FUTURE PROOFING UK SUSTAINABLE HOMES UNDER CONDITIONS OF CLIMATIC UNCERTAINTY

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Publications

The following journal and conference papers were published based on the findings of this thesis. Copies can be found in Appendix 3

- Sajjadian S M, Lewis J and Sharples S, Heating and cooling loads in high performance construction systems - will climate change alter design decisions? Proceedings International Conference on Sustainable Design, Engineering and Construction ICSDEC 2015, Chicago, 10-13 May 2015

- Sajjadian, S.M, Lewis, J and Sharples, S, The Potential of Phase Change Material to Reduce Domestic Cooling Energy Loads for Current and Future UK Climate, Energy and Buildings **93** (2015), pp 83-89

- Sajjadian, S.M, Lewis, J and Sharples, S, Quantifying the Effect of Shading Devices to Improve Comfort in Current and Future UK Housing through Integrated Simulations with High and Low Thermal Mass Construction Systems. Proceedings of the International Conference on Adaption and Movement in Architecture ICAMA, 476-484,Toronto, 10 -11 October 2013

- Sajjadian, S M, Lewis, J and Sharples S, Interpretation and determination of thermal comfort in climate change context. Proceedings of the International Post Graduate Research Conference IPGRC, 1106-1113, University of Salford, Salford, 8-10 April 2013

- Sajjadian, S M, Lewis, J and Sharples S, Risk and Uncertainty in Sustainable Building. In Håkansson A, Höjer, M, Howlett, R J and Jain, L C (eds) *Sustainability in Energy and Buildings* Proceedings of the 4th International Conference on Sustainability in Energy and Buildings (SEB'12), 903-91222, Stockholm, 3-5 September 2012, Springer

Abstract

Research relating to the potential impacts of climate change on UK housing has increased in recent years. The future performance of dwellings that are currently considered sustainable may change under a changing climate. For example, well insulated, air tight homes that are energy efficient and comfortable now may be at risk of overheating in the future. Decision-making for sustainable house designs may become more challenging regarding dwellings that will perform well now and be resilient to climate change risks, such as overheating, in the future.

This study evaluates the effect of overheating risk and future climatic uncertainty in designing UK dwellings. The main focus of the research is on the thermal performance of the external building envelope. The foremost aim is to future proof current designs in order to provide the best possible thermal comfort under likely warmer weather conditions produced by climate change. This research examines a number of constructional design options to reduce energy consumption and improve thermal comfort on the basis of climate change predictions up to 2080. The study develops a methodology by means of computer simulations to assess and predict the performance (in terms of total energy input, both heating and cooling, required to maintain thermal comfort) in a range of current, 'high performance' construction systems used on simple and typical UK house models in London and Manchester.

The findings of this study show that UK sustainable homes, in their present format, are susceptible to a future overheating risk. It is argued that the substantial part of the overheating risk can be alleviated by the integration of modern smart materials and conventional design solutions, such as shading devices and earth-to-air heat exchangers (EAHE). The research also proposes a new method of integrating phase change materials into the building envelope to reduce domestic cooling loads and overheating hours in the coming decades.

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Nomenclature

C = specific heat capacity of material (J/kg°C)

D = thermal diffusivity ($m^2/\ S$)

K = conductivity (W/m°C)

M = mass of material (kg/s)

M_{air} = mass of air (kg/s)

q = heat flux (W/m^2)

Q = quantity of energy input/output (kW)

R = resistance or R-Value (m^2°C$/W$)

r = resistivity (m °C/W)

T_1 = initial temperature (°C)

T_2 = final temperature(°C)

Tc = comfort temperature(°C)

To = outdoor air temperature

Ti= mean indoor air temperature

Tn,i = neutral temperature on the basis of mean indoor air temperature (°C)

Tn,o = neutral temperature on the basis of mean outdoor air temperature (°C)

ΔT = temperature difference (°C)

U = thermal transmittance coefficient or U-Value (W/m^2°C)

ρ = density of material (kg/m^3)

Acronyms and Abbreviations

ACH: Air Changes per Hour (unit)
BB: Brick and Block wall
CSH: Code for Sustainable Homes
CCS: Carbon Capture Storage
DB: DesignBuilder
EAHE: Earth Air Heat Exchanger
ICF: Insulated Concrete Formwork
IPCC: Intergovernmental Panel on Climate Change
MMC: Modern Methods of Construction
PH: Passive House standard (Passivhaus)
PCM: Phase Change Material
PMV: Predicted Mean Vote
PPD: Predicted Percentage Dissatisfied
PUR: Extruded Polyurethane
SAP: Standard Assessment Procedure
SD: Shading Device
SF: Steel Frame Wall
SIP: Structural Insulated Panel
TF: Timber Frame
UK: United Kingdom
UKCIP: UK Climate Change Impacts Program

Chapter 1. INTRODUCTION

1. Introduction

The construction and operation of buildings are now the main causes of carbon emissions and environmental damage, from the sourcing of raw materials, to the energy used for occupants' comfort, to the disposal of the building elements once they come to the end of their life cycle. Approximately half of the UK's carbon emissions come from buildings' energy consumption (DTI, 2005).

It is now widely accepted that a warming climate during the rest of this century appears inevitable. Adaptation of buildings to climate change is becoming increasingly necessary. Adaptation, a responsive adjustment to decrease or remove risk, will be critically important since, in even the most optimistic projection of climate-change scenarios, temperatures will increase considerably around the world. It is very unlikely that the mean summer temperature increase will be less than 1.5°C by 2080 (IPCC, 2010).

In an attempt to tackle the risk of climate change an ambitious target was set for all new UK houses to meet a zero carbon standard from 2016 (although this target has since been modified). On the same theme, the UK Government established the modernization of the construction sector by the promotion of Modern Methods of Construction (MMC) as well as stricter regulations and standards implementation (DCLG, 2008). In order to meet sustainability targets the goal is to improve the quality of newly built houses. Modernization and integration of new technologies to the house-building sector through the promotion of modern methods of construction are pathways to achieving this goal. In addition, with a changing climate, architects can no longer assume a constant static condition for their designs, and there is a necessity to consider the values of design variables for future years.

Furthermore, sustainable building design principles will be comprehensively concerned with the various trade-offs between several parameters. However, the majority of building performance assessment models do not incorporate a sufficiently broad range of future impacts on the sustainability considerations and, therefore, do not have long term efficiency. In present design practice, the uncertainties in many of the performance likelihoods are not explicitly quantified - for example, the performances of buildings in areas such as annual energy consumption and thermal comfort. In previous studies on the simulation of these performance aspects, uncertainties have been identified to some extent but still numerous issues have been left unresolved.

Initially, it has been recognized that in some cases, it may not be possible to comprehensively assess uncertainties by statistical analysis of available data. This raises concern about which methods could be used to measure these uncertainties and whether such methodologies would be appropriate in decision making. Secondly, although arguments have been put forward to highlight the relevance of quantitative uncertainty data or design choices, no studies have been made to indicate how a decision maker could utilize this information for design improvement.

1.1 Research questions, aims and objectives

Current approaches in sustainable design decision-making processes have often been criticized on the grounds of a lack of attention to long-term issues. Climate change impacts could raise even more concerns because climate change predictions introduce considerable changes in building performance (Holmes & Hacker, 2007). This project attempts to propose a methodology to quantify the uncertainty and provide sensible recommendations for decision makers. In order to limit the scope of this study to a practicable level, this research centres on the design of the external envelopes of domestic-scale buildings and their role in determining the thermal performance of those buildings. The main research questions are:

1. How will current sustainable UK house design approaches perform in the future?
2. Are current UK domestic sustainable standards capable of delivering substantially greater energy savings in the future?
3. What are the design options and implications to maintain thermal comfort in UK homes for future climate scenarios?
4. Will conventional construction methods currently used in the UK be capable of reducing the climate change overheating risk in the future?
5. Are available passive construction technologies, such as smart materials, the solution to deal with climate change overheating risk?

This thesis investigates the likelihood and magnitude of risks and uncertainties of summertime overheating in UK dwellings for sustainable design, with the focus on the building envelope. Currently, changes in building regulations indicate an increase in insulation levels that will reduce the heating season and create buildings that are much more sensitive to any alteration in energy inputs, especially if they are built using certain common MMC configurations.

Furthermore, research investigations indicate that a changing climate makes decision-making more complicated (Holmes & Hacker, 2007). Therefore, the main research aims are to evaluate current sustainable design standards in the light of increasing temperatures, and to eventually reduce complexity to support decision-making processes in sustainable design for current and future UK housing. Therefore, in order to answer the research questions, the following steps are classified:

- Clarify the understanding of risk, uncertainty and future proofing for the built environment in a changing climate
- Quantify the impact of risks and uncertainties from future climate scenarios on building performance (in terms of thermal comfort and energy consumption) as a potentially useful method for sustainability optimization
- Evaluate the thermal behavior of widely used, high performance wall systems in current and future UK housing
- Provide particular aspects of advice and quantify the consequences of practical design solutions by decision maker, including the use of novel materials

1.2 Limits of the study

In order to answer the research questions, a number of existing design options have been studied. However, this study focuses on the building envelope for the assessment of sustainable standards in buildings which have already met the minimum requirements of sustainability standards. The research concentrates on methods intended for the primary phases of a design process. Design decisions considered in this study are the type, configuration and amount of wall cladding system and thermal mass in building envelopes. Decisions regarding the active design strategies, as well as design and operation of HVAC systems, are not considered.

The performance of house models with respect to achieving optimum thermal comfort and less energy usage is assessed. Only extreme climate change uncertainty related to the high emission scenario for residential buildings in the UK is evaluated, and low and medium emission scenarios are not considered. Sensitivity analysis is considered but not reliability analysis. Analysis of the uncertainty is performed by computer-aided design modeling for quantification and optimization process.

There are some other uncertainty sources that could affect design decision-making in this study, such as likely energy and resources costs, human responses, material performance, building maintenance cost, etc. However, the study has only considered the likely energy cost and resources trends because of the high level of their importance on future decision-making and the availability of prediction scenarios.

1.3 Methodology

As described, this research centres on the assessment of current sustainable design standards with the focus on building envelope in order to deal with climate change. For this purpose, initially, building standards including England and Wales building regulations Part L, Passivhaus and the Code for Sustainable Homes (CSH) are considered and differences in their thermal performance assessment criteria (U-value factor) are clarified.

Furthermore, future challenges in UK housing and energy and the terminology of heat transfer mechanisms and influential factors in buildings are investigated before introducing the initial models for simulations. Five of the most typical construction systems from both Modern Methods of Construction and traditional ones (detailed explanation is given in section 8.1) are chosen and located in Manchester and London to quantify the differences on the basis of thermal comfort (interpretation is explained in section 8.5) and energy consumption in four time slices of 2011, 2020, 2050 and 2080.

Future climate data for the UK are available from the UK Climate Impact Programme (UKCIP), which provides monthly values of climate data for the UK until 2080 (Murphy, et al., 2012). The University of Southampton has developed an Excel file named “CCWeather Gen” to create future weather files for simulations from UKCIP predictions (SERG, 2012). These files, which provided hourly weather data, are used for modeling future impacts on the models used for this thesis.

A model adapted for the worst scenario is highly likely to be the most robust design i.e. a model which is resilient to the greatest change in future climate. Therefore, in developing appropriate projections for modeling, the ‘extreme’ climate change for three climate periods used as it represents the worst-case scenario for change. Extreme climate change characterizes the high emissions scenario at 90% probability (where change is highly unlikely to be more than a given value) (Murphy, et al., 2012).

The modelling software Ecotect and DesignBuilder (DB) were available to the author for the period of this study for thermal simulation purposes. However, DB was selected for the simulations as it is more reliable and highly validated (Baharvand, et al., 2013) (Zhou, et al., 2008). (Northumbria University, 2009). Integrating other passive design strategies, such as shading devices and earth-to-air heat exchangers, as well as new technologies, such as phase change materials, are considered for developing the performance (on the basis of energy consumption and thermal comfort) of the models.

This study uses five house models for simulations, starting with a simple cell, then a more sophisticated model with a functional zone (the second model) and, finally, to three of the most typical UK housing models. The prospective design of the new UK houses from three major typologies (semi-detached, detached and purpose built flat) are chosen and on the basis of the result achieved from the initial models, the developing strategies to improve the performance are taken. Although a future increasing air temperature will impact on winter energy needs, the major focus of this study is on alleviating the summertime overheating risk in dwellings by conventional methods and smart materials.

1.4 Outline of the thesis

The structure of the thesis is as follows:

Chapter 1: Introduction

Chapter 2: Reviews future UK energy supplies, the likely changes and future costs. This chapter demonstrates that future proofing in the construction sector is important

Chapter 3: Introduces the principles and most effective influential elements of passive design strategies, establishing the scene for the development of this study.

Chapter 4: Demonstrates the promotion of the use of MMC and their thermal performance

Chapter 5: Clarifies the understanding of risk, uncertainty and future proofing for decision making process

Chapter 6: Demonstrates the likely climate change impacts on Manchester and London weather

Chapter 7: Provides a background study on heat transfer in building and influential factors in heat storage as well as investigating common materials

Chapter 8: Assesses thermal storage capacity of common construction methods updated to meet maximum U-value in different scenarios

Chapter 9: Integrates conventional design strategies, including shading devices and EAHE, to optimize thermal performance of the model

Chapter10: Introduces phase change materials as a new technology to replace heavy mass in buildings to alleviate temperature fluctuations and improve comfort

Chapter 11: Introduces the prospective design of e new UK homes and modeling results for decision-making simplification.

Chapter 12: Conclusions, limitations and further work

Chapter 2. UK FUTURE ENERGY CHALLENGES

Any attempt toward sustainable building design needs to consider the likely changes in energy supplies and energy costs in the future. This Chapter investigates some of the UK's future challenges on short-term and long-term decarburization policy in the energy sector. In essence, this Chapter provides the picture of likely changes and obstacles in the UK low carbon development path and, consequently, the likely changes that might affect sustainable design decision-making process.

Initial studies in this field considered the possibility of CO2 reduction scenarios, the significance of available technologies and the fundamental uncertainties for their development. Also, subsequent studies were meant to create visions on more inflexible aims (available alternatives), and on risks and uncertainties that may make aims stricter to achieve.

As this study aims to suggest UK future homes become low energy consumers and more environmentally benign, this Chapter tries to demonstrate that attempts towards a more sustainable future is practically feasible in terms of energy cost and, therefore, is of high importance in the UK. This Chapter shows the uncertainties in the energy sector and demonstrates likely changes and potential expectations in future in order to establish the necessity for future proofing UK homes.

2.1 Potential energy resources and outcomes

Ensuring the UK's energy supplies and addressing climate change are the most significant goals in UK energy policy (BERR, 2007 (a)). To follow international policies on addressing climate change at G8, UN and EU levels, the UK has set a reduction target of 80% (compared to 1990 levels) in greenhouse gas emissions by 2050 (CCC, 2008). In a similar vein, the UK government also aims to increase the market share of renewable energy resources to 15% by 2020 (CEC, 2008). From 2009 onwards the major tools to address this aim are Renewable Obligations (RO) for electricity generation, Renewable Transport Fuel Obligations (RTFO) for road transport fuel sales and Renewable Heat Program (RHP) for heat in commercial, residential and public buildings (DECC, 2009). Furthermore, according to Hammond (2000), in order to meet the target, a 45% to 75% reduction in energy consumption is also required.

Since the Industrial Revolution, fossil fuels have dominated the UK energy market (BERR, 2007 (a)) [see Figure 1]. Clearly, their impact on energy prices is considerable. However, fossil fuel markets are hard to predict and are affected by many variables.

Fossil fuels are global commodities and price fluctuations may be due to a variety of unpredictable reasons, including technical, political and economical (OPEC, 2011).

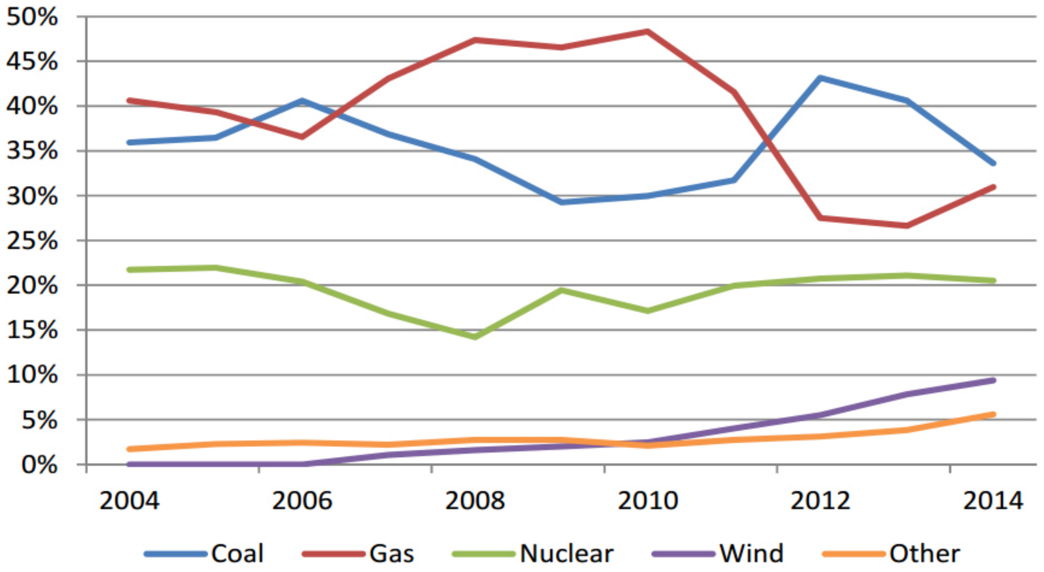

Figure 1 UK shares of electricity generation, Source: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/463676/Electricity.pdf

Although the future cannot be predicted with any degree of certainty, examining previous trends in oil, gas and other fossil fuels prices can provide a reasonable basis for considering possible future trends. Figure 2 shows oil, gas and coal price trends from 1950 until 2008.

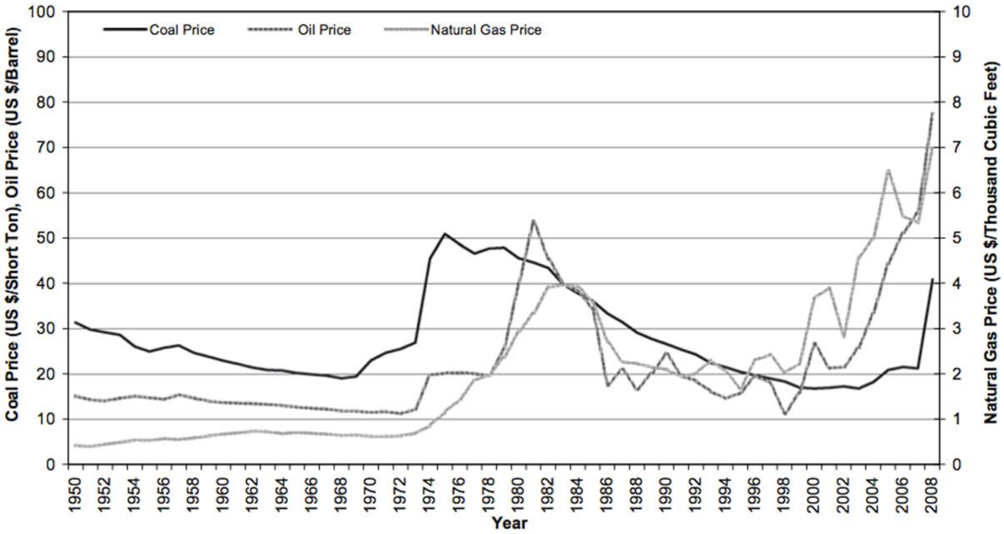

Figure 2 The average annual historical fossil fuel prices trends from 1950 to 2008, source: (Shafiee & Topal, 2010)

A gradual price increase after the 1980's sharp decrease confirms the instability and considerable fluctuations in this market. Furthermore, there is another uncertainty on the fossil fuel global – lifetime of remaining resources. One estimation for oil, coal and gas is given below (Hammond, 2000):

- Oil: 20 to 40 years
- Natural Gas: 40 to 70 years
- Coal: 80 to 240 years

Furthermore, in the UK, oil, gas and coal production has decreased considerably for about 30 years [see Figure 3]. If this trends continues, which is likely to be the case, then there will more risk for securing energy supplies inside the country and more uncertainty on prices.

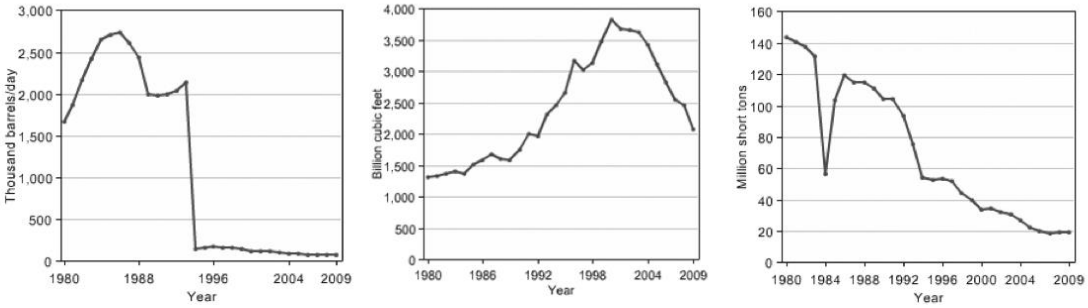

Figure 3 UK oil, gas and coal production history from 1980 to 2009. Source: http://www.eia.gov/countries/country-data

However, although fossil fuel depletion seems inevitable, sustainable utilization and technological advances can cause a delay in this process. Also, as the scope of this thesis is up to 2080, any sudden and final fossil fuel removal from energy supply options is highly unlikely to happen in this period and could not be considered as an influential factor in design decision-making. Other options that can decrease or remove the share of fossil fuels in the UK market include renewables and nuclear power[1]. According to Coelho and Goldemberg (2004) "*renewables enhance diversity in energy supply markets; secure long-term sustainable energy supplies and reduce local and global atmospheric emissions*". Therefore, increasing the renewables share of the UK energy market seems to be a reasonable option. As the UK aims for sustainable development and carbon reductions, then renewables are likely to have a growing role in the energy market.

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[1] Safety, sustainability, reliability and cheaper prices are the major advantages for nuclear power (Duffy, 2005). Deutch (2005) also added that, "nuclear power is an important means of diversifying energy supply and reducing carbon emissions" Pasche (2002) also underlined the inevitability of opting for nuclear power in the future for policy makers.

2.2 Zero carbon technologies

The UK has great potential in some renewable energy resources in comparison with the other European countries. The potential of wind energy in Scotland (Riso, 2000) and biomass developments (Elliott, 2003) might be able to compete with fossil fuel in the market in the long term. However, their electricity price, intermittency issues and visual amenity considerations are major challenges that add a considerable uncertainty in their development process.

UK energy production from renewables has gradually increased, as shown in Figure 4. However, AEA (2011) has identified three possible scenarios [see Figure 5], which clarify that the UK might not necessarily be able to maintain this growth. Therefore, it is not clear yet to what extent renewables can contribute in the energy market, although this share is not predicted to be less than 15% AEA (2011).

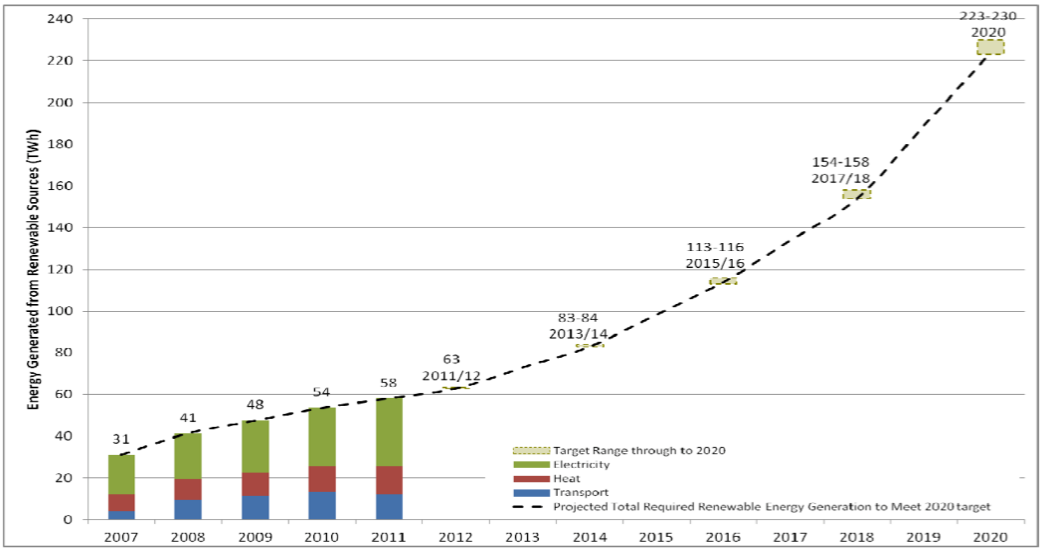

Figure 4 Development in renewable energy supply, source: (DECC, 2012)

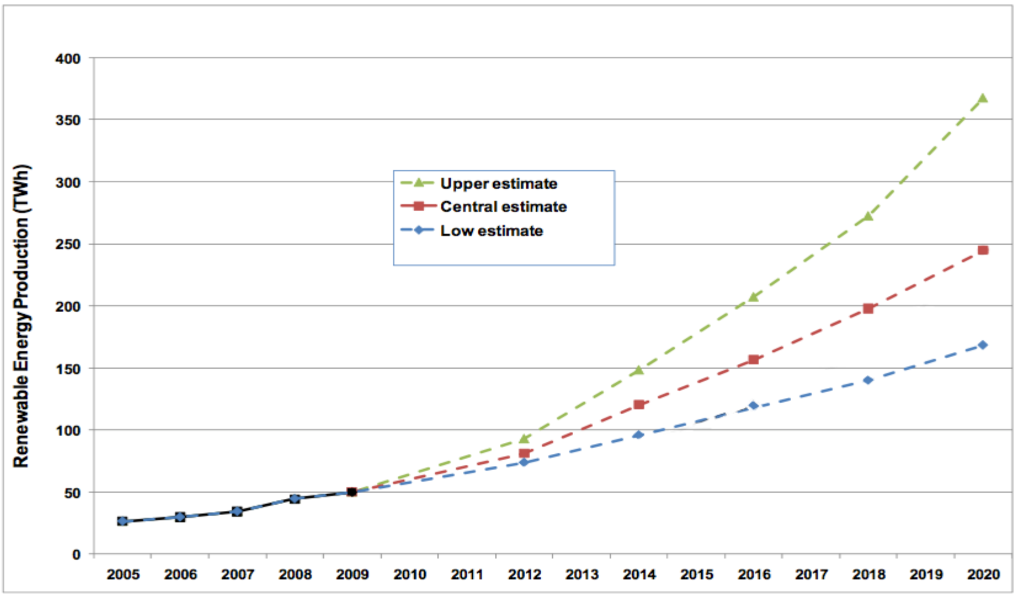

Figure 5 UK renewable energy production 2005 to 2020, source: (AEA, 2011)

Another significant reason for the remaining uncertainty in developing renewable energy technologies is likely to be in terms of their commercialism, as some renewables are not yet completely developed (Foxon, et al., 2005) and therefore predicting their exact share would not be possible in the long-term. Figure 6 illustrates the commercial maturity of renewables.

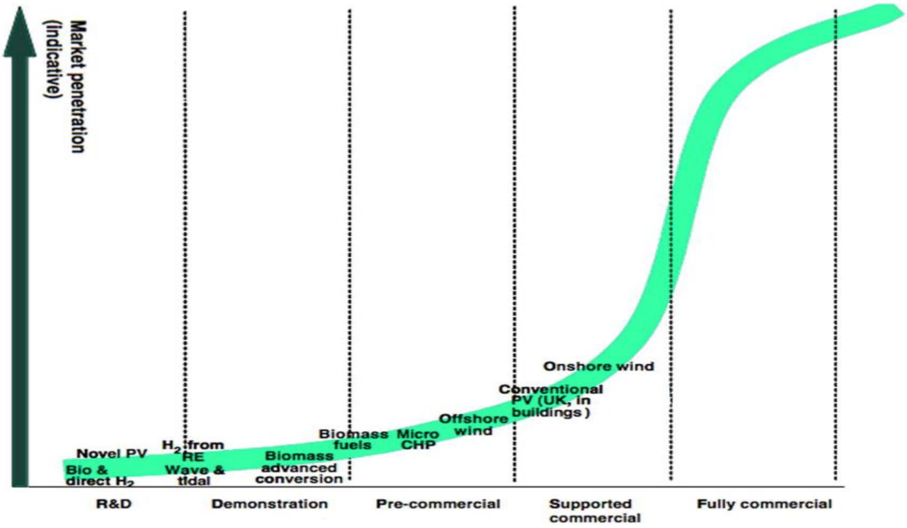

Figure 6 Commercial maturity of renewables, source: (Foxon, et al., 2005)

It seems that solar photovoltaics (PV) and wind turbines have been more successful in comparison with other renewables. This could be due to the UK Government’s energy policy in developing solar and wind energy. However, widespread adoption of these technologies are still relatively new and their market risks are still high in comparison with fossil fuels and nuclear power. The risk is related to the uncertainty in supporting policies and regulations in energy markets. What is not clear is whether supporting schemes can reduce the risks for long term investment attraction in this sector. However, short-term policies, until 2020, seem to be likely to succeed (Higgs, et al. 2008).

Other renewables, such as biomass, are not at the same level as wind and solar in terms of market maturity and will require high levels of technology to compete with others in energy market (Foxon, et al., 2005). Therefore, it is uncertain whether renewables other than wind and solar can have any possible effects on short and long term energy decision making.

2.3 Gaps, risks and future expectations

At different levels, there are a number of technologies in the UK renewable energy plan. Although some successes have been achieved thus far, current systems are not able to bring all of the available technologies to a successful market. Technologies might develop toward technical and commercial maturity as a result of systemic relationships between a range of stakeholders. However, irregular failure might happen during these phases (Foxon, et al., 2005), such as:

- Shift from demonstration to pre-commercialization level
- Shift from pre-commercialization to commercialization level

Failures and gaps might take place in both phases, but Kemp et al (1998) stated that '*Policy incentives which create and support market may help to bridge this gap*'. However, incentives levels should be sufficient to control the price. Transitions between any of the above mentioned phases have considerable levels of uncertainty that could make technologies unfeasible for large-scale development. Meanwhile, major risks in this transition are categorized below (Kemp et al, 1998)[2]:

- Technology risk; whether acceptable performance is achievable or not

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[2] As a consequence of uncertainty in any categories of supports from government, different influences may affect project finances due to the risk involved. This indicates that any support require a perseverance to secure the implementation agenda whilst technologies can develop toward commercialization. Additionally, a clear policy is required to secure the stability of the framework to reduce uncertainty for long-term period. In such levels, in order to have more ability to reduce future risks, exit strategies should also be clarified and redlines for technologies should be demonstrated, as supports could be withdrawn if the technologies failed to become commercially feasible

- Market risk: whether reasonable future finance can be provided by markets to develop technology or not
- Regulatory risk; whether regular changes from policy makers can make markets remain adopted
- Systems risk; whether the necessary changes can be developed properly (this might be more serious for disruptive technologies like biomass)

Although energy companies are keen to support green energy markets, they are concerned about profitability. Basically, the question is to what extent the energy market can support considerable quantities of renewables. The answer for this question would demonstrate the role of renewables in the long term and their potential impacts on design-decision making. It is clear that the interaction between government policies, market and technology development will decide the role of renewables in future.

Theoretically, climate change and energy security are significant concerns for energy suppliers. Both energy efficiency options and environmentally friendly renewables are effective solutions for environmental concerns and energy consumption reduction, but the cost of new electricity generating technologies is of decisive importance. Figure 7 demonstrates the estimated cost of new electricity generating technologies in 2007. It seems that the cost of generating electricity from renewables is higher than the other resources, thereby increasing the risks regarding their future development.

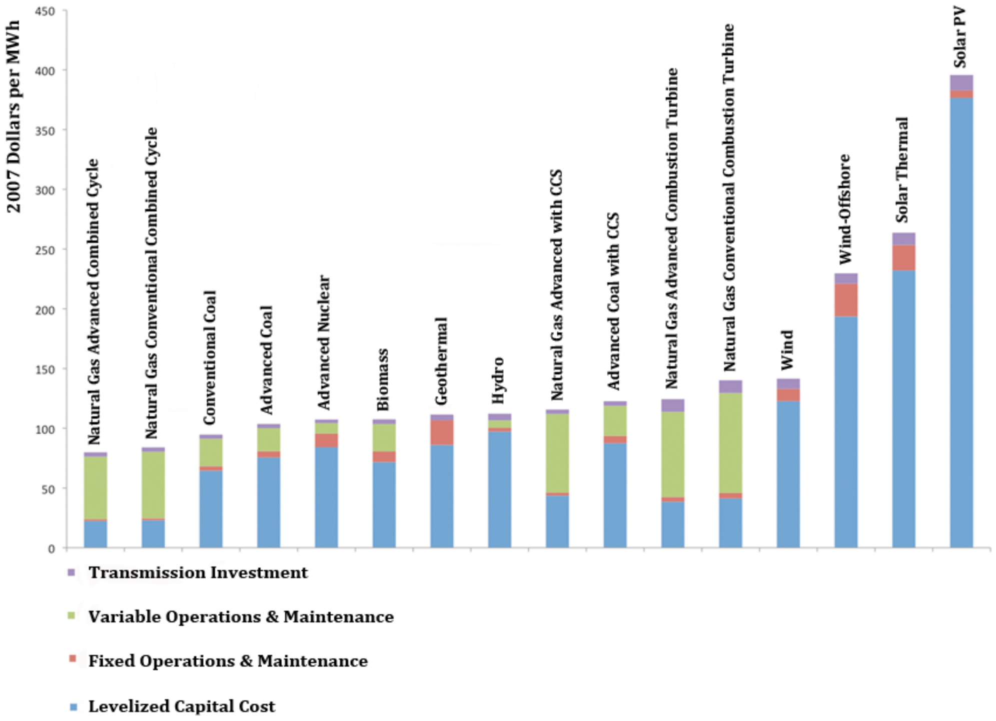

Figure 7 Estimated cost of new electricity generating technologies. (source: http://www.eia.gov/oiaf/aeo/electricity_generation.html)

There is quite less pressure from energy markets to develop cheaper options rather than expensive wind and solar technologies. However, Figure 7 does not consider comprehensive cost analysis and ignores negative environmental impacts as well as possible accidents that might exist in cheaper options[3].

Furthermore, the European Union Emission Trading Scheme (EU ETS) arranged a price on carbon emissions, which means that each company that exceeds their limit in carbon emissions is obliged to buy permits (Greenhalagh & Azapagic, 2009). These regulations are meant to limit carbon emissions but will also add extra risks to the costs. Figure 8 shows carbon emissions generated from each type of energy resources.

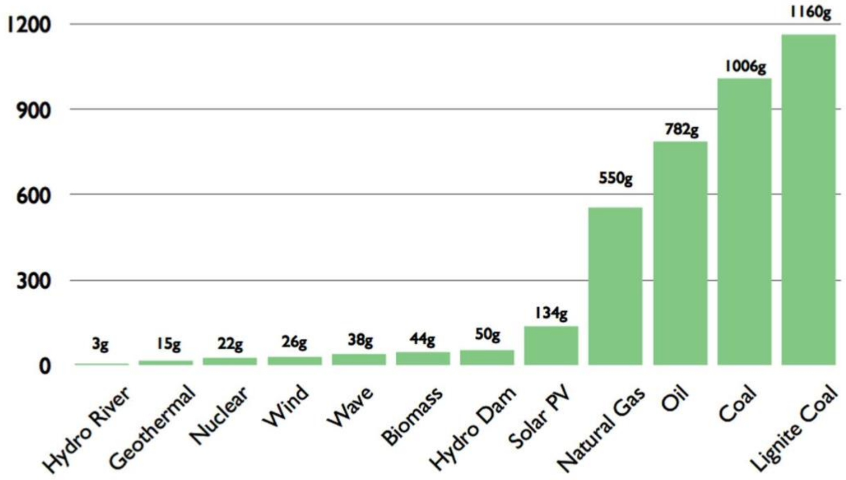

Figure 8 Greenhouse gas emissions (g CO_2-3q. /kWh) from each type of energy resource, source: http://www.iaea.org/Publications/Booklets/GreenhouseGas/greenhous egas.pdf

Not only is the security of energy resources for the UK important, but also carbon emissions reduction.[4] In terms of energy supply, reducing carbon emissions and efficiency, none of the other fossil fuel energy resources can compete with nuclear. Furthermore, there is a capability of upgrading to higher outputs whenever needed

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[3] Both environmental impacts and accidents risk should be included in every cost assessment of nuclear power development. However, a major problem is that there is not a generally agreed calculating methodology for these types of risks. Therefore, it stills remain uncertain for any further prediction (Joskow, 2006).

[4] In 2007, the UK Prime Minister announced that ‘It is not possible for Britain to rely on an energy policy that makes the country wholly dependent on one or two countries in the world. That is why we have to continue with nuclear power’ (NEI, 2007). Furthermore, in 2008, the UK energy minister also mentioned that choosing nuclear energy is a crucial step in climate change policy (Hansard, 2008).

(Loannis, 2010). Therefore, it is unlikely that there will be no share of nuclear power in UK energy market in the short and medium term. This is also verified by RCEP (2000) that ‘if the aim is to reduce carbon emissions by 60% until 2050, then every scheduled nuclear station closure is a direct conflict to climate change’.

Furthermore, the World Energy Council (2010) clarified that uncertainty would remain in developing nuclear energy until 2020 and stated that ‘if the energy innovation effort in the future stresses on improved energy efficiency, renewables, and the decarbonized fossil energy strategies, then by 2020 it will much more feasible to know than now if nuclear power will be required on a large scale to meet sustainable energy targets’.

2.4 Further aspects

Another barrier in front of UK government for expensive renewables (and perhaps a stimulus for developing cheaper options) is the final energy price. Almost 2.5 million households in Britain confront fuel poverty, which means that they have to spend more than 10% of their income on energy necessities to heat their accommodations (BERR, 2007(b)). Clearly, these fuel-poor households add to the concerns as to whether expensive sources of energy can shape a considerable part of future electricity generation. Fuel poverty certainly adds to the need to reduce domestic energy consumption, at least until a reduction has taken place in price of electricity generation from renewables. Figure 9 demonstrates the percentage spent on energy from an average weekly income in UK.

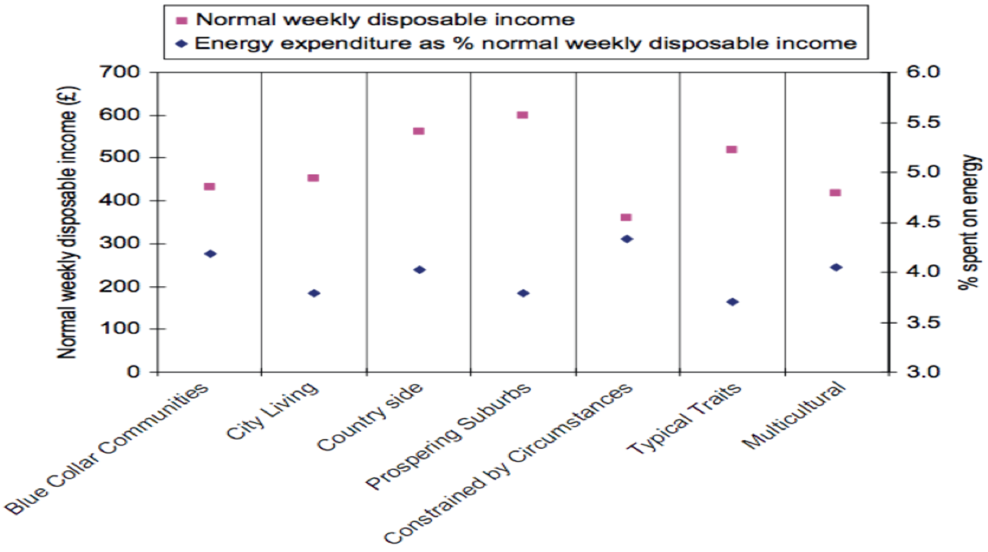

Figure 9 Percentage spent on energy from average weekly income. Source: (Jackson & Druckman, 2008)

As it can be seen from Figure 9, energy costs play an important role in UK household budgets. Therefore, a building's energy performance, household income and energy cost are important issues that might cause changes in energy trends.

There are different approaches to predicting energy policy trends and each of them has particular methodologies. In order to articulate how extreme the uncertainty in this category could be, this study has chosen the most commonly used examples of them. These predictions are categorized in two different approaches of (i) transition pathway (version 1.1) and (ii) MARKAL model.

2.5 Transition pathways to a low carbon UK

An association of UK engineers, policy and social analysts has been developing a range of 'transition pathways' to a low carbon economy by 2050. Past transitions are utilized to predict future transitions and possible scenarios that form the basis of characterizing the current energy systems, recognizing dynamic processes and identifying interactions that might influence transition pathways. Three selected pathways are as follows (Foxon, et al., 2010):

- Market rules (MR)

Theoretically, this assumption is based on the market domination pattern and minimum possible interference from government, in which the government specifies the aims of the system and sets up institutional structures. Large energy companies are expected to dominate and pressures such as energy security and climate change cause companies to choose carbon emissions reductions and focus on large-scale technologies, such as nuclear power, carbon capture-ready coal and offshore wind. This means that small-scale renewables will fail to grow in the energy market. Carbon Capture Storage (CCS)[5] technology will develop from 2020, and with high carbon price, nuclear and large-scale renewables become cost effective (Allen, et al., 2008) [see Figure 10].

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[5] Carbon Capture and Storage (CCS) is a technology that can capture up to 90% of CO_2 emissions from the usage of fossil fuels, preventing emissions from entering the atmosphere
(Allen, et al. 2008)

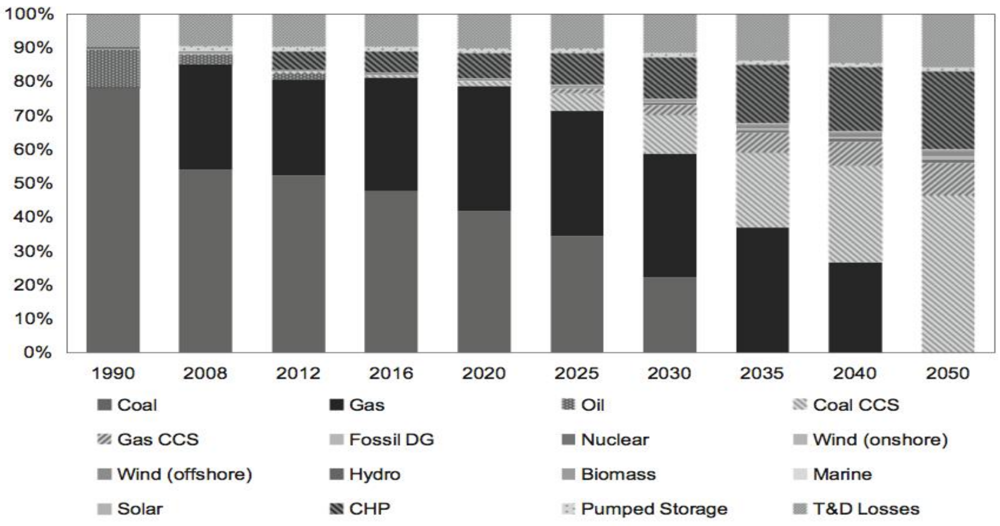


Figure 10 UK power generation from 1990-2050 under the 'Market rules' assumptions. Source: (Geoffrey, et al., 2013)

- Central co-ordination (CC)

In this assumption, the opposite of MR, government has dominance over energy systems but the focus will still be on carbon reductions and centralized generation technologies such as CCS, onshore and offshore wind, etc. There will be a minor emphasis on small-scale technologies too, but still not considerable (Foxon, et al., 2010) [see Figure 11].

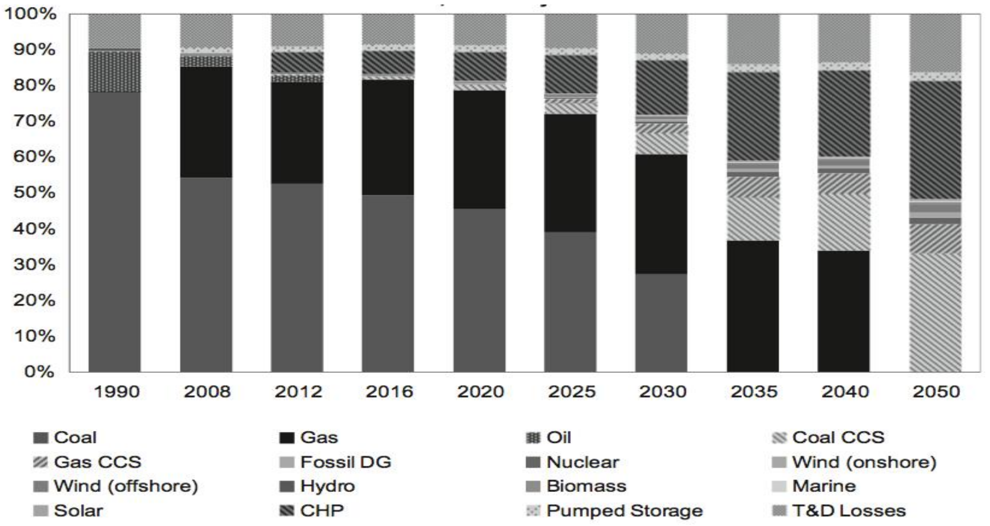


Figure 11 UK power generation from 1990-2050 under the 'Central co-ordination' assumptions. Source: (Geoffrey, et al., 2013)

- Thousand Flowers (TF)

In this assumption, the focus is more on local energy resources such as solar PV, wave and tidal, and small wind turbines, rather than large scale ones, but their share would not go more than 50% of total power generation. The other 50% will be generated from centralized sources of energies (Foxon, et al., 2010) [see Figure 12].

