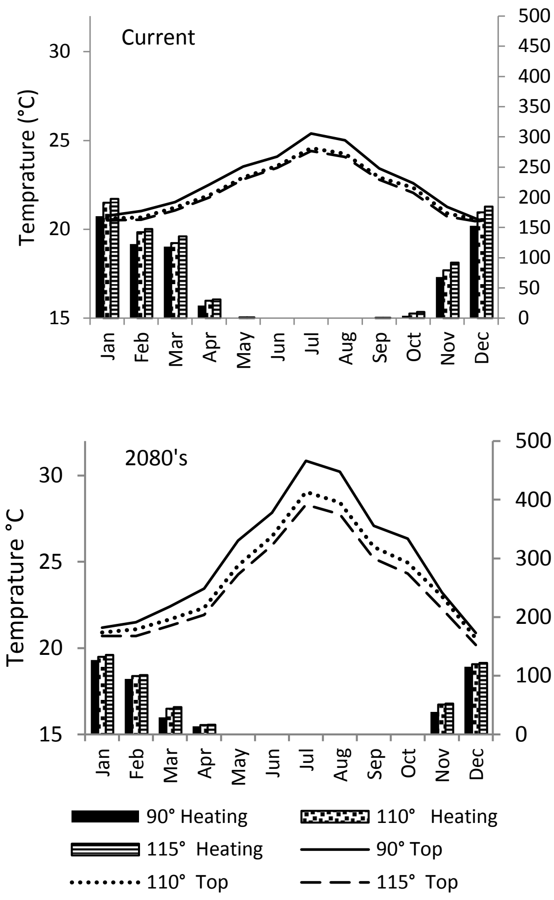

Figure 4: Living room operative temperatures and heating loads for current (top) and 2080s (bottom) climates

Fig. 4 indicates an indoor temperature reduction of up to 2°C degree for the hottest months when comparing the 115° tilted façade to the vertical façade. The difference between the two tilted façades is very small for the current climate; however, due to elevated temperatures and solar radiation levels in the future this difference becomes more pronounced for 2080. There is also a slight increase in heating load for the tilted facades, which is higher for the current climate. Despite this, the increase the heating demand always remains within the Passivhaus limitation of 15 kWh/m2. As a result of changing the façade angle, indoor air temperatures dropped for most of the time. The impact of tilting the façade for current climate was small, while the temperature drop for the hottest month in the 2080's was up to 2.5°C for average monthly calculations. The reduction in indoor temperature was higher during summer months but for the coldest months of the year i.e. January and February, the change in temperature was imperceptible.

Table 2 summarises the annual overheating percentages for the living room and bedroom for both benchmark temperatures i.e. >25˚C and >26˚C/28˚C.

Table 2: Percentage of overheating time

Period	Space	Vertical 90°	Tilt 110°	Tilt 115°
Current	Living room>25°C	28.2%	14.6%	12.2%
	Living room>28°C	2.9%	0.5%	0.1%
	Bedroom>25°C	12.3%	1.7%	1%
	Bedroom>26°C	4.9%	0.4%	0.2%
2030s	Living room>25°C	43.3%	26%	21%
	Living room>28°C	11.2%	4%	3%
	Bedroom>25°C	21.6%	10.5%	7.7%
	Bedroom>26°C	15.2%	7%	5.6%
2050s	Living room>25°C	48.1%	30.4%	25.5%
	Living room>28°C	16.3%	8.6%	7.4%
	Bedroom>25°C	27.7%	15.8%	11.8%
	Bedroom>26°C	21.3%	11.9%	8%
2080s	Living room>25°C	58.1%	41.5%	35.4%
	Living room>28°C	28.2%	17.6%	15.3%
	Bedroom>25°C	38.3%	22.1%	18.9%
	Bedroom>26°C	31.2%	18.5%	14.3%

Although this study has focused on the risk of summer overheating, it is necessary to measure the impact that the proposed tilted geometries will have on heating demand in winter. Weather data were analysed to select a typical day in both summer and winter of current and future climate to indicate an actual performance of the different facades. The chosen days are representative of summer and winter climates. Fig. 5 compares a daily breakdown of the indoor temperature fluctuations and transmitted solar radiation through the windows for the three facade alternatives. During a cold day for current and future climates there is a marginal variation in the indoor temperatures when implementing the tilted façade. It is shown that the solar gain transmitted into the room is reduced during midday and early afternoon when implementing the inclined façades.