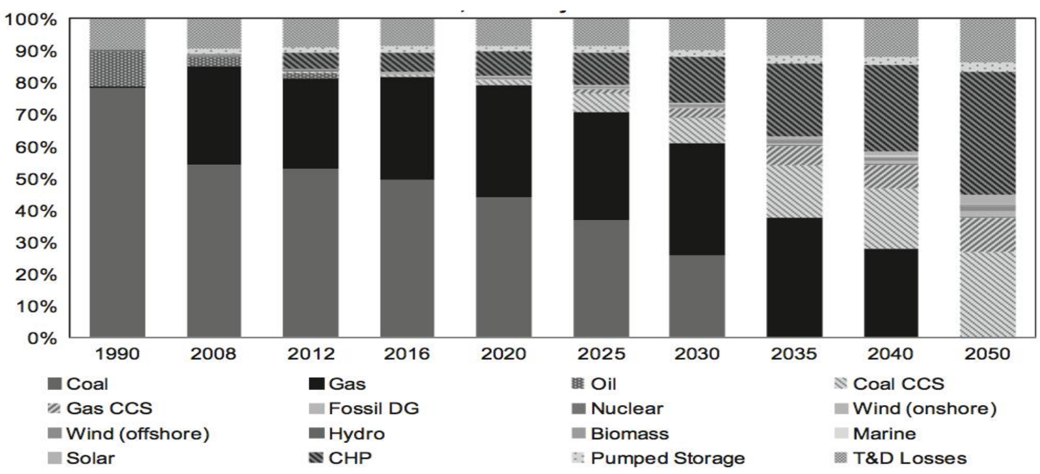


Figure 12 UK power generation from 1990-2050 under the 'Thousands flowers' assumptions. Source: (Geoffrey, et al., 2013)

As the basis of transition pathways are hypothetically in the direction of less environmental impact, this model uses a life-cycle approach as a major criterion to evaluate the "what if" analysis results.

2.6 Life Cycle Assessment

ISO 14040 (2006) describes Life Cycle Assessment (LCA) as 'A technique for assessing the environmental aspects and potential impacts associated with a product'. The LCA aim is generally to recognize opportunities to improve environment by identifying the most important impacts (Allen, et al., 2008). Energy, pollutants and materials as a result of an activity or product are quantified in full LCA assessment (Heijungs, et al., 1992).

LCA includes four main stages of scoping and goal definition, inventory analysis, impact assessment and recommendations (ISO 14040, 2006). Therefore, in each study different categories (such as climate change, acidification, eutrophication, ozone depletion, etc) might be under focus and for the assessment purposes every classification in each category (for example, CO_2, NO_2 in the climate change category) is weighted by eco-points (Pts) (Khasreen, et al., 2009). Figure 13 demonstrates the assessment of three transition pathways by LCA.

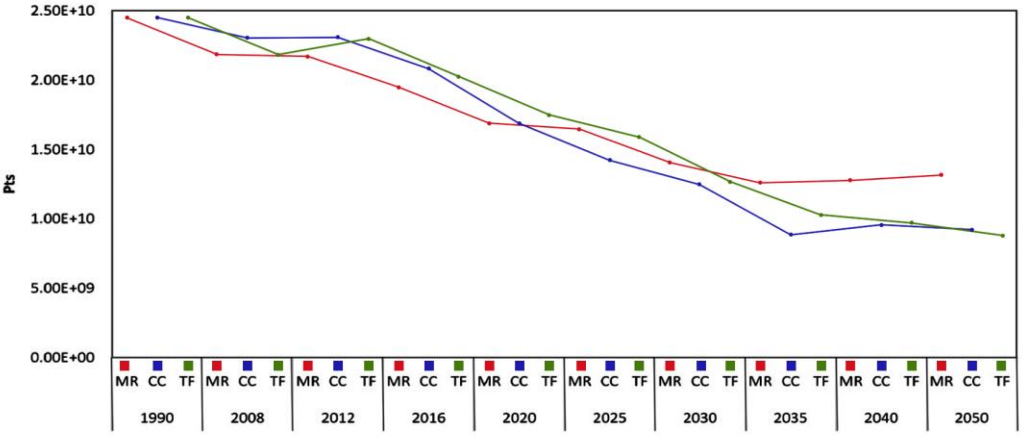


Figure 13 The assessment of three transition pathways by LCA. Graphic by author, data from Geoffrey, et al., (2013)

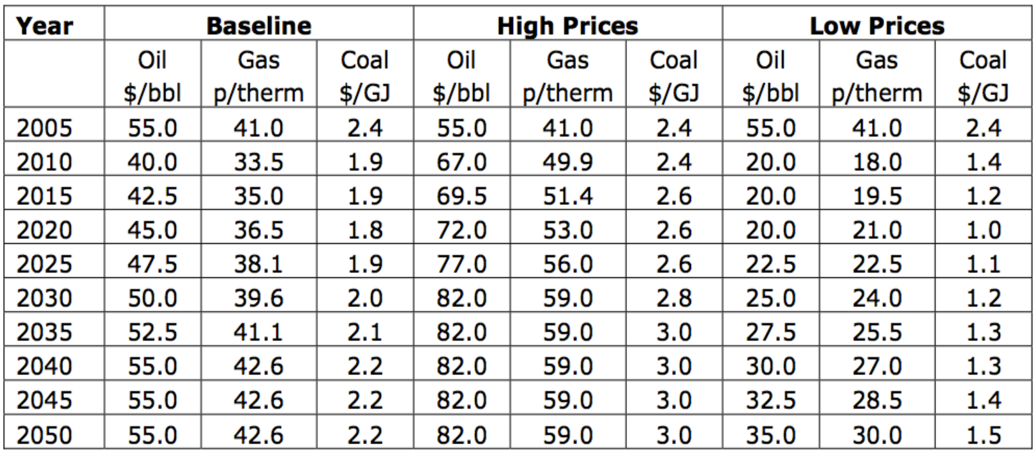
It can be seen that there is no considerable difference between the transition pathways until 2035, but after that MR would have the most negative effects in terms of LCA assessment, although all three pathways would have less impacts in comparison with previous years. However, the amount of uncertainty is quantifiable from a LCA point of view and there is a certainty that all of the transition pathways will gradually become more environmentally friendly.

2.7 MARKAL energy system modeling

The UK MARKAL model (acronym for MARKet ALocation) is a widely used dynamic programming model that was developed in the 1970s and continuously supported by the International Energy Agency (IEA). Basically, MARKAL represents the whole UK energy system from domestic production of fuel resources and imports through the supply and fuel processing, infrastructures, conversion to secondary energy carriers and energy service demands in residential, commercial, industrial, transport and agricultural sectors and end-use technologies (UKERC, 2008).

MARKAL is not necessarily a predicting model but that does not mean that it cannot be calibrated to the available projection forecasts in the short and medium terms. It is an organized tool to investigate the trade-offs between energy supply, emissions, energy system pathways and the cost. In general, it seeks to quantify sensitivities through a “what-if” analysis. UK MARKAL is adjusted on its base year (2000) to figures within 1% of actual energy consumption, resource supplies, installed technology capacity, electricity output and CO_2 emissions. MARKAL then improves, via 5-year increments through to 2050 (DUKES, 2006). In terms of energy prices, Table 1 shows fossil fuel import price estimation in three different scenarios of Baseline, High and Low prices until 2050 (DTI, 2006).

Table 1 Fossil fuel import prices, Source: (UKERC, 2008)



Year	Baseline			High Prices			Low Prices		
	Oil $/bbl	Gas p/therm	Coal $/GJ	Oil $/bbl	Gas p/therm	Coal $/GJ	Oil $/bbl	Gas p/therm	Coal $/GJ
2005	55.0	41.0	2.4	55.0	41.0	2.4	55.0	41.0	2.4
2010	40.0	33.5	1.9	67.0	49.9	2.4	20.0	18.0	1.4
2015	42.5	35.0	1.9	69.5	51.4	2.6	20.0	19.5	1.2
2020	45.0	36.5	1.8	72.0	53.0	2.6	20.0	21.0	1.0
2025	47.5	38.1	1.9	77.0	56.0	2.6	22.5	22.5	1.1
2030	50.0	39.6	2.0	82.0	59.0	2.8	25.0	24.0	1.2
2035	52.5	41.1	2.1	82.0	59.0	3.0	27.5	25.5	1.3
2040	55.0	42.6	2.2	82.0	59.0	3.0	30.0	27.0	1.3
2045	55.0	42.6	2.2	82.0	59.0	3.0	32.5	28.5	1.4
2050	55.0	42.6	2.2	82.0	59.0	3.0	35.0	30.0	1.5

The model does not predict considerable changes in Baseline scenario but in low and high prices scenarios the rates shows considerable fluctuations. It seems that the amount of uncertainty is high in this aspect. In terms of energy demand, the model prediction of yearly growth rates for service demand is shown in Table 2 for 2000-2050.

Table 2 Service demand yearly growth rate for end-use sectors, 2000-2050 (UKERC, 2008)

	2000-2030	**2030-2050**
Space Heating	0.70 %	0.04 %
Cooling	9.13 %	2.73 %
Water Heating	0.50 %	0.31 %
Lighting	0.83 %	0.49 %
Refrigeration	0.84 %	0.49 %
Cooking hob	0.83 %	0.49 %
Cooking oven	0.83 %	0.49%
Other Electrical	0.88 %	0.52 %
Chest freezer	0.72 %	0.43 %
Upright freezer	0.98 %	0.57 %
Fridge freezer	0.86 %	0.51 %

It seems that a considerable decrease in growth rate from 2030 onwards will take place. This is highly likely related to the technology improvement in appliances and building standards or behavioral change.

Since projecting the evolution of the UK energy system until 2050 is a complex task, a number of scenarios were examined to develop a range of estimates. However, UK Energy Research Centre (UKERC) was chosen to form the purpose of this Chapter as their objectives (60% reduction by 2050 and the role of international drivers) and their sensitivity analysis scope (fuel prices, availability of technologies and resources, rates of innovation and overseas credits) are more comprehensive and feasible to achieve in comparison with the others such as the Institute for Public Policy Research (IPPR) with the aim of 80% carbon reduction by 2050. (Stracham, et al., 2009)

All the scenarios are not meant to provide a prediction of what could happen from now until 2050, but they will provide a systematic 'what-if' analysis to deliver reductions in carbon emissions and possible costs. A full set of scenarios and the description of the selected scenarios are given in Table 3 (UKERC, 2008).

Table 3 Set of MARKAL scenarios, Source: (UKERC, 2008)

Scenario	Scenario Description
M-BASE	Base (MARKAL)
M-C60	60% CO_2 reduction applied as 30% decrease in 2030 and in a regular path to 60% in 2050
M-C60SLT	60% CO_2 reduction as straight line from 2010
M-BASE H	The same as M-Base with high global resource prices
M-BASE L	The same as M-Base with low global resource prices
M-C60 H	The same as M-C60 with high global resources price
M-C60 L	The same as M-C60 with low global resource price
M-Base_R10	The same as M-Base with innovation restricted to no technologies beyond a 2010 level
M-Base_R20	The same as M-Base with innovation restricted to no technologies beyond a 2020 level
M-C60_R10	The same as M-C60 with innovation restricted to no technologies beyond a 2010 level
M-C60_R20	The same as M-C60 with innovation restricted to no technologies beyond a 2020 level
M-C60_NN	The same as M-C60 with no new nuclear
M-C60SLT_NN	The same as M-C60SLT with no new nuclear
M-C60SLT-nCN	The same as M-C60SLT with no new nuclear nor Carbon Capture Storage technology (CCS)

Table 3 shows different range of predictions that can be generated to estimate the likelihood of electricity generation in future by implementing MARKAL model and the integrated scenarios. The major assumptions are demonstrated in detail from Figure 14 to 18.

Figure 14 shows details of electricity generation for the M-Base. As shown, gas and coal are the major sources up to 2020, after which coal would be the major source and the role of renewables would slightly increase due to the falling costs and incentive policy development. Nuclear power has no share after 2020 as existing plants are retired and no new build is expected (UKERC, 2008). The domination of coal might be because of decreasing price prediction in low prices and baseline prices as shown in Table 1. Even in a high price scenario the price of coal is not going to increase considerably.

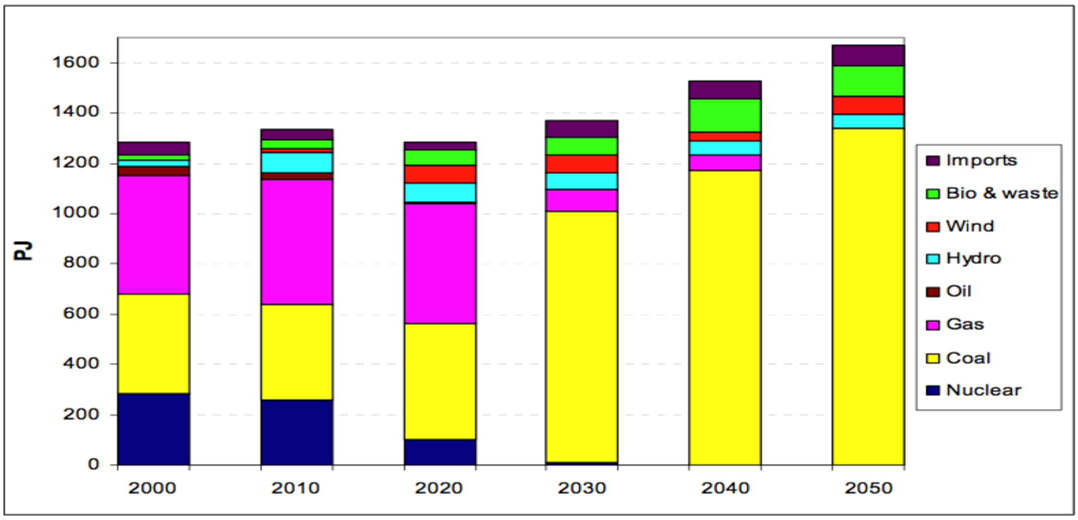


Figure 14 Electricity generation: M-Base scenario (2000-2050), Source: (UKERC, 2008)

Figure 15 illustrates the predictions in M-C60 scenario (CO_2 constrained scenario), which shows Coal CCS plants have the major share in electricity generation from 2030. There is a considerable share for nuclear power (new generations) and the same as M-Base, the share of renewables increases considerably and the wind energy seems to be dominant in renewables share.

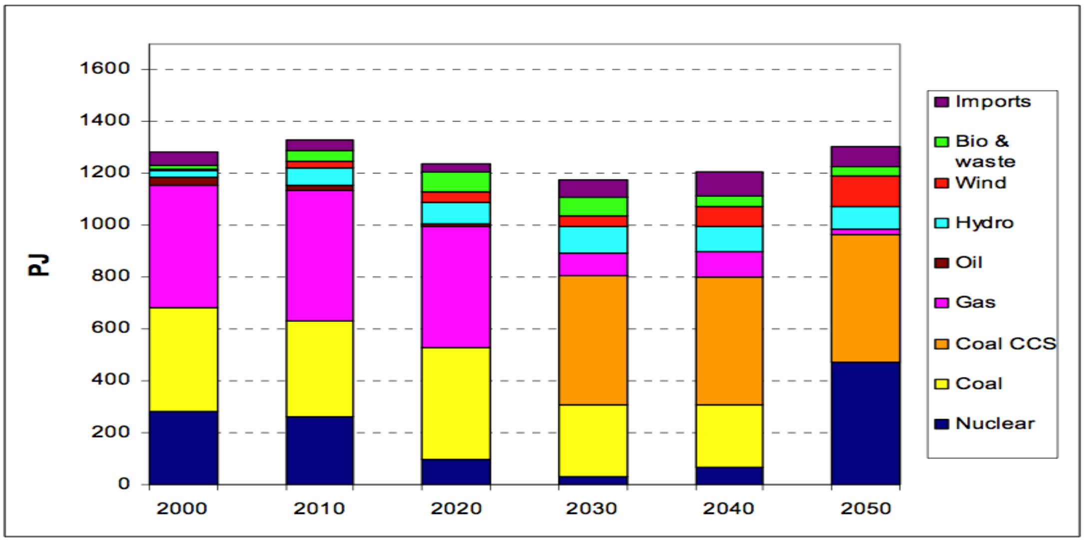


Figure 15 Electricity generation: M-C60 scenario (2000-2050), Source: (UKERC, 2008)

More scenarios in electricity generation are compared in Figure 16 in 2050. The uncertainty is high, and there are considerable differences between them. However, the growth of renewables, domination of fossil fuels and considerable share of nuclear power in most of them is remarkable.

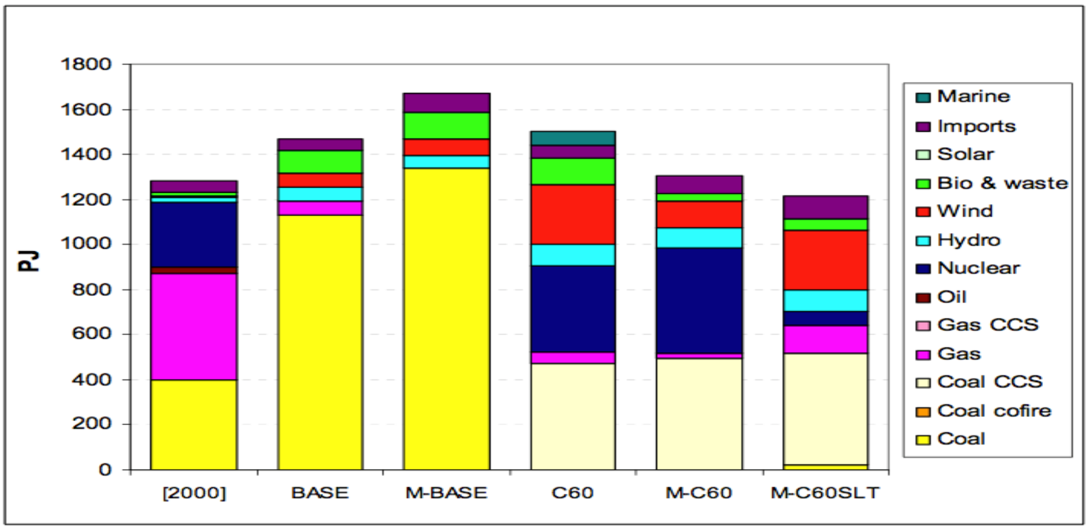


Figure 16 Electricity generation: 2050 comparison, Source: (UKERC, 2008)

Figure 17 compares the M-Base and M-C60 case with high and low resource cost scenarios. The differences are the share of gas and renewables. The share of gas in the low price scenario will increase and in the high price scenario will decrease considerably. The role of prices does not seem to have an major effect in electricity generation for mentioned scenarios in 2050.

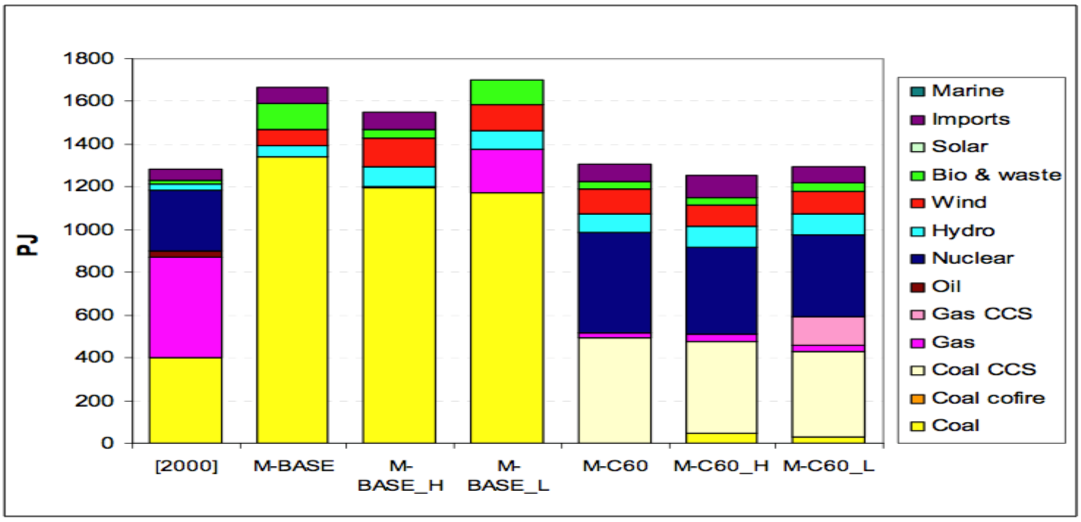


Figure 17 Electricity generation: resource prices – 2050, Source: (UKERC, 2008)

Figure 18 compares M-Base and M-C60 case with the scenarios that consider technology evolution. It seems that the effect of technology is fundamentally higher than prices that might totally change the predictions, which predicts more share for renewables and lower share for fossil fuels.

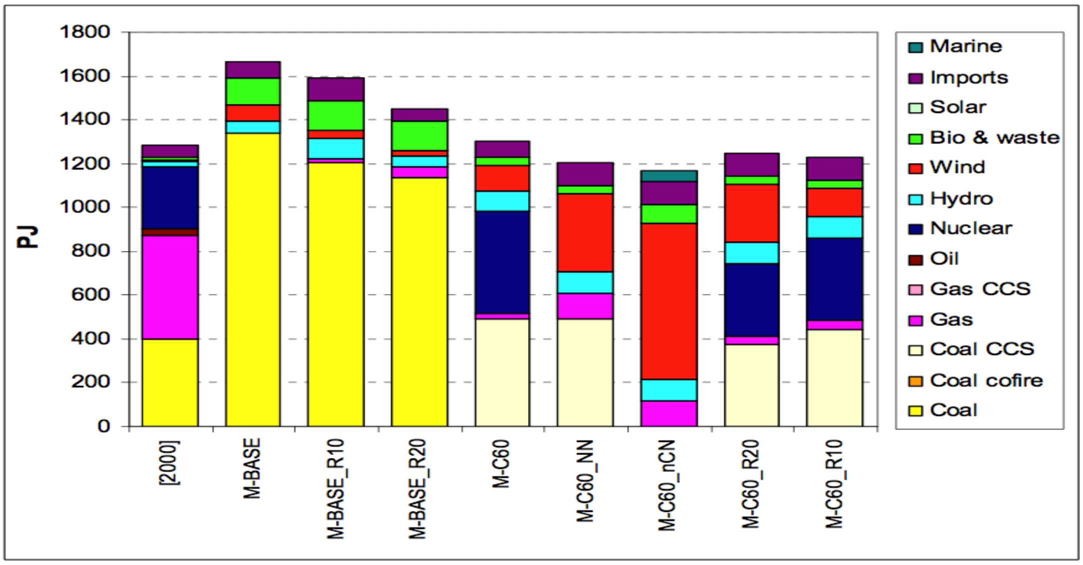


Figure 18 Electricity generation: technology scenarios -2050, Source: (UKERC, 2008)

Due to several influential factors on energy policy, such as technology improvement and price, the amount of uncertainty is clearly high when developing a clear picture for midterm and long-term period. However, for short term period a slightly increase in renewables, stability in nuclear share and a slight decrease in fossil fuels imports are expected. Besides, it is unlikely that the UK can achieve its ambitious target in carbon reductions without nuclear power. Therefore, any prediction that does not consider nuclear power development does not seem to be feasible.

If renewables became dominant energy resources in 2050, this would considerably affect design decision-making, as they are a free resource source of energy. However, substantial uncertainties remain for future technology costs and the relative infrastructures for them. If renewable technologies remain immature then the role of fossil fuels and nuclear power will be dominant. In all scenarios, less energy consumption would lead to improved energy security, lower imports and lower environmental risk. Therefore, it is important to develop sustainable design standards in building construction (a major energy consumer) and provide a guideline of how the industry would behave in the future to determine the optimum course of action today.

2.8 Summary

- The MARKAL model and low carbon transition plans provide valuable insights for the midterm period but both fail to have a comprehensive approach for energy modeling as they ignore political aspects.

- Reducing dependency on fossil fuel imports to decrease uncertainties and improve future decision-making policies seems feasible, although some predictions expect price reduction for them.

- In the short term, it is highly unlikely that wind and solar energies can play key roles in the UK renewable energy market. It is also highly unlikely that the other sources of renewables can have a considerable share in the short term as there are several issues that still remain uncertain in terms of technology maturity, and prices, etc. Presently, PV panels are an expensive option to integrate into the buildings design; however, it is expected that, assisted by UK government incentives, they can play a role in the short term, especially if Building Integrated PVs (BIPVs) and replacement roofing materials become more mainstream in the construction industry.

- In general, it is expected that an overheating risk will add to the desire for energy consumption, which could increase carbon emissions from fossil fuels. Current model predictions and literatures are unable to provide a definitive picture of how renewable in UK might offset this increased demand. Therefore, it is reasonable and sensible to decrease energy demands and tackle the risk of overheating by passive design options. This approach forms the key focus of this study.

- This study started in 2011 and at the time of the study the most recent information was provided in this Chapter. However, although where possible some information were updated accordingly later on, some may remained the same by the time of submitting this thesis in 2015. Therefore, in some cases some changes have happened. For example, Renewable Obligation as stated in page 7 is no longer valid.

3. SUSTAINBLE DESIGN, STANDARDS AND APPLICABILITY

The UK Climate Change Act of 2008 set an ambitious target of an 80% reduction in carbon emissions below 1990 levels by 2050 (UK Parliament, 2008). As a result, numerous policies have been adopted towards a considerable decrease in carbon emission from British housing (DCLG, 2008). In December 2008, zero carbon houses had been defined by government on the basis of the following categories (DCLG, 2008):

- Energy efficient fabric
- Efficient heating and cooling services
- Other practical solutions to deal with remaining emissions such as appliances

The residential sector is now responsible for almost half of UK carbon emissions (UKGBC, 2008); therefore, it is an important time to encourage the implementation of environmentally friendly strategies in construction. This Chapter serves to review passive design elements and addition to building standards that will help to improve comfort levels and reduce energy consumption in UK housing. This and the next Chapter provides:

- The current design implications and sustainability approaches in buildings
- Current paths in the modernization and promotion of construction methods in the UK

3.1 Energy efficient, environmentally-friendly and sustainable buildings

Nowadays, sustainability and high performance buildings seem to be gaining significant momentum. The ASHRAE Standard 189.1 defines the high performance green building as a "building designed, constructed and capable of being operated in a manner that increases environmental performance and economic value over time"[6]. However, one of the basic challenges in the long run is uncertainty, and since sustainability by any definition refers to the long run, the question arises how to describe and manage sustainability under uncertainty. In this interaction the following must be answered:

- What are the factors that need to be sustained?
- At what level and for how long are they to last?
- Under what degree of uncertainty?

Indeed, sustainability is about thoughtful choices, without spending more on non-

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[6] ASHRAE standard is also used further in this study for thermal comfort analysis because the software available to the author used this standard in calculations.

essential options, with the confidence of earning a return on the investment. In a general sense, it is about dealing with nature – not ignoring it. Additionally, it is not about constructions that are apparently environmentally responsible but which eventually sacrifice occupant comfort.

It has become clear, therefore, that ‘Sustainability in Buildings’ is a multi-criteria subject, which includes interlinked parameters of economics, environmental issues, and social parameters (Vesilind, et al., 2006). To achieve sustainability, development steps are needed. Therefore, a methodology of several steps towards environmental protection and energy conservation in buildings should be considered. The initial step is to focus on standard methods of energy efficiency, which are economically achievable. The second step is to support the energy-savings measures, which are environmentally friendly. The third step is to find a balance between present and future energy needs and environmental necessities whilst, at the same time, saving energy resources and preserving the environment for the future. Therefore, three types of buildings can be classified according to the proper steps mentioned (Chwieduk, 2003):

- Energy-efficient buildings
- Environmentally-friendly buildings
- Sustainable buildings

3.1.1 Energy-efficient buildings

Energy efficiency is introduced by building standards energy requirements. The average yearly energy requirement for space heating and cooling is defined in the form of thermal-energy consumption factors for space heating and cooling articulated in energy [kWh] per square metre of heated area per year.

3.1.2 Environmentally friendly buildings

Building standards affect building energy consumption. The energy-efficient building’s thermal properties and heating and cooling systems should be in a proper condition to facilitate the building to consume less energy and, consequently, benefit the environment. However, a significant issue for the environment is the type of fuel which is consumed for energy production, what method is applied for energy conversion and, consequently, how much of the environment is affected as a result of specific energy generation processes, energy transmission and the end-use of the energy.

3.1.3 Sustainable buildings

The approach toward sustainability is developed when all energy performance, environmental and indoor climate standards are met and the proper quality of service is guaranteed. In this case, energy consumption details and environmental effects are implemented by using Life Cycle Analysis (LCA). Therefore, LCA considers environmental and energy effects of the buildings from start to end-use. Undoubtedly, embodied energy-analysis plays a significant part.

Emphasis in sustainable building is generally on three most significant “flows” through a building - water, energy and materials (Anink, et al., 1998). In sustainable buildings, elements of environmentally friendly and energy efficiency factors must be found, However, the emphasis is on quality promotion which includes the following (Chwieduk, 2003):

- Quality of materials
- Quality of indoor environment
- Quality of residential areas

In building evaluation, from a sustainable point of view, utilizing renewables and recycled sources are also encouraged. Renewables and recycled materials can cause minimum environmental impact for the entire lifetime of a building. Consequently, any impacts on the environment caused by the building or the surroundings during creation, occupation and demolition are decreased. Furthermore, quality of life and life in the residential area are strongly connected with the quality of the environment.

Buildings would be self-energy sufficient by utilizing renewables and recycling wastes. However, self-energy sufficient buildings require integrating high-tech systems, which might be economically infeasible. Besides, the embodied energy in relative elements can be high, which may result in raw materials extraction and production as well as their relative systems causing environmental pollution.

Another type of new and energy-efficient buildings is intelligent building. Basically, the name derived from the intelligent Building Management System (BMS). The key target of this system is to operate all systems in the building to guarantee a suitable management of the energy demand, to save energy and to promote comfort levels. Therefore, it would be beneficial from an energy saving point of view. However, occasionally the role of a human being can be lost. Furthermore, cost and embodied energy are significant issues (Chwieduk, 2003).

3.2 Features, design implications and applicability of sustainability approach for buildings

One of an architect’s main functions is to create an environment that has both physiological and psychological effects on the occupants which, in turn, affect human productivity, operational energy and natural resource use. Obviously, local climate characteristics, site location, building orientation and geometry, site location, building envelope and space arrangement are all factors that should be addressed.

Buildings that properly integrate the application of sustainable design generally provide higher level of psychological and physiological advantages for the occupants. This would also affect carbon emissions and resource consumption and result in buildings having a longer life and less maintenance demands.

3.2.1 Passive design strategies

Passive design is a building design approach that uses building architecture to improve thermal comfort and reduce energy consumption. The fundamental aim is to completely eliminate active mechanical system requirements by maintaining occupants comfort (Mikler, et al., 2008). Basically, passive strategies can be categorized to passive cooling, heating, ventilation and day lighting. This section aims to highlight factors that basically shape these categorizations.

3.2.2 Passive heating and cooling

Capturing internal gains and harnessing solar radiation are the basis of the passive way to add thermal energy to the building. Some of the most effective elements that contribute to these include:

- Building shape
- Orientation
- Buffer spaces and double façades
- Space Planning
- High performance windows and window to wall ratio
- External shading
- Thermal mass
- Insulation
- Minimized infiltration
- Mixed-mode heat recovery system

Passive heating strategies might cause the risk of overheating in some cases; therefore, passive cooling strategies are needed to decrease the effects of this risk by removing internal heat gains and blocking solar gains. Clearly, cooling function is achieved by ventilation airflows when the outside air temperature is colder than the building’s internal temperature, therefore these strategies sometimes could be related to each other. Elements that contribute to passive cooling consist of:

- Shading
- Passive ventilation
- Windows type and windows to wall ratio
- Thermal mass
- Ducts
- Passive evaporative cooling

3.2.3 Passive ventilation

Natural airflow patterns are the basis of shaping passive ventilation strategies in order to introduce outdoor air into the space. These kinds of strategies can be taken to enhance airflow and optimize indoor air quality inside the building. As many architectural features have impacts on airflows through a building, passive ventilation should be considered early in the design process. Design features must achieve a balance between air distribution, privacy/noise concerns and wind effects.

Basically, three different approaches for passive ventilation exist, which include: single sided window, cross ventilation and stack effect and atrium in larger buildings (Figure 19). Therefore, most effective passive elements that contribute to natural ventilation include the following:

- Windows
- Building shape
- Buffer spaces and double façade
- Lobbies and atriums
- Wind towers
- Orientation
- Space planning and corridor organizations

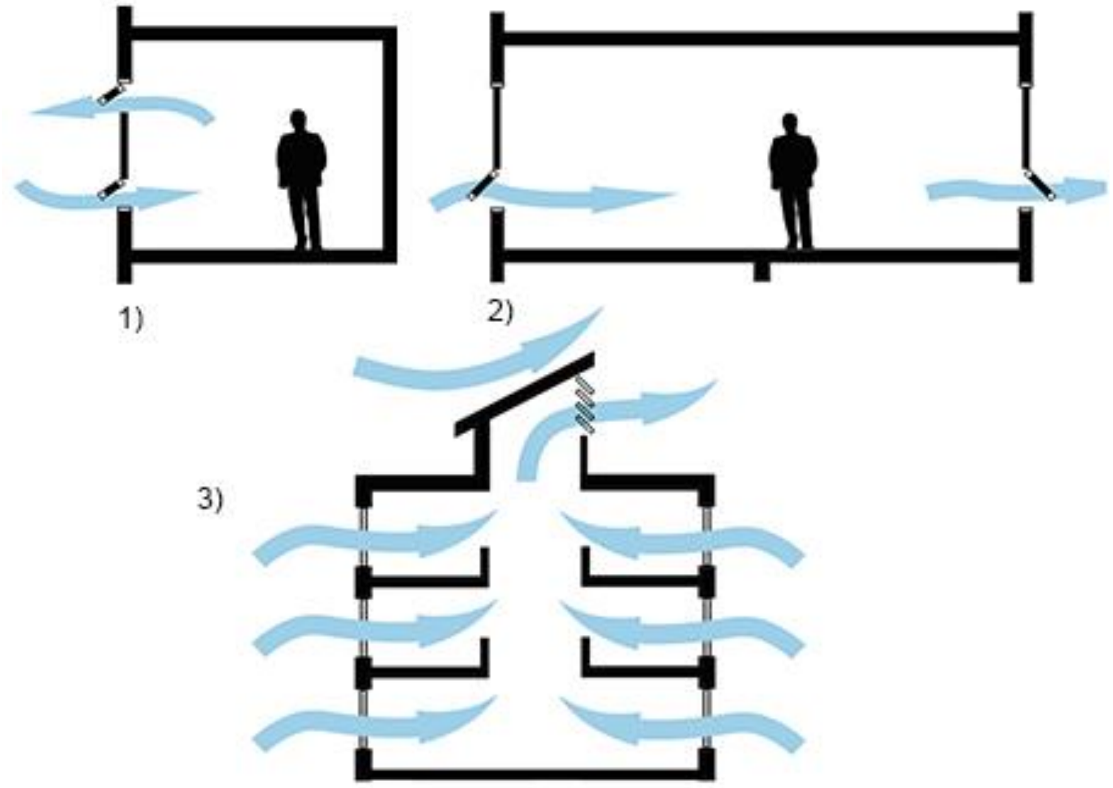

Figure 19 Approaches for passive ventilation; 1) single sided window, 2) cross ventilation 3) stack effect and atrium.

3.2.4 Daylighting

The key advantage of daylighting in terms of energy saving is to reduce electrical lighting energy requirements. Indirectly, it might also have an impact on cooling loads. The most effective elements that contribute to a daylighting strategy are:

- Space planning
- Orientation
- Windows size and windows to wall area ratio
- Interior surface colors
- Skylights and clerestories

3.3 Building standards

Building standards are necessary documents to provide guidance for designers and building constructors. They typically present a range of regulations for a set of situations; therefore they are usually seen as restrictive and inflexible. The first standard of practice in Britain was published in 1948 and developed to the current regulations (DCLG, 2010). The UK standards apply to refurbishments and new buildings for all industrial, commercial and domestic sectors. The UK technical guidance is ordered from part ‘A’ to ‘P’. This study will only focus on Part L (Conservation of Fuel and Power), Part L1A (new dwellings).

3.3.1 Part L

As this study only concerns thermal performance, it considers the limiting fabric parameters suggested by the standard. The approved Part L document published in 2010 strengthened the U-Values (overall heat transfer coefficient) proposed in 2006 because improving U-Values could improve the level of energy efficiency in buildings (DCLG, 2010). Figure 20 demonstrates the limiting U-Values set by Part L1A 2010.

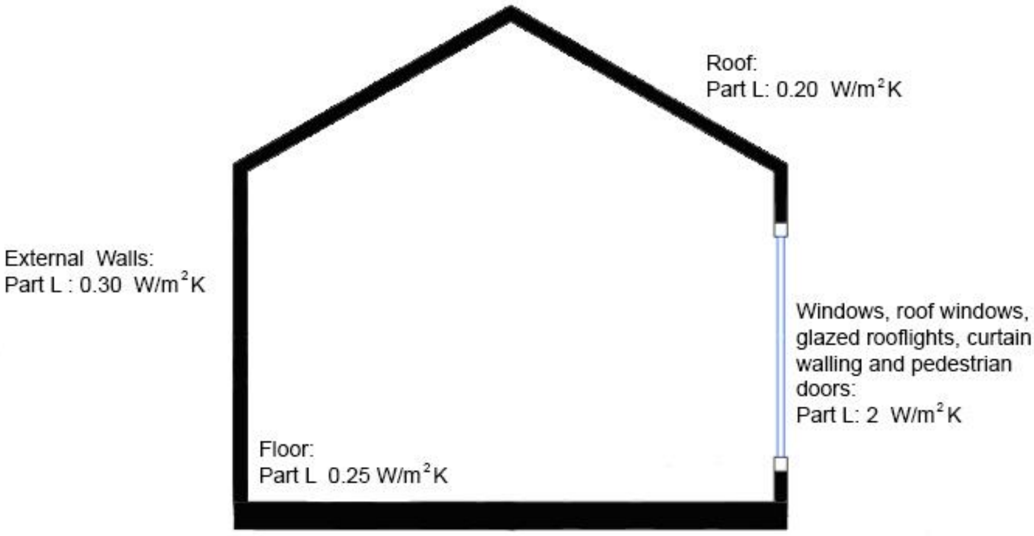

Figure 20 Part L1A 2010 restrictive fabric parameters

The Standard Assessment Procedure (SAP) estimates the annual energy savings of the building in order to illustrate compliance with Part L. Basically, SAP uses Target Emission Rate (TER), Dwelling Emission Rate (DER) and Heat Loss Parameter (HLP) to evaluate a building. Parameters in HLP include external surface area, airtightness and insulation. These values were the basis of the Code for Sustainable Homes (CSH) (DCLG, 2008).

Building codes simply set a minimum standard to design a sustainable building. To address the UK government’s ambitious target to achieve zero carbon houses, the CSH became an aspirational standard to inspire new homes to be built to higher levels of sustainability. Figure 21 demonstrates the present timeline for zero carbon policy (please refer to appendix 1 for larger version).

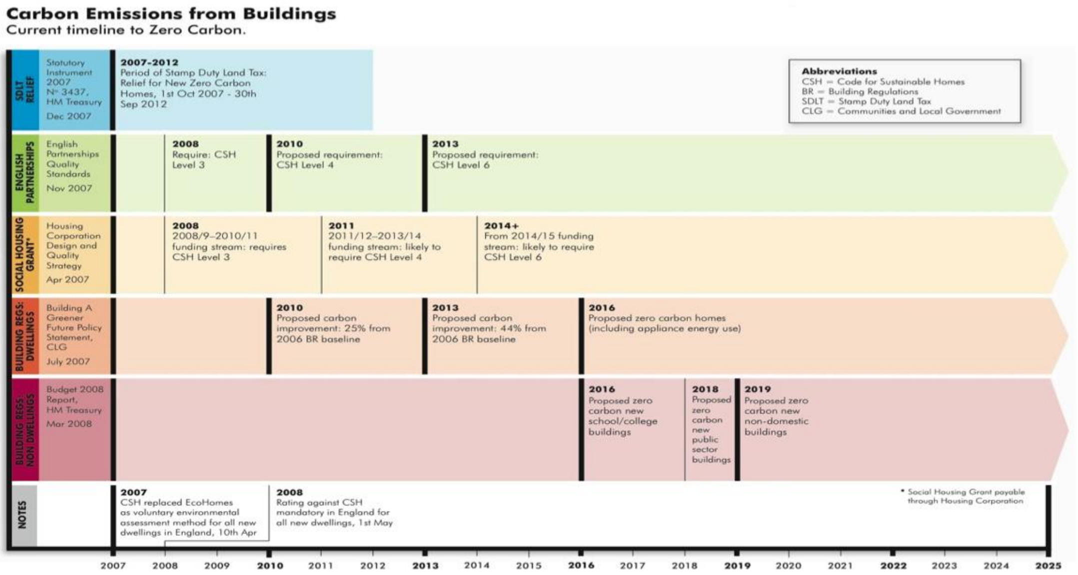

Figure 21 Current timeline to zero carbon, source (UKGBC, 2008)

3.3.2 Code for Sustainable Homes

The CSH was introduced in 2006 and became available in less than a year after in April 2007 and very soon became compulsory in 2008. Basically, this code included nine categories of sustainable design mentioned in Table 4. Table 5 also demonstrates minimum requirement points in each level as well as the improvement over Part LA1 (Percentage reduction in DER over TER) (DCLG, 2010):

Table 4 Categories of environmental impact and contribution of each in total credit

Categories of Environmental Impact	Weighting Factor (% points contribution)	Total Credits in each Category
1- Energy and CO_2 Emissions	36.4 %	31
2- Water	9.0 %	6
3- Materials	7.2 %	24
4- Surface Water Run-off	2.2 %	4
5- Waste	6.4 %	8
6- Pollution	2.8 %	4
7- Health and Well-being	14.0 %	12
8- Management	10.0 %	9
9- Ecology	12.0 %	9

Table 5 Code for Sustainable Homes improvements over building regulations part L

Code Level	Minimum Percentage Improvement in Dwelling Emission Rate (DER) over Target Emission Rate (TER)	Total Points Score out of 100
1	0% (Compliance with Part L 2010 only is required)	36
2	0 % (Compliance with Part L 2010 only is required)	48
3	0 % (Compliance with Part L 2010 only is required)	57
4	25 %	68
5	100 %	84
6	Net Zero Carbon	90

As can be seen, the rating system is divided into 6 levels and in order to achieve higher levels minimum credits should be met. The major disadvantages regarding this standard are:

- Not directly considering passive design measures
- Restrictive with innovative design features
- Difficulty to applying percentages in practice

However, it shows a building’s possible performance in a glimpse and does its job in providing a measure in comparing houses. To give an illustration of how the levels could be achieved, for example, a typical building in Bristol that achieved level 5 has highly insulated walls and roof, low air permeability, high performance windows, rainwater harvesting, green roof, passive solar design strategies, the use of environmentally friendly materials, low energy lighting, PV panels and Mechanical ventilation with Heat Recovery (MVHR) system. Furthermore, the limiting U-Values for walls and roof are 0.1 w/m^2K, windows 1.1 w/m^2K and the air permeability of 1.2 m^3/h@50pa. The breakdown of credits for this building is shown in Figure 22 (DCLG, 2009):

Figure 22 CSH credit levels in each category on the left and view from building on the right. Source: (DCLG, 2009)

The target is to achieve Code Level 6 for all new residential building in UK. Therefore, as seen in the typical building in Bristol, a combination of both passive and active design strategies is needed to achieve the goals. Figure 23 demonstrates values that are required to be achieved for different levels in CSH in comparison with Part L 2010 assuming that the percentages in Table 4 can directly be applied.

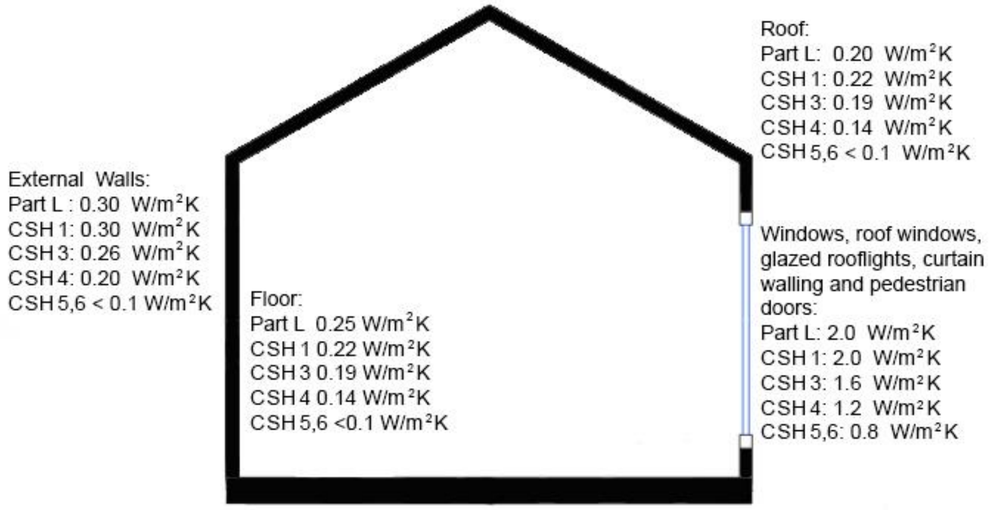

Figure 23 Comparison between levels of CSH and Part L1A 2010 restrictive fabric parameters

Despite its high aspirations and high profile, the UK government decided to scrap the Code for Sustainable Homes in 2014 and, instead, to place all housing energy requirements within Buildings Regulations, which would have minimum standards set to be equivalent to Code Level 4.

3.3.3 Passivhaus standard

The Passivhaus (the German as ‘passive house’) is a German standard for residential and non residential buildings. The major principle in this standard is that thermal comfort is achievable with minimum energy consumption both in winter and summer. Basically, the standard includes three elements (Passive house Institute, 2007):

- Thermal comfort
- Heating and cooling energy limit
- A set of passive systems that allow thermal comfort and energy limit to be cost-effective

Typical design features of the German Passivhaus standard include high performance insulation that includes minimizing thermal bridges and well-insulated windows, along with using an efficient heat recovery system and high levels of good airtightness. A software package, Passive House Planning Package (PHPP), is used to check compliance with the standard, and has the following requirements (Passive House Institute, 2012):

- Heating demand up to maximum 15 kWh/m^2
- Primary energy demand for all heating, hot water and electricity is limited to 120-kWh/m^2 in total.
- Thermal comfort criteria should be met for all areas, this requires that the minimum air temperature must not be less than 17℃ and ventilation should be suitable for air hygiene (DIN 1946) and noise emission should be less than 25 dBA. This require a low U-Value for all areas as compared with Part L and CSH in Figure 24
- Building envelope should meet a pressurization test result of no more than 0.6 ACH at 50 Pascal inside-outside pressure difference

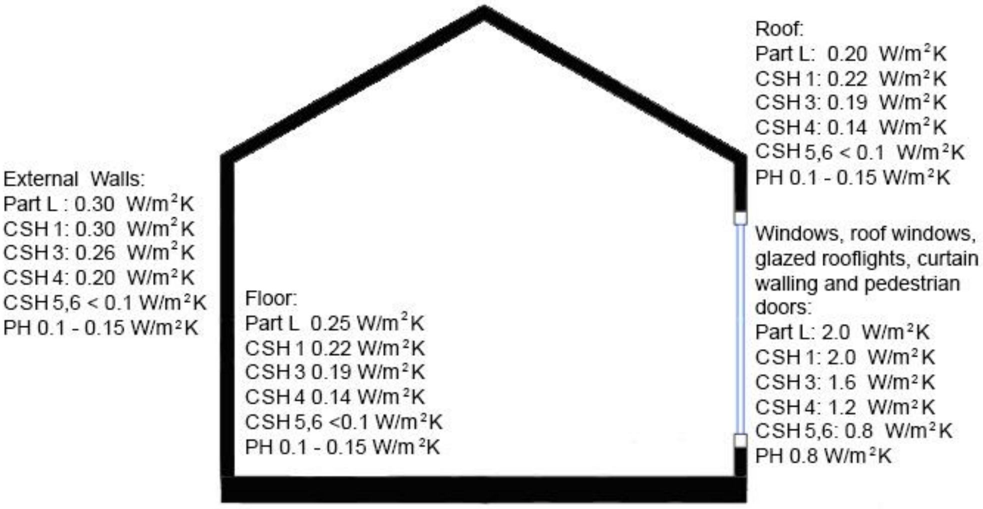

Figure 24 Comparison between levels of CSH, Part L1A 2010 and Passivhaus restrictive fabric parameters

In the Passivhaus standard the whole heat distribution system is simplified to a heat recovery system. This would typically result in lower cost energy delivery, although the initial investment would increase due to the mechanical ventilation system installment cost (Table 6 demonstrate typical construction costs as well as heating and cooling energy demands for passive houses and standard ones in 6 countries). According to the Passivhaus Institute in 2007, "Contemporary construction is quite airtight, therefore the air replacement from infiltration is not sufficient. Ventilating by opening windows is not a convincing strategy either. Getting a sufficient volume of fresh air is not just a question of comfort, but a requirement for healthy living conditions. Therefore, mechanical ventilation is the key technology for all new construction as well as refurbishment of existing buildings".

Table 6 Comparison of construction costs, heating and cooling energy demand in Passivhaus and typical standard houses. (Passive-On, 2007b)

	Construction Cost/ Standard House [Euro/m^2]	Construction Cost/ Passive House [Euro/m^2]	% Increase	Heating Demand / Standard House [kWh/m^2 yr]	Heating Demand / Passive House [kWh/m^2yr]	Cooling Demand / Standard House [kWh/m^2yr]	Cooling Demand / Passive House [kWh/m^2yr]
Germany	1,400	1,494	6.71 %	90	15	0	0
Italy	1,200	1,284	7 %	111	10.5	4.63	3
France	940	1034	10 %	69.6	17.4	n/a	5
Spain	720	740	2.85 %	59	8.7	23.1	7.9
Portugal	800	858	7.15 %	73.4	5.8	32	3.7
UK	881	930	5.54 %	59	15	0	0

In general, the Passivhaus standard seems to be successful in colder parts of Europe. By 2010 more than 25,000 houses were built that conformed to the Passivhaus rules. However, it seems that the standard failed to respond to warmer climates, both in Europe and in the other part of the world, such as the USA, with the number of houses following the standard being around 13 (Zeller, 2010). That was the reason for the EU Passive-on project to improve air ventilation systems, which might not be suitable in warmer climates.

3.3.4 The Passive-on project

The Passive-on project was established to promote passive house standards in warmer climates. Although this might not seem to be applicable for the scope of this thesis, the possibility of confronting higher temperatures due to the climate change scenarios will be discussed in UK housing, and so the design features' developed in the Passive-on project can be useful. The further and improved points that define the Passivhaus standard for warmer climates include (Passive-On, 2007a):

- Cooling energy demand up to maximum 15 kWh/m^2
- In warm seasons, operative temperature must remain within the comfort range mentioned in EN 15251 (European Standard for Indoor Environmental Criteria for Design and Calculation of Energy Performance of Buildings). If an active cooling system is in operation, the operative temperature must be kept under 26℃
- Active ventilation requirement removal: either passive or active ventilation must secure appropriate air quality
- Building envelope should meet a pressurization test result of no more than 0.6 ACH at 50 Pa for airtightness criteria. For locations which winter design temperatures are above 0 ℃, 1.0 ACH is suitable to achieve the heating criterion.

As observed, like the other standards, Passivhaus standard and the improvement project aim to improve indoor air quality and reduce energy consumption. Therefore, the role of thermal comfort is highly important for the evaluation purpose (thermal comfort will be discussed in Chapter 8).

According to the Energy Saving Trust (2005) a major criticism regarding building codes is that they do not address the main issues on overheating risk in dwellings. Thus far, it seems that no considerable improvement has taken place in these regulations and it does not yet consider the likely impact of future climate change (MPA, 2012). Hopefully, the revisions will include this aspect.

3.4 Summary

- For quantification purposes, building standards can provide adequate guidance. However, not all passive design measures are taken into account. For example, Part L1A did not completely consider issues related to overheating.

- The Passivhaus standard has been successful, mostly in colder parts of the Europe; the Passive-on project came about to promote passive house standards in warmer climates.

- The now defunct Code for Sustainable Homes (CSH) basically relied on Standard Assessment Procedure (SAP) results, which it used to demonstrate compliance with building standards for dwelling, including Part L1A.

- In general, this Chapter articulates the scope of sustainable design principles. It shows what the agenda is for designing and improving construction systems, as applied to house models later on in this study.

4. CURRENT TRENDS IN UK HOUSING CONSTRUCTION

4.1 Modern methods of housing construction in UK

Modern Methods of Construction (MMC) is a collective term to express a number of construction methods. MMC aims to resolve concerns regarding shortages in housing supply and construction skills, housing quality, building regulations revisions and environmental performance. Currently, there is much current debate in order to clarify what exactly MMC includes, since there is no universally agreed definition. However, the most agreed classification has two major categories - on-site methods such as insulated concrete formwork (ICF) that tend to be used in sustainable materials in modern process, and off-site methods which includes (NHBC, 2006):

- Volumetric

Three-dimensional units that are also known as modular construction, produced in a factory before being transported to a site. Units can be made from light gauge steel frame, concrete and composites, timber frame, etc. Volumetric construction could be most effective when used for a large number of identical units.

- Panelized

Flat panel units produced in a factory before being transported to a site in order to create a three-dimensional structure. Many types of panel exist but the main types are concrete panels, composite panels, structural insulated panels (SIP), etc.

- Hybrid

Hybrid construction is basically the integration of panelized and volumetric units in order to create three-dimensional pods.

- Sub-assemblies and components

Larger components that can be placed into either MMC or conventionally built dwellings that are both factory made and site assembled such as floor and roof cassettes.

Within the scope of this study, MMC might have the advantages of improving cost and time certainty, reducing the risk of infiltration due to quality improvement and smaller on-site faults. However, the critical factor, which is the thermal performance in dealing with climate change uncertainties, is to be investigated in this study.

4.2 Viability of prefabrication in UK housing industry

Following the housing affordability crisis (DCLG, 2007), and the housing stock shortage, the UK government plans to create 3 million houses by 2020; a shift towards prefabrication has taken place. Prefabricated housing is now a significant item in UK housing construction and is expected to rise as shown in Table 7 (DCLG, 2007)):

Table 7 Prefabrication in UK

Prefabricated system	Proportion of UK total 2005	Expected Proportion of UK total 2016
Timber Frame	18.6 %	30%
Steel Frame	3.9 %	25%
Precast Concrete	1.5 %	High Growth predicted
SIP	0.3 %	4%
Volumetric	0.7 %	4%
Hybrid	0.15 %	No Data

Whilst there is strong support from government and industrial groups for prefabrication, there are still obstacles to further improvements. These barriers include (Prescott, 2005):

- Finance

From the 1990s house prices in the UK have increased more rapidly than average incomes, and after the economic recession in late 2008, this trend seems to be continuing. Therefore, there is a necessity for the market to seek out more cost effective construction techniques.

- Land

Britain has historically had limited land availability and the “green-belt” agenda did much from the 1950s to constrain new developments around metropolitan areas. Although the “brown-field” area can offer some capacity for new housing, there is not general agreement that there is enough for 3 million new home by 2020 (DCLG, 2007).

- Desire

This can be categorized in two parts - supply side and demand side. As there is a serious government plan for developing MMC, and some manufacturers have been introduced onto the market, there does not seem to be any problem on the supply side. In contrast, on the demand side, the UK housing market has been based on a brick building industry and new developments require more investments (Davies C. , 2005).

- Quality

By developing new standards, it seems that the quality should no longer be a serious concern. However, quality is not just limited to the end product but also refers to process. To be completely successful, MMC developers will require assuring that all supply chain deliveries either in factories or onsite are effectively properly coordinated.

Considering all the barriers mentioned above, it seems that prefabrication could continue to play a minor role in UK market. However, in order to meet the government's ambitious target by 2020, both in terms of environmental performance and volume, it seems that developing prefabrication could just be a complementary approach to traditional techniques. Therefore, for the purpose of this research both traditional and prefabricated construction systems are assessed in this study.

4.3 Thermal performance and MMC

The concept of thermal storage and related issues is investigated in more depth in Chapter 7. However, most MMC construction methods generally use lightweight materials which, in combination with other factors, can produce airtight and highly insulated buildings. On the one hand, this can cause a reduction in energy consumption, but on the other hand, the risk of overheating in building is highly likely to increase without any air-conditioning system or thermal mass effect.

Thermal mass is a term that refers to the ability of a material to store heat, which is essential to control temperature fluctuations. The most commonly used construction materials that are used for heat storage include brick and concrete that are generally used on-site and are heavyweight (MPA, 2012). However, the recent usage of MMC in UK housing has caused a new debate on the value of thermal mass. A number of works have been presented that suggest well insulated building with low thermal mass might result in higher room temperatures (Gething, 2010) (Hacker, et al., 2005).

Bill Dunster Architects and Arup R&D (2005) revealed the importance of alleviating climate change consequences by passive design features to offset the predicted temperature rises. The study also recognized that thermally lightweight homes could cause levels of discomfort to occupants by creating higher room temperatures. The research emphasized that masonry houses with inherent thermal mass can result in less energy consumption over their lifetime compared with a lightweight timber frame house.

According to a study by Orme et al in 2003, a high level of insulation and a reduction in the level of thermal mass may cause overheating not only in summer but also in spring and autumn. Their study focused on four housing types using lightweight timber frame and night cooling. The effects of solar shading, internal gains reduction and thermal mass were investigated. They found that none of these could completely eliminate overheating risk, although the combination of all them could lessen degree hours over 27℃ by 80%. They also found thermal mass and nighttime ventilation to be the most effective design solutions. Other studies related to the impact of climate change on the UK residential sector are shown in Table 8:

Table 8 Recent climate change studies

Study and methodology	Location (s)	Typologies	Key findings
Hacker, Belcher and Connell, Computer simulation	London, Manchester and Edinburgh	New and previous detached and semi-detached house	- Ventilation and solar shading were discovered to be efficient - Due to insulation levels and air-tightness newly built house were even more successful
Three Regions Climate Change Group, Computer simulation	London, East and South east England	1930 and 1960 houses and flats	- Improved air movement, ventilation, solar control, cooler floors and increased façade reflectivity were efficient in decreasing overheating hours
Gaterell and McEvoy, Computer simulation	Southeast England	1968 Detached house	- Double glazing and Loft insulation found to be effective
Zero Carbon Hub, Computer simulation	Different UK locations	Semi-detached house	- Reducing air leakage, additional insulation and enhancing solar gain cause less comfort hours in summer
Collins, Natarajan and Levermore, Computer simulations	London, Manchester, Edinburgh and Cardiff	Entire UK housing stock	Heating loads will be the prominent load rather than cooling loads till 2080

Source: (Hacker, et al., 2005), (Three Regions Climate Change Group, 2008), (Gaterell & McEvoy , 2005), (Zero Carbon Hub, 2010), (Collins, et al., 2010)

Furthermore, Dunster’s 2005 study demonstrated the poor performance of lightweight construction in hot periods of the year. His study compared lightweight buildings with a high thermal mass construction system and discovered that a high thermal mass system considerably reduced temperature fluctuations. Hacker and Saules achieved similar results in a study in 2008. However, Gorgolewski (2007) argued that “most framing systems - both steel and concrete - have about the same effect in terms of energy consumption”. His article described the glazing-to-wall ratio and U-Value factor as more effective in energy consumption in comparison with high thermal mass systems. He found the role of thermal mass complex and difficult to predict.

Mendonca and Braganca in 2006 examined an innovative mixed weight solution in housing construction. They evaluated a test cell with a lightweight shell and a heavyweight central area, which caused considerable less environmental cost in comparison with a completely traditional heavyweight construction. It seems that the usage of hybrid construction might have considerable advantages in the UK housings’ sustainability approach.

Apparently, there are different views in both supporting and criticizing thermal performance of MMC but neither side focuses on their performance in dealing with future climate change effects comprehensively. Therefore, this study combines both MMC and traditional construction systems in its scope and investigates their performance in Chapter 8 of this thesis and focuses on integrating effective passive design strategies for optimization process.

4.4 Summary

- In general, as this study includes both MMC and traditional construction systems, this Chapter provides an insight to the likely growth, thermal performance and future potentials of MMC in a changing climate.

- Regardless of all the barriers and obstacles to develop MMC, the growth of the MMC in the UK seems to be inevitable. Therefore, this study chooses both MMC and traditional construction systems that meet the requirements of building standards. Further investigation in thermal simulations and the assessment of integrating passive design strategies will be provided in the following chapters.

- The scopes of published works assess MMC mostly on social and financial issues and only a few investigate thermal performance. Apart from that, none of the works completely assess the role of uncertainty in this area, such as uncertainty in future climate predictions and uncertainty in measuring thermal comfort, cost, etc.)

5. RISK, UNCERTAINTY AND FUTURE PROOFING SUSTAINABLE DESIGN CONCEPT

Forthcoming Chapters will present the likely effect of climate change in UK and the potential risks and uncertainties involved which have to be dealt with. As there is no generally agreed definition of risk and uncertainty, this Chapter will thoroughly look at the existing literatures to clarify their meanings. Additionally, the concept of future proofing will also be explored.

5.1 Risk, Uncertainty, Similarities and Differences

This section investigates numerous literatures in engineering, mathematics and economics on the subject of defining risk and uncertainty. The significance of this investigation is because there is no general definition for risk and uncertainty as these terms are context dependent. Also, nearly every definition is problem-specific, implying that a new definition is stated every time. Therefore, for decision-making process and simplification of the assessment, it is a necessary step to clarify the definitions.

5.1.1 Risk and uncertainty are equivalent

Risk could be equivalent to uncertainty when it has orientation to the uncertainty or financial loss, the reason for the loss, or the likelihood of loss. In this case, risk could be measured by the probable variation of real experience from predictable experience. Lower variation percentages were correlated with smaller risk (Mehr & Cammack, 1961). In a similar vein, "the uncertainty of unfavorable contingency has been termed risk" (Magee, 1961). When there is a probability of loss there is a probability of risk. Typically, when there are different hazards that supply the chance of loss, the risk could be the sum total of the hazard.

Philippe (2001) defined risk as "the uncertainty of the outcomes. It is best measured in terms of probability distribution functions''. More specifically, it could be understood that a quantification of uncertainty is assumed; also, he anticipates that the distribution is followed by uncertainty and a range of distributions contributes to quantify uncertainties that are defined as risk. Conversely, in some decision-making processes, unquantifiable uncertainties might be observed without any specific distribution, with just lower and upper boundaries (Samson, et al., 2009). For example, ranges of climate change emissions are classified as non-quantifiable uncertainty.

5.1.2 Uncertainty and risk are not equivalent

Willett (1901) described risk as the ''objectified uncertainty regarding the occurrence of an undesirable event'' and emphasizes that it could be quantified with the likelihood of arguments. He characterizes subjective uncertainty as ‘‘resulting from the imperfection of man’s knowledge’’. He clarifies that uncertainty is maximum when the probability degree is ½, since with this possibility there is nothing to illustrate what the outcome might be. As the probability rises or declines the uncertainty always decreases and, finally, when the probability is either 1 or 0, there could not be any uncertainty. Evidently, uncertainty and risk cannot be equal now.

Knight (1921) placed an emphasis on the distinction between quantifiable uncertainty and non-quantifiable uncertainty and clarifies quantifiable uncertainty as risk and non-quantifiable uncertainty as uncertainty. In essence, uncertainty should be taken as radically different from the familiar idea of risk. Accordingly, the term uncertainty must be restricted to non-quantitative types. On the other hand, Keynes (1937) stated “Uncertainty does not mean merely to distinguish what is known as certain from what is only probable. There is no scientific basis on which to form any calculable probability on these matters whatsoever. We simply do not know.’’

Kaplan (1981) stressed that when risk is evaluated three aspects of risk are actually being assessed: What can happen? How likely is it to happen? What are the consequences if it does happen? Consequently, he described risk as a triplet. Lough et al (2005) added that risk could be defined as ‘‘the chance that an undesirable event will occur and the consequences of its possible outcomes.’’

Even though uncertainty and risk are classified as two different concepts, there is debate about how they are related. One group of researchers considers that the riskiness of a system depends on the uncertainty of the system environment and the other group considers that the uncertainty in the system depends on the risk. Besides, there is some argument that there is not necessarily any relationship between risk and uncertainty.

5.1.3 Risk and uncertainty are independent

When a choice has to be made between two actions then this is decision-making in the classification of certainty-risk-uncertainty. The certainty classification applies if each action is known to lead methodically to a definite result; risk classification applies if each action leads to one range of possible specific results, each outcome occurring with a known probability; and the uncertainty classification applies if either action or both has as its consequences a set of possible specific outcomes (Luca & Riffa, 1957). It can be noticed that this definition is similar to Knight’s argument in the sense that uncertainty is described as a non-quantifiable notion and risk as a quantifiable one.

5.1.4 Risk and uncertainty are dependent

Regarding an increased concentration in uncertainty in the engineering community, two kinds of uncertainty are clarified. Aaleatory (stochastic) uncertainty is irreducible and describes the essential variation associated with the physical system or the environment, while epistemic uncertainty is reducible and derives from some level of inadequate information and can be termed as subjective (Helton & Burmaster, 1996).

Zimmermann (2000) strongly contends that uncertainty cannot be modeled context-free and suggests that there is no single method that can model all kinds of uncertainty equally well. In the same vein, Crowe and Horn (1967) mentioned that ‘‘it may be true that situations where risk gives rise to uncertainty are the most important. Here no harm seems to be done if one regards risk as a kind of proximate cause of uncertainty’’. Therefore, according to this statement, the question can be asked “Can uncertainty increase the possibility of risk occurrence?” It seems that the answer is highly likely to be negative since risk concept is mainly an objective phenomenon. But, the opposite could also be true, when risk frequently gives rise to uncertainty.

Willet (1901) argued that risk depends on uncertainty and intimates that ‘‘the greater the probable variation of the actual loss from the average, the greater the degree of uncertainty.’’ This statement is also endorsed by Markowitz (1952), who considered ‘‘expected return a desirable thing and the variance of return an undesirable thing’’. Furthermore, Holton (2004) states that ‘‘risk entails two essential components: exposure and uncertainty.’’ He describes uncertainty as ‘‘a state of not knowing whether a proposition is true or false’’ and exposure as ‘‘a self-conscious being is exposed to a proposition, if the being would care whether or not the proposition is true’’ and defines risk as ‘‘exposure to a proposition of which one is uncertain.’’ He illustrates his argument with the following example to justify how both uncertainty and exposure is required for any occurrence of risk: ‘‘suppose a man leaps from an airplane without a parachute. If he is certain to die, he faces no risk.’’

Evidently, the above-discussed classifications of uncertainty and risk could not be a complete literature review of this subject. This discussion is a subjective sample of definitions for developing a model of uncertainty and risk in dealing with climate change scenarios. A multitude of definitions for these concepts exist in areas like probability and statistics, which is not covered here. Correspondingly, this debate does not comprise works, which make use of different concepts of risk in decision-making process like regret, robustness, sensitivity analysis, etc. In conclusion, it can be summarized that uncertainty and risk could be different concepts because:

1- Risk is objective but uncertainty is subjective
2- Risk is quantifiable but uncertainty is not quantifiable
3- Risk is the possibility of loss but uncertainty could be loss or gain
4- Risk is Unknown “Known” but uncertainty is Unknown “Unknown”

On the other hand, uncertainty and risk could be similar because:

1- Both are dynamic and unstable phenomena
2- Both are not definitely predictable

In a changing climate condition, the increase of temperature is a potential risk but the amplitude is uncertain. Therefore, they are not considered the same in this research but they are considered as dependent and cannot be assumed as entirely different terms. The worst-case scenario of climate change prediction is an uncertain condition that is applied to simulations in this study and the risk of overheating is quantified as a consequence of likely increasing temperature conditions.

5.2 Future proofed design concept

There is no widely accepted term for “future proofing” but it refers mostly to design processes that consider energy trends and full lifecycle perspectives until at least 2050 (Georgiadou, et al., 2012). However, CABE (2011) defines future proofed design as ‘‘buildings and energy systems with enough flexibility to respond to changing technologies and ways we use energy’’. Jewell et al. (2010) mentioned future proofing as designing building to be resilient to uncertainty arising from the future, including mitigation of negative influences and getting benefits of future opportunities. Similarly, the Royal Academy of Engineering in 2011 simplifies adaptation to climate change as a future-proof theme to deal with a range of predictable conditions.

Current definitions of future proofed designs seem to have an emphasis on a particular trend like future climate influences. A more complete definition might also acknowledge comprehensive trends, as listed in Table 9.

Table 9 Comprehensive framework for trends that have an influence on energy performance of buildings up to 2050.

Social	Technological	Economic	Environmental	Political
Demographics: Population growth Ageing Population Shrinking of household size Larger living space per person	Innovation: Novel energy efficient measures (demand side) Modern fuel types, mainly renewable energy sources (supply side) New construction practices Accuracy in energy consumption data	Higher energy prices Fuel poverty High price of renewable energy implementation Economic incentives (e.g. subsidies) for energy efficiency and low carbon technologies	Climate change and temperature increase leading to hotter and drier summers, overheating and urban heat island effect	Energy security Building regulations
Lifestyle changes: Housing unit and tenure types Energy-intensive behaviors (e.g. increased level of thermal comfort)				
New working and living patterns				

Sources: (IEA, 2003), (Lane, et al., 2005) (Shell, 2008) (O'Brian, et al., 2009) (WEC, 2007)

Nonetheless, the aim is to avoid planning an infrastructure which assumes all the likelihoods about future scenarios are completely reliable. The goal is to have a method in place that guarantees comprehensive thinking about predictable scenarios and informs design decision-making options. According to CIBSE (2005), ‘‘a good low-energy design offers the best future-proof solutions''. Low energy design does not essentially form a comprehensively future-proofed building, but will indicate aspects to improve this concept. Three main attributes that develop future thinking in energy performance include (Georgiadou, et al., 2012):

- Analysis of sustainability subjects: Magnitude of considering sustainability pillars (financial, environmental, socio-economic)
- Lifecycle view: Magnitude of considering energy design implications through the whole lifecycles stages
- Accepting risks and uncertainties: Magnitude of considering expected, reasonably expected, and uncertain trends over the long-term.

5.3 Future-proofed design types and examples

According to Georgiadou (2012), four types of future proofed design includes following:

- ***'Straightforward'***

The 'straightforward' type defines the present situation, which includes conventional design developments for the construction of low-energy and cost-effective buildings. This type indicates minor or no consideration of futures thinking. Some examples of this type include (Mumovic & Santamouris, 2009):

1) Energy efficiency of building fabric including passive and active systems such as orientation and location, daylighting, thermal mass, shadings, airtightness, energy efficient lighting and appliances, etc.
2) Zero or low carbon technologies with short payback periods such as solar thermal panels, photovoltaic (PV) panels and wind turbines.

- ***'Lifecycle-oriented'***

The 'lifecycle-oriented' type develop a lifecycle approach through regular monitoring of the operational energy and the collection of building solutions on the basis of embodied energy concerns, design for durability and the usage of recognized LCA methods. Some examples of this type include the selection of environmentally friendly materials and the use of low embodied energy solutions (e.g., masonry construction vs. timber framed).

- ***'Uncertainty-oriented'***

This type basically shows an energy design that exceeds the existing policy framework and improves adaptability to continue efficiency over the long-term. It also uses dynamic risk management models in dealing with the future. Examples can be divided into two classifications:

1) Flexibility to address overheating in dealing with climate change scenarios, which basically includes passive design techniques; i.e., solar shadings, thermal mass, natural ventilation, optimum insulation and green walls and roofs (Mumovic & Santamouris, 2009). The analysis of dynamic overheating is on the basis of probabilistic weather files from UKCP09 projections (UKCP09, 2012).

2) Adaptability to shifting conditions in both user need and building fabric, which includes new technologies (i.e., triple glazing, smart facades, heat pumps, phase change materials), flexibility in building envelope (i.e., PV-ready roofs and space for energy storage systems) and designing to developed standards to stay complaint with forthcoming policy like the zero carbon homes requirement by 2016 (DCLG, 2008).

- ***'Comprehensive'***

'Comprehensive' future proofing targets combines both lifecycle thinking and considering risks and uncertainties. Statistical probability distribution such as Monte Carlo simulations, Bayesian analysis, or Scenario Planning into the LCA methodology might be incorporated in the analysis. These new LCA tools are still complicated and expensive to apply, therefore more research is necessary for development. The current focus is mainly on 'straightforward' design solutions. However, there is a necessity to consider future proofing by 'uncertainty-oriented' or ideally 'comprehensive' types. Therefore, this study aims to develop uncertainty oriented future proofing by including both smart and traditional design solutions, providing a picture of future energy suppliers and consequently demonstrate the potential outcomes.

5.4 Summary

- In general, the picture below can describe that risk and uncertainty might have some similarities but they are not entirely equivalent or separate. For climate change implications, these terms are dependent and risk of overheating is the outcome of the uncertain condition.

- Presently, developers focus largely on ‘straightforward’ design solutions; however, there is a necessity to include future proofing by ‘uncertainty-oriented’ or ideally by using ‘comprehensive’ types in design decision making. Therefore, building energy codes should improve their future-orientation approaches. This study considers the uncertainty-oriented design solution to tackle the risk of climate change and by means of dynamic simulations quantifies the risk and by applying both traditional and new technologies demonstrates the possibility and flexibility to improve building performance.

6. CLIMATE CHANGE AND FUTURE UK TEMPERATURE PREDICTIONS

6.1 Background to climate change

Throughout history, climates have constantly changed due to natural factors such as changes in solar output, volcanic activities, changes in the Earth's orbit and oscillations in climate change system such as El Niño Southern Oscillation (ENSO) and North Atlantic Oscillation (NAO). The difference between the recent changes and natural cycles is the rate at which the change has occurred (Cavan, 2011).

However, natural causes are not the only causes of the recent climate change (Smith & Lawson, 2011). In fact, it has been attributed to greenhouse gas emissions from burning fossil fuels The human-generated emissions include carbon dioxide (one of the major greenhouse gasses), which has increased by over 34% compared to pre-industrial levels. It is now impossible to avoid some degree of climate change because of historical emissions. The extent of future warming will depend on the future emissions and some other issues such as land use change and natural systems (Jenkins, et al., 2007).

In order to create climate change projections in the UK for the coming decades, it is necessary to make assumptions about future human-generated greenhouse gas emissions. The assumptions are made on the basis of future development emissions, which in turn depend on socio-economic development and technological and demographic changes. These emission scenarios include a range of low to high emission levels (Cavan, 2011). However, although the high emission scenario is the most extreme case, recent carbon emissions estimates indicate an increase of over 3% per year between 2000-2004, compared with an increase of 1.1% per year between 1990-1999. The 3% rate is faster than any assumptions from emission scenarios from the United Kingdom Climate Impacts Programme UKCIP (Raupach, et al., 2007).

Therefore, adaptation of buildings to the extreme scenario of climate change is becoming increasingly necessary. Adaptation, a responsive adjustment to decrease or remove risk, will be critically important since, even in the most optimistic projection of climate-change scenarios, temperatures will increase considerably around the world and it is very unlikely that the mean summer temperature-increase will be less than 1.5 ℃ by the year 2080 (IPCC 2010). Figures 25 and 26 illustrates a range of increasing temperatures in the UK in summer and winter with 90% probability level. As this study considers the extreme scenario for simulations and further problem solving processes, the 'high emission scenario' is presented below. The building construction adapted for the extreme case should be the most robust design; a design that is durable in both the current climatic condition and the high level of change in future climate.

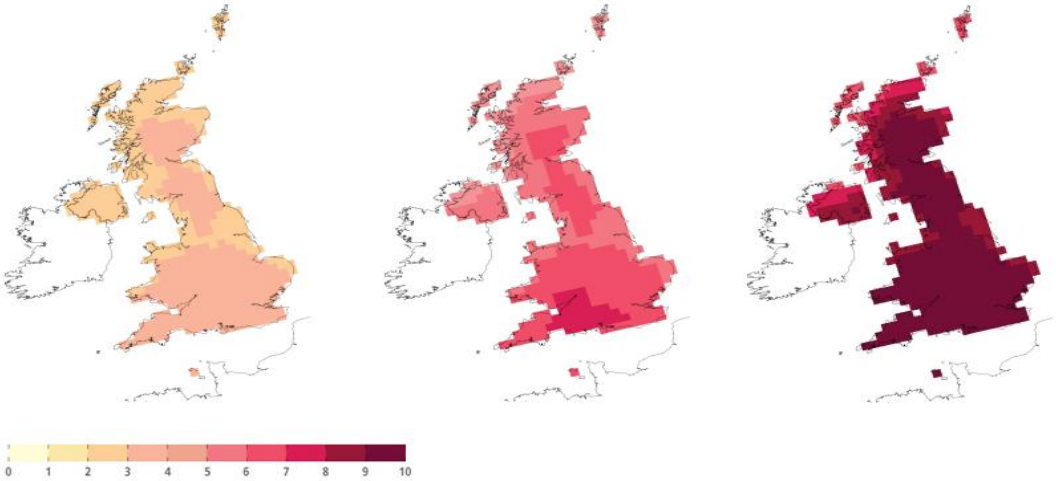

Figure 25 summer mean temperature increase in 2020, 2050, 2080; 90% probability level, very unlikely to be greater than the degrees shown on maps

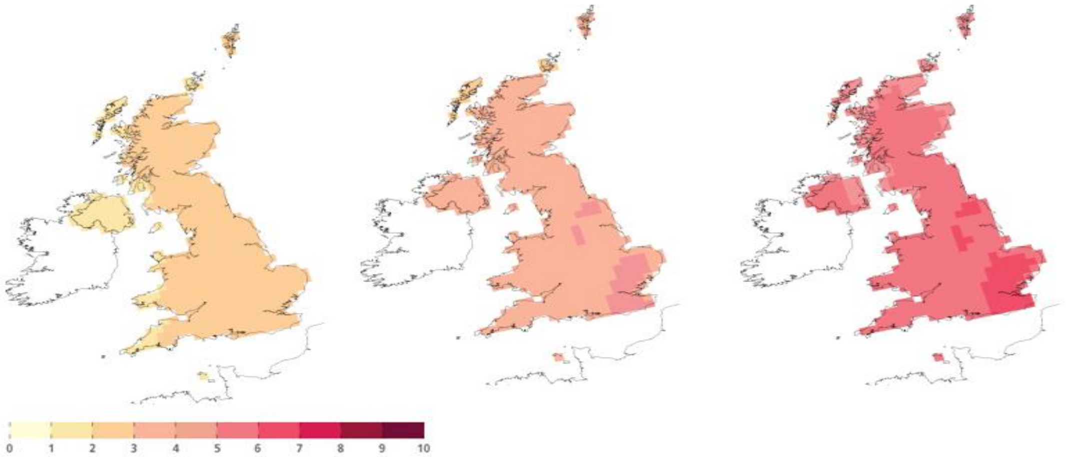

Figure 26 winter mean temperature increase in 2020, 2050, 2080; 90% probability level, very unlikely to be greater than degrees shown on maps. Source: http://www.ukcip.org.uk/resources/publications

Climate change is potentially a double-edged sword, with both positive and negative impacts. On one hand it could reduce heating loads in buildings while on the other hand it could increase cooling loads. In order to most efficiently reduce the risk in future, it is necessary to consider that adaptation approaches might have either contradictory or negative consequences (Wilson and Piper 2010).

Realizing the potential impacts of climate change scenarios involves the design decision-making process to optimize both the thermal comfort of occupants and future energy consumption regardless of active design impacts. In essence, this approach causes effective and practical adaptation strategies for decreasing the potential for overheating and overcooling in UK houses.

Currently, it has been observed that a large number of dwellings in the UK have no active cooling systems. Therefore, increases in summer temperatures have considerable potential to increase occupant vulnerability to overheating as well as the potential to considerably increase cooling energy consumption (Collins, et al., 2010).

With regard to the expected durability of buildings, design adjustments for the 2080's are beneficial. The many different emissions scenarios are due to the uncertainty of economics, population growth as well as politics. It is likely that the emissions scenarios will be refined in the future as understanding of probabilistic change improves. This implies that an epistemic uncertainty is a major issue for the mechanism of dealing with optimizing design process.

All the work done in this study considered the climate of two UK cities, Manchester in the North West of England and London in the South East of England. Obviously, the chosen weather data have a significant impact on the result of simulations and, consequently, on the design decision making process.

6.2 Manchester Climate

Figure 27 shows low, mean and high monthly average air temperatures in Manchester. The city has a temperate climate, with cool weather throughout the year. The annual average temperature is around 10℃, the lowest temperature is below -5℃ and highest exceeds 27℃. Both overcooling and overheating risk exist during the year (the comfort zone shown in Figure 27 is on the basis of ASHRAE 55-2004).

In order to see how the likely temperature increases by 2080, future climate data for the UK are available from the UK Climate Impact Program (UKCIP), which provides monthly values of climate data for the UK until 2080 (Murphy, et al., 2012). The University of Southampton has developed an Excel file named "CCWeather Gen" to create future weather files for simulation in DB from UKCIP predictions (University of Southampton, year unknown). These files, which provide hourly weather data, are used for the modeling of future impacts in the models used for this study.

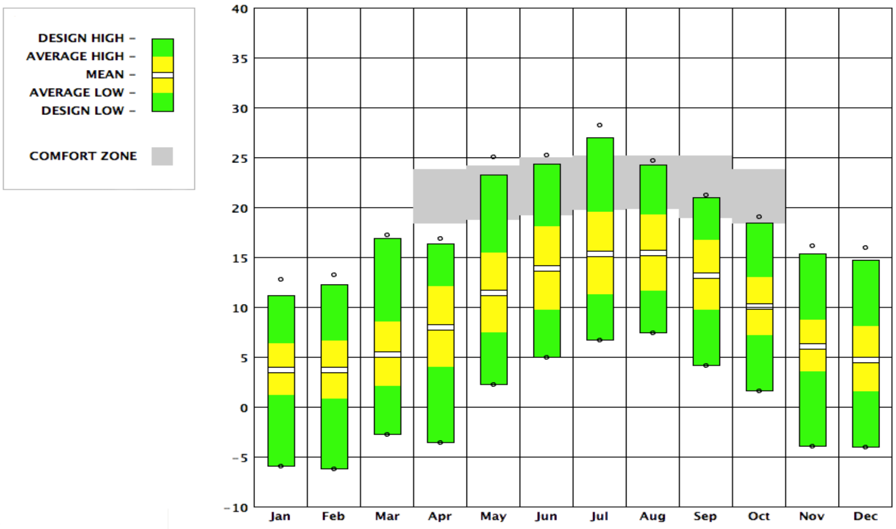

Figure 27 Low, mean and high monthly temperature in Manchester 2011[7]

In Manchester the humidity level is never below 70% and could increase to 90%, as shown in Figure 28. The high level of humidity throughout the year would not help to decrease an overheating sensation and consequently this work has focused on reducing temperature. The high level of humidity also implies the necessity to consider natural ventilation to improve thermal comfort throughout the year. Besides, the very limited hours of sunshine implies a limited capability for renewable energy technologies (on a small scale) such as solar panel, although on a larger scale the usage of wind turbines would be effective due to the strong winds coming from South and South-East, as shown in Figure 29.

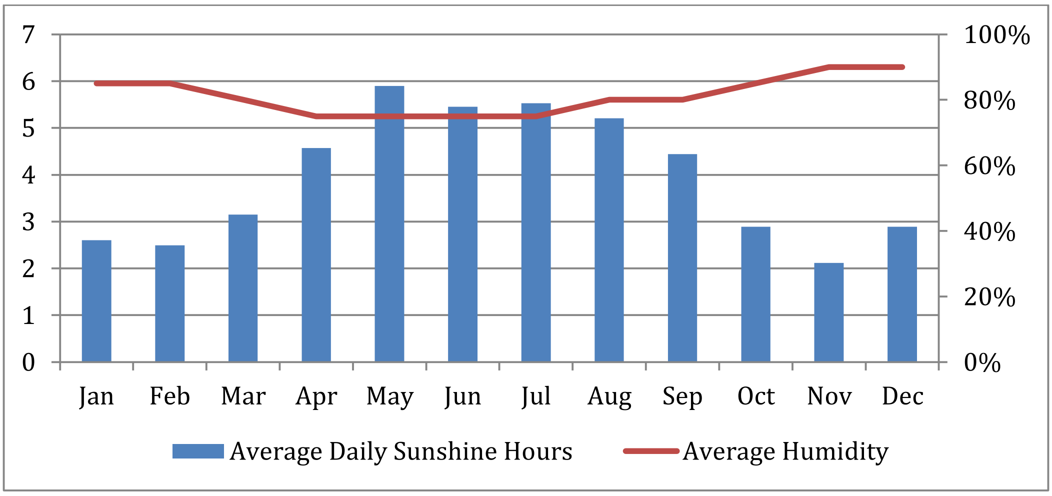

Figure 28 Average daily sunshine hours and humidity in Manchester 2011

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[7] Round dots are the highest and lowest Dry Bulb temperature in the EPW file. Top and bottom of yellow bars are the average of the highest or lowest dry bulb temperatures. Open slot is the average of Dry bulb temperature in that particular month. Design high or low are used to calculate the size of heating and cooling equipment.

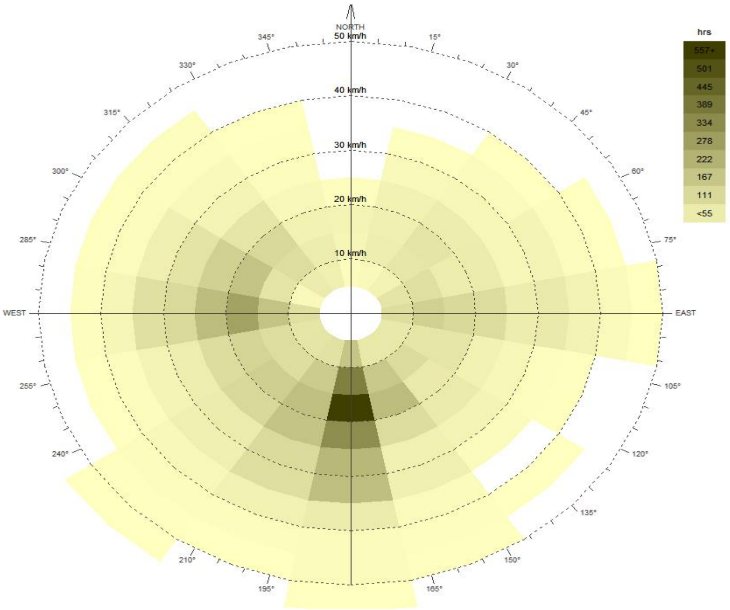


Figure 29 Wind speed and direction in Manchester 2011

Figure 30 shows likely average temperatures in Manchester in 2080, and it can be observed that the minimum temperature would be above 0℃ and maximum temperature would almost reach 30℃. The annual mean temperature would increase by over 3℃. Clearly the risk of overcooling would be alleviated to some extent and less heating load is expected to provide thermal comfort. However, overheating risk would increase considerably and, therefore, more cooling load is required to provide thermal comfort in that time.

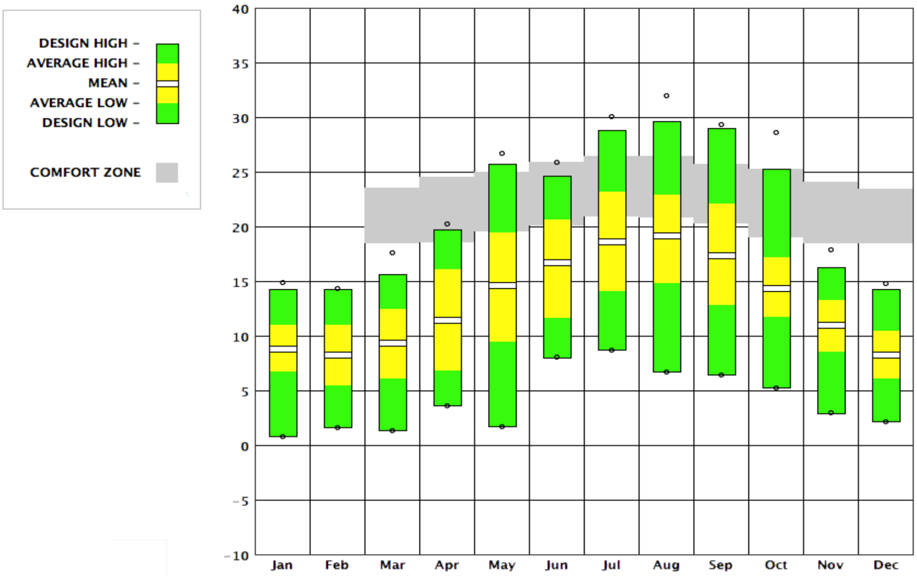


Figure 30 Low, mean and high monthly temperature in Manchester 2080

6.3 London Climate

Figure 31 shows low, mean and high monthly average air temperatures in London. Similar to Manchester, London also has a temperate climate with cool weather throughout the year. The annual average temperature is around 12 °C, the lowest temperature would be below -3°C and the highest exceeds 30°C. Both overcooling and overheating risk exist during the year.