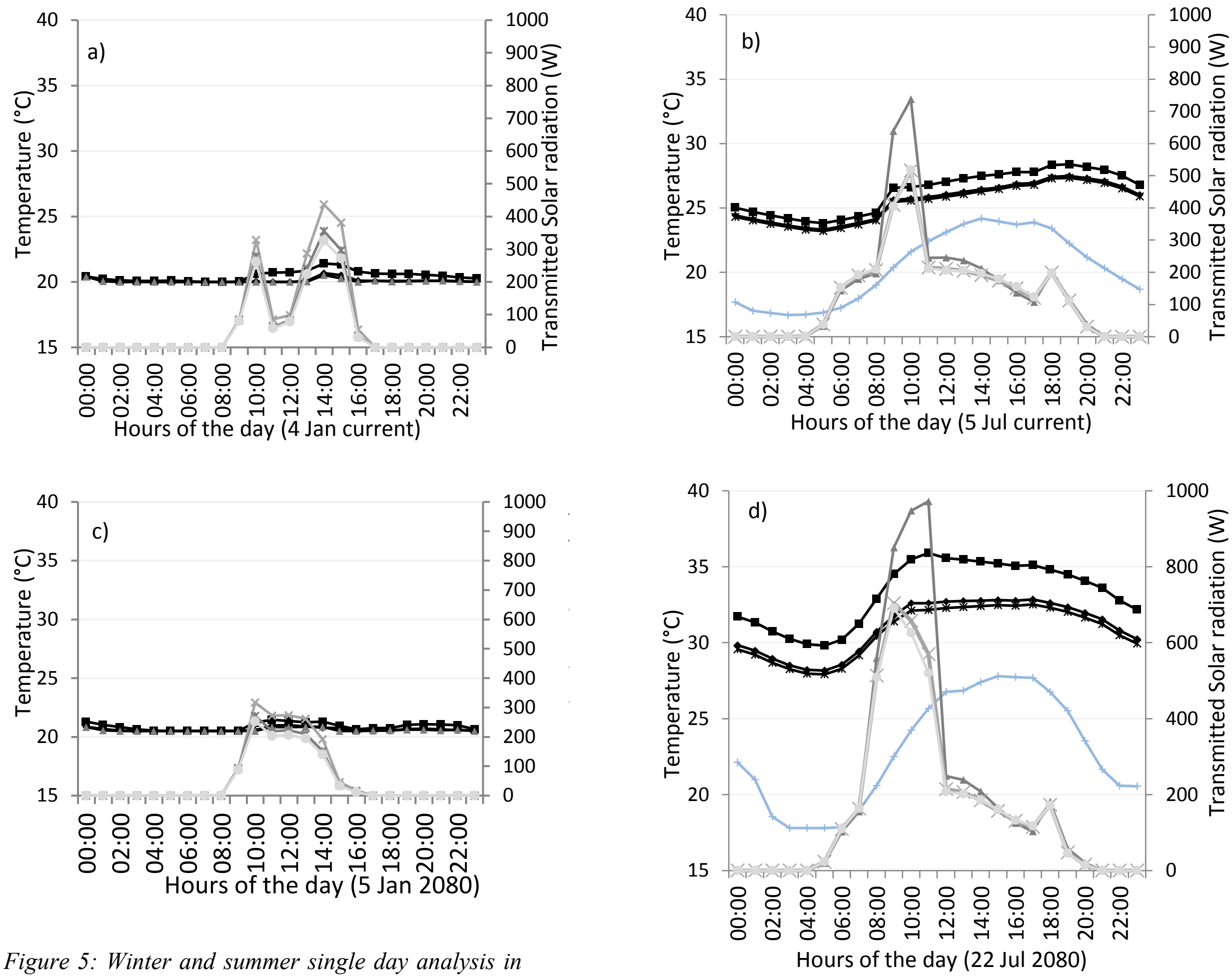

Figure 5: Winter and summer single day analysis in the living room: a) 4th January-current climate; b) 5th July-Current climate; c) 5th January-2080; d) 22nd July-2080.

DISCUSSION

For current climates the tilted facades have a significant impact on reducing the predicted percentage of overheating compared to the vertical wall. Significant reductions are also evident for future climate climates, with overheating times typically being cut by a half. However, by 2080 overheating is still evident, even for the 115° tilted south façade, and other measures would be need to establish comfort.

According to the predicted data, applying a tilted wall with a 115° inclination angle is effective for reducing potential overheating for current and future climate. There is a significant drop in operative temperature when using a 115° tilted wall whereas operative temperature will not significantly drop in winter. Analysis showed that the implementation of a steeper façade will reduce beneficial solar gain in winter. However, the impact on the operative temperatures (and so thermal comfort and heating requirement) are not severe.

CONCLUSION AND FUTURE WORK

Passivhaus in the UK implies passive interventions to achieve free-running thermal comfort in summer. These interventions are mostly user-dependent and so may not always operate efficiently or effectively due to malfunction of the systems or occupant behaviour. Consequently, as was the case for Larch House, the dwelling may get overheated in summer, even for current climates. The paper considered a novel intervention in which inclined walls were used to create a self-shading strategy for the predominantly glazed south façade of an existing Passivhaus. The proposed tilted façades were analysed alongside with the performance of the existing vertical wall.

It is concluded the overheating risk under the current climate was significantly reduced using a 110° tilted south façade and it was almost fully eradicated using a 115° inclination. However, this reduction of overheating was followed by an increased heating load in the current climate, but which was almost negligible for future climates. The house remained thermally comfortable during winter for all climate scenarios and never exceeded the Passivhaus criteria for heating demand. However, the living room and main bedroom did experience significant overheating for projected future London climates. This risk was reduced by half using the self-shading façade. The geometric consideration could not solely eradicated overheating risks in future.

Manipulating the tilt of the south facing wall will clearly have other impacts on, for instance, daylighting and natural ventilation air flows, and these parameters will be examined in further work using the lighting and computational fluid dynamics CFD algorithms in DesignBuilder.

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