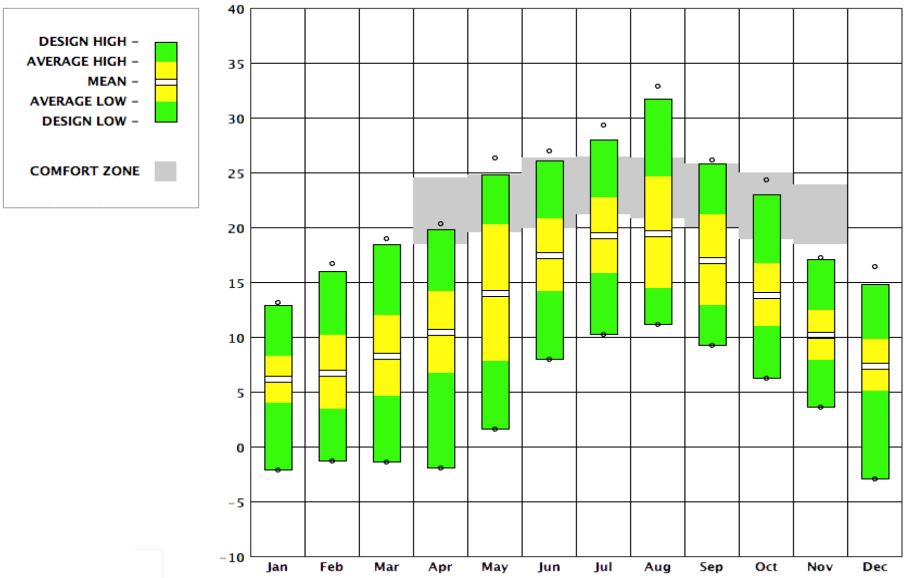


Figure 31 Low, mean and high monthly temperature in London 2011

Compared to Manchester, lower humidity levels and more sunshine hours can be seen in London, as shown in Figure 32. Therefore, it is expected that the risk of overheating becomes more extreme in this city. Obviously, some design options like shading devices could perform more effectively in order to reduce solar gains and the use of solar panel to produce more electricity from solar radiation could also be more effective. Similar to Manchester, London has strong winds from the South-West, as shown in Figure 33.

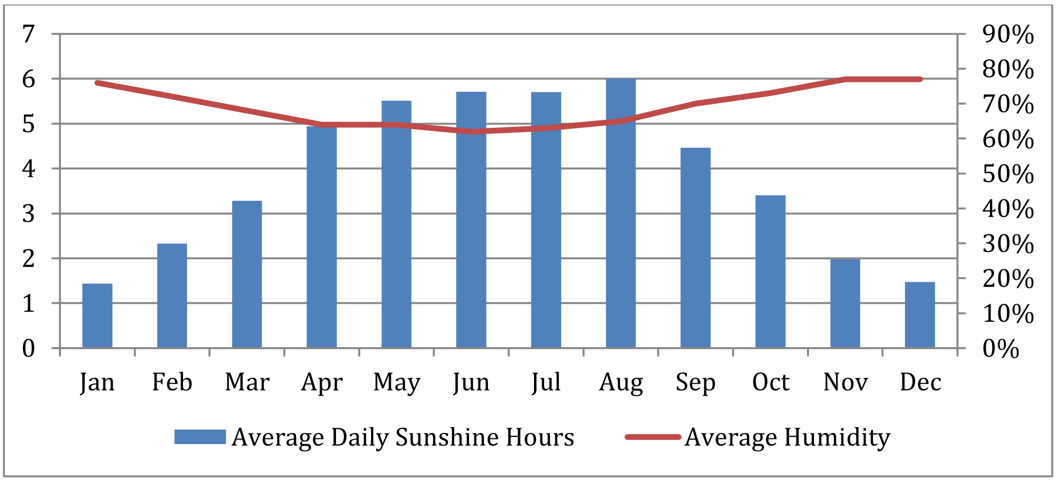


Figure 32 Average daily sunshine hours and humidity in London 2011

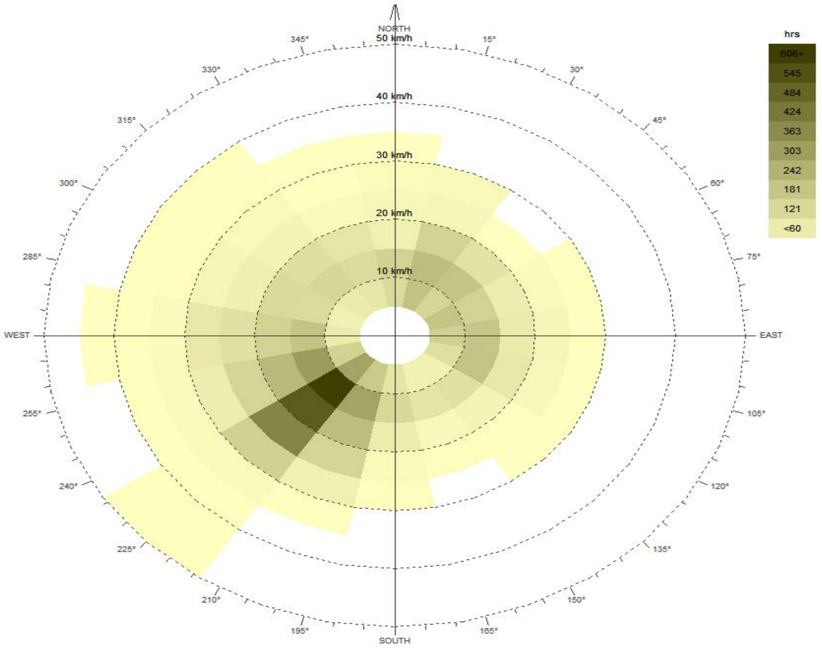


Figure 33 Wind speed and direction in London 2011

Figure 34 demonstrates that the effect of climate change would cause temperature increases to around 35℃ and minimum temperature would be around 0℃. The annual average temperature would increase by 3℃. Overheating risk is more considerable in summer in London 2080 compared to present times and obviously overcooling risk would be alleviated by the considerable shift towards warmer weather.

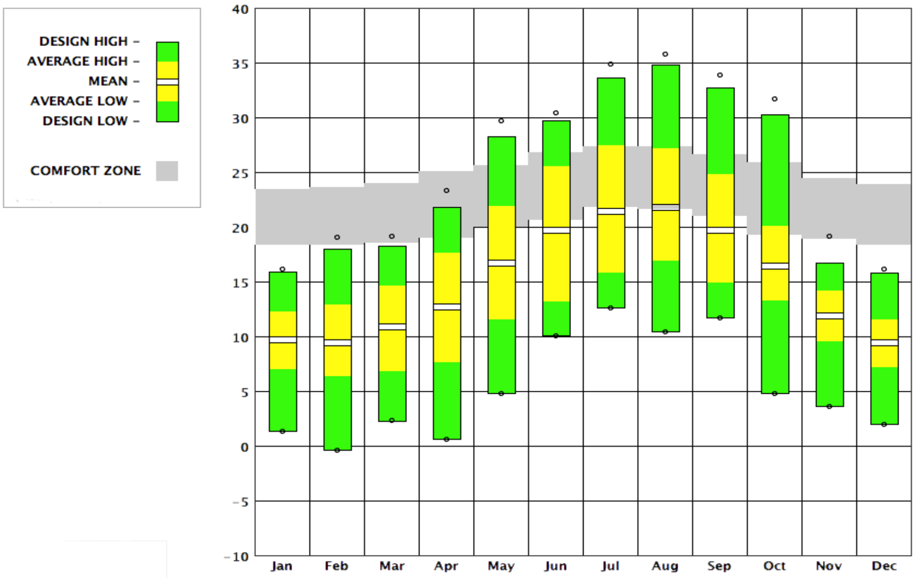


Figure 34 Low, mean and high monthly temperature in London 2080

This thesis also considers 2020 and 2050 predicted weather data for simulations. However, only extreme situations have been shown above to provide a picture of the likely temperature increase in both cities.

6.4 Summary

- The worst case scenario is chosen in this study because the model which is resilient to the greatest changes in future climate is highly likely to be the most robust design.

- Temperature increases in UK are likely to continue until 2080 and will have an extreme effect on the sustainable design decision-making process.

- In London, an increase of up to 5°C is expected, which will cause considerable overheating risks in summer months. The increase in Manchester is lower but the risk still exists for both cities. Therefore, in the following chapters the impact of this likely increase of temperature is quantified and sustainable design decision-making and potential design solutions are investigated to alleviate the overheating risk.

7. TERMINOLOGY OF HEAT TRANSFER IN BUILDINGS

7.1 Heat transfer mechanisms

The movement of energy because of temperature differences is called heat transfer. It can occur by convection, conduction or radiation. In conduction and convention energy movements occur through matter but with radiative heat transfer energy movement occurs by electromagnetic waves. It is radiative heat transfer from the sun to the Earth that is the not only the primary example of this heat transfer mechanism but also the origin of most energy sources on the planet. Solar radiation moves through the Earth's atmosphere primarily as shortwave radiation. When the radiant energy hits a surface it is transmitted, absorbed or reflected in different ways depending on the types of surface. The energy that is absorbed by surface will be radiated back as long wave radiation. For instance, virtually all the shortwave solar radiation is transmitted through glass but long wave radiation is absorbed and retransmitted as heat energy. This is the cause of what is called the 'greenhouse effect' (ASHRAE, 2005). To realize how each material reacts to radiation, the following properties are used:

- Reflectivity (ρ): The capacity to reflect radiant energy, which depends on the texture, color and clarity of the material.
- Absorptivity (α): The capacity to absorb radiant energy, which depends on the wavelength of the radiation and the temperature of the body.
- Emissivity (ε): The capacity to radiate absorbed energy, the darker the material, the closer to 1 the emissivity ratio
- Transmissivity (τ): The fraction of the radiant energy transmitted through a transparent object, which depends on wavelength of the radiation and the temperature of the body.

7.2 Thermo-physical properties of materials

The major properties of a material in thermal analysis include density (a material's mass which fills a unit volume, kg/m^3), specific heat (the amount of energy necessary to cause a temperature change in the mass of material, J/kg ℃) and thermal conductivity (a material's ability to conduct heat, W/m℃). These features are time dependent because of material temperature or moisture fluctuations. The properties of some common building materials, which have been used in this study, are shown in Table 10 (Clarke, 2001).

Table 10 Thermo physical properties of some common building materials

Material	Conductivity (W/m℃)	Density (kg/m^3)	Specific Heat (J/kg ℃)
Concrete - Heavyweight	1.3	2400	840
Concrete - Lightweight	0.2	620	840
Concrete – Medium weight	0.32	1060	840
Expanded polystyrene (EPS)	0.035	23	1470
Gypsum Plasterboard	0.16	800	840
Hardwood	0.05	90	2810
Softwood	0.17	550	1880
Steel	45	7800	480
Water (Liquid at 20 c)	0.58	1000	4200
Cement screed	1.4	2100	650
Block – Masonry medium weight	0.6	1350	840
Brick	0.3	1000	840
Cement (regular)	0.72	1860	840
Ceramic tiles	1.20	2000	850

The magnitude of the conductivity indicates how easily heat moves through a material. Thermal resistivity is the reciprocal to conductivity, and indicates the material's resistance to conduct heat, as demonstrated in the equation below:

$$r = \frac{1}{k}$$

r = resistivity (m ℃/W)

k = conductivity (W/m ℃)

Insulation materials normally have low specific heat capacities, low thermal conductivities and low thermal mass. As a result, materials used for insulation reduce heat transfer but are unable to store heat. Since air is not a good thermal conductor, the most typical way to make a good insulation is by trapping air. Therefore, a good insulator is not only a substance with low thermal conductivity but also a material which does not provide easy pathways for radiation and convection heat transfer.

To explain how the described properties have an impact on thermal storage, the following breaks down the process into phases:

1. The thermal source radiates the heat to the surface of the material
2. Heat is conducted from warmer part to the cooler part
3. As soon the surface becomes warmer than its surrounding the heat radiates back to the space around and become cooler again
4. The cycle restarts on heat energy moving from the warmer part

Therefore, a thermally useful building material should have a high heat capacity for effective thermal mass, moderate density and conductance as well as a high absorptivity and emissivity. As Table 10 shows, steel does not provide good thermal mass due to its very high conductivity and low emissivity, wood performs similarly due to its very poor conductivity. On the other hand, masonry products, water and concrete have good thermal mass performance due to their moderate conductance and high density. However, other material properties should also be considered. For example, as shown in Table 10, ceramic tiles can have a good thermal mass performance but as they have a reflective surface, they can absorb less radiant energy.

Consequently, high thermal mass depends on a variety of factors, which are not easily quantifiable. Figures 35 to 38 map commonly-used materials in building construction. Materials which can effectively be called a type of ‘high thermal mass’ and those that can be good insulators (with conductivity and densities close to zero) are both grouped in the same region. The material in yellow is a phase change material, which is added to the graph as a reference for discussion in Chapter 8.

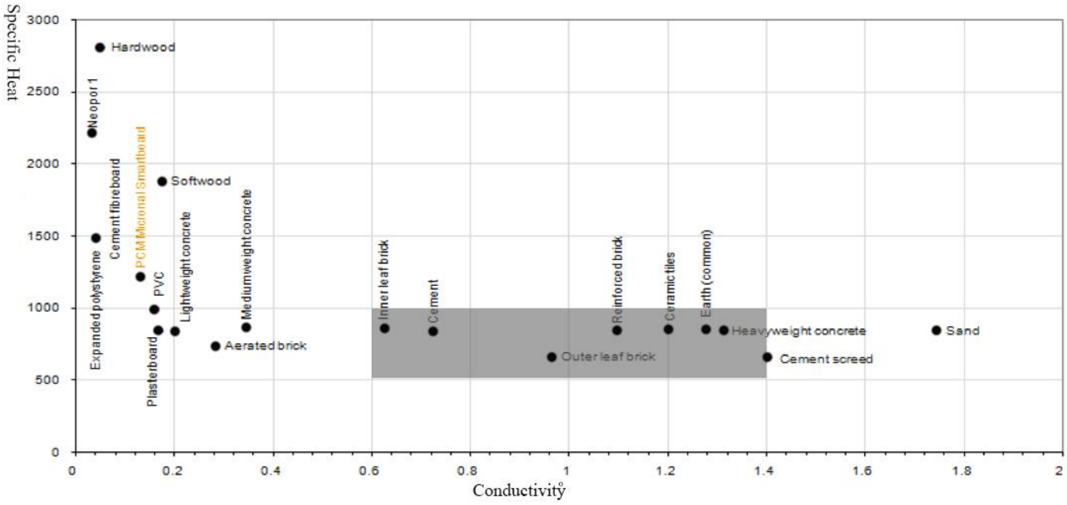


Figure 35 Mapping the most common materials in construction – Specific Heat Capacity (J/Kg°C) vs. Thermal Conductivity (W/m°C)

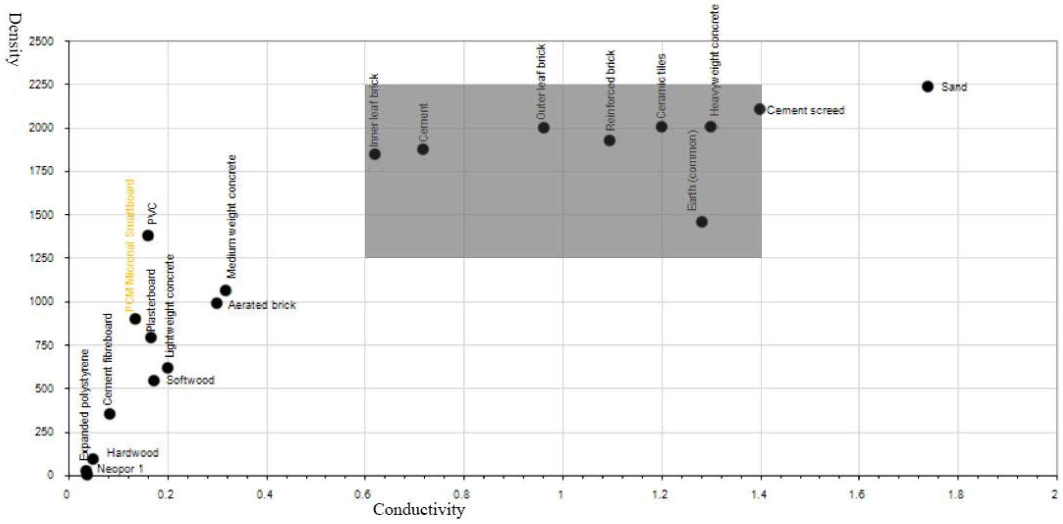


Figure 36 Mapping the most common materials in construction – Density (kg/m^3) vs. Thermal Conductivity (W/m°C)

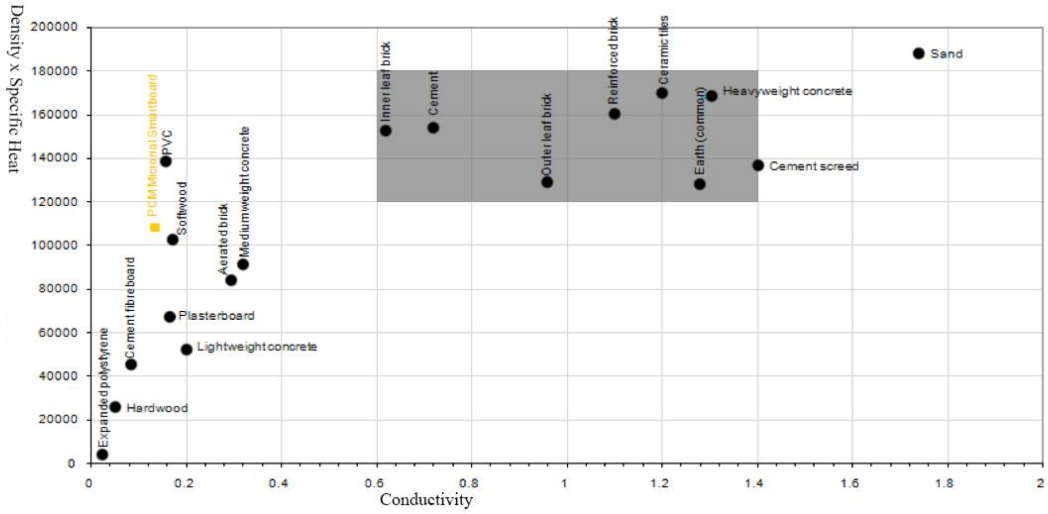


Figure 37 Mapping the most common materials in construction – Density x Specific Heat Capacity (J/m^3K) vs. Thermal Conductivity (W/m°C)

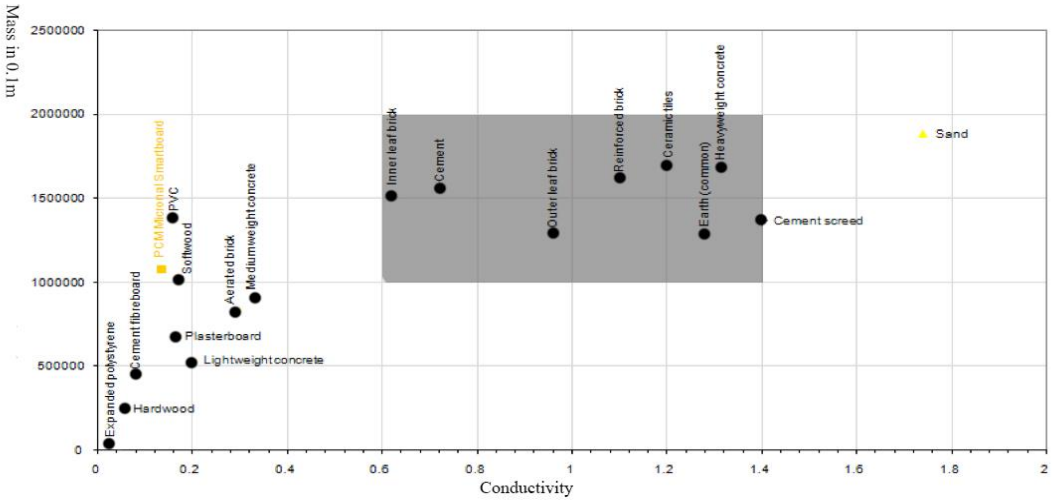


Figure 38 Mapping the most common materials in construction – Mass for 0.1m of material (J/m^2K) vs. Thermal Conductivity (W/m°C)

These graphs can help designers to choose a material with a high thermal mass, although their thermal mass efficiency also depends on how the mass is utilized in construction along with their thickness, exposure and surface finishes. The next chapter will consider the thermal performance of selected construction systems using dynamic thermal modelling software.

7.3 Heat transfer quantification in buildings

This section describes heat transfer quantification methods in buildings, which includes both steady state and dynamic heat transfer calculations. It will be determined that dynamic heat transfer calculations are more precise for thermal simulations in building, therefore software that uses this approach, such as DesignBuilder (DB), is used in this study.

7.3.1 Steady-state heat transfer

Fourier’s law of heat conduction states that the rate of heat flow can be obtained from the equation below (where q= heat flux, W/m^2. k=conductivity, W/m°C). $\Delta T/\Delta x$ = Temperature gradient, $°C/m$):

$$q = -k \frac{\Delta T}{\Delta x}$$

By applying this equation to a building wall, where L is the thickness of the wall (m) and heat flows from higher temperature (T1) to the lower (T2) then the equation below can be obtained:

$$q = -k \frac{T1-T2}{L}$$

Therefore, to study the thermal behavior of a building it is necessary to consider the thickness of the walls. Thermal resistance is the relation between materials thickness and its resistivity, which can be seen from the equation below (R = resistance, $m^2°C/W$; r = resistivity, m°C/W. L=thickness, m)

$$R = r \times L$$

Consequently, the thinner the material layer is, the lower its resistance to heat flow. Thermal resistance is also known as R-value, which is referring to 1m^2 of a sample material with 1m thickness with a 1 °C temperature differences between surfaces. Every building element contains not just the thermal resistance of the solid layers but also surface resistances (related to how easily heat can enter or leave a surface) and also, if there are any air cavities, the thermal resistance of the air layer. The total thermal resistance of a building element is found by adding together all the individual resistances. The reciprocal of the total thermal resistance is called the thermal transmittance or U-value ($W/m^2°C$).

$$U = \frac{1}{R1+R2+\cdots+Rn}$$

The U-value is an important factor in the steady state heat loss and gain calculations for building envelopes (BSi, 2003). The heat flow q (W) through a building element with an area of A and a inside-outside air temperature difference of ΔT is given by

$$q = U\Delta T$$

In general, two walls with the same R-value or U-value will conduct the same quantity of heat in steady state. This is the traditional way of assessing heat loss in buildings, but this approach does not consider the dynamic behavior of the materials - two walls made from the same materials will have the same U-values but perform differently in different construction designs. For example, a wall with its thermal insulation on the external side will, thermally, perform differently from the same wall with its insulation on the internal side.

7.3.2 Quasi steady state heat transfer

In quasi steady state heat transfer there is a variation of heat flow or temperature with time, but this variation is repetitive and takes the same form with time. Figure 39 compares the difference between quasi steady state and steady state heat transfer mechanisms (Gomma & Al Taweel, 2005).

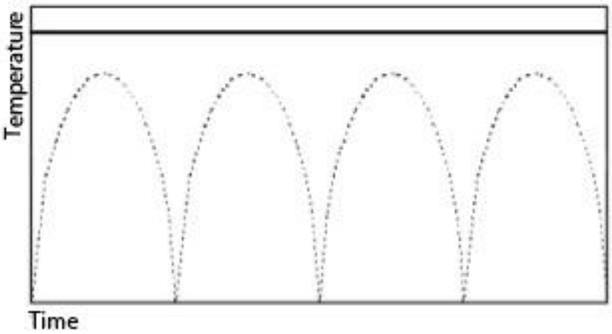


Figure 39 Steady State heat transfer mechanism (straight line) in comparison with quasi steady state heat transfer mechanism (dash line)

7.3.3 Transient heat transfer

Figure 40 demonstrates transient heat flow in a wall section and Figure 41 illustrates the difference compared with a steady state calculation. It can be observed that heat transfer takes time to happen and will be in different locations in different times

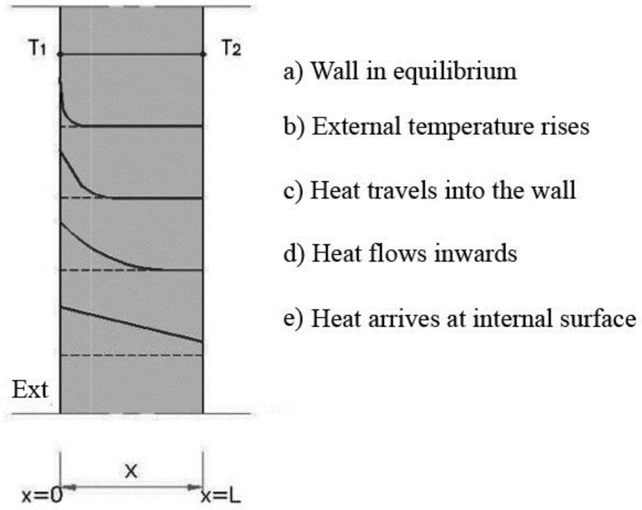


Figure 40 Heat flux in transient heat transfer prediction

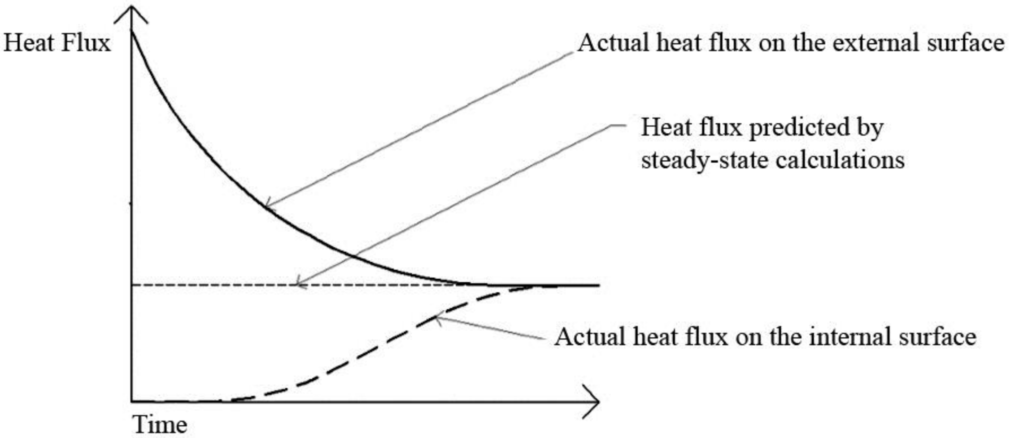


Figure 41 steady state and transient heat transfer

As can be seen in Figure 41, the final heat fluxes are estimated to be the same in both steady state and transient heat transfer. But if the steady state method was used to calculate through the building envelope, the results achieved would be incorrect. This means that the ultimate steady-state condition will not be reached until a definite quantity of energy is conducted through the building envelope.

Thermal diffusivity (D) is a quantity that can be obtained from dividing the ability of material to store energy divided by its ability to conduct heat

$$D=\frac{k}{\rho c}$$

where D is thermal diffusivity (m^2/s), k is conductivity (W/m°C), ρ is material density (kg/m^3) and c is the material's specific heat capacity (kJ/kg°C)]. Thermal diffusivity indicates the rate at which the temperature profile travels through the wall core, which is a useful value of illustrating thermal mass (Clarke, 2001). Materials with high diffusivity respond faster to any temperature fluctuations compared to those with lower diffusivity. Thermal effusivity (which is often referred to as thermal inertia) illustrates the transfer of heat through a material's surface. A higher effusivity rate indicate a material's tendency to absorb heat flux at a surface (Kalogirou, et al., 2002). Figure 42 compares diffusivity and effusivity for common building materials.

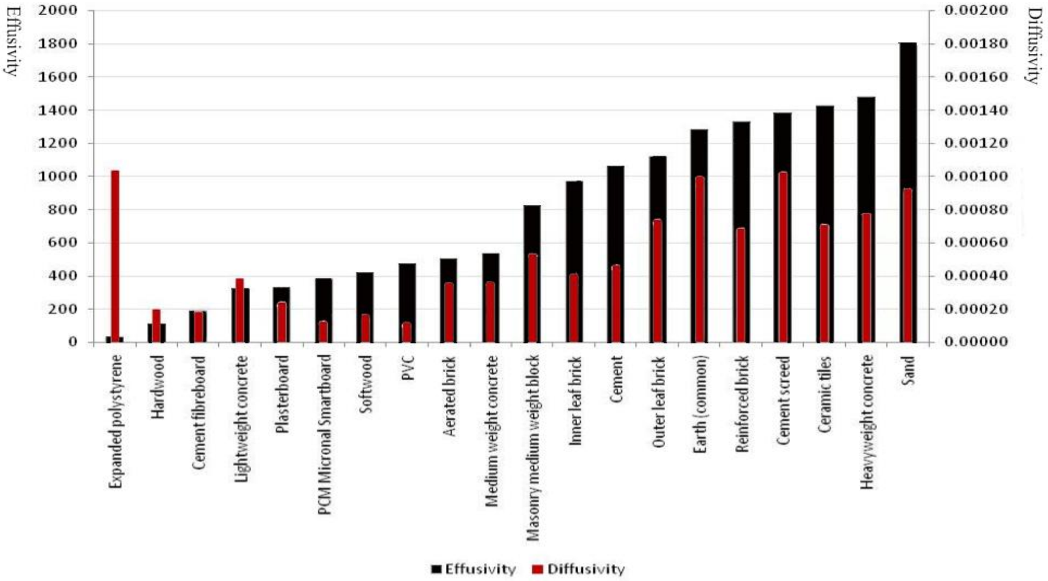


Figure 42 Diffusivity and Effusivity of some common building materials

Diffusivity and effusivity are useful values to understand a material's thermal mass capacity but they do not do so entirely. The other two factors that are necessary to consider are time lag (the time taken the maximum outside temperature to make its way to a maximum inside temperature) and decrement factor (the ability to decrease the amplitude of temperature from outside to the inside, see Figure 43). (Childs et al., 1983).

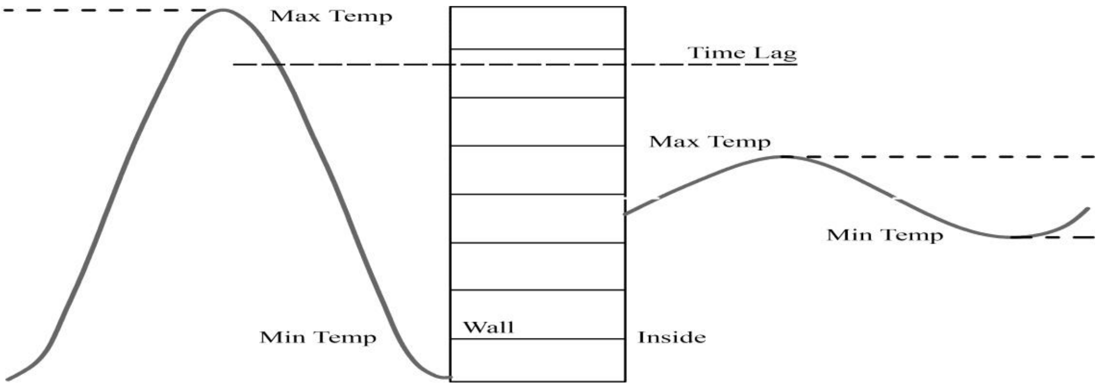


Figure 43 Time lag

7.4 Dynamic Heat Transfer

As observed, steady state calculation methods are limited in the way they quantify heat transfer in buildings. Brisken and Reque (1956) suggested a method on the basis of approximating outdoor temperature pulses into triangular temperature pulses and the overall heat flux is ascertained as a result of the response to all pulses. This is called the response factor method (RFM) and is used by many building simulation softwares (Davies M. , 2004).

Essentially, the response factor method comprises two divisions that are the time-domain and frequency domain response function methods. The time-domain approach analyzes hourly indoor conditions on the basis of hourly weather data information, whereas the frequency domain response method generates a cyclical system response on the basis of a periodic weather cycles (Clarke, 2001).

Several methods exist for the purpose of assessing the dynamic thermal performance of buildings including the admittance method, which is advocated by the UK Chartered Institution of Building Services Engineers (CIBSE) and based on the frequency-domain method. This method utilizes a material's time lag, decrement factor and admittance to explain its dynamic response (CIBSE, 2006).

Thermal admittance is basically a factor which shows the quantity of heat that travels through a material (measured in W/m^2K). In steady state quantification this is similar to the U-value but it is different when a time factor is considered. Constructions with high thermal mass materials are likely to have a high admittance factor and those with high level of insulations are likely to have lower admittance ratios.

Therefore, the admittance factor can be a good indicator of thermal mass in construction and can be considered as a dynamic U-Value (BSi, 2007). The Concrete Centre (2006) has also suggested using admittance as a factor to measure thermal mass but Saulles (2009) expressed a criticism, saying that it might cause errors in actual ultimate cooling capacity of high thermal mass structures by up to 50% compared to more advanced thermal modeling methods which utilize real weather data.

7.5 Thermal mass impact in heat transfer

In general, thermal mass refers to materials that have the capacity to absorb, store and release heat. Therefore, thermal conductivity, specific heat capacity and density as well as the heat transfer mechanisms which have already been discussed can help to characterize thermal mass. There are two major aspects that have to be considered in thermal mass: firstly, the heat flux variation will decrease when traveling through the wall. Secondly, mass is capable of causing a delay to the time of maximum and minimum heat flux occurrence through the wall (Childs et al., 1983).

Consequently, time is a significant issue that has to be considered in the design decision-making process. It will be difficult to use the thermal mass if the time lag is too long - for example if it is more than 12 hours, heat will still move to the indoor space when there is more heat available. Also, excessive thermal mass thickness can be unfavorable in cold seasons as the space will take longer to become warm. Studies by Orme and Palmer in 2003 shows that only 10W of excessive heat gain over losses can cause the temperature in a $17m^2$ room to rise by 17 °C in ten hours. This indicates the importance of the whole building energy balance consideration.

Therefore, it can be noted from the above discussions that, an effective way of optimizing the usage of thermal mass is to maximize the surface of a material rather than its thickness since this causes heat transfer enhancement between mass and the space. Furthermore, it seems reasonable to provide insulation on the external wall surface to retain the stored heat. Kosny et al (1998) confirmed lower performance of insulation when installed on the interior side of the building envelope.

CIBSE Guide A gives a comprehensive list of thermal admittance, decrement factor and thermal transmittance values for a variety of construction systems. This provides valuable insights on thermal properties and their usage in thermal simulations. However, a clarification is needed for the commonly used brick-cavity-block. This is usually considered as a heavyweight construction, but different types of block can have different performances (see Table 10 above). Brick is normally installed behind the insulation and it is the only part to act as the thermal mass in this construction arrangement.

Basically, there are two primary methods of employing materials in order to act as thermal mass:

- Diffuse thermal storage materials which rely on convective and radiative heat transfer and can be placed in a building envelope
- Direct thermal storage materials which should be exposed to solar radiation

Concrete, brick, concrete block, stone and earth are the most common materials utilized for thermal storage. Materials with dark colours can absorb more solar radiation and therefore are advantageous in this case. The use of water (e.g. distributed inside containers built in floors and walls) is less common but more efficient as thermal mass. Careful consideration should also be given to wall finishes (wallpaper, painting, plasterboards, etc.) as they might hinder the heat transfer between mass and the space (Orme & Palmer, 2003).

7.6 Other influential Factors

Factors such as thermal bridging, fenestration and ventilation can alter, enhance or constrain heat transfer in buildings. Consideration of these features are important in assessing building thermal performance, although they are not the focus of this thesis. However, the following will consider them briefly.

7.6.1 Fenestration

Exterior openings (such as windows) is called fenestration. In following the line of energy efficiency, windows are an essential part of the design and performance of the building envelope because of their importance concerning daylight, solar radiation and ventilation as well as view and other features. Therefore, it is a real challenge for architects to incorporate these elements in fenestration design. For instance, designing large windows to maximizing daylighting can cause significant heat loss or excessive solar gain in buildings. On the other hand, minimizing window sizes may cause occupants dissatisfaction and less utilization of daylighting. Dealing with daylight optimization is not within the scope of this study but is an issue that has a considerable effect in the thermal performance of buildings.

Therefore, the energy performance of windows and any transparent elements should be considered. Ideal transmittance and conductance (U-Value) of these elements are given in Chapter 3. Generally, a window’s U-Value includes three components: the frame the glazing and their interaction (CIBSE, 2006).

7.6.2 Ventilation

A short description of ventilation and the possible strategies to be adopted are given in Chapter 3. However, this part focuses on its thermal impact aspect. Suitable ventilation design is necessary for heat and cooling distribution to reach thermal comfort and subsequently has an effect on the energy efficiency. In the UK, during summer, temperatures in buildings may exceed external temperatures by 3 $°C$. The combination of thermal mass and ventilation can help buildings to cool down. Orme (1998) emphasized the importance of ventilation in energy efficiency and stated that about 30% of energy waste can occur because of inadequate ventilation strategy.

Airflow velocity is also an important factor of thermal comfort. Although it is very subjective, from 0.5 m/s to 1.5/s is considered a proper velocity in buildings. More than 3.0 m/s is considered as disturbing and greater than 10 m/s is unpleasant outside (Szokolay, 2008). An air velocity of 0.8 m/s can cause a 3 $°C$ cooling perception (Rennie & Parand, 1998) which is considerable and shows the significance of ventilation strategies in buildings, especially in summer.

Ventilation can also be provided by mechanical methods. The aim of heating, ventilation and air-conditioning (HVAC) systems is also to deliver and keep indoor conditions within the conditioned space. Therefore, the selection of HVAC systems on the basis of building types and financial budget is quite important for energy saving and cost savings aims. Furthermore, as the consequences of natural ventilation are usually uncertain and hard to control, mechanical ventilation becomes more significant and an essential part in the design decision-making process.

7.6.3 Air-tightness and thermal bridging

Air tightness is beneficial in terms of avoiding uncontrolled heat loss, decreasing moisture flow and protection from outdoor pollution, although it may cause health risks if infiltration is entirely removed. Basically, energy losses are from conduction through the building envelope or convection via infiltration (Stephen, 2000). The German building energy standard PassivHaus suggests an ideal infiltration rate of 0.6 air changes per hour (ACH) at 50Pa, as mentioned in Chapter 3.

Thermal bridging is a consequence of the heat gain and loss through the building material junctions. Thermal bridging is quite high where poor insulation is implemented in building. The major heat loss will occur when a material such as steel beam is near the envelope surface and heat can travel by conduction to the outside of the building. Consequently in design process careful consideration should be given to reduce or entirely remove this issue and its influences should be no more than 10 to 15% of the entire transmission heat loss (CIBSE, 2006).

7.7 Summary

- The utilization of thermal mass is an ancient tactic to provide a more comfortable internal environment. However, considering thermal mass performance in highly insulated building envelopes is a new approach. This becomes more significant in the UK where currently there is tendency for lightweight construction systems. Furthermore, the risk of overheating due to future climate change will increase the advantage of the good usage of thermal mass.

- In the passive design decision-making process, a material's reflectivity, transmissivity, absorptivity and emissivity are important features to be considered to realize the amount of reflected, transmitted or absorbed energy. In order to have an adequate thermal mass performance, materials should have high heat capacity, adequate conductance and density as well as high emissivity.

- Depending with various conditions, thermal mass can considerably reduce temperature fluctuations, by absorbing excessive heat, storing it and then releasing it to indoor space at a later time. This also means it can reduce energy consumption. The admittance factor is the simplest way of assessing the ratio of thermal mass as well as time lag and decrement factor.

- The exposure and surface of materials should be carefully chosen for maximum contact with solar exposure or any source of heat energy. Heavy weight constructions are not necessarily the ideal option for this.

- Evidently, the amplitude of temperature fluctuations can decide the level of thermal mass performance. Therefore, it may not be a suitable decision for places with low daily temperature variations. The question remains whether increasing/decreasing insulation thickness or increasing/decreasing amount of thermal mass is the correct design solution for current/future UK housing. There is concern about the uncertain future and the possible risk of overheating and the following chapters use dynamic heat transfer simulation to investigate this topic.

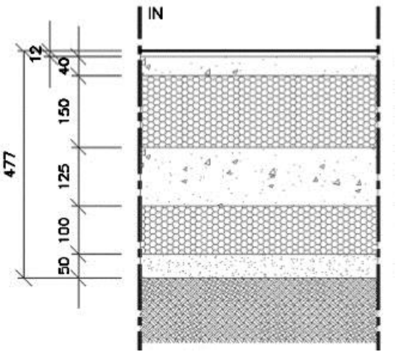
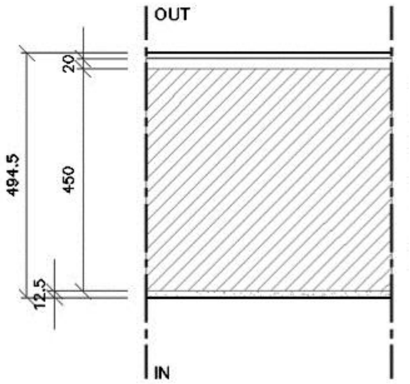
8. MODELING HEAT STORAGE AND PERFORMANCE ASSESSMENT

Building simulation software can determine the thermal processes within a building based on mathematical calculations. This chapter introduces selected wall types that are popular in the UK and demonstrates how they would perform in two different models on the basis of thermal comfort and energy consumption.

8.1 Wall Types

The simulations in this study focus on the assessment of wall types. Therefore, roof and floor were kept the same in each model, as shown in Table 11. Decrement factor (the ability to decrease the amplitude of temperature from outside to the inside), time constant (the time takes the maximum outside temperature makes its way to a maximum inside temperature), admittance (building fabric response to a swing in temperature) and U-value (overall heat transfer coefficient) (BSi, 2007) are considered to characterize the performance of wall types in thermal modeling.

Table 11 Ground floor and roof

	Ground Floor From top to bottom; 12mm Pine Wood floor, 40mm Concrete Screed, 150mm Extruded Polystyrene (EPS), 125mm Concrete Slab, 100mm Extruded Polystyrene (EPS), 50mm Sand, Crushed Brick
	Roof From top to bottom; Clay Roof tile, Roofing Felt, 20mm Air Cavity, 450mm Rockwool, 12.5mm Plasterboard

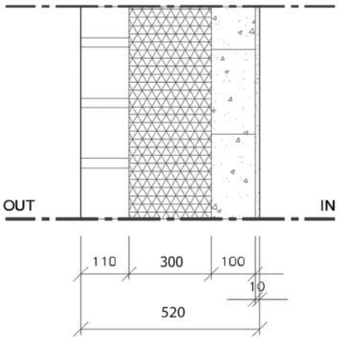
Five wall types have been selected on the basis of the following criteria:

- Recent use for housing in the UK so detailed information is available
- Method appropriate for use in UK housing
- The potential of achieving Part L of UK thermal building regulations
- All walls were designed to have the same U-Value of 0.1 W/m°C

The construction systems examined were:

- **Brick and block wall (BB)**

Housing data for England during 1990-2009 showed that brick and block is the most typically used construction technique in Britain, with an 88% distribution. This type of construction has a number of variations but the sample in this study is the most common one (DCLG 2008). The thermal performance requirements can be met by filling the cavity with insulation to achieve the required U-Value (Chudley and Greeno 2008).

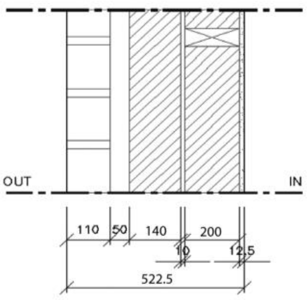


Decrement Factor (0-1) : 0.23
Time constant (Hours) : 7.7
Admittnce (W/m^{2}K) : 5.3
U-Value (W/m^{2}K) : 0.1
Thickness (mm) : 520

Figure 44 Brick and Block wall type. From Out to in: 110mm Brick Outer Leaf, 300mm Phenolic Insulation, 100mm Aerated Concrete Block, 10mm Lightweight Plaster

- **Timber frame wall (TF)**

Timber-frame is the second most commonly used housing construction technique, used for 7% and 29% of residences in England and Scotland respectively (DCLG 2008). It is typically composed of factory-made panels and can receive a range of different cladding. Based on the type and thickness of insulation used, which is usually mineral wool, optimal thermal performance could be achieved (Chudley and Greeno 2008).

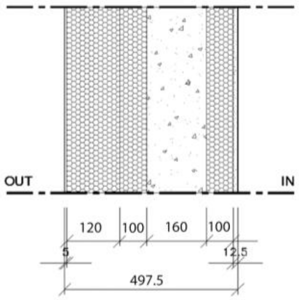


Decrement Factor (0-1) : 0.2
Time constant (Hours) : 3
Admittnce (W/m^{2}K) : 1.54
U-Value (W/m^{2}K): 0.1
Thickness (mm) : 522.5

Figure 45 Timber Frame. From Out to in: 110mm Brick Outer Leaf, 50mm Air Gap, 140mm Rockwool, 10 mm Plywood, 200mm Rockwool, 12.5mm Plasterboard

- **Insulated concrete formwork (ICF)**

Insulating concrete formwork is one of the common modern methods of construction techniques in the UK. Both off-site and on-site assembly methods are possible and the insulation is fixed as part of the structure. The thermal mass of the insulated concrete causes this wall to achieve a high time constant (MacLaren, et al., 2012).

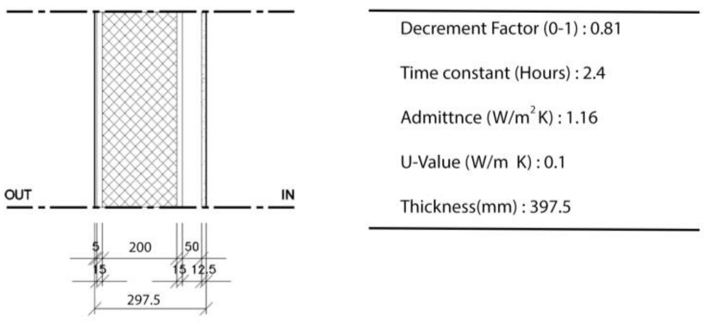


Decrement Factor (0-1) : 0.47
Time constant (Hours) : 5
Admittnce (W/m^{2}K): 2.96
U-Value (W/m^{2}K) : 0.1
Thickness (mm) : 497.5

Figure 46 Insulated Concrete Formwork. From out to in: 5mm Rendering, 120mm Extruded Polystyrene (EPS), 100mm Extruded Polystyrene (EPS), 160mm Heavyweight concrete, 100mm Extruded Polystyrene (EPS), 12.5mm Plasterboard

- **Structural insulated panel (SIPs)**

Structural insulated panel is considered to be one of the common modern methods of construction techniques in the UK. Flexibility in the design because of light and strong features cause thermal bridging and infiltration to be effectively minimized, although this might cause the risk of more hours of overheating in the summer time and the advantage of less loss of thermal loads in the winter (Bregulla and Enjily 2004).

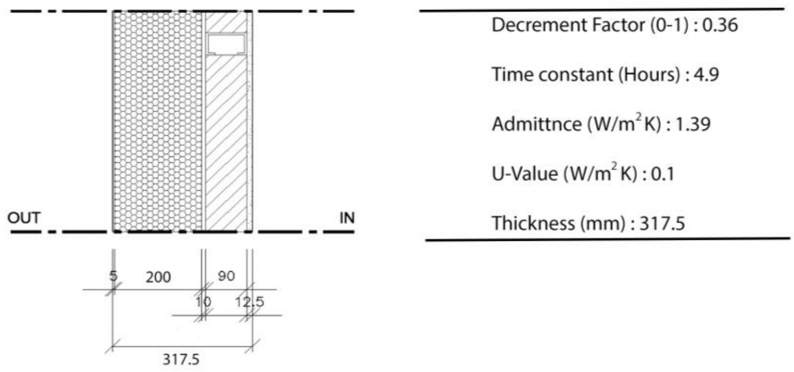


Decrement Factor (0-1) : 0.81
Time constant (Hours) : 2.4
Admittnce (W/m^{2}K) : 1.16
U-Value (W/m K) : 0.1
Thickness(mm) : 397.5

Figure 47 Structural Insulated Panel. From out to in: 5mm Rendering, 15mm Softwood board, 200mm Extruded Polyurethane (PUR), 15mm Softwood board, 50mm Air Gap, 12.5mm Plasterboard

- **Steel frame wall (SF)**

This wall type is quite similar to timber-frame, having considerable design flexibility; various cladding options as well as the popularity of prefabrication are the main advantages (MacLaren, et al., 2012).



Decrement Factor (0-1) : 0.36
Time constant (Hours) : 4.9
Admittnce (W/m^{2}K) : 1.39
U-Value (W/m^{2}K) : 0.1
Thickness (mm) : 317.5

Figure 48 Steel Frame. From out to in: 5mm Rendering, 200mm Extruded Polystyrene (EPS), 10mm Plywood, 90mm Rockwool, 12.5mm Plasterboard

8.1.1 Wall properties comparison

Admittance, decrement factor and the thickness of the five wall types are shown in Figure 49 for easy comparison. The Concrete Centre (2006) suggests the admittance factor as a simple measure of thermal mass. As can be seen, a range of high, medium and low thermal mass performances are selected for thermal simulations.

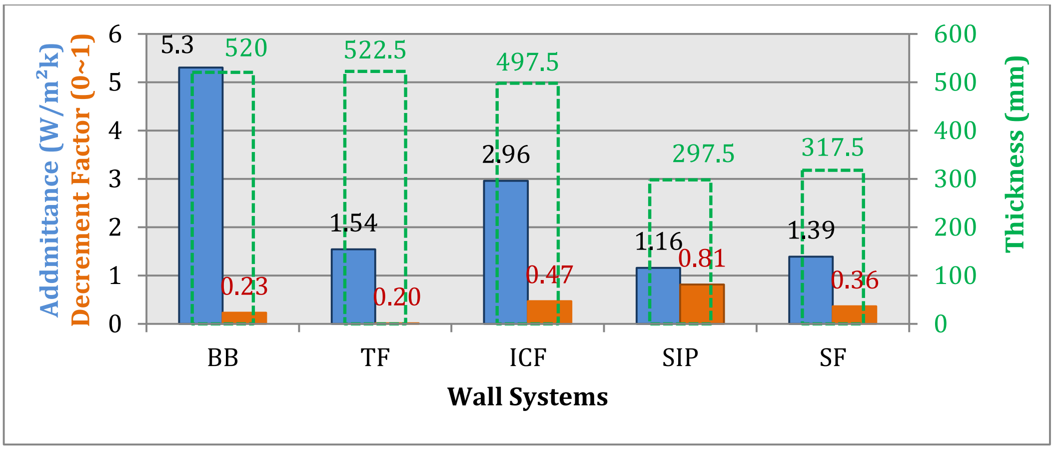


Figure 49 Admittance, decrement factor and thickness of walls

Figure 49 also shows that a thicker construction does not necessarily have a higher admittance. Timber frame TF has a very low decrement factor in comparison with the others, which implies a very low conductivity. Steel frame SF and structural insulated panels SIP have slightly different properties in comparison with each other and brick and block BB shows the highest admittance rate, although TF becomes the thickest wall to achieve a 0.1 U-Value. The dynamic thermal performance of each wall type will be assessed in this Chapter to realize if these Figures are meaningful to characterize the performance.

In order to meet the Passivhaus and Part L minimum U-Value requirements in examined construction systems, traditional insulation types including Rockwool, Phenolic foam, Extruded Polystyrene (EPS) and Extruded Polyurethane (PUR) have been used. These kinds of insulations have all been categorized as organic types, as shown in Figure 50.

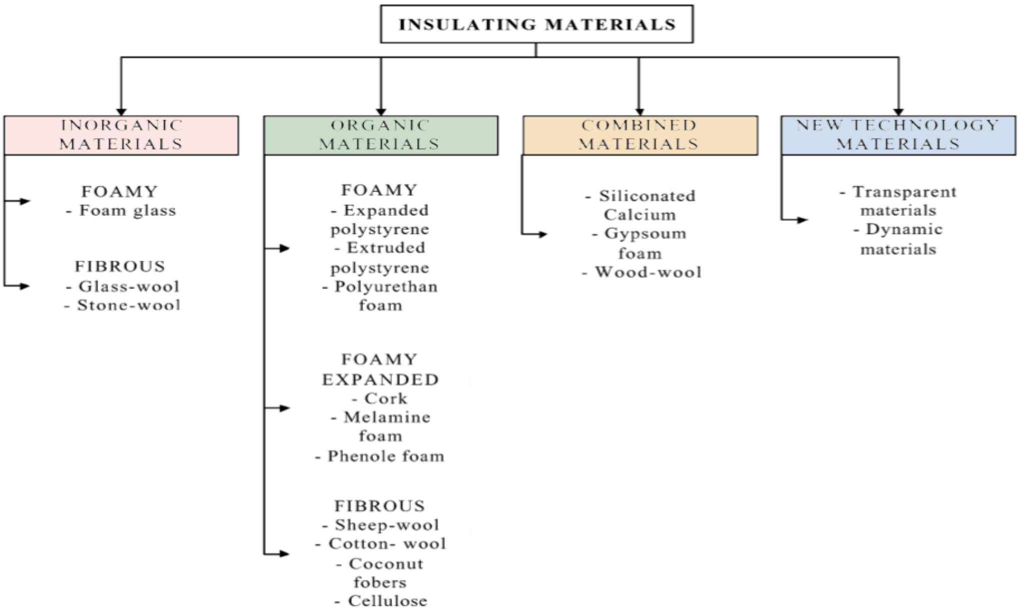


Figure 50 Categorization of typical insulating materials, Graphic by author, data from (Papadopoulos, 2005)

However, one of the major disadvantages of traditional insulations is their high thickness. Figure 51 demonstrates that in the examined construction systems, insulation thickness is a considerable part of each wall types in order to achieve a 0.1 W/m^2K U-Value.

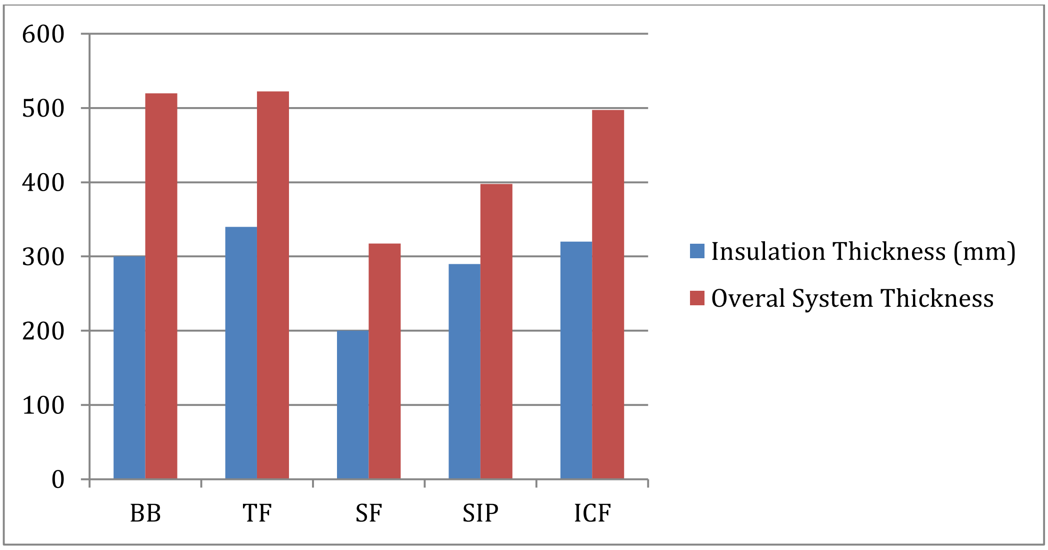


Figure 51 Insulation thickness in examined construction systems to achieve 0.1 U-value

8.2 Potential future modifications

As observed from Figure 51, in order to achieve the required level of U-Value, traditional insulations resulted in the wall being considerably thick. Although traditional insulations have been used for all simulations in this study, in order to demonstrate the likely future potential of new types of insulation,, which could cause lower construction thickness with similar thermal performance, have also been studied. Some examples include dynamic insulation, vacuum insulation panels, nano insulation, multi foil insulation and aerogel insulation, and some of these are briefly described below as potential replacements in the future.

8.2.1 Vacuum Insulation Panel (VIP)

A VIP is an open porous material with a multilayer envelope. It generally includes a core, envelope (could be thick metal sheets or other materials for protection) and getters (which are inserted inside the panel to absorb water vapors and gases) (Tenpierik and Cauberg, 2006). Figure 52 demonstrates a schematic view of VIP components.

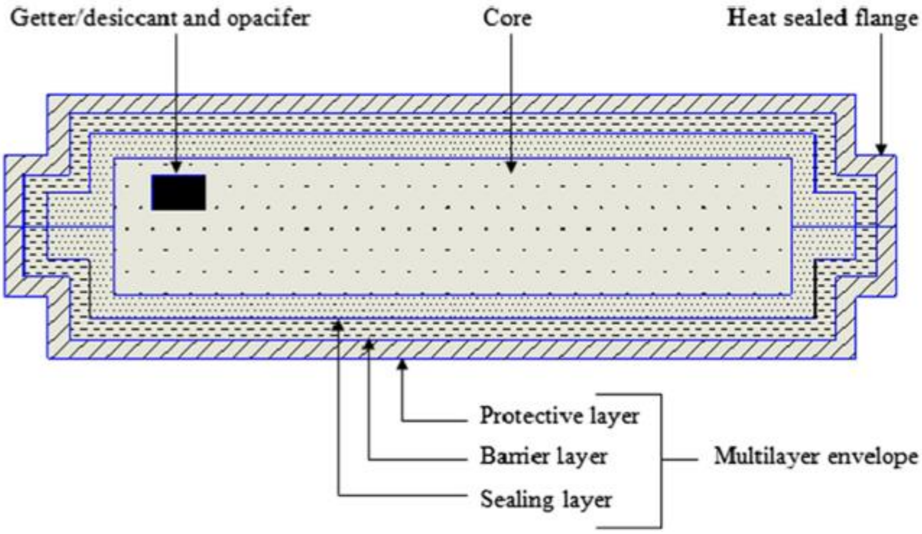


Figure 52 Schematic view of VIP; source (Alam, et al., 2011)

The thermal resistance of VIPs is five to ten times higher compared to the equivalent thickness of traditional insulations (IEA, 2010). Figure 53 compares the possible thickness of traditional insulation with vacuum insulated panel (VIP) when applied to a typical masonry cavity wall of a semi-detached house in the UK. As can be observed, there is a significant advantage to VIP in comparison with the others (refer to Appendix 2 for potential payback period).

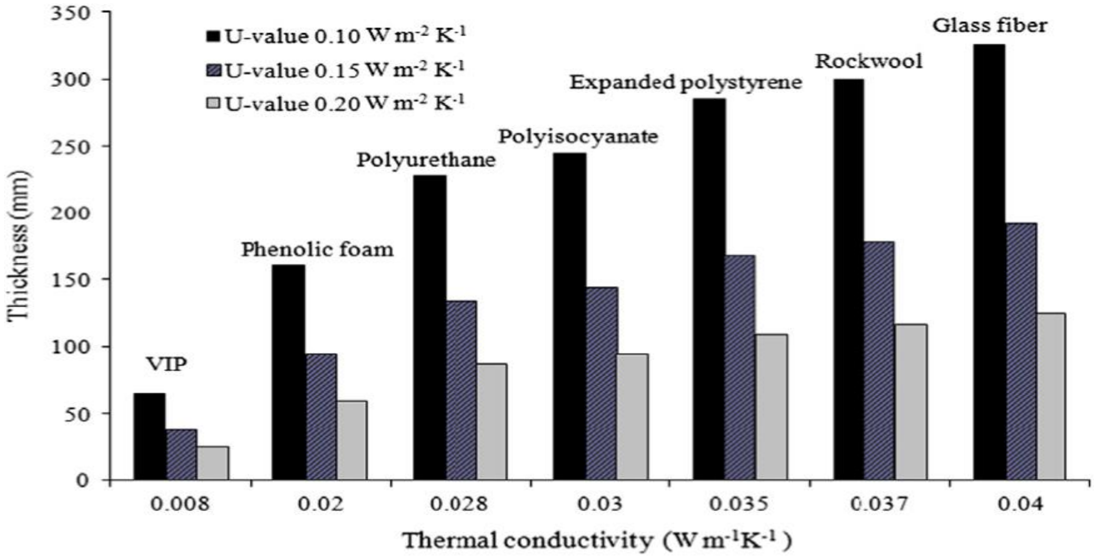


Figure 53 Traditional and VIP insulation material thickness required achieving different U-values for a typical masonry cavity wall with U-value 0.53 source: (Alam, et al., 2011)

However, utilizing VIPs is not without disadvantages as they are fragile compared to conventional insulation panels and edge effects are important, requiring cautious design and fabrication. Also, they cannot be shaped on site (Roberts, 2008).

8.2.2 Nano Insulations

Nanotechnology is a field of knowledge concerned with the control of particles with dimensions between 0.1nm and 100nm (Silberglitt, et al., 2006). The focus for thermal insulation materials is shifting from particles to pores in the nano range (Jelle & Gustavsen, 2010). The difference in structure from VIPs to nano insulation materials (NIM) is illustrated in Figure 54. In this type of insulation, the pore size is reduced below a certain level to achieve better thermal conductivity.

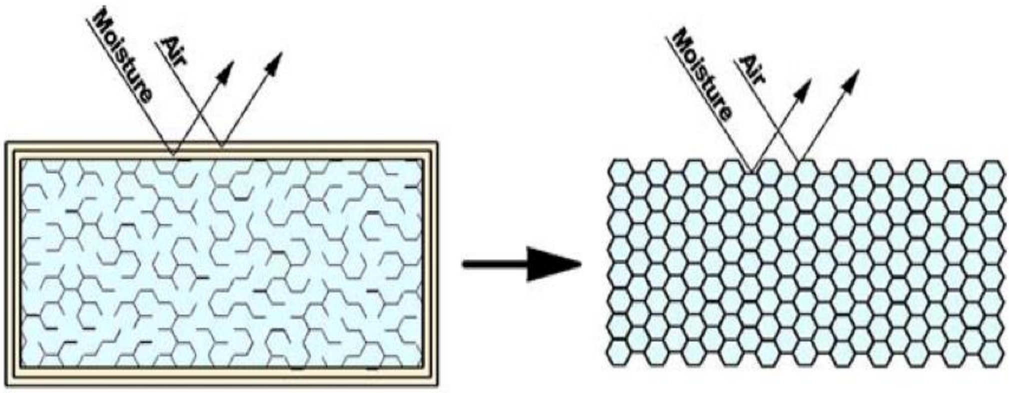


Figure 54 The improvement from VIP to NIM, source (Jelle & Gustavsen, 2010)

8.2.3 Multi-foil insulation

Another technology which has existed in the market now for over a decade is multi foil insulation (Tenpierik and Hasselaar, 2013). These materials include numerous layers of metallized polymer film or thin metallic foil with spacer materials in-between (Timmerhaus, 2007). They have very high thermal resistance (up to 5 or 6 m^2 K/W) as radiation through the insulation is considerably reduced due to the low emission coefficient of the foils (Spinnler, et al., 2004). However, there is ongoing uncertainty on whether these claims are precise.

Figure 55 compares traditional insulation thickness in examined construction systems with VIP insulations when a 0.1 U-Value is applied. With 30 to 45 mm VIP insulation, a similar U-Value can be achieved. Figure 56 also compares some traditional insulation thickness with VIP for the same performances in a practical experiment.

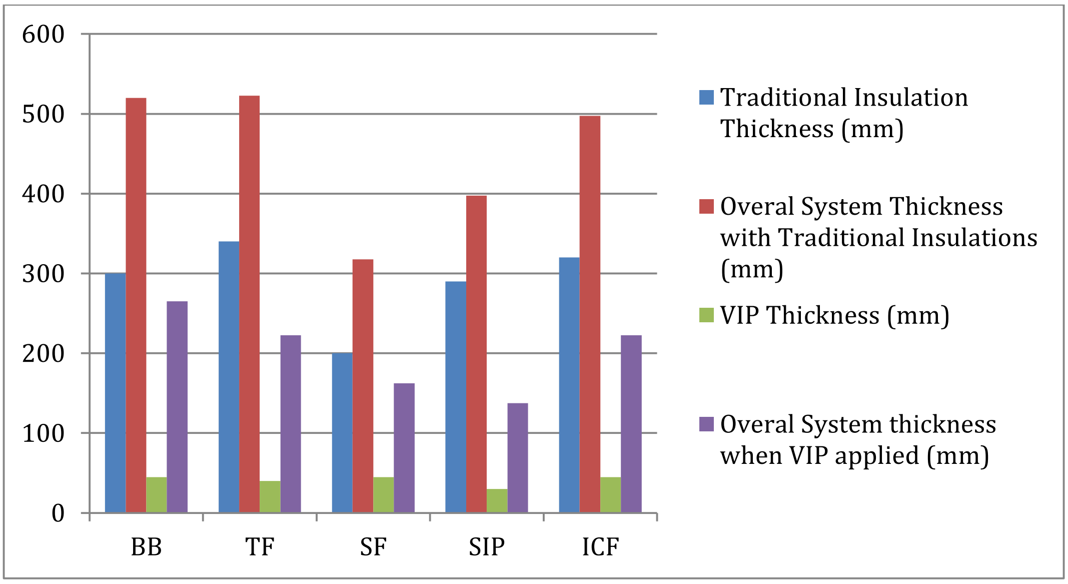


Figure 55 Thickness comparison of VIP insulation with traditional insulations with similar U-value in examined construction systems

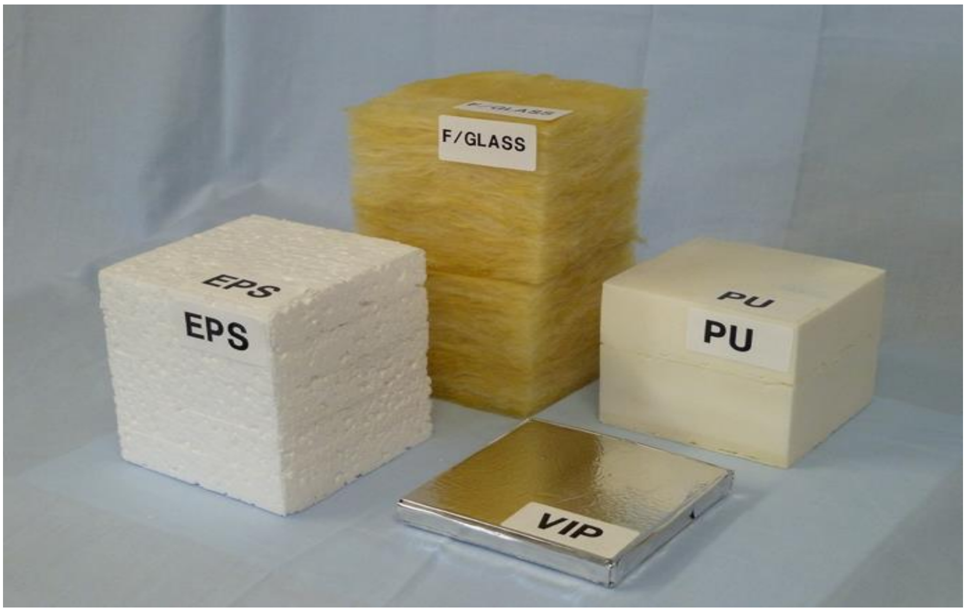


Figure 56 VIP, EPS, PU and F/Glass thickness, source: http://www.nanopore.eu/index.php/about_nanopore/

8.2.4 Aerogels

Aerogels are considered to be one of the modern and high-performance thermal insulation materials. They have 2 to 2.5 times lower thermal conductivity compared to traditional insulations (Baetens, et al., 2011). Figure 57 compares examined traditional insulation thermal conductivity with aerogel and VIP. As can be observed, VIPs have the lowest thermal conductivity but are more vulnerable to air and moisture compared to aerogels, which may affect their thermal conductivity to a lower rate after a period of time (Baetens, et al. 2009). Additionally, aerogels are also available as a transparent insulation material which could be used for highly insulated windows.

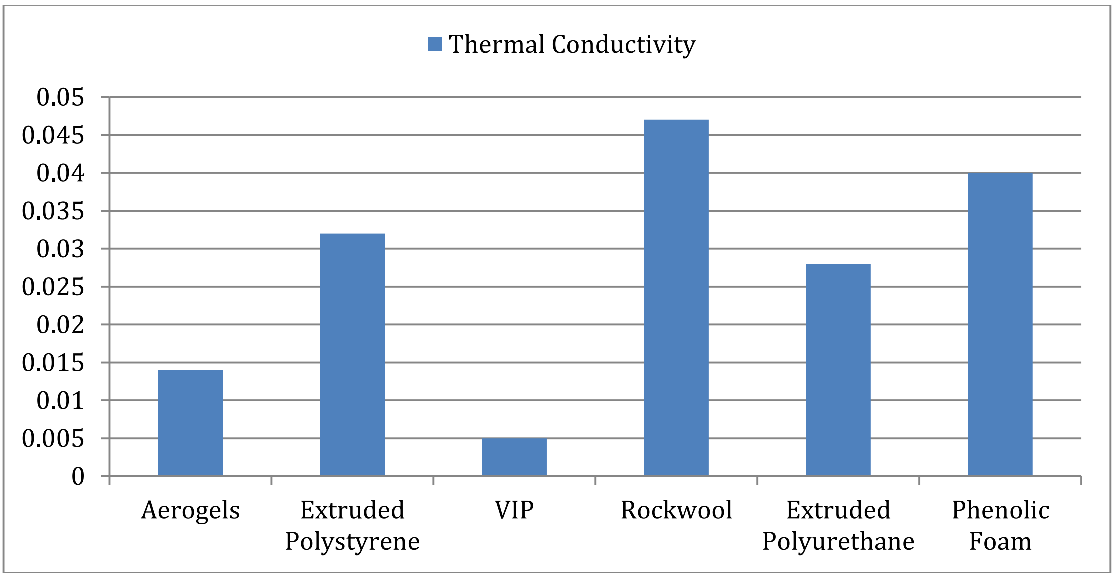


Figure 57 Examined insulation types thermal conductivity

Figure 58 compares traditional insulation thickness in examined construction systems with VIP and aerogel insulations when a 0.1 U-Value is applied. As can be observed, lower thickness with VIP and aerogel can be achieved.

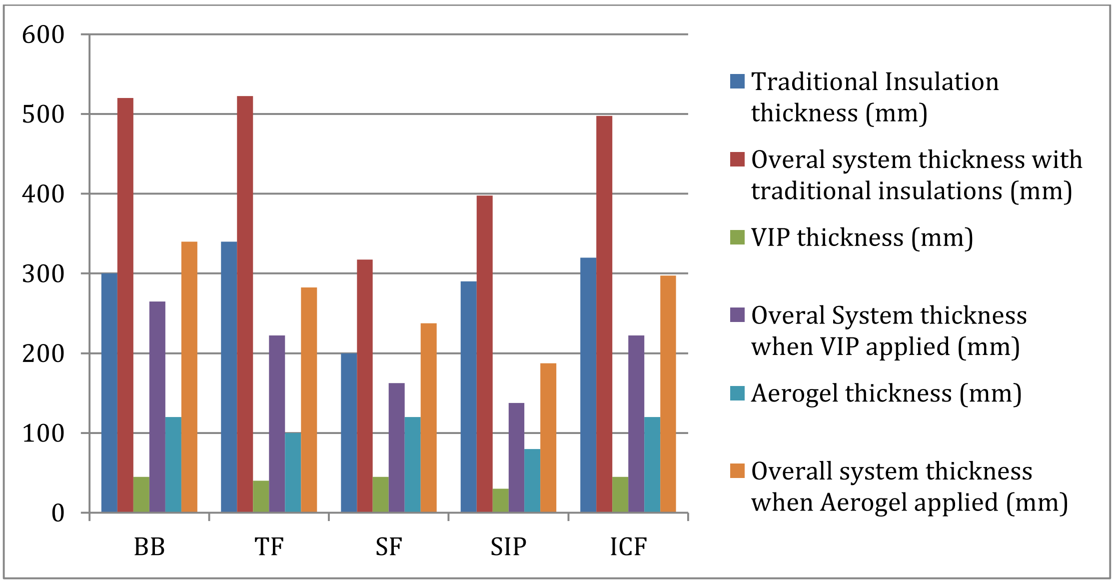


Figure 58 Thickness comparison of VIP insulation with aerogel and some traditional insulation with similar U-value in examined construction systems

8.3 Dynamic simulations

The software DesignBuilder (DB) was used for dynamic thermal simulation in this study. For a model to be successful, it is necessary to examine its accuracy to check the reliability of results. For building energy modeling, Emily et al (2012) stated that comparing models to empirical data could be an “absolute truth standard” but emphasized that the behaviour of occupants is a difficult parameter for measurements. However, Loutzenhiser et al (2009) and Crawley et al (2008) investigated the accuracy of building simulation programs by considering parameters related to the building and highlighted behaviour of occupants as an “idealized validation” and believed it is accurate enough for decision making.

In order to validate the results of DB for this study, some comparisons between DB and other programs or practical experiments were studied and the findings verify a high level of accuracy for this software. For instance, Diarce et al. (2013) studied ventilated active façades with phase change materials (PCM) by DB and compared the results with practical experiments and observed good agreement with experimental data from DB results, although moderate differences were also observed. Also, Baharvand et al. (2013) examined air velocity and temperature disturbution and found that the DB results were reliable and acceptable, although some errors did exist. Furthermore, a study by the Northumbria University (2009) compared the analysis of Computational Fluid Dynamics (CFD) by DB with Phoenics, a specialist commercial CFD modelling package, and highlighted that the results from DB are in a reasonable accordance with Phoenics. Therefore, results from DB seem to be accurate enough for decision making and are highly reliable although minor errors might occur. However, these minor errors would not affect the reliability of the decision making.

8.4 The base case model

The initial model for simulations is shown in Figure 59. It is composed of one zone of 80 m^2 (8m x 10m) with a volume of 240 m^3. The ground floor and roof are as shown in Table 11 and the windows are assumed to have a 0.8 U-Value (triple glazed window with argon filling in a UPVC frame). Infiltration is assumed as 0.60 ACH and natural ventilation has also been considered (window size is 1.2m x 5m).

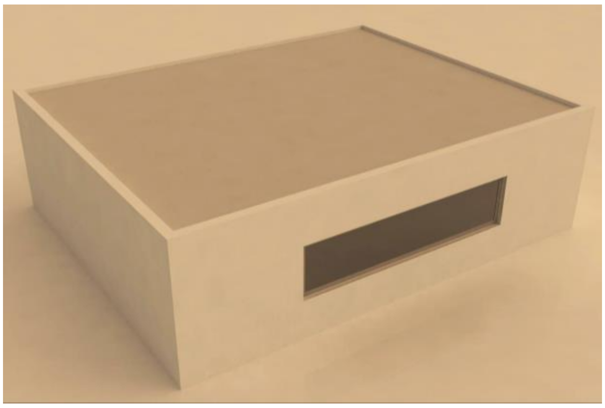


Figure 59 **First model used for simulations (south facing window)**

8.4.1 Wall types thermal performances assessment

The thermal performance of the base case model for the five wall types was assessed using current (2011 or 2020) and future weather data (2050 and 2080) for Manchester and London. Figures 60 and 61 demonstrate the range of hourly temperatures experienced inside the model in Manchester and London respectively during a year for all the wall types. Using a simple base case model with one zone allows for a better understanding of the impact of each wall type on the operative temperature. As the result of the present time (2011) and 2020 in Manchester is almost similar, 2020 is therefore removed from the graphs in this study in some cases.

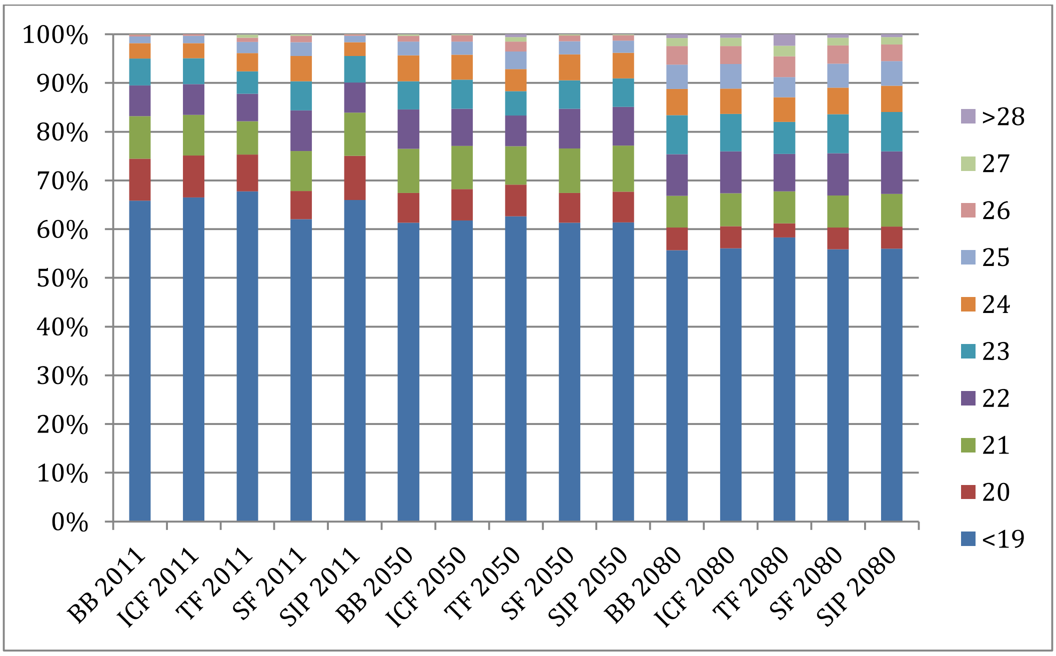


Figure 60 Temperature distribution inside the model with examined wall types, Manchester

Figure 60 shows that TF experienced the highest percentage of time of temperatures less than 19°C, which is highly likely to be overcooling in current and future times. Figure 60 also shows that TF had the highest percentage of time with temperature over 28°C in 2080, which would be highly likely overheating hours inside the model. The behaviour of TF is due to it having the lowest decrement factor compared to the other wall systems. Therefore, more temperature fluctuations were expected inside the TF model, creating more discomfort hours inside the model.

BB, with the highest admittance factor (and, therefore, highest thermal mass) showed the lowest number of hours of operative temperature less than 19°C for all times but SF has almost demonstrated a similar result with a low level of admittance factor compared to other systems. Therefore, the results do not show a significant advantage for a high level of thermal mass for all times in Manchester.

Figure 61 demonstrates the results in London for all times, and shows very similar behaviour to Manchester. However, less overcooling and more overheating in future times can be observed. In addition to operative temperature, there are a number of other factors which might impact upon occupants' comfort inside the model. The next section discusses thermal comfort interpretation and determination and what is considered for simulations in this study.

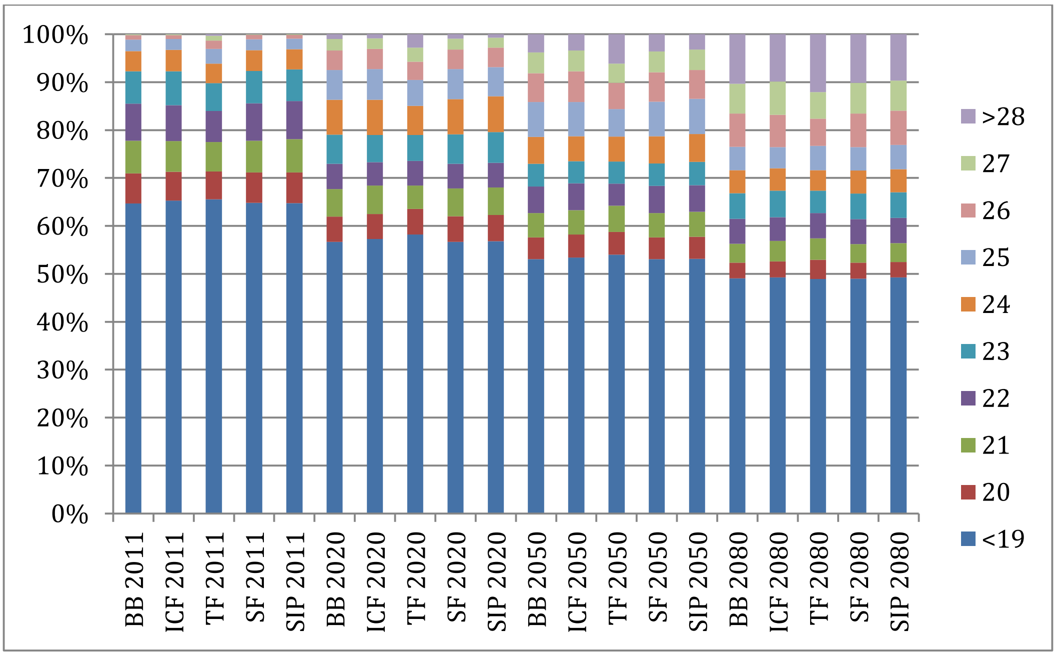


Figure 61 Temperature distribution inside the model with examined wall types, London

8.5 Thermal comfort

Hensen (1991) defined thermal comfort as a state in which there are no driving impulses to correct the environment by the behaviour''. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) also defined it as ''the condition of the mind in which satisfaction is expressed with the thermal environment'' (ASHRAE 2004). Satisfaction is associated with the thermal sensation of "neutral" or slightly warm or cool.

ASHRAE (1992) stated that to create "thermal environmental conditions for human occupancy, is to specify the combinations of indoor space environment and personal factors that will produce thermal environmental conditions acceptable to 80% or more of the occupants within a space''.

The clarification of an acceptable thermal comfort for occupants is important to the success of a building, not only because of the air quality, but also because it will decide a building's energy consumption and consequently has impacts on its sustainability. Therefore, specific thermal comfort standards are essential to assist building designers to provide an indoor climate which will be found thermally comfortable by occupants.

Thermal comfort is closely associated with the thermal balance of the body. This balance is influenced by two major categories (CIBSE 2006):

1) Environmental parameters including:

- Mean Radiant Temperature (MRT,°C)
- Air Temperature (AT,°C)
- Relative air velocity (V, m/s)
- Relative Humidity (RH, %)

2) Personal parameters including:

- Activity level (unit: Met)
- Clothing level (unit: Clo)

8.5.1 Thermal comfort approaches

Currently, there are two approaches to defining thermal comfort: the rational or heat-balance approach and the adaptive approach. The heat-balance approach uses data from climate chamber studies, best illustrated by the Fanger model, while the adaptive approach is based on the field studies of occupants in building.

8.5.2 Heat balance approach

The most well-known method in this category is the "Predicted Mean Vote" (PMV) and "Predicted Percentage of Dissatisfied" (PPD) model proposed by Fanger which combines the impacts of theories of heat balance with the physiology of thermoregulation factors into a specific value on a thermal sensation scale which has been accepted widely (Fanger, 1972). Figure 62 shows the relationship between PMV and PPD in the Fanger model.

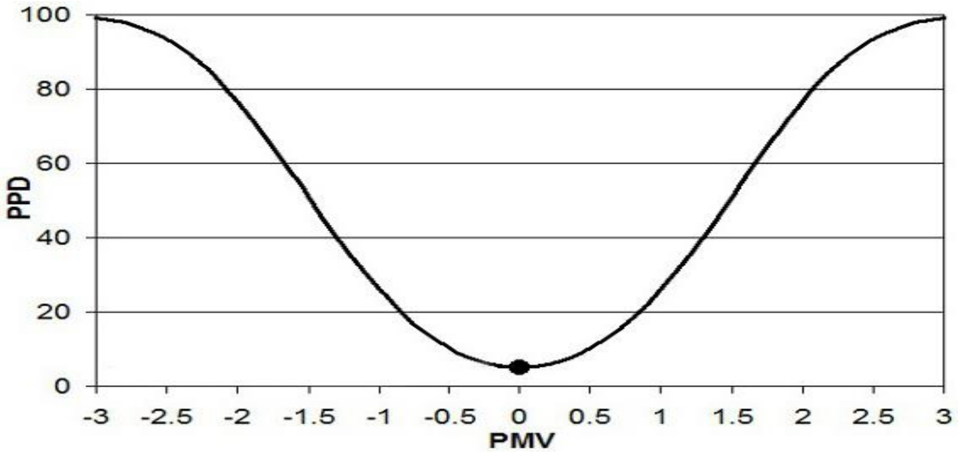


Figure 62 Relationship between PMV and PPD, Source: http://www.intechopen.com/books/air-quality/a-review-of-general-and-local-thermal-comfort-models-for-controlling-indoor-ambiences-

According to Fanger's theory, the human body employs physiological processes, such as sweating and shivering, to keep a balance between the heat gains and losses. However, Fanger highlighted that ‘‘man's thermo-regulatory system is quite effective and will therefore create heat balance within wide limits of the environmental variables, even if comfort does not exist’’ (Fanger, 1970). The Fanger model on thermal comfort was a groundbreaking contribution to the evaluation of indoor thermal environments as well as to the theory of thermal comfort. It is generally accepted and widely used for the assessment of thermal comfort.

8.5.3 Adaptive approach

Fanger's model has come to be regarded as applicable across a wide range of building types, populations and climate zones (Parsons, 1994). But this approach has been challenged by many researchers who argue that his model ignores significant cultural, social, climatic and contextual dimensions of comfort, leading to an exaggeration of the demand for air conditioning (de Dear & Brager, 2001). Therefore, as can be seen in Figure 63, although the Fanger model shows reasonable accuracy in most air-conditioned buildings, it fails considerably in naturally ventilated buildings,

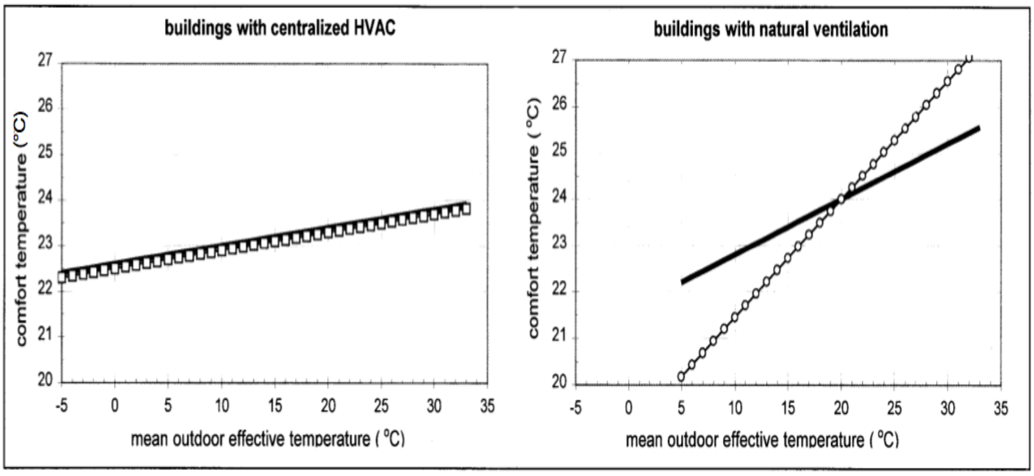


Figure 63 mean outdoor effective temperatures in centralized HVAC and natural ventilation, the black line shows the predicted lab-based PMV model and the dash line shows the observed field based adaptive model, Source: (de Dear and Brager 1998)

Significant differences in results for naturally ventilated buildings and a rising dissatisfaction with static, fixed comfort temperatures, has driven interest in a variable indoor temperature standard. For naturally ventilated and passive buildings a variable indoor temperature standard based on the adaptive model of thermal comfort would have more particular relevance than static models. An adaptive standard links thermal comfort to the climatic context of the building and considers past thermal experiences as well as occupants' current thermal expectations. Past thermal history and contextual factors are assumed to modify thermal preferences and expectations (de Dear & Brager, 1998)

The adaptation term could be broadly assumed as the gradual reduction of the organism's response to frequent environmental stimulation. Therefore, it is possible to classify three categories of thermal adaptation - behavioral, physiological and psychological adjustment. Behavioral adjustment could be further sub-classified into technological (such as turning on/off cooling or heating systems), personal responses (such as removing or adding clothes) and cultural responses (such as having a siesta). In fact, unconsciously or consciously, these modifications are totally specific responses for thermal comfort. Physiological adjustment includes any changes in the physiological responses that might result from exposure to thermal environmental factors, and would cause a gradual adaption to such exposure. Physiological adaptation can be classified into genetic adaptation and acclimatization. Psychological adjustment refers to a reaction to and perception of physical information related to expectations and past experiences (Clark & Edholm, 1985).

In adaptive models, the interaction between occupants, the environment and the building determines the comfort temperature. The main contextual variables are the climate, the building and time. Of all the variables, climate has the most effect on the psychological, physiological and behavioral adjustment of people and thus on the design of the buildings. Although climate may not change the fundamental mechanisms of human interaction with the thermal environment, a number of detailed ways exist in which people are subjective to them, and these play an increasing role in peoples' reaction to the indoor climate. Buildings are the second major context of comfort surveys by virtue of their services services and time is the third contextual parameter. Therefore, comfort temperature is repeatedly fluctuating. The magnitude of these fluctuations and the rate at which they occur is of significant concern (Nicol & Humphreys, 2002).

Nicol and Roaf (1996) suggested the Eq. (1) as the model for occupants of naturally ventilated buildings. Other adaptive models have also been suggested, such as the Humphreys models for neutral temperature as given by Eqs. (2) and (3) (Humphreys, 1976). Auliciems and de Dear established relationships for calculating group neutralities on the basis of mean indoor and outdoor temperatures as shown in Eqs. (4), (5), (6) and and (7), which were recommended by ASHRAE in Eq. (7) (ASHRAE, 2004).

$$Tn,o = 17 + 0.38To \qquad (1)$$

$$Tn,1 = 2.6 + 0.831Ti \qquad (2)$$

$$Tn,o = 11.9 + 0.534To \qquad (3)$$

$$Tn,i = 5.41 + 0.731Ti \qquad (4)$$

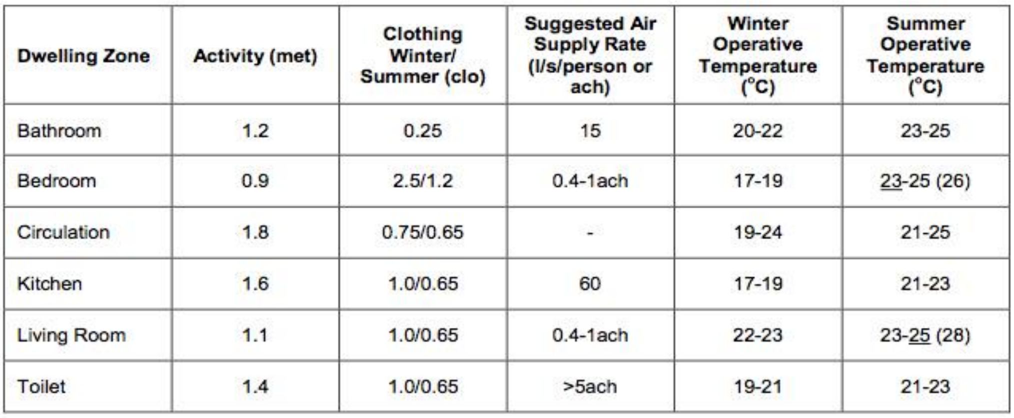
$$Tn,o = 17.6 + 0.31To \qquad (5)$$

$$Tn,i,o = 9.22 + 0{:}48Ti + 0.14To \qquad (6)$$

$$Tc = 17.8 + 0.31To \qquad (7)$$

In the equations above, Tc is the comfort temperature, To is the outdoor air temperature, Ti is the mean indoor air temperature, Tn,i is the neutral temperature on the basis of mean indoor air temperature, and Tn,o is the neutral temperature on the basis of the mean outdoor air temperature. CIBSE (2006) also recommended comfort temperature based on common environmental and physiological factors, as shown in Table 12.

Table 12 Recommended comfort temperature range for a dwelling based on common environmental and physiological factors, source: (CIBSE, 2006)



Dwelling Zone	Activity (met)	Clothing Winter/ Summer (clo)	Suggested Air Supply Rate (l/s/person or ach)	Winter Operative Temperature (°C)	Summer Operative Temperature (°C)
Bathroom	1.2	0.25	15	20-22	23-25
Bedroom	0.9	2.5/1.2	0.4-1ach	17-19	23-25 (26)
Circulation	1.8	0.75/0.65	-	19-24	21-25
Kitchen	1.6	1.0/0.65	60	17-19	21-23
Living Room	1.1	1.0/0.65	0.4-1ach	22-23	23-25 (28)
Toilet	1.4	1.0/0.65	>5ach	19-21	21-23

Therefore, a temperature range of 18-26℃ is highly likely to be within the comfort range. Moreover, ASHRAE 55-2004 clarified thermal comfort as a subjective response which is defined as the ‘state of mind that expresses satisfaction with existing environment’. It can be observed by this definition that a specific value cannot be assigned to thermal comfort since “state of mind” generally depends on individual perception and expectation. However, ASHRAE-55 is based on the static heat balance and four environmental variables, i.e. temperature, mean radiant temperature, relative humidity and air velocity as well as activity and clothing level of the occupants. This includes PMV/PPD calculation methods and the concept of adaption (ASHRAE, 2004). Therefore, this study uses this standard for quantification purposes and simplification of decision-making for all simulations.

Figure 64 shows the range of likely comfort conditions in the ASHRAE Standard. Any other condition is considered as discomfort. For instance, less than 18°C and over than about 30 °C are classified as discomfort, regardless of any other factors that might have an impact like humidity or clothing level. Discomfort hours are therefore defined as hours inside a model that temperature is above or below comfort zone level as shown in Figure 64. This is used for all simulations in this study.

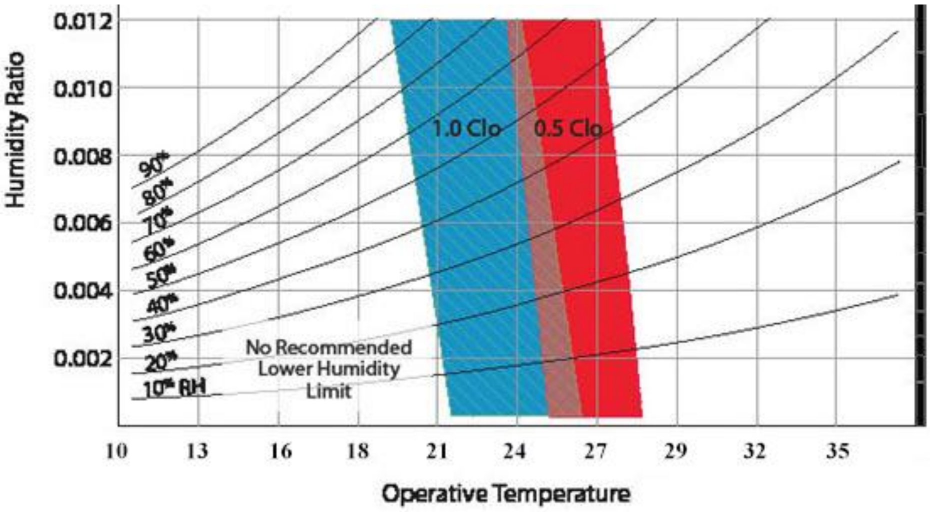
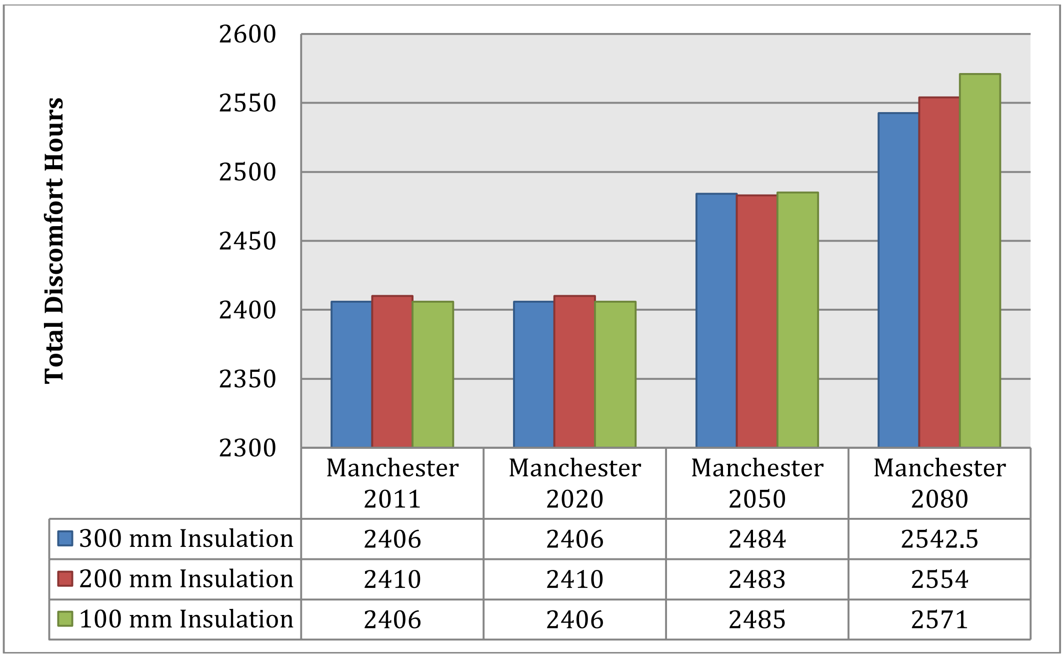


Figure 64 ASHRAE comfort zone, source: (ASHRAE, 2004)

Recent updates from ASHRAE 55 for 2010 and 2013 have also been reviewed but since the recent versions are more sophisticated (for example metabolic rates of the human body are included), the most recent DB version was not able to utilize it in the simulation and therefore the 2004 version was used for all simulations. In terms of occupancy rate, for all thermal comfort simulations in this study the occupancy rate is assumed at 0.02 people/m^2 which shows that one occupant is considered by the software for each 50 m^2 area.

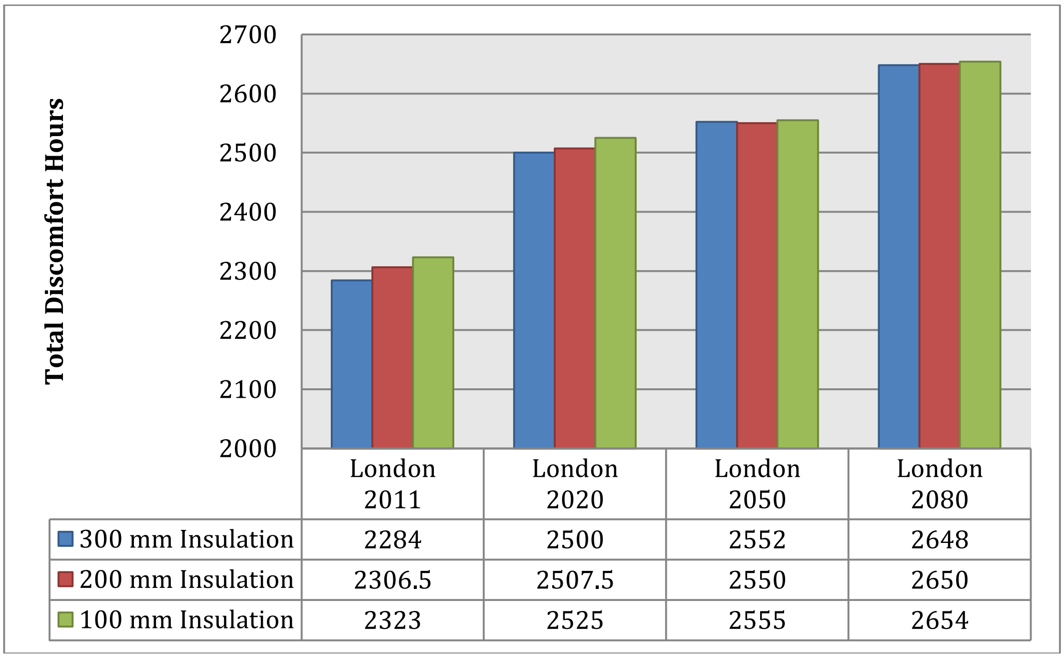
8.6 Insulation effect

According to simulations shown in Figure 60 and 61, a construction system with high thermal mass does not necessarily perform better in comparison with lower thermal mass ones. This section investigates the effect of insulation thickness and attempts to ascertain an optimum level of insulation to deal with the risk of climate change. Figures 65 to 74 show the comparison of insulation thickness on the performance of wall types on the basis of thermal comfort for all times in Manchester and London (for all simulations in this study on the basis of thermal comfort, clothing level is considered 1 for the period of 1 October to 31 March and 0.5 for the period of 1 April to 30 September). The reduction of insulation thickness was on the basis of a U-Value increase of up to 0.35 W/m^2K Part L standard level.



	Manchester 2011	Manchester 2020	Manchester 2050	Manchester 2080
🟦 300 mm Insulation	2406	2406	2484	2542.5
🟥 200 mm Insulation	2410	2410	2483	2554
🟩 100 mm Insulation	2406	2406	2485	2571

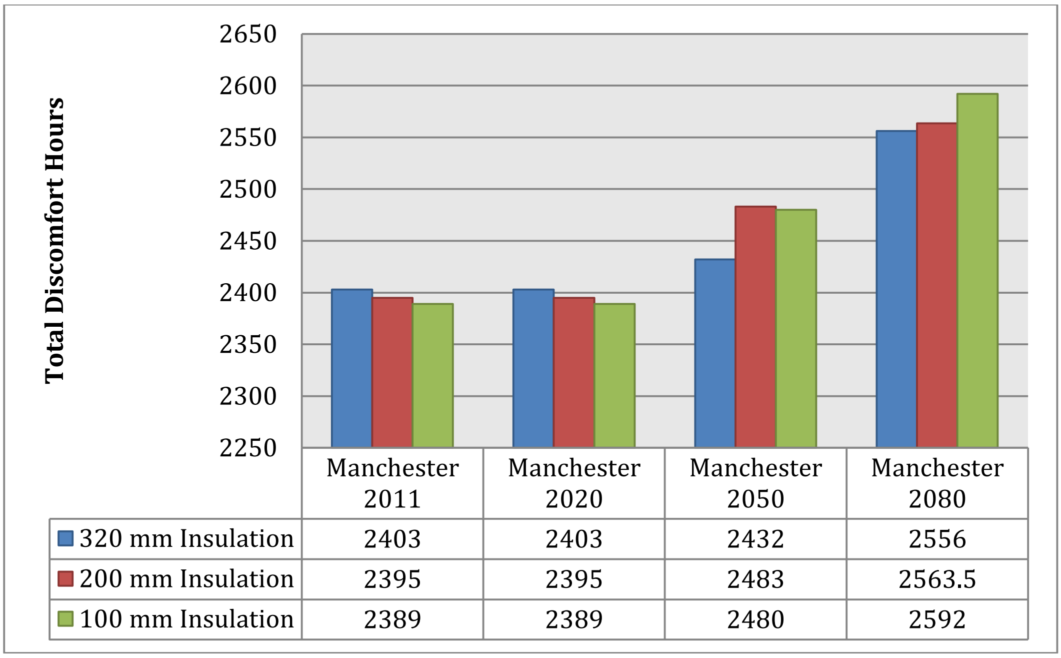
Figure 65 Comparison of insulation thickness in BB construction, Manchester



	London 2011	London 2020	London 2050	London 2080
🟦 300 mm Insulation	2284	2500	2552	2648
🟥 200 mm Insulation	2306.5	2507.5	2550	2650
🟩 100 mm Insulation	2323	2525	2555	2654

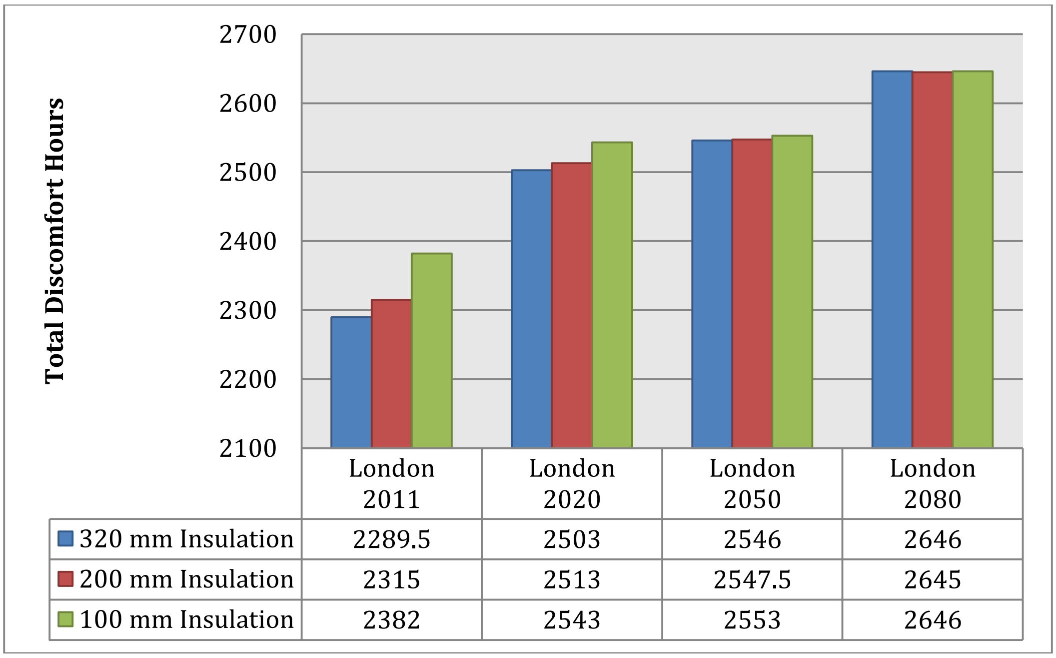
Figure 66 Comparison of insulation thickness in BB construction, London

Figure 65 and 66 demonstrate that the maximum insulation thickness with 0.1 U-Value does not seem to have a considerable advantage in comparison with 0.13 and 0.2 U-Values with 200mm and 1700 mm insulation thickness respectively. The same performance as in Manchester can be seen in London.



	Manchester 2011	Manchester 2020	Manchester 2050	Manchester 2080
🟦 320 mm Insulation	2403	2403	2432	2556
🟥 200 mm Insulation	2395	2395	2483	2563.5
🟩 100 mm Insulation	2389	2389	2480	2592

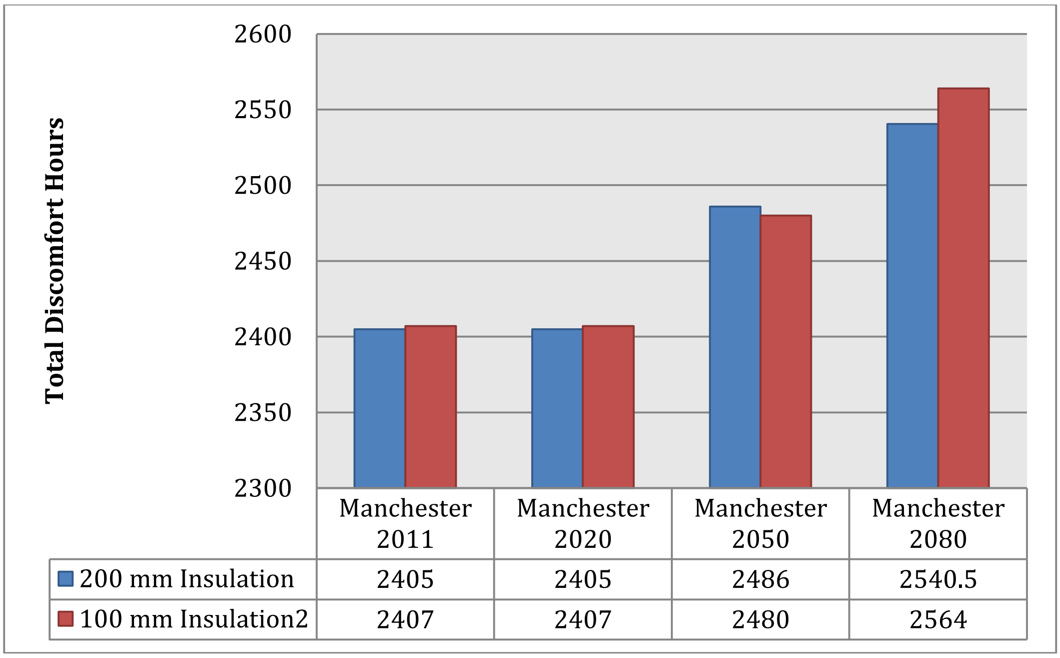
Figure 67 Comparison of insulation thickness in ICF construction, Manchester



	London 2011	London 2020	London 2050	London 2080
🟦 320 mm Insulation	2289.5	2503	2546	2646
🟥 200 mm Insulation	2315	2513	2547.5	2645
🟩 100 mm Insulation	2382	2543	2553	2646

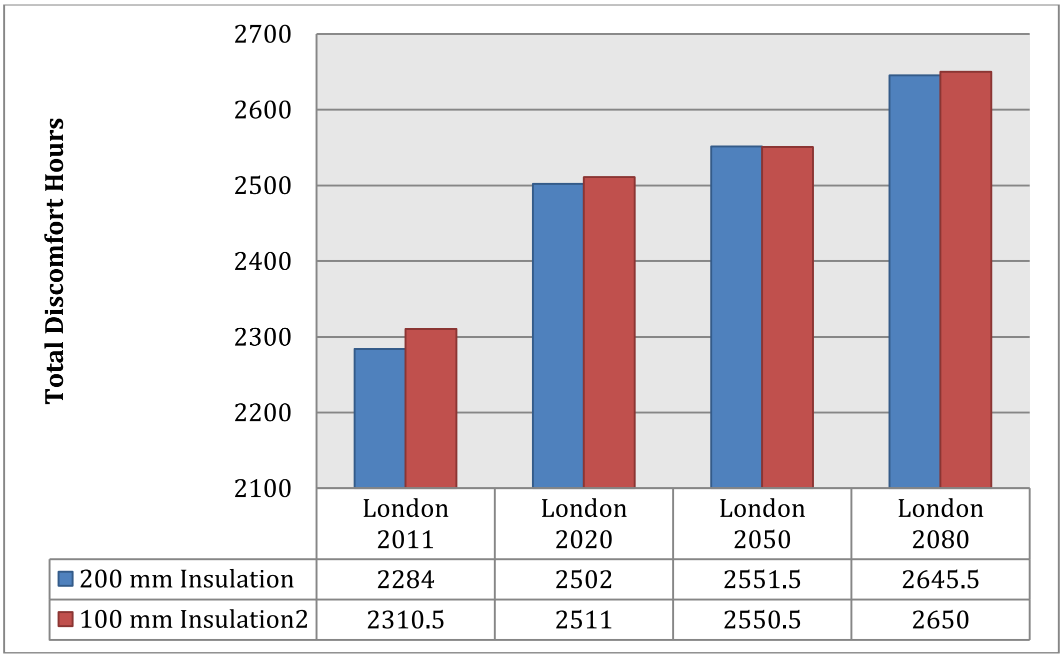
Figure 68 Comparison of insulation thickness in ICF construction, London

In the ICF wall type, a maximum insulation thickness with 0.1 U-Value has a minor advantage in both London and Manchester although it is not considerable. A 200mm thickness with 0.15 U-Value and a 100mm thickness with 0.28 U-Values seem to be effective and a more reasonable choice (100mm insulation performs slightly better for Manchester in 2011 and 2020 but not for later periods. For London, in 2050 and 2080, the thickness appears irrelevant).



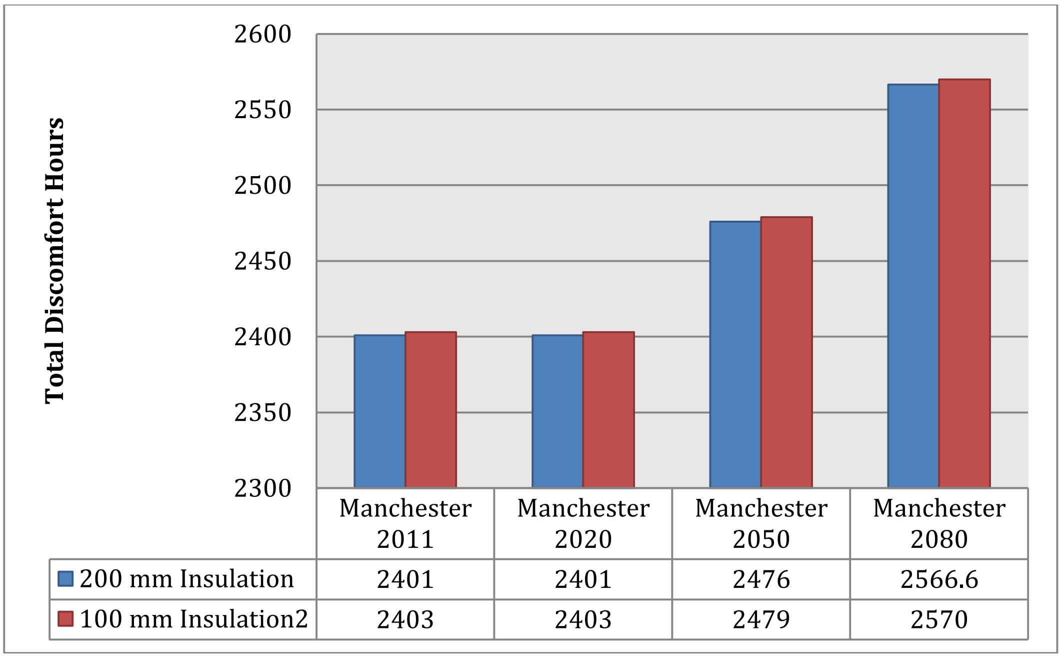
	Manchester 2011	Manchester 2020	Manchester 2050	Manchester 2080
🟦 200 mm Insulation	2405	2405	2486	2540.5
🟥 100 mm Insulation2	2407	2407	2480	2564

Figure 69 Comparison of insulation thickness in SF construction, Manchester



	London 2011	London 2020	London 2050	London 2080
🟦 200 mm Insulation	2284	2502	2551.5	2645.5
🟥 100 mm Insulation2	2310.5	2511	2550.5	2650

Figure 70 Comparison of insulation thickness in SF construction, London



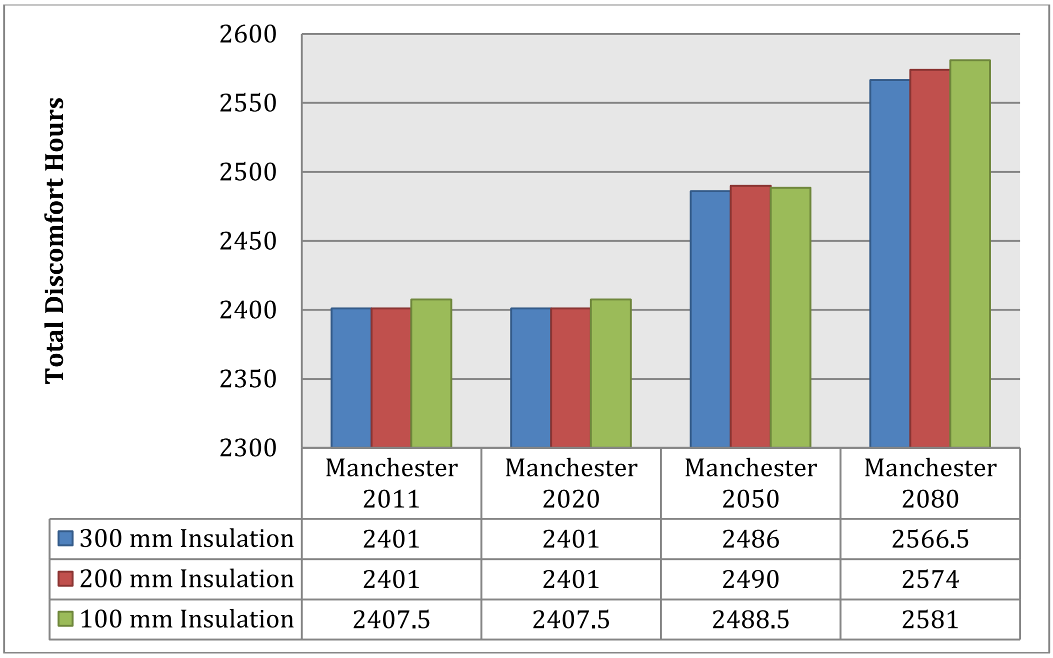
	Manchester 2011	Manchester 2020	Manchester 2050	Manchester 2080
🟦 200 mm Insulation	2401	2401	2476	2566.6
🟥 100 mm Insulation2	2403	2403	2479	2570

Figure 71 Comparison of insulation thickness in SIP construction, Manchester

	London 2011	London 2020	London 2050	London 2080
🟦 200 mm Insulation	2284	2498	2545	2638
🟥 100 mm Insulation2	2286	2501	2548	2642

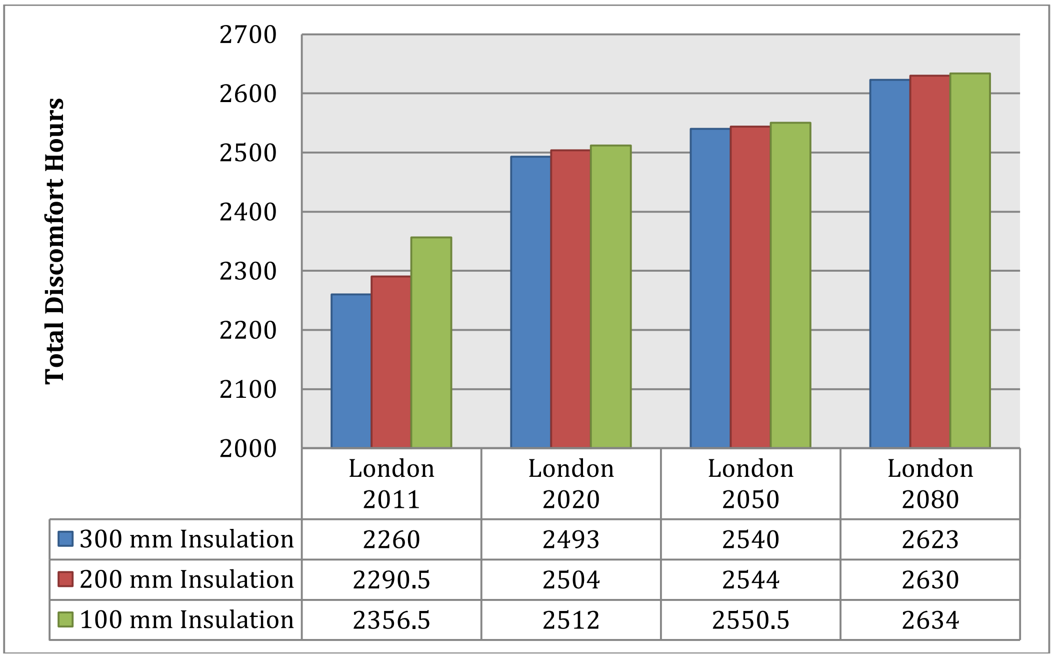
Figure 72 Comparison of insulation thickness in SIP construction, London

In SF and SIP systems a 100mm decrease in insulation does not seem to have any significant effects on total discomfort hours. 0.1 and 0.14 W/m^2K U-Values seem to perform similarly in both London and Manchester.



	Manchester 2011	Manchester 2020	Manchester 2050	Manchester 2080
🟦 300 mm Insulation	2401	2401	2486	2566.5
🟥 200 mm Insulation	2401	2401	2490	2574
🟩 100 mm Insulation	2407.5	2407.5	2488.5	2581

Figure 73 Comparison of insulation thickness in TF construction, Manchester



	London 2011	London 2020	London 2050	London 2080
🟦 300 mm Insulation	2260	2493	2540	2623
🟥 200 mm Insulation	2290.5	2504	2544	2630
🟩 100 mm Insulation	2356.5	2512	2550.5	2634

Figure 74 Comparison of insulation thickness in TF construction, London

As with other construction systems, any minimization in insulation thickness does not result in any significant effects on total discomfort hours for TF in all tests except London with 2011 weather data, even though the U-Values increased to 0.15 and 0.24 with 200 and 100 mm insulation thickness respectively. In general, it seems that any changes in insulation thickness within the discussed standards in Chapter 3 ranges will not result in any considerable changes. However, it has to be mentioned that minimizing insulation thickness is likely to reduce overheating risk and increase overcooling risks but as the study considers total discomfort hours, this has not been highlighted.

Decreasing insulation thickness will cause more heat loss in buildings according to Fourier's law (q=UΔT) (Clark & Edholm, 1985). Figure 75 demonstrates differences in a medium thermal mass performance system (ICF) with 300 and 100 mm insulation thickness. The result confirms more high temperatures (over 28℃) and fewer low temperatures (less than 14°C) in 300mm insulation compared to 100 mm insulation. However, as the focus of the previous simulations was on thermal comfort hours in total, minor effective differences can be observed.

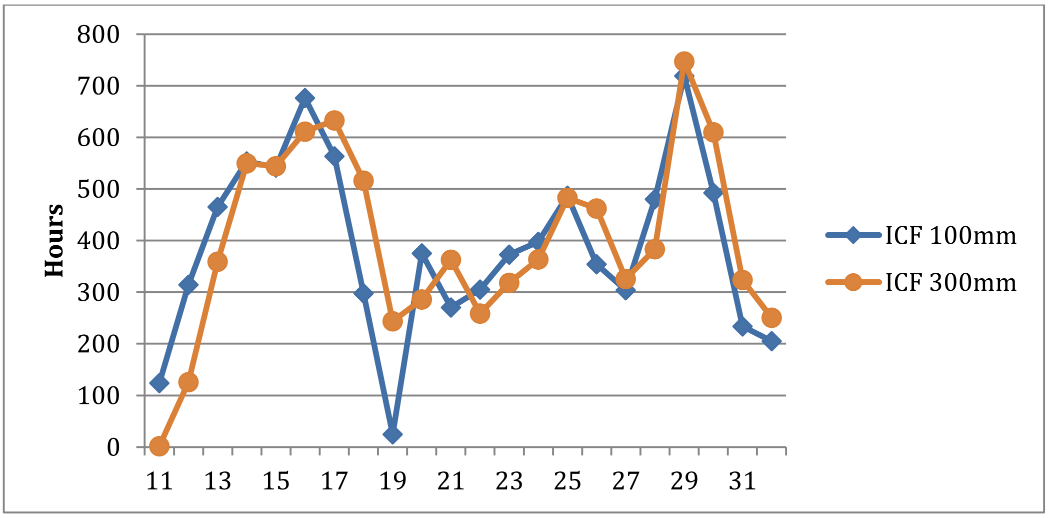


Figure 75 Temperature distribution (°C) in model with ICF (100 and 300mm insulation)

Figures 76 and 77 compare the effect of thermal mass and U-Value in the examined construction systems. They demonstrate that in each time particular combinations performs better and there is no one single answer for all times. For example, in current Manchester weather, low thermal mass (admittance factor between 0-2 W/m^2K) with a low U-Value shows the lowest discomfort hours but in 2080, high thermal mass (admittance factor between 4-6 W/m^2K) with a high U-Value shows the lowest discomfort hours. In London, high thermal mass with low U-Value seems to be the best current solution but from 2020 onwards, a medium level of thermal mass (admittance factor 2-4 W/m^2K) with low U-Value seems to have the lowest discomfort hours compared to the other combinations.

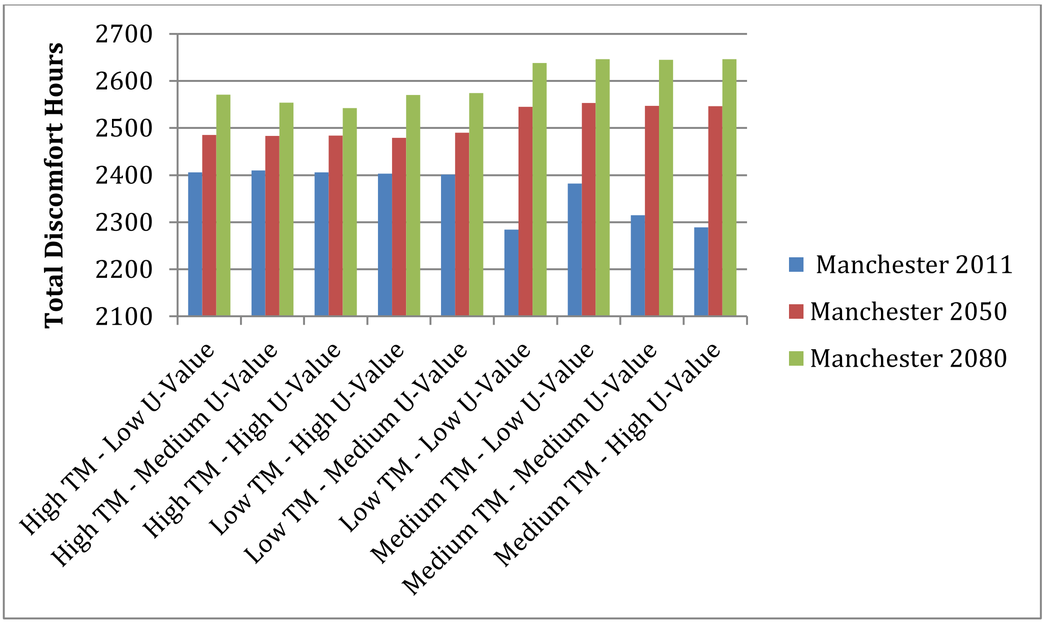


Figure 76 The comparison of thermal mass and U-Value effect on the basis of thermal comfort, Manchester

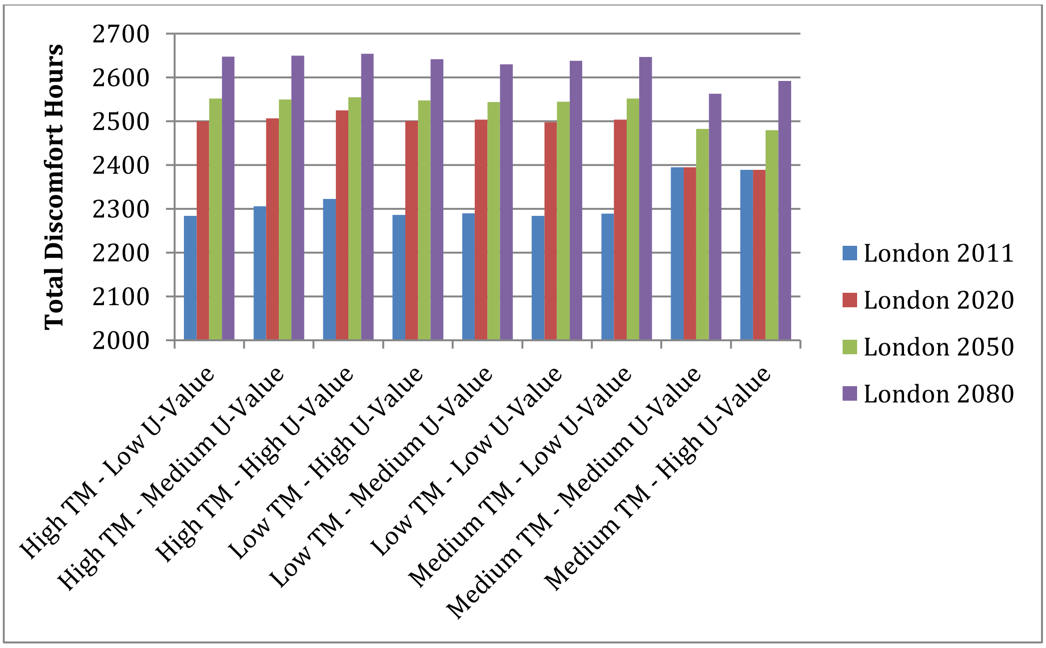


Figure 77 The comparison of thermal mass and U-Value effect on the basis of thermal comfort, London

In the above simulations, the suggested approach models the effect of thermal mass and insulation thickness in dealing with future climate change weather probability and quantifies the performance of wall types on the basis of thermal comfort. One 'correct' decision for all examinations accomplished in this study cannot be suggested to decision-makers, although reducing the insulation thickness down to 200 mm does not seem to create more than 100 discomfort hours differences (the highest difference observed was for TF in London current weather with about 96.5 hours difference) in thermal comfort hours in most of the simulations.

Zero Carbon Hub (ZCH) studied semi-detached house in different UK locations and achieved similar results by computer simulations (Zero Carbon Hub, 2010). The Three Regions Climate Change Group (TRCCG) has also undertaken similar studies in 1960s houses and flats in London and the East and Southeast of England and discovered ventilation strategy, solar control, cooler floors, etc. as more effective strategies compared to increasing insulation thickness to improve comfort in UK housing (Three Regions Climate Change Group, 2008).

8.7 Second Model

In the base case model, the emphasis was on realizing how wall types would behave purely (without any other impacts) for current and future weather scenarios. In the second model a more realistic building design was developed. Four separate zones were considered, similar to a typical single storey house. The infiltration rate was the same as base case model (0.6 ACH) and windows, roof and ground floor were the same as in base case model. Ventilation strategy is also considered. Figure 78 to 81 shows the plan, elevations and 3D model. Figure 82 and 83 compare construction systems on the basis of overall discomfort hours in the second model in all times in both cities and further simulations investigated how much energy was required to remove discomfort hours in the model. For all simulations in this study fan coil unit is used for cooling and heating loads. Heating set point is 18℃ and cooling set point is 28℃. The coefficient of performance (COP) of the system is 1.6.

The second model had four separate zones (bedroom, bathroom, kitchen and living area) and for each zone a particular activity was considered. The windows to wall ratio was changed considerably compared to the first model and obviously this would affect the behavior of the construction systems due to solar gain. However, overall floor area, infiltration rate and ventilation strategy remained the same as the first model.

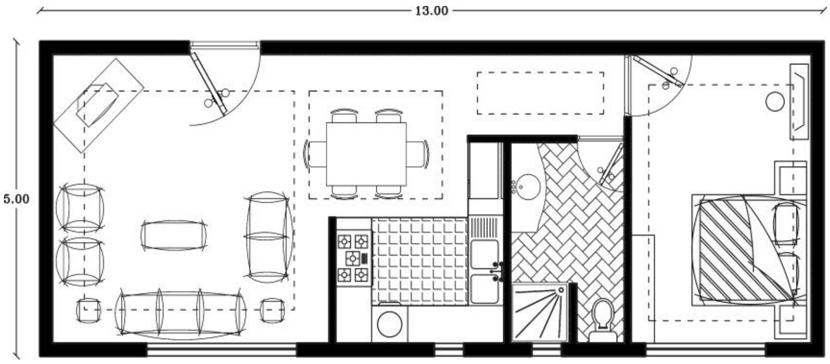


Figure 78 Second model plan

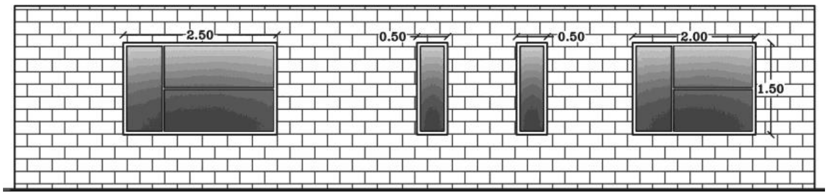


Figure 79 Second model south elevation

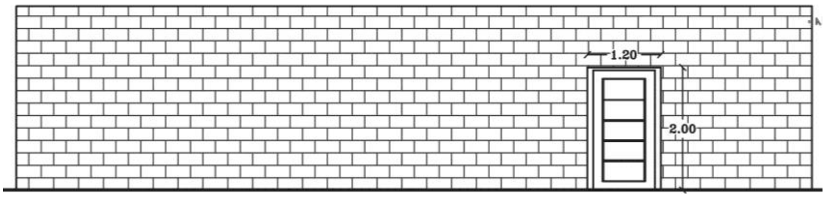


Figure 80 Second model north elevation

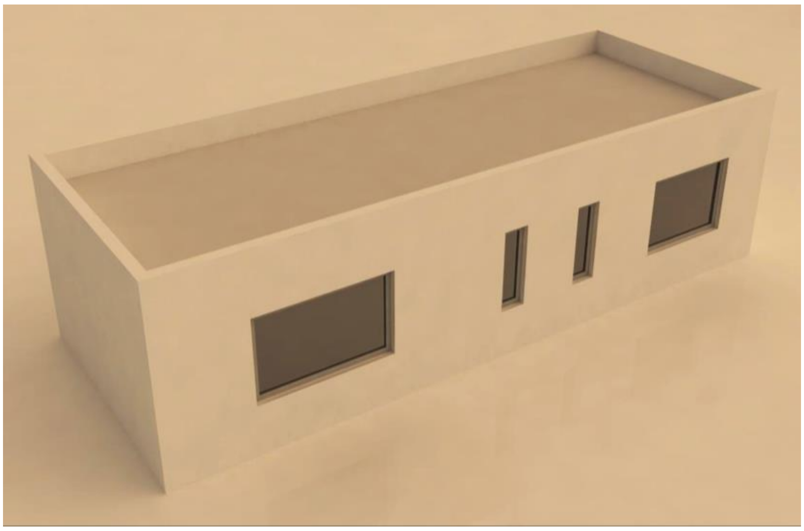


Figure 81 3D Model used for simulations (south facing windows)

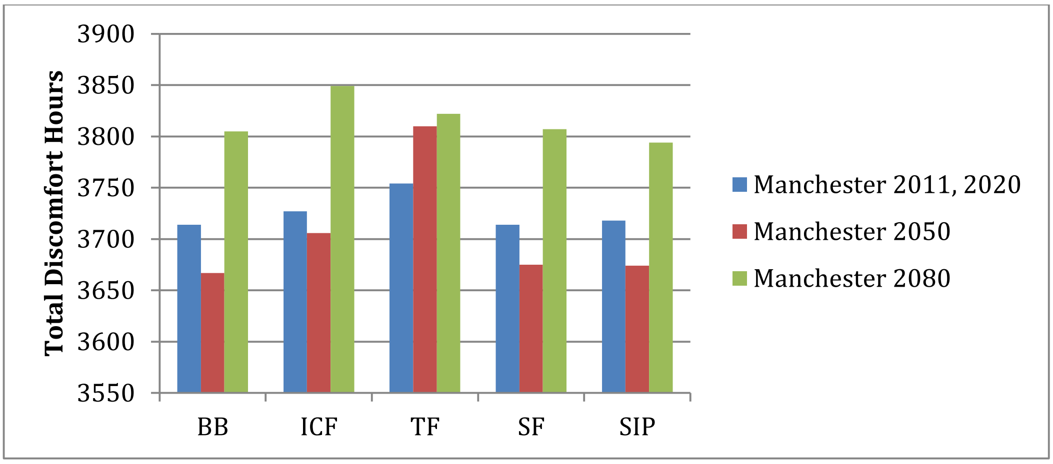


Figure 82 Overall discomfort hours in second model, Manchester

Comparison of each construction system behavior in Manchester (Figure 82) shows the lowest performance for TF (highest discomfort hours) compared to others in the present time (2011/2020). Both BB, with a high level of thermal mass, and SF, with a low a level of thermal mass, show lower discomfort hours in the present time (2011/2020). The behaviour of the systems remains almost the same in 2050 but the differences become more significant. In 2080, the behavior of ICF comes as a surprise with the highest discomfort hours.

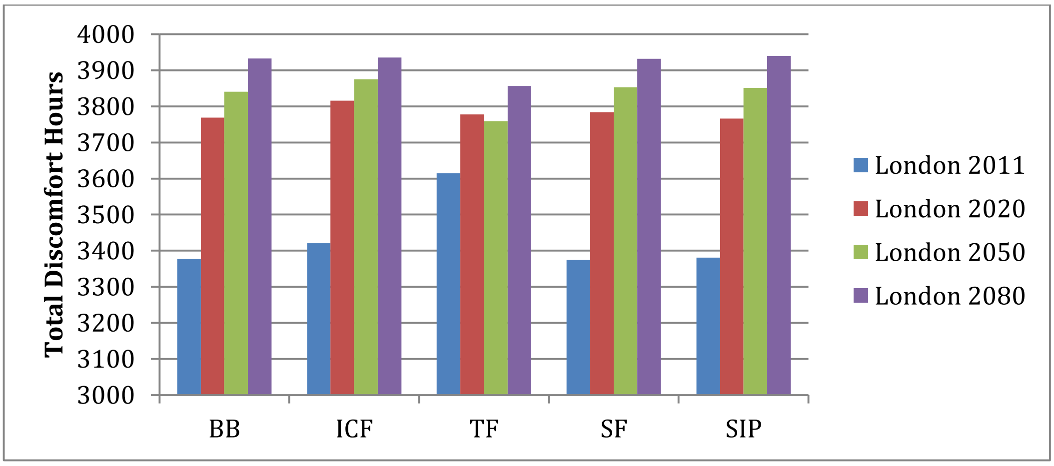


Figure 83 Overall discomfort hours in second model, London

In London in 2011, the behaviour of BB is almost similar to Manchester with a minimal advantage with the high level of thermal mass compared to the other systems. Also, ICF shows the highest discomfort hours from 2020 until 2080, in which it almost has a similar performance to SIP. The behaviour of TF in 2050 and 2080 is also surprising, showing the lowest discomfort hours. As in London, the temperature considerably increases in Manchester from 2050, which means the lower level of decrement factor would cause more heat loss and better thermal comfort inside the model.

Compared to the result from the first model, discomfort hours in the second model were apparently considerably higher for the five construction systems. This could be due to several influential factors in the second model, including more glazing area and having separate zones with specific appliances; for example, in the kitchen zone different cooking appliances could potentially impact upon the operative temperature inside the model. Besides, although considerably higher discomfort hours were seen in the second model, this may not necessarily reflect a considerable difference in operative temperatures inside two models. For example, above 28℃ is certainly considered as discomfort hours but 27℃ is considered within the comfort zone.

The study has also considered the amount of energy required to remove discomfort hours inside the model. However, decision making on the basis of discomfort hours and energy consumption may not necessarily always show similar qualitative results. For example, if two systems cause indoor air temperatures of 29℃ and 30℃, they both cause discomfort hours as they are above the ASHRAE 55 standard. However, the amount of energy to reduce these two temperatures to a comfort level cannot be the same. Figure 84 and 85 demonstrate the amount of energy required to remove discomfort hours in the second model for Manchester and London.

The comparison of construction systems on the basis of energy consumption shows slightly different results with disadvantage for TF in both cities in all times. TF has the minimum decrement factor compared to the other systems and this obviously has affected this system. In both cities and in all times, BB and SIP show better performance compared to others. SIP has the highest level of decrement factor and BB has the highest level of thermal mass compared to the other systems.

The results of the simulations from Figure 85 and 86 show that in London, energy consumption continues to rise until 2080 but in Manchester, the current period is demonstrated to consume maximum energy. As explained in the climate change Chapter, the likely temperature increase in London is greater than in Manchester and this result shows considerable shift in cooling loads in London. As UK homes tend not to have cooling devices, improving passive design solutions and novel technologies could reduce and perhaps remove the need for active cooling in UK housing in future.

Because of DB limitations in distinguishing overcooling and overheating hours inside the model, heating and cooling loads in each month are shown from Figure 86 to 88 in Manchester for all times. This can provide a picture of overcooling and overheating hours in the model, which was not possible to show in discomfort hours graphs.

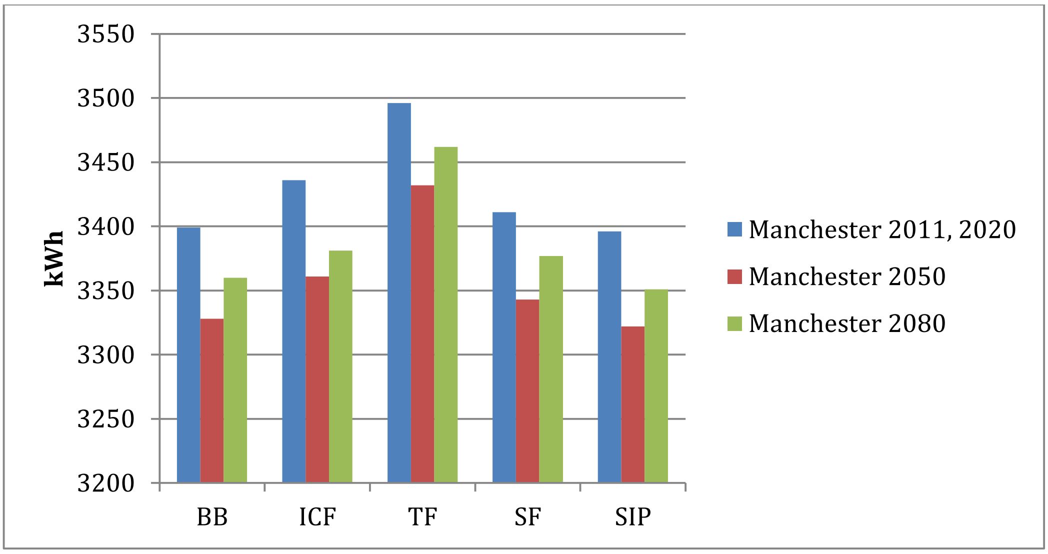


Figure 84 Overall energy consumption in second model, Manchester

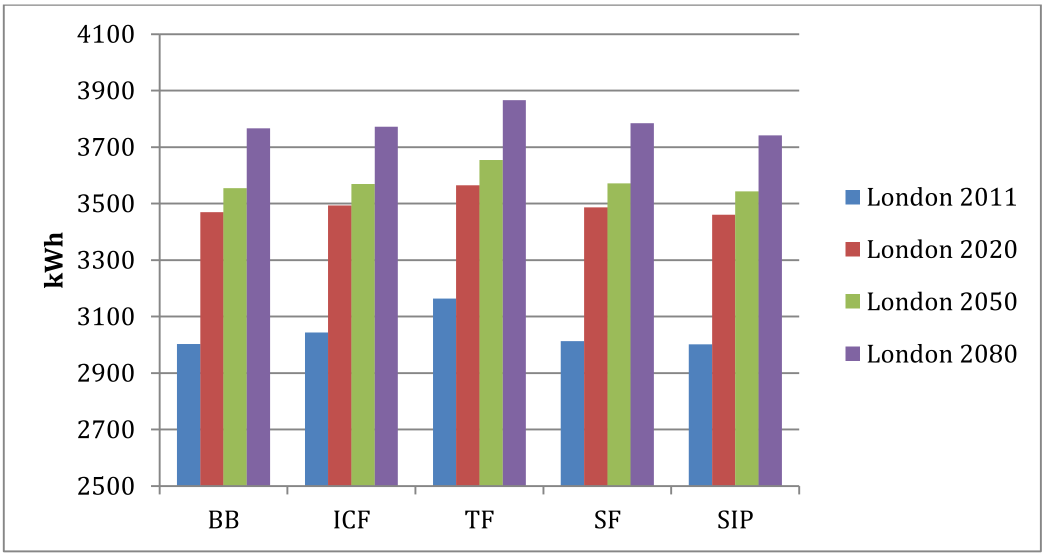


Figure 85 Overall energy consumption in second model, London

As can be observed from Figures 86 to 88, TF surprisingly seems to have almost better performance in most of the cold months from 2011 to 2080 in terms of heating loads as it consumes less energy compared to the others. ICF show the lowest performance with maximum energy consumption from 2011 onwards. Figures 89 to 92 shows heating loads in London from 2011 until 2080.

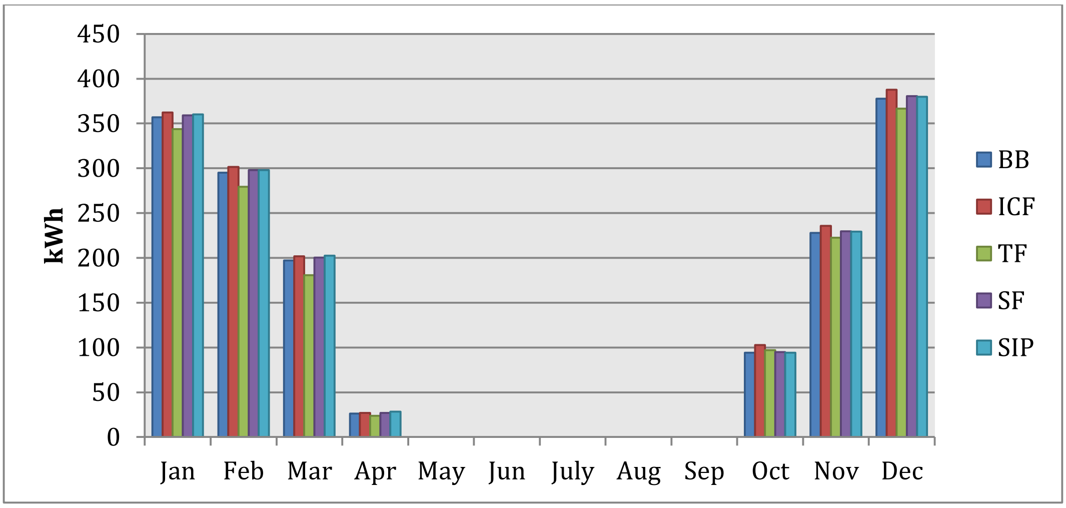


Figure 86 Monthly comparison of heating loads (kWh) with occupancy in the second model, Manchester 2011,2020

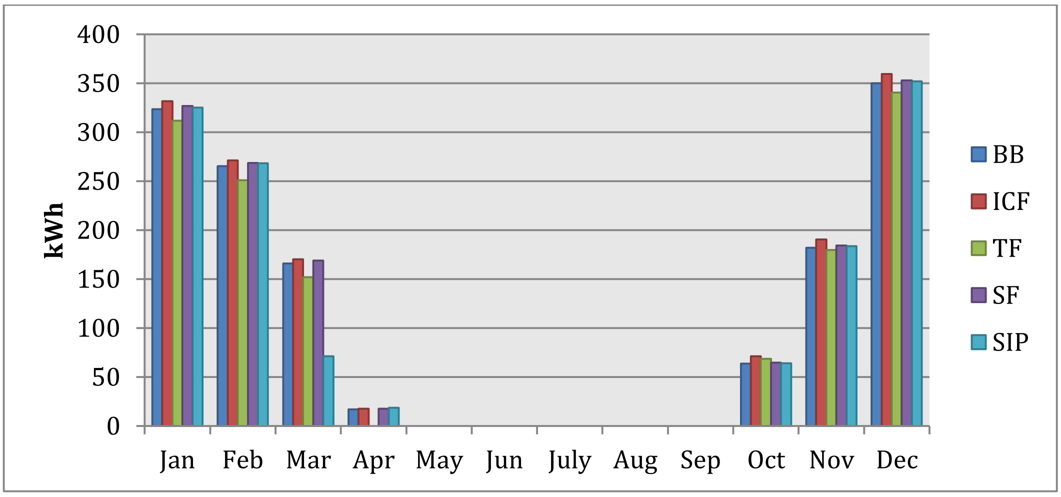


Figure 87 Monthly comparison of heating loads (kWh) with occupancy in the second model, Manchester 2050

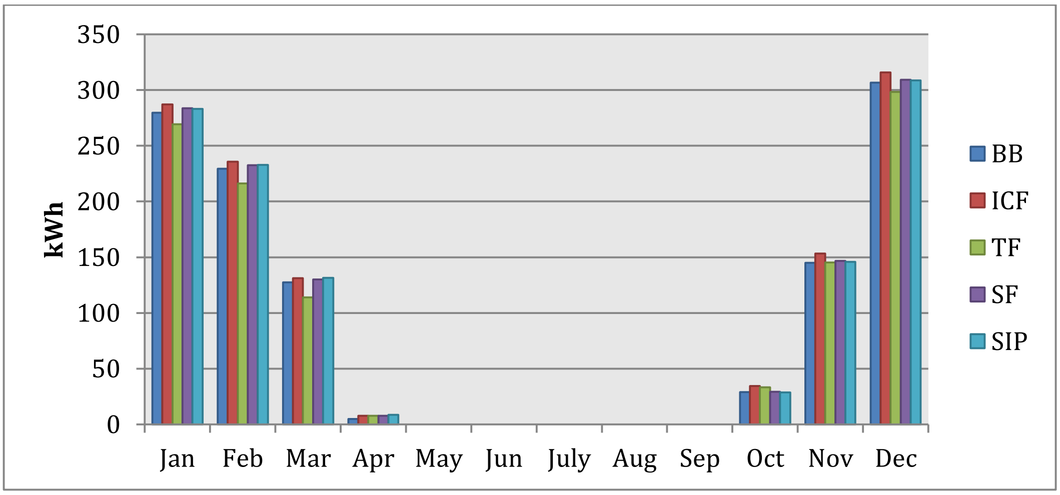


Figure 88 Monthly comparison of heating loads (kWh) with occupancy in the second model, Manchester 2080

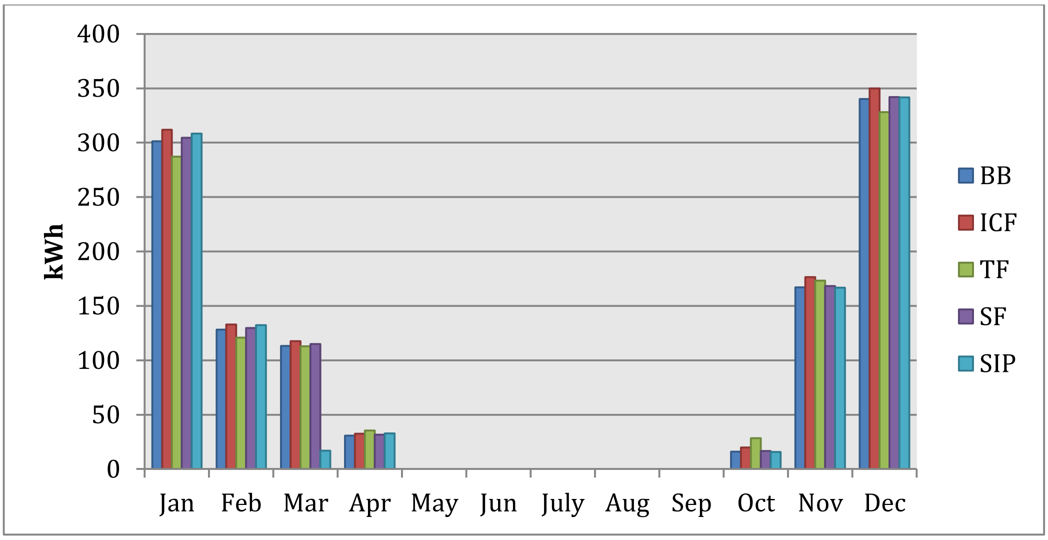


Figure 89 Monthly comparison of heating loads (kWh) with occupancy in the second model, London 2011

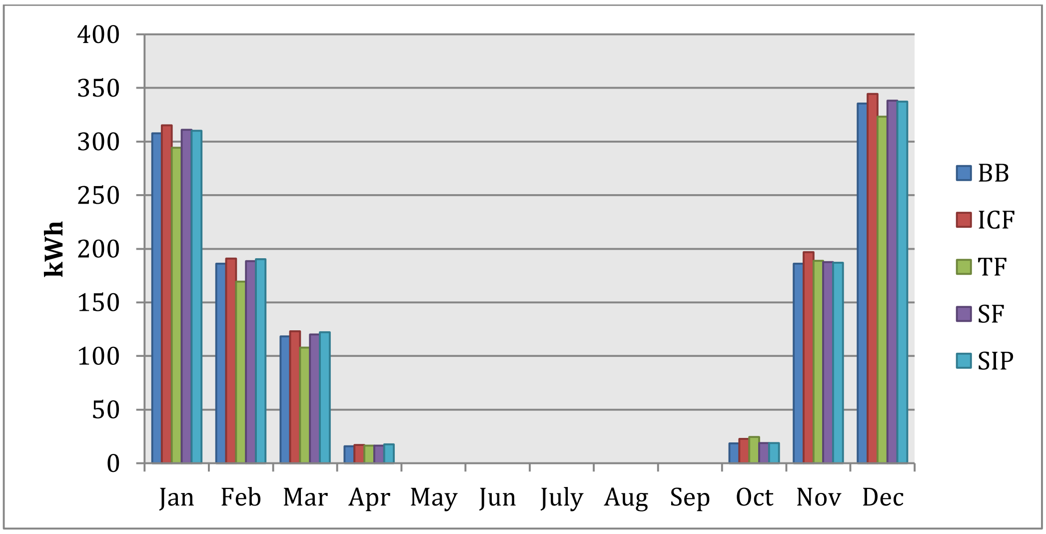


Figure 90 Monthly comparison of heating loads (kWh) with occupancy in the second model, London 2020

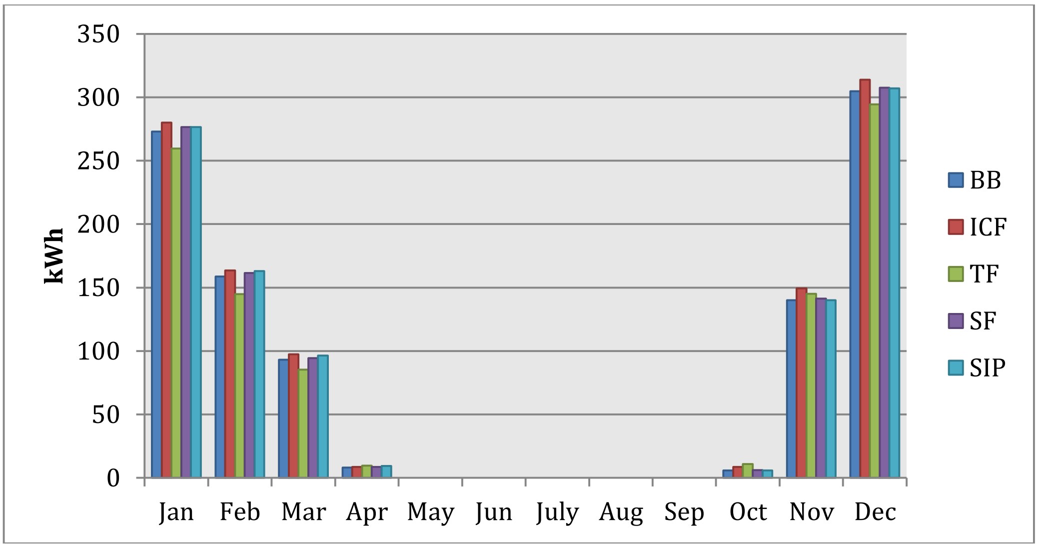


Figure 91 Monthly comparison of heating loads (kWh) with occupancy in the second model, London 2050

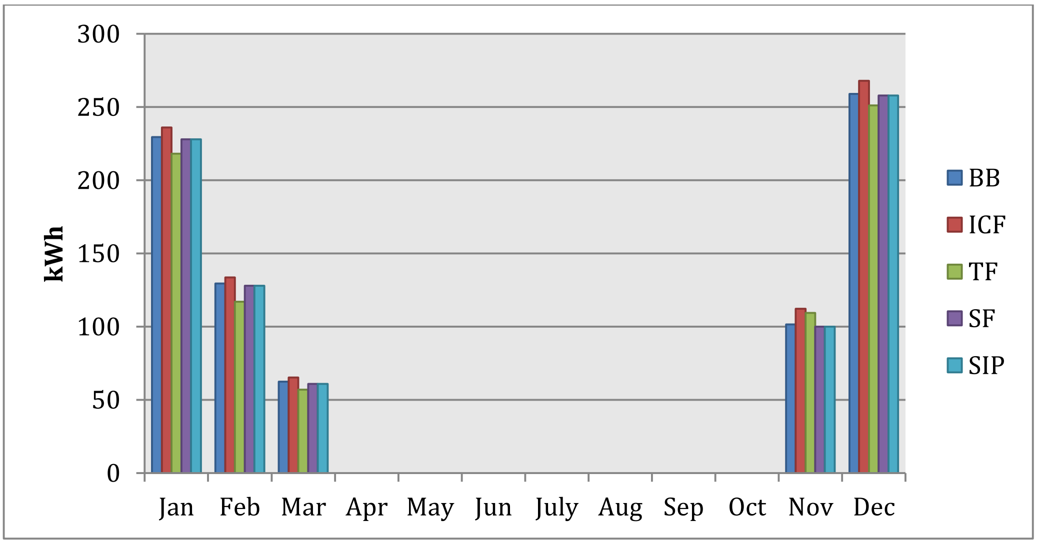


Figure 92 Monthly comparison of heating loads (kWh) with occupancy in the second model, London 2080

Similar to Manchester, a noticeable disadvantage for ICF and advantage for TF can be observed in all times. Besides, a high level of thermal mass does not have any advantage compared to the others. The lowest decrement factor for the TF system caused an advantage when the weather was cold in Manchester and London (2011). Figures 93 to 95 demonstrates the cooling loads required to remove discomfort hours in hot period of the year.

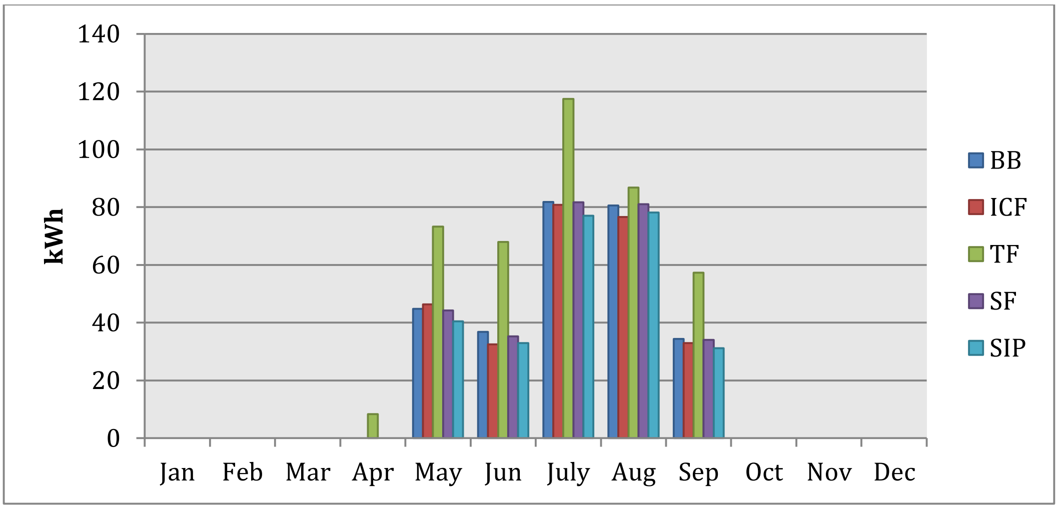


Figure 93 Monthly comparison of cooling loads (kWh) with occupancy in the second model, Manchester 2011, 2020

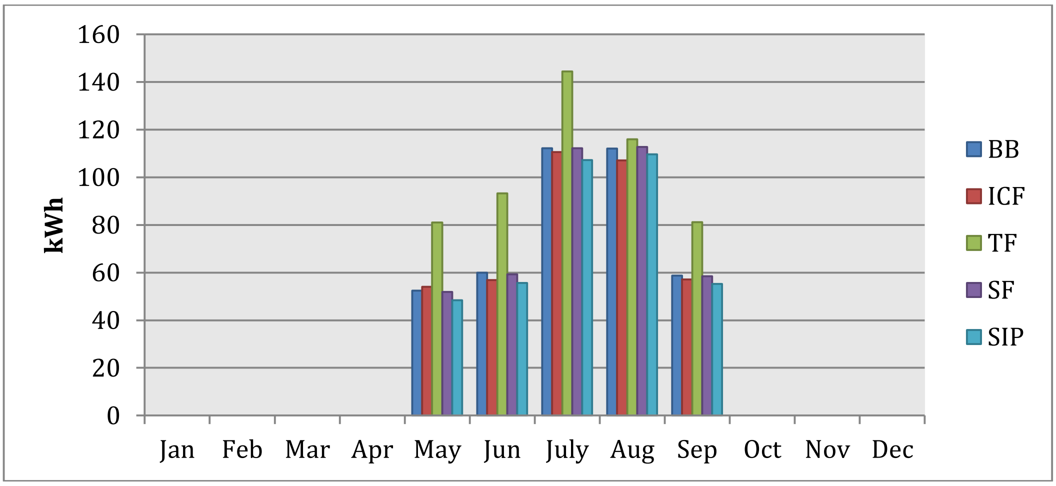


Figure 94 Monthly comparison of cooling loads (kWh) with occupancy in the second model, Manchester 2050

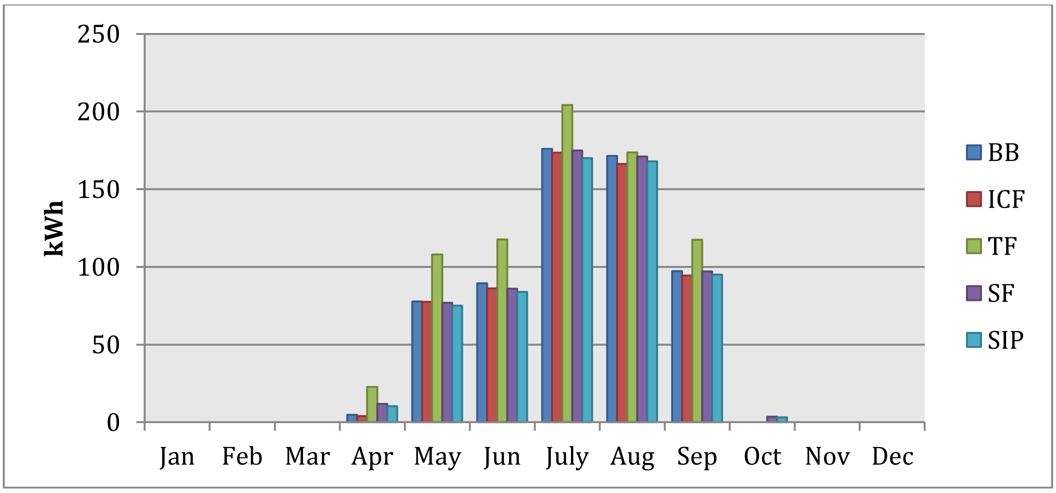


Figure 95 Monthly comparison of cooling loads (kWh) with occupancy in the second model, Manchester 2080

As Figures 94 to 97 show, TF shows the lowest performance in hot months of the year in all times in Manchester. Minor differences can be observed from the other wall types and BB with the highest thermal mass performance does not show any advantage. Figures 96 to 99 show cooling load consumptions in London.

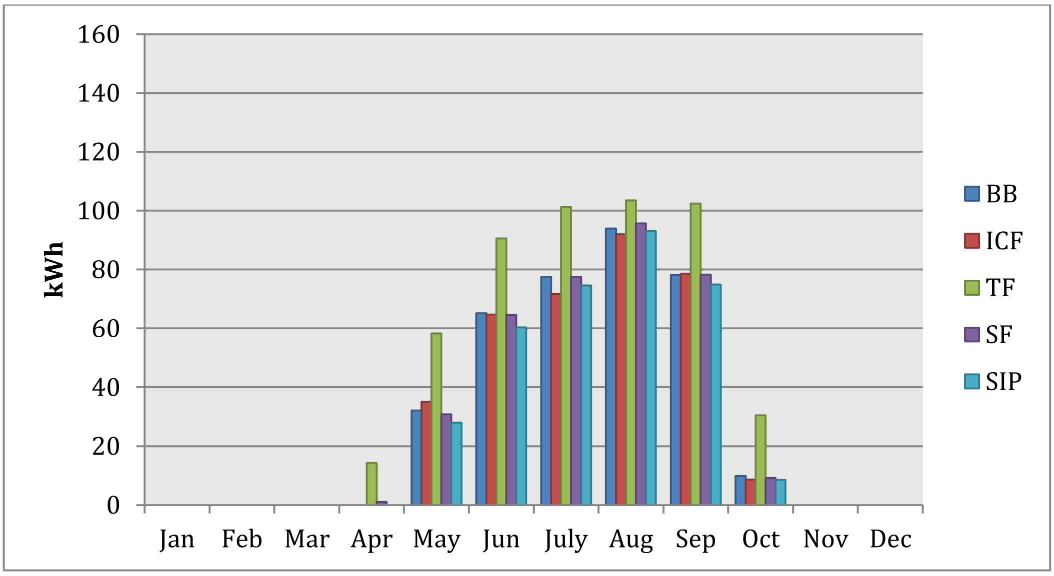


Figure 96 Monthly comparison of cooling loads (kWh) with occupancy in the second model, London 2011

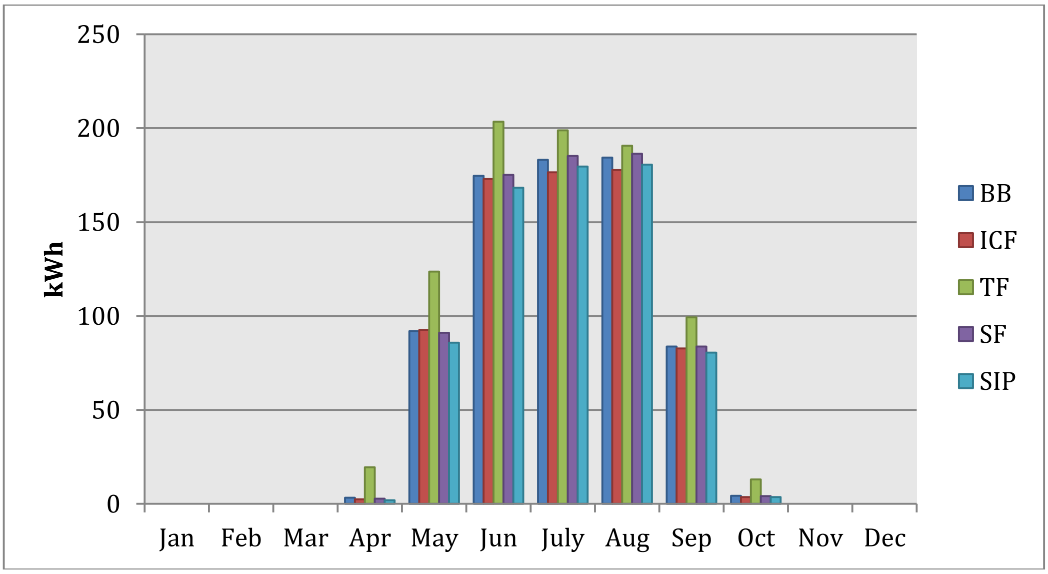


Figure 97 Monthly comparison of cooling loads (kWh) with occupancy in the second model, London 2020

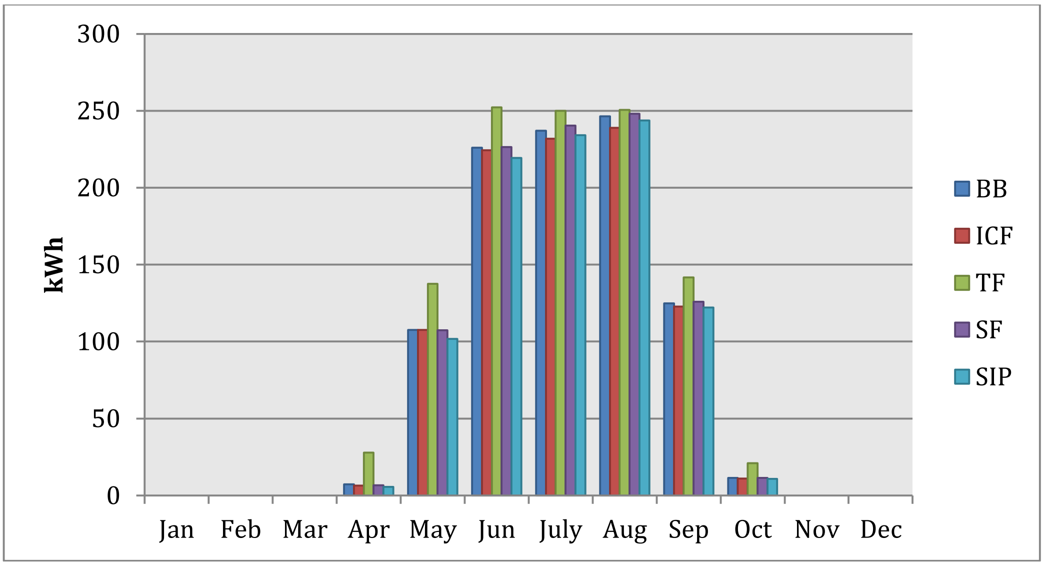


Figure 98 Monthly comparison of cooling loads (kWh) with occupancy in the second model, London 2050

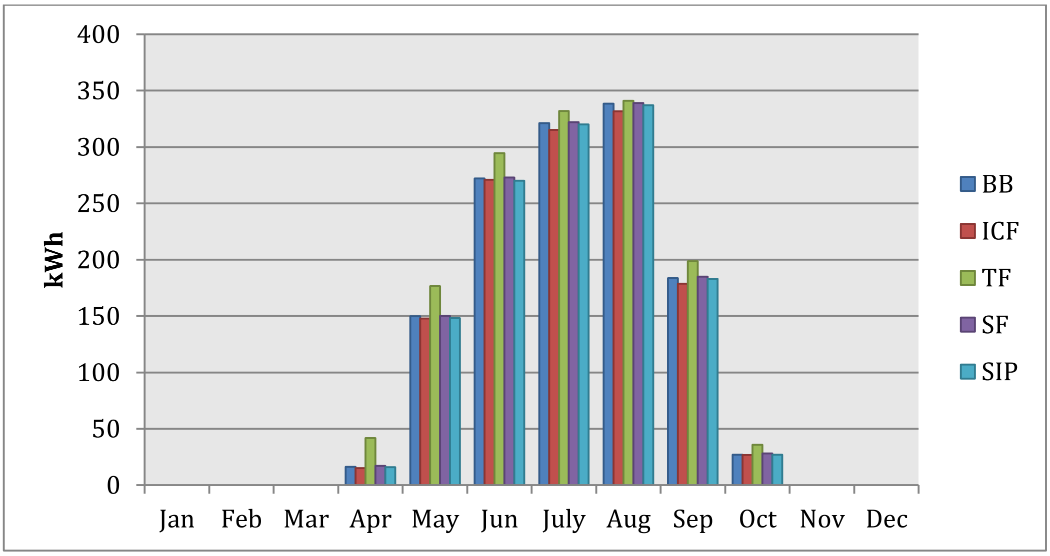


Figure 99 Monthly comparison of cooling loads (kWh) with occupancy in the second model, London 2080

Similar to Manchester, TF has a disadvantage compared to the other wall types in London. The minimum decrement factor characterizes the behavior of the systems as TF shows more fluctuations compared to other systems. These results are comparable to those of Dodoo et al. (2012) who found lesser advantage (overall cooling and heating loads) of timber frame building compared to a concrete construction system in the cold climate of Sweden. Noren et al. (1999) also found similar results by emphasizing the low advantage of high thermal mass in cold climates.

8.8 Computational Fluid Dynamics simulations

The aim of utilizing Computational Fluid Dynamics (CFD) in this study was to illustrate the uncertainty in thermal distributions in buildings. CFD is particularly suitable for indoor modeling, which are difficult in another simulations tools for prediction purposes (Hajdukiewicz, et al., 2013). To realize the uncertainty in each case, the extreme climate change scenario, which is London 2080, is shown with Manchester 2011 in Figure 100 and 101 for December and July.

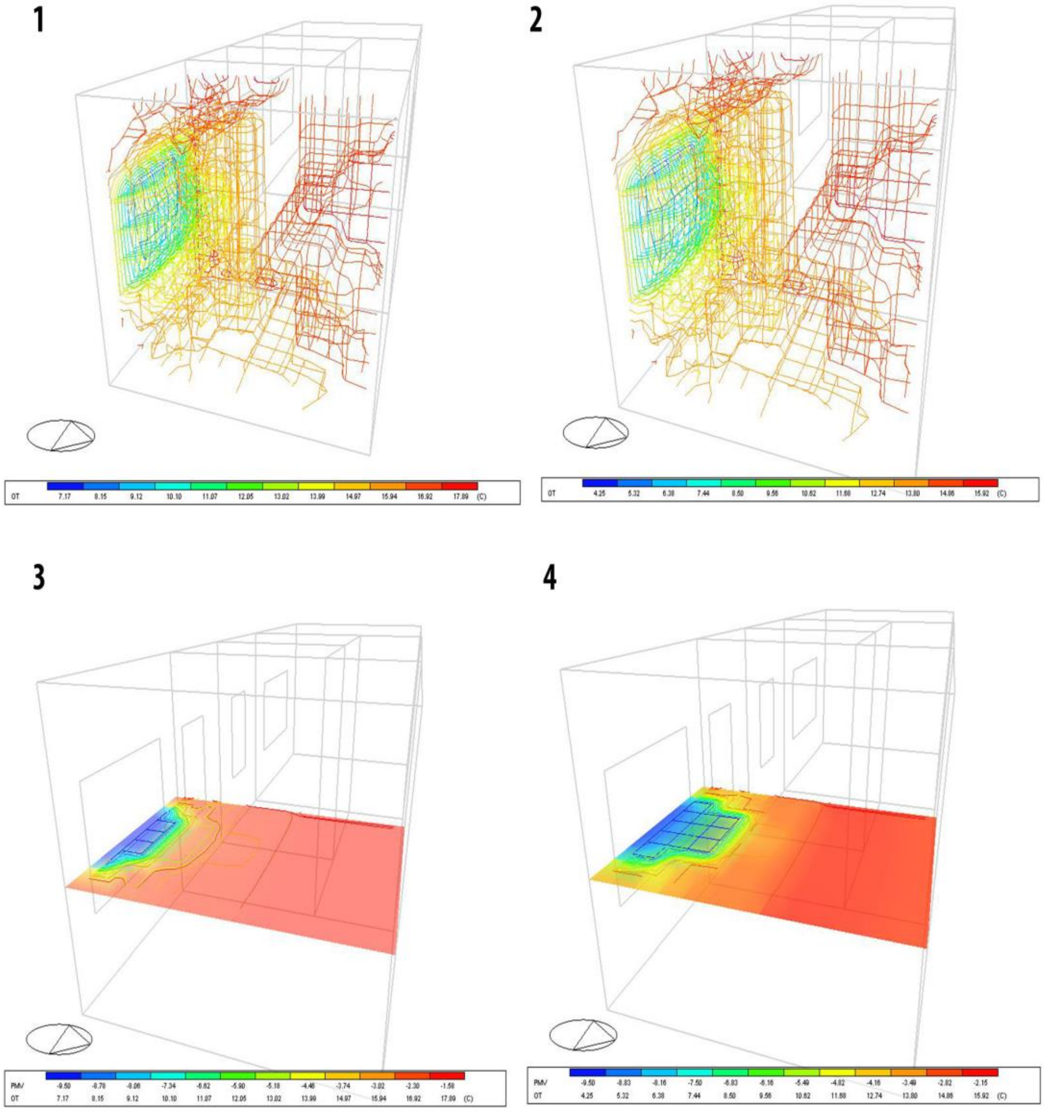


Figure 100 CFD modeling in Dec, 1-London 2080 (temperature distribution), 2-Manchester 2011(temperature distribution), 3- PMV (London 2080), 4- PMV (Manchester 2011)

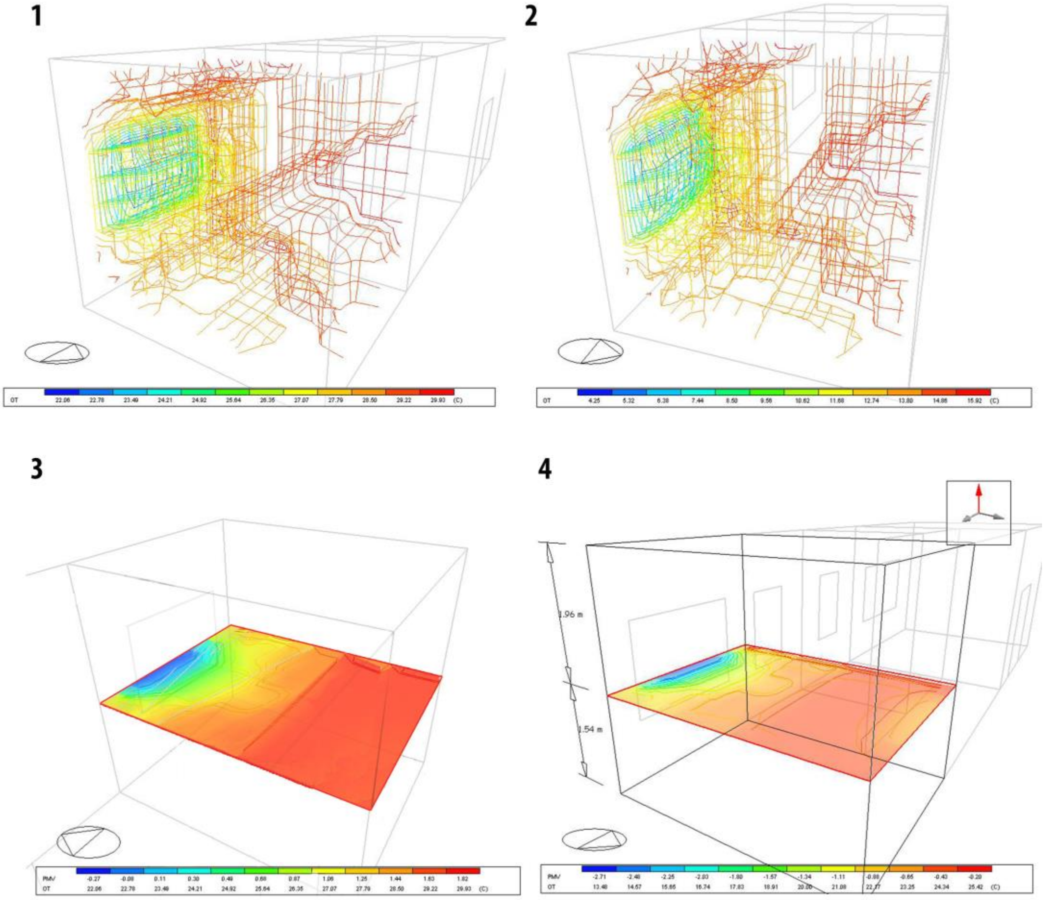


Figure 101 CFD modeling in July, 1-London 2080 (temperature distribution), 2-Manchester 2011(temperature distribution), 3- PMV (London 2080), 4- PMV (Manchester 2011)

It can be observed from Figures 100 and 101 that even when it is mentioned that the examined room temperature is, for example, 25℃, there is still differences in each point of the zone, which might be almost be between 23℃ to 28℃. This uncertainty can be seen in any time and there is no observation that can claim when the temperature goes higher the amount of uncertainty would change or not. The CFD modeling in this session is to only show the uncertainty in saying temperature inside the model and this research is not to going to investigate this issue any further.

8.9 Summary

- Five different wall constructions were chosen in this study as representing the most common types used in UK housing construction. The differences between them were in their thermal mass performances (admittance factor from 1.16 to 5.3 W/m^2K) and other thermal properties such as decrement factor (from 0.01 to 0.81) as well as their thickness. However, a U-Value of 0.1 W/m^2K was the same for all of them. TF demonstrated considerable fluctuations (lower heating load and higher cooling load) in most cases compared to the other systems in both Manchester and London due to its lowest decrement factor. This would cause advantage in cold months and disadvantage in hot months.

- The result have suggested that the effect of thermal mass system has been largely exaggerated in recent works and, although it have some advantages, lightweight systems have also demonstrated comparable result with BB in terms of energy consumption in both models.

- The base case model was built for easy understanding of each wall construction types' impact and behaviour. The parameters decrement factor, admittance and time lag do not seem to comprehensively characterize a wall type regarding thermal comfort and energy consumption in this model.

- The sensitivity analysis carried out was unable to directly suggest an optimum solution in design decision-making process, as each parameter needed a pre-observation of designer concepts. However, it is a relevant method for specific design strategies development.

- Maximizing thermal comfort is a significant challenge, to which there is no single answer. According to the simulations there is no 'one size fits all' solution for each situation and each project in each time should be considered using additional passive design solutions for optimum performance.

- In general, this Chapter quantifies the potential impact of climate change on overheating risk in the UK and provides the picture of the likely trends in energy consumption and thermal comfort in London and Manchester. Therefore, this Chapter highlights the need for potential design solutions to alleviate the risk. The following chapters review the effective solutions by means of computer simulations and literature review before the assessment of typical UK models.

9. THE USE OF SHADING DEVICES IN BASE CASE MODEL

Previous chapters illustrated how current sustainable standards would perform for current and future weather scenarios and quantified overcooling and overheating risk when typical construction systems were applied to simple models. This Chapter considers a traditional method, shading devices (SD), an applicable tool to tackle the risk of climate change.

9.1 Solar gain and shadings mechanism

The Earth constantly receives solar radiation. However, the amount of solar radiation reaching the Earth's surface depends on cloud cover and absorption in the atmosphere (Gueymard, 2008). Fixed SDs, as shown in Figure 102, can block solar radiation and reduce thermal loads during the summer (Dubois, 1997).

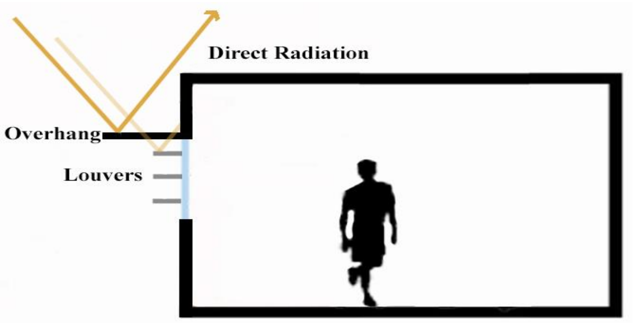


Figure 102 SDs (Overhang and louvers) mechanism in blocking solar radiation

9.1 Base case model with overhang (0.5 and 1m) and louvers

It is assumed that shading devices can reduce overheating and consequently improve thermal comfort inside the simple model. Simulation results for 0.5 and 1m overhang and louvers systems in Manchester for the five construction types are shown in Figure 103.

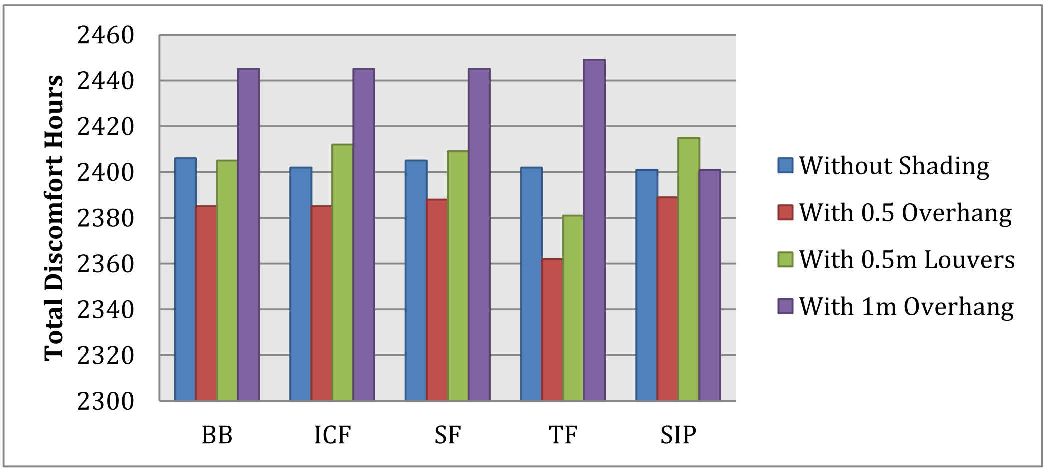


Figure 103 Total discomfort hours in base case model with and without shading devices Manchester 2011

Figure 103 demonstrates that a 0.5 m overhang shading gives the lowest discomfort hours compared to 1m overhang and louvers for all of the wall types. TF with 0.5 overhang shading has the lowest discomfort hours compared to the others. Louvers do not seem to be considerably effective and a 1m overhang causes more discomfort hours in total. The difference between the highest discomfort hours (1m overhang with TF) to lowest discomfort hours (0.5m overhang with TF) is approximately 87 hours in overall. Figure 104 illustrates that in warmer periods of the year (1 April to 30 September) a 1m overhang increases the risk of discomfort hours. However, Figure 105 clarifies that at the hottest time of the year (July), this length of shading can cause less discomfort hours.

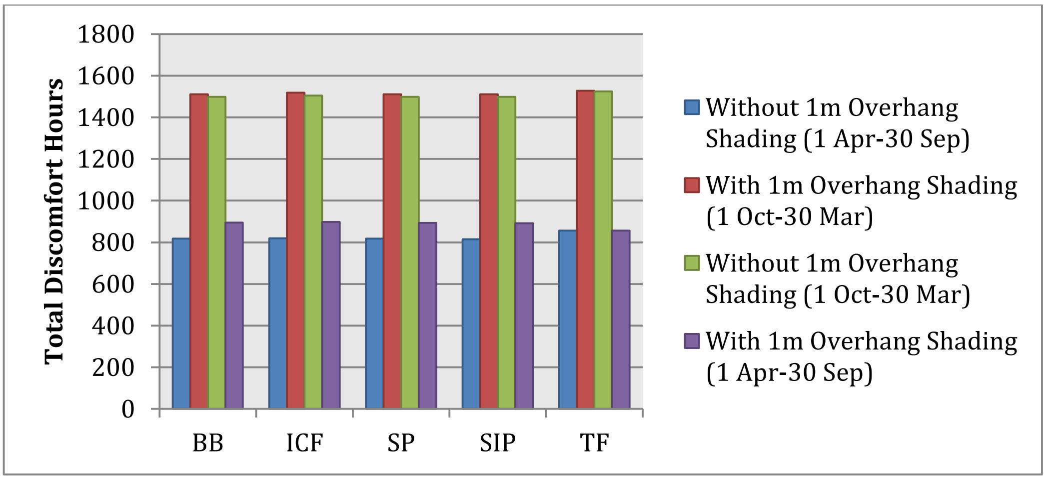


Figure 104 Model with and without 1m-overhang shading Manchester 2011

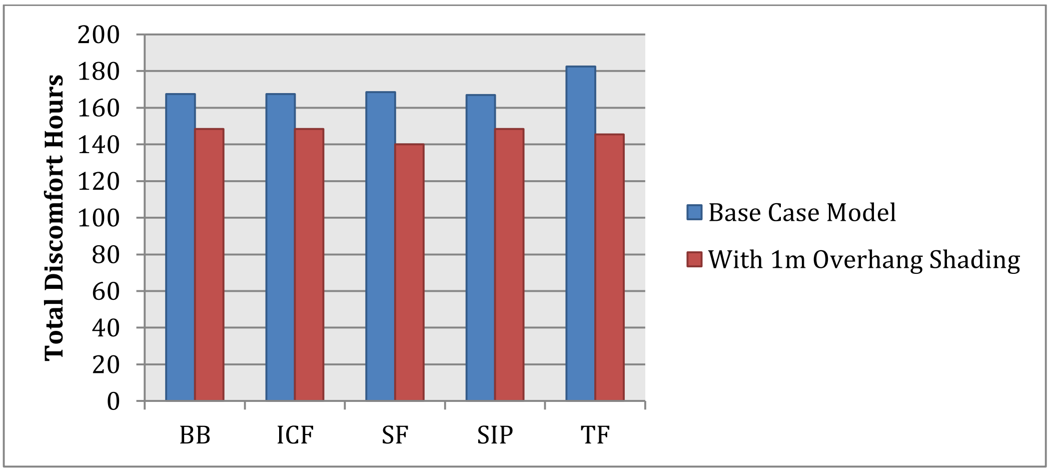


Figure 105 July month with and without shading Manchester 2011

As observed, 1m-overhang can only cause less discomfort hours in the hottest time of the year and the difference is at most around 37 hours and only when TF is applied to the model. Therefore, it cannot be an appropriate design solution to alleviate discomfort hours risk in total. Figures 106 to 108 demonstrate how shading devices will affect discomfort hours inside the model for Manchester in 2020, 2050 and 2080

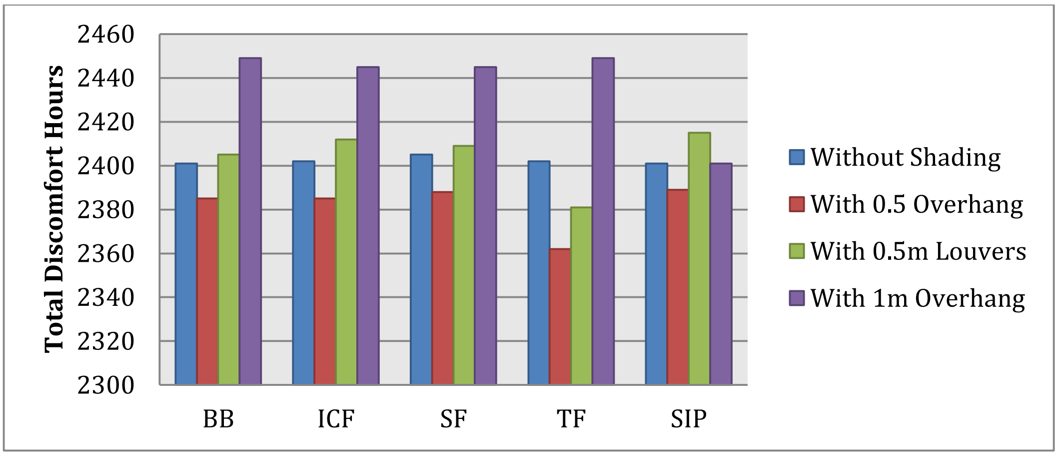


Figure 106 Total discomfort hours in base case model with and without shading devices Manchester 2020

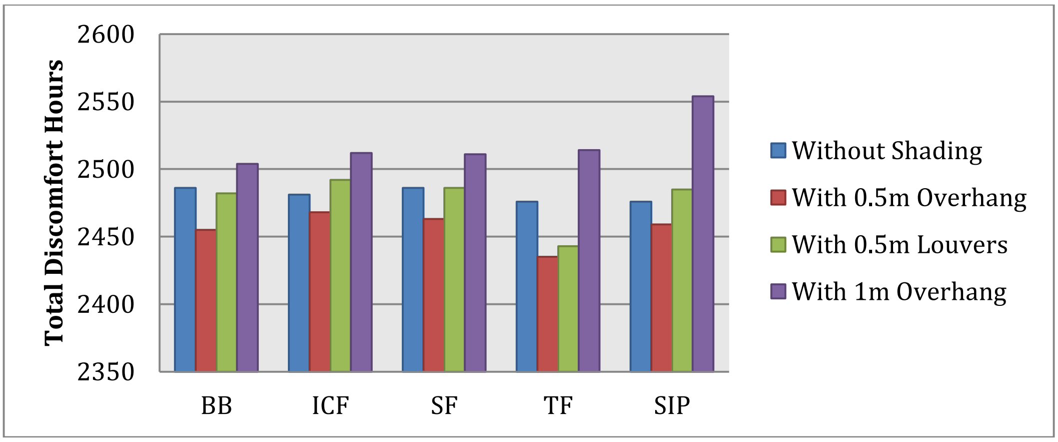


Figure 107 Total discomfort hours in base case model with and without shading devices, Manchester 2050

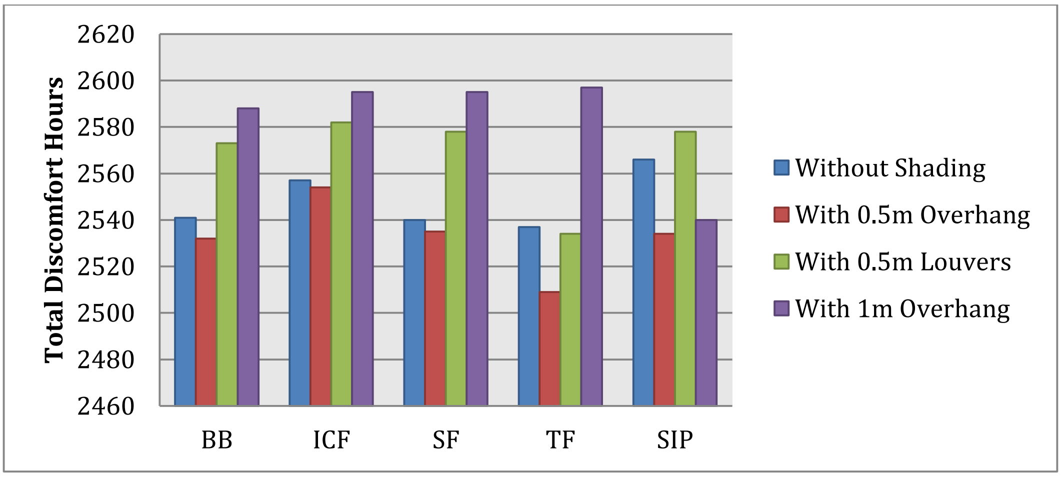


Figure 108 Total discomfort hours in base case model with and without shading devices Manchester 2080

Similar behaviours from wall types can be seen in 2020, 2050 and 2080 as shown in Figure 106, 107 and 108. A 0.5m overhang causes less discomfort hours compared to the others and a 1m overhang causes the most discomfort hours. Therefore, a 0.5m-overhang can be suggested as a more effective design solution among the examined shadings in Manchester. Furthermore, a 0.5m overhang with the TF wall type shows the lowest discomfort hours compared to the other systems. For example, in 2080 a 0.5 overhang with TF shows 45 fewer discomfort hours compared to the ICF system with the same shading device. However, in London different results are observed, as shown in Figures 109 to 112.

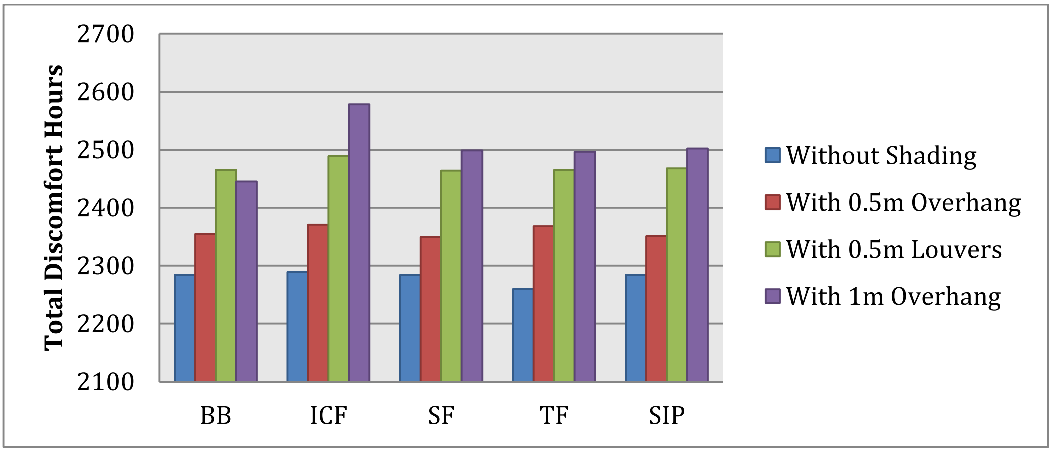


Figure 109 Total discomfort hours in base case model with and without shading devices London 2011

Surprisingly, neither of the shading devices causes less total discomfort hours in London, 2011. This is highly likely due to the increase in overcooling hours. Less solar gains can cause a considerable increase in discomfort hours in cold period of the year. Therefore, shading advantages are lower than their disadvantages in this instance. Figure 110 to 112 demonstrates their effect for future climates. Figure 110 shows that the temperature increases in London, 0.5m and 1m-overhang shadings cause less total discomfort hours. Better performance from the 1m-overhang shading compared to the 0.5 louvers was surprising. However, TF with a0.5m-overhang has the lowest discomfort hours compared to the others. The difference in the extreme case (TF + 0.5m louvers compared to TF + 0.5m overhang) is around 173 hours. Also, this wall type with louvers has the highest discomfort hours compared to the other systems. Figure 111 shows total discomfort hours in 2050 and 2080.

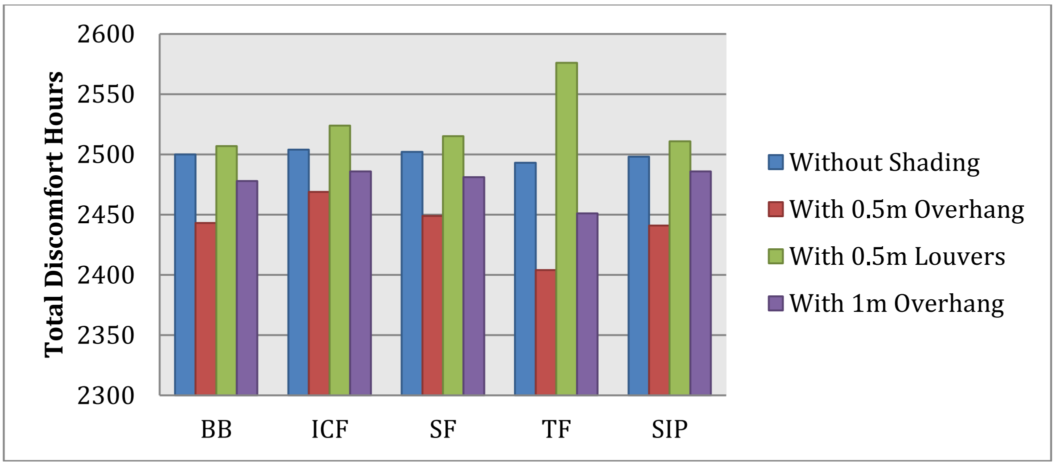


Figure 110 Total discomfort hours in base case model with and without shading devices London 2020

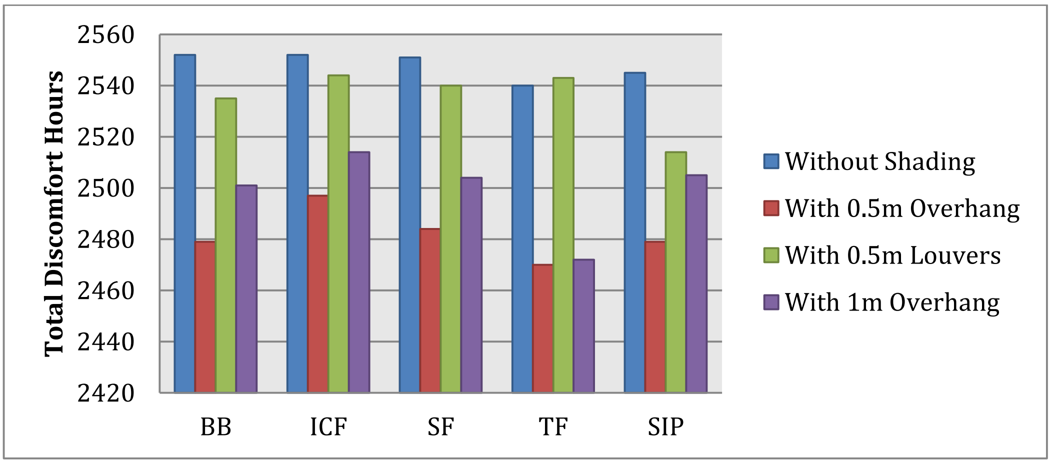


Figure 111 Total discomfort hours in base case model with and without shading devices London 2050

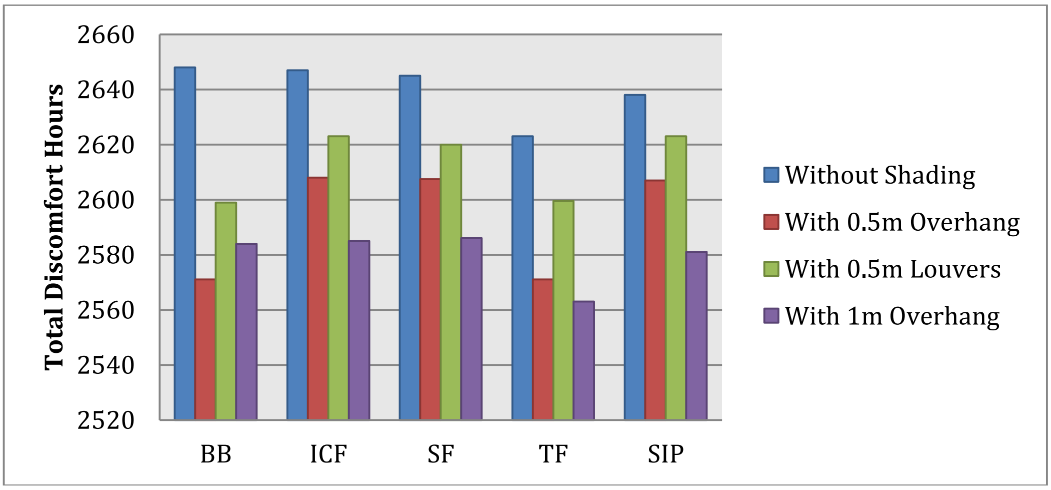


Figure 112 Total discomfort hours in base case model with and without shading devices London 2080

Figure 111 and 112 show that, from 2050 afterwards, all shading devices reduce discomfort hours considerably and that a 0.5m overhang seems to be the most effective overall shading type in most cases. This is despite the most effective system being TF with 1m overhang which shows over 85 hours lower discomfort hours compared to the BB system without SDs. It can be generally observed that shading devices as a type of 'flexible strategy' that could be added or removed from buildings have the potential to reduce the risk of discomfort hours effectively in future when the weather become warmer and the risk of overheating becomes greater.

Figure 113 and 114 consider a monthly breakdown of discomfort hours in London 2080 with BB as a high thermal mass system and SF as a low thermal mass system. Results show that differences in each month are more noticeable compared to the total comparison as demonstrated above. For example, the 1m overhang causes the lowest discomfort hours in June with 130 overall discomfort hours but the highest in April (280 hours) and May (230 hours) with the high thermal mass system (Figure 114) and the differences become even more marked with low thermal mass in June (over 10 hours difference) and July (over 20 hours difference) (Figure 114).

In general, shading devices have potential to reduce discomfort hours risk in the hot periods of the year as they could considerably reduce solar gains into buildings and therefore could be more beneficial in London and in future times. Besides, SDs could be added to the building for retrofitting at low costs compared to the other design solutions. Therefore, SDs could be an encouraging design solution for design decision makers in the UK.

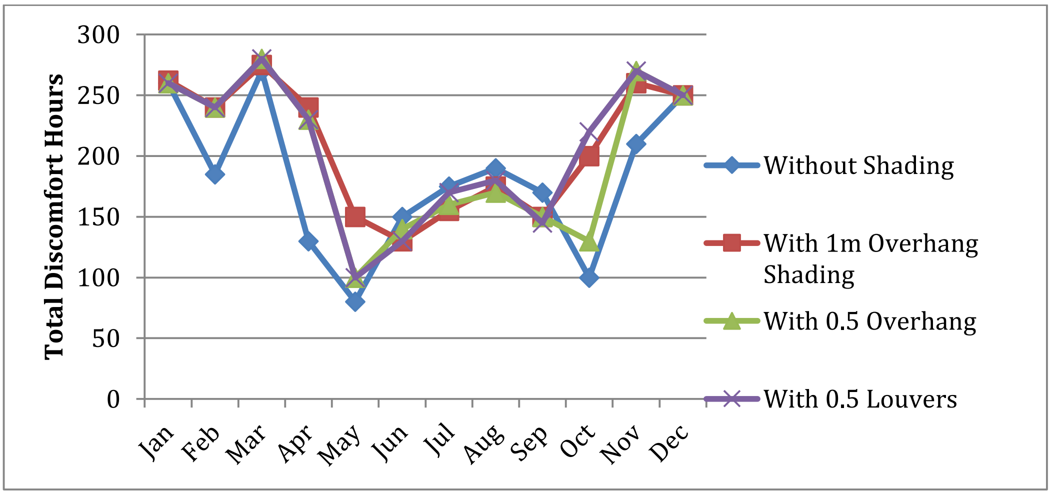


Figure 113 Monthly breakdown of discomfort hours in model with BB construction system, London 2080

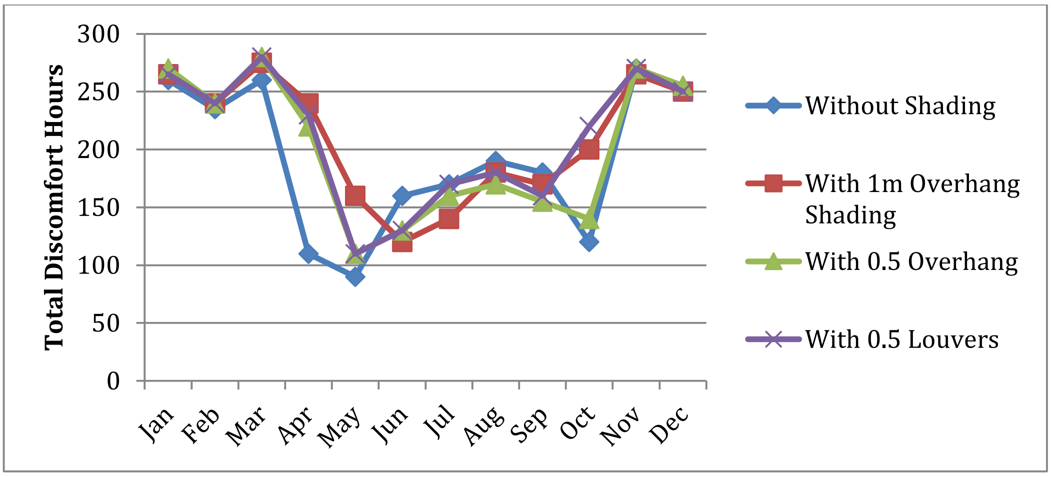


Figure 114 Monthly breakdown of discomfort hours in model with SF construction system, London 2080

9.2 Summary

- In most cases, a 0.5m overhang seems to have the best effect in reducing discomfort hours. The difference in the extreme case (TF + 0.5m louvers compared to TF + 0.5m overhang in London 2020) is around 173 hours. Generally, a 0.5m overhang will reduce energy load demand in most cases.

- The study considers total discomfort hours but further investigation for London 2080 clarified that considerable differences exist in each month (even in excess of 100 hours in April).

- Different angles of SDs might change their efficiency and cause more or less comfort hours in buildings. Further studies might focus on enhancing solar shading angles to deal with future climate scenarios.

10. INCORPORATING NOVEL MATERIALS

10.1 Utilizing smart materials in building envelopes

Following the sensitivity analysis in Chapter 8, significant temperature fluctuations caused by climate change have been observed as a major challenge. The potential overheating risk is of greater concern than overcooling as the energy required to cool down temperatures by 1°C is higher than the energy needed to heat it (Littlefair, 2005). Therefore, overheating is more energy-consuming compared to overcooling. Besides, warmer future weather conditions would reduce overcooling to some extent. It is possible that integrating smart material such as Phase Change Material (PCM) in to building envelopes can enhance the thermal performance of wall types.

The concept of utilizing PCM is to combine thermal mass without adding weight to the system. PCMs are materials that undergo a phase change process by reorganizing their microstructure, causing heat release or heat storage. Therefore, PCM is meant to store heat at a particular temperature and will maintain that temperature level to reduce ambient cooling or heating, meaning a state of programmable inertia can be reached by controlling the melting temperature and PCM quantity in total.

PCMs are energy storage materials that have considerable thermal energy storage densities and are able to absorb or release large quantities of energy by undergoing a phase change. Microscopically small containers of PCMs in wallboards start absorbing heat and store it in phase change when there is an increase in temperature over a defined temperature threshold (for example, 21°C, 23°C, 25°C or 27°C). When the temperature decreases below the temperature threshold, the stored heat is re-released and this cycle will continue to regulate indoor temperature (Carter, 1981). This chapter discusses this influence in detail as a possible solution to reduce overheating risk.

10.2 Suitable PCM for building envelope

In order to characterize PCM, Farid et al. (2004) and Sharma et al. (2009) suggested the following properties:

1- Thermal properties:

- High thermal conductivity to assist discharging and charging of heat,
- To minimize the essential physical size, high latent heat per unit volume is required (latent heat capacity is the quantity of heat energy needed for state change of a unit mass of a substance, J/kg) (Bird & Ross, 2002).

- Adequate PCM phase-transition temperature to match the operative temperature of buildings

2- Physical properties:

  - High density to make containers smaller
  - Small volume change during the phase transformation

3- Chemical properties:

  - Long-term durability for stable capability
  - Non toxic to minimize health and safety risks
  - Completely reversible melting and freezing cycle

4- Kinetic properties:

  - Adequate crystallization rate when freezing to allow the system to meet heat recovery demand
  - Adequate nucleation rate to prevent super cooling whilst the melting point is exceeding the solidification point

5- Economics

  - Cost effectiveness and abundance

10.3 PCM classification

Generally, PCMs are divided into eutectic, organic and inorganic types. Organic types are mainly paraffin and fatty acids which have high latent heat and low conductivity. Inorganic types are mainly metallic and salt hydrates which have higher latent heat compared to organic ones as well as high thermal conductivity and lower costs. Eutectics mainly consist of two or more components and can be organic-inorganic or inorganic-organic (Pasupathy & Velraj, 2008).

Furthermore, encapsulation is a significant issue in PCM technology. A number of techniques are applied to integrate PCMs into a building fabric, which include microencapsulation and direct immersion. Direct immersion is the cheapest technique to integrate PCM elements into the buildings. Wallboards are the most common example of utilizing this technique. In the microencapsulation technique, usually 10 mm or larger containments hold the substance (Khudhair & Farid, 2004).

10.4 PCM applicability in building

The way in which a PCM is applied in a building envelope is important for their performance. On the basis of time and power, their availability should match the demand. For example, design decision makers should regulate how much heat is needed to be absorbed by PCMs, when is the peak time (in terms of the heat) and whether the discharge time is short enough to be efficient before the next cycle.

PCMs can store heat energy but cannot remove it. Therefore, an appropriate ventilation strategy is necessary before integrating PCMs into the building envelope. This has the potential to become a serious issue in well-insulated buildings. Heat is returned back to the space when the air temperature drops below the PCM temperature. Bruno (2005) added that latent thermal storage performs adequately when the storage is regularly discharged. Therefore, if the PCM is coupled with mechanical ventilation, then heat discharge can be regularly accomplished and the system can perform well.

Integrating PCMs into the building envelope has a considerable additional advantage in terms of reducing energy consumption. This is mainly because storage occurs inside the same room where the load occurs. Therefore, there are no costs and losses due to the energy transport. Figure 115 demonstrates three different ways of using PCMs for heating and cooling of buildings, which include: passively, coupled with active cooling and coupled with active heating (Zhang, et al., 2007). As can be seen from Figure 115, PCMs can be incorporated in to floors, roofs and walls.

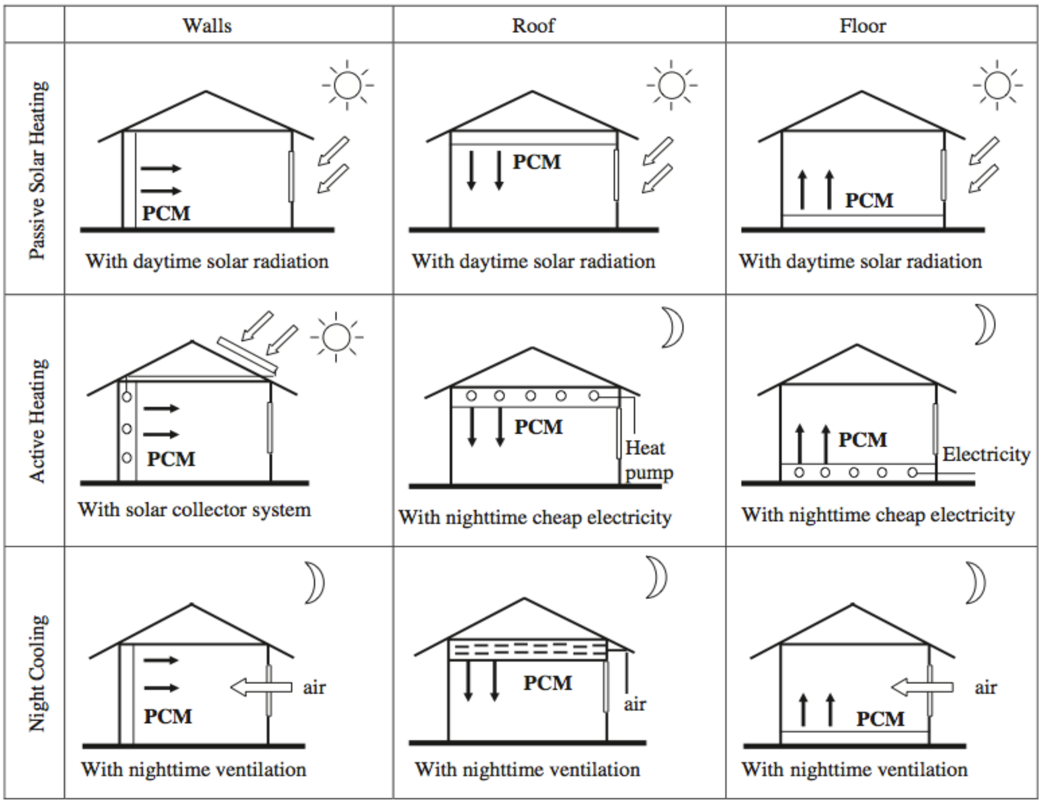


Figure 115 Forms of integrating PCM into the building envelope. Source: (Zhang, et al., 2007)

10.5 PCM in walls

Carter (1981) compared two PCMs in Canada with 21°C and 27 °C melting points and investigated how much PCM was required. His study showed that the high phase change in temperature could lead to overheating and the low phase change requires a large surface area. He discovered that in locations with low solar radiations and mild winters (like the UK), those PCMs which have their change of phase above the thermal comfort average work properly.

Principi et al. (2005) compared three boxes with PCM, PCM + ventilated air gap and without PCM and concluded that the two with PCM consumed 50% less energy while the one with air gap did not show any significant advantages. In 2005, Shilei et al installed PCM boards in a room and found that PCMs are effective in reducing indoor temperature fluctuations in summer and winter.Voelker et al (2008) performed similar studies in Germany and concluded that PCMs with a temperature range of between 25℃ to 28°C can reduce indoor peak temperature by up to 4°C. They also discovered that in the absence of proper ventilation, PCM will lose its heat storage capacity after a few consecutive hot days.

Feustel and Stetiu (1997) also found PCMs to be effective in decreasing indoor air temperatures in California; they emphasized that when the outside temperature is more than 18 ° C, utilizing mechanical ventilation is necessary for optimal performance. However, Neeper (2000) suggested wallboards with 400kJ/m^2 latent heat capacity can perform almost identically to exposed masonry in internal surfaces.

10.6 PCM in ceilings and floors

Ceilings can be a better position for PCM incorporation because ceilings are more exposed than walls and floors, which often have furnishings cover them. Also, ceilings are more exposed to warmer air since warm air rises. Turnpenny et al (2001) examined PCM systems in a ceiling with a melting point around 28℃ and freezing around 24℃ and discovered that the system could reduce overheating risk in the UK as well as cause considerable energy and CO2 emission reductions. Yanbing et al (2003) performed a similar experiment and discovered that PCM can considerably improve comfort levels inside a building.

Pasupathy and Velraj (2008) found that ingetrating PCMs in the ceilings of Indian houses could reduce temperature fluctuations. However, it cannot be effective when the inside temperature is above the phase change temperature for a long period of time. A consultancy company in the UK, Faber Maunsell, also examined the installation of PCM with shading devices in Stevenage Borough Council offices in the UK and reported a 5°C indoor temperature reduction achievment (Barnard, n.d.).

Furthermore, Hittle (2002) utilized PCM in flooring and found a 24% annual reduction in overall energy consumption compared to a similar room without PCM in the floor. Zhang et al (2006) conducted a similar study and mentioned PCM in floors considerably reduced temperature fluctuations. Weinlader et al (2005) used encapsulated PCM in transparent containers in a double glazed window and recorded 50% less heat gains and a 30% reduction in heat losses in south oriented facades which cause more comfort hours both in winter and summer. Simliarly, Ismail and Henriquez (2001) suggested a coloured PCM is more effective than trasnparent and emphasized green is the most effective.

Other authors investiagted the integration of PCM in Tromble walls, solar heated water, etc and all came to positive conclusions regarding the use of PCMs. However, most of the mentioned systems are not commercially available and there is a gap between the experimental stage and the commercial level for using PCMs. However, the next section describes available PCM boards in the UK market.

10.7 Available PCM wallboards in the UK market

Despite the fact that PCMs have been generally used in building cooling and heating systems, only a few PCM construction products are available in the world, perhaps because they are very new to the construction industry. However, at the time of this study three types of prefabricated PCM wallboards were found to be available.

10.7.1 The BASF Knauf Micronal PCM Smartboard

According to the company, this product has been giving acceptable results in terms of improving thermal comfort. It is available at three melting point temperatures (21°C, 23°C and 26 °C) and can be used as a substitue to plaster or incorporated in to aerated concrete blocks as well as ceiling panels. Knauf Smartboards are claimed to be thermally equivalent to 365 mm of brick or 140 mm of concrete (Schmidt, 2007). Table 13 demonstrates comprehensive details of this product.

Table 13 Knauf Micronal PCM Smart Board

Operative temperature	19-23 °C
Thickness	15mm
Width	1250 mm
Length	2000 mm
Weight	11.5 kg/$\boldsymbol{m^2}$
Density	900 Kg/$\boldsymbol{m^3}$
Latent heat storage capacity	110 kJ/kg
Specific heat storage capacity	1.2 kJ/kg°C
Total heat storage	110 kJ/kg
Thermal conductivity liquid phase	0.18 W/$\boldsymbol{m^2}$k
Thermal conductivity solid phase	0.18 W/$\boldsymbol{m^2}$k
Quantity of PCM per square meter	3 kg
Recommended use per 100Wh	1 $\boldsymbol{m^3}$

Source: http://www.micronal.de/portal/streamer?fid=290930)

The company examined 6kg of PCM per m^2 wallboards in Ludwigshafen, Germany, where the temperature did not increase beyond 28°C, and claimed that the inside air temperature did not exceed 26°C in the test room while their reference room exceed 28°C (Schmidt, 2007).

10.7.2 The DuPont Energain board

Dupont maintains that Energain panels behave almost like a 150 mm brick layer and their recent experiment confirmed an up to 15% reduction in air-conditioning costs in a building located in Liverpool, UK. Table 14 shows details of Energain PCM wallboards (DuPont, 2011).

Table 14 DuPont Energain wallboard

Operative temperature	18-22 °C
Thickness	5.26 mm
Width	1000 mm
Length	1198 mm
Weight	4.5 kg/m^2
Density	810 Kg/m^3
Latent heat storage capacity	85 kJ/kg
Specific heat storage capacity	95 kJ/kg°C
Total heat storage	180 kJ/kg
Thermal conductivity liquid phase	0.18 w/m^2k
Thermal conductivity solid phase	0.17 w/m^2k
Quantity of PCM per square meter	2.43 kg
Recommended use per 100Wh	0.47 m^3

Source: (DuPont, 2011)

10.7.3 The F.E.S Datum board

According to the company, they produce both wallboards and ceiling tiles and they claimed a 55% energy reduction in an office project located in London (Datum, 2012). Table 15 gives the product’s detail.

Table 15 F.E.S Datum board

Operative temperature	20-24 °C
Thickness	25mm
Width	600/700 mm
Length	1200 mm
Weight	19.5 kg/m^2
Latent heat storage capacity	85-169 kJ/kg
Thermal conductivity liquid phase	0.35 W/m^2k
Thermal conductivity solid phase	0.35 W/m^2k

Source: (http://www.datumphasechange.com/F.E.S-BoardBrochure.pdf)

This study has also considered the application of Earth to Air Heat Exchangers (EAHE) as a novel construction technology to reduce likely overheating risk in UK housing. However, the study was unable to quantify their effect and so only general description and literature review is provided in the next section.

10.8 Earth to Air Heat Exchangers

The main concept of Earth to Air Heat Exchangers (EAHE) is to utilize earth mass to dissipate heat by passing air through underground pipes. The pipes should be buried deep enough to avoid temperature swings and need to be long enough for heat exchange. As this system consumes a low amount of energy and considerably reduces temperature fluctuations (Rye, 2005), it could be an effective strategy to tackle climate change risks in the UK. This technique was used in ancient Persian architecture (sometimes combined with water) and was known as qanats. Similar approaches were found in ancient Rome and Egypt (Rye, 2005). Figure 116 demonstrates the mechanism of this system.

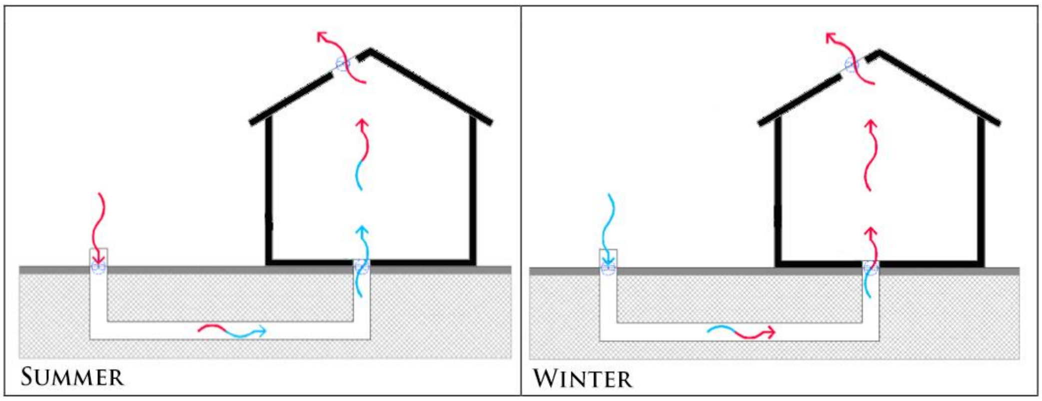


Figure 116 EAHE mechanism in summer and winter

In summer warm outdoor air gives its heat to the cooler soil and delivers cool air into the building. In winter, as the air passes through the pipe, it gains heat from the warmers earth. Usually, the system requires a fan due to the pressure losses.

10.9 Potential energy savings

EAHE application can cause considerable energy savings in building. The equation below is used to calculate EAHE's potential energy savings:

Q (EAHE) = m (air) C (air) ΔT + mΔh (latent)

where Q is the quantity of cooling or heating energy delivered, m is the mass of air, c is the specific heat capacity of air (1.0112 kJ/kg°C), ΔT is temperature difference and Δh is specific latent enthalpy of water)

However, this equation does not necessarily provide accurate predictions of energy savings for the EAHE system as uncertainty remains in time of operation, design of the system, soil temperature, the inlet air temperature and the airflow. Besides, the EAHE systems also needs a control strategy as it might warm up or cool down the building at unnecessary periods (ASHRAE, 2005).

10.10 Practical experience of EAHE applications

Breesch et al (2005) compared nighttime ventilation with the EAHE system in an office building in Belgium and concluded nighttime ventilation was considerably more effective in improving thermal comfort. Another study (Sodha, et al., 1985) examined EAHE system in a hospital near Delhi, India and discovered that when ambient temperature was at 43 ℃, the EAHE can deliver air between 23 to 28 ℃ and in winter, when outside temperature was around 4 to 21℃, a temperature of between 12 to 20 ℃ was delivered by the system. They concluded that the system was more effective in summer than winter.

Hollmuller and Lachal (2001) examined the application of EAHE in an office building in Geneva and stated that the system maintained an inside temperature below 26℃ in summer without fluctutations. They also emphasized that EAHE systems are more effective than conventional HVAC systems during the summer. A similar study by Thiers and Peruportie (2008) in the north-west of France examined a residential building complying with the Passivhaus standard at an air exchange rate of 1.5ach and came to the conclusion that the EAHE system caused a 60% reduction in overheating hours. A summary of some other studies which examined the EAHE system are provided in Table 16.

Table 16 Examined EAHE systems and results

Name	Location	Soil	System and Length	Depth	Max temp drop
Alma Verde Village and Spa (Fjaerem, 2004)	Protugal	14℃	2 pipes, 25m each	2 m	12 ℃
Harmon's house (Mother Earth News Editors, 1986)	USA	23-27℃	4 pipes, 30m each	1m	Not specified
French timber house (Trombe & Petit, 1991)	France	Not specified	1 pipe, 42m	2.5m	12℃
The SEA house (Zhang, et al., 1994)	Japan	25-35℃	10, 20m each	2m	10℃

As observed from the Table, between 1.5m and 2.5m is a typical depth for pipe installations. Furthermore, it seems that installation costs are highly dependent on excavation and pipes length. However, the EAHE system examined by Fjaerem (2004) saved around 33,400 kWh, which translated to 3,300 euros, compared to a conventional cooling system during the examination period. It was found to have less than a 9 year payback period.

There are some construction issues which might affect the efficiency of an EAHE system, including:

- Condensation risk

Condensation reduces air quality and occurs during autum and summer time in the UK. However, it is possible that transfering air through the pipe may considerably reduce this risk (Rye, 2005).

- Cleaning and maintenance
- Inlets and outlets

All inlets sould be carefully sheltered from rain and screened for protection from insects, birds and animals. Fans are usually placed at the outlet or inlet and can be controlled electronically. The position of fans do not cause any significant differences in system effiiency.

- Trenches

The most important factors to be considered when digging a trench to install a system are soil type, trench depth and its water content. There is a high risk of collapsing walls that can be alleiviated by making sloped walls and enlarging trenches. However, this can considerablly increase the cost and time of construction.

- Combination with other systems

Either mechanical ventilation or natural ventilation could be combined with EAHEs. Delivering air for internal distribution is an important factor to be considered by designer which can improve internal conditions.

10.11 Available commercial systems in the UK

Atelier Ten is one of the commercial companies that have completed several EAHE project across the Europe, and their first project was in Doncaster, UK. There is no detailed information available for their projects (Atelier Ten, 2013).

Rehau has developed an EAHE systems which is named Awadukt. Rehau claim that their products are enriched with an anti-microbial layer which can improve air quality inside buildings (Rehau, n.d.). Rehau has a cooperation with a company named ICAX which exists mainly to provide interseasonal heat transfer by collecting and storing solar energy in summer which is a similar concept to EAHEs (ICAX, n.d.).

The next Chapter will quantify the effect of PCM in typical UK housing by means of computer simulations, but the study was unable to run simulations for EAHE due to software limitations.

10.12 Summary

- Most of the published works about PCM were experiments in laboratories and few were real life applications. However, it seems small amounts of PCM can replace heavy conventional thermal mass and will effectively reduce temperature fluctuations and improve comfort.

- PCMs can be installed in walls, ceiling and floors as well as in double-glazed windows and curtains. However, they will be more effective in roofs because of furnishing effects. Conclusions from experiments show that mechanical ventilation will increase the efficiency of PCMs. Night time ventilation cannot always effectively accomplish the discharge process therefore has limited capability.

- In locations like the UK with low availability of solar radiation and mild winters, the PCM transition temperature should be above the comfort zone.

- There are barriers to PCMs being readily commercially abundant which the author speculates it might be due to the several reasons. Firstly, because they result in added extra cost to the building, which can be considerable. Secondly, they are not considered in most of the commonly used simulation softwares for design decision makers. Thirdly, their durability has not clearly been investigated and experienced in buildings, so it might add considerable risk for further considerations. Finally, PCMs need mechanical ventilation to perform well.

- Life cycle assessments have not been carried out for PCMs and obviously their production consumes a considerable amount of non-recyclable and toxic materials. Therefore, one may argue that they are not completely adequate for sustainability goals.

- EAHE is an expensive product, which is a barrier for rapid development. However they are cheap to run, which is attractive for buyers. EAHE can cause less temperature fluctuation and reduce overcooling and overheating risks.
- There are several risks involved in installing EAHEs system in buildings such as condensation and maintenance problems. However, well-designed drainage, good construction and air filtering can alleviate these risks.

- There is no long term and well-documented data available for the performance of EAHEs. Besides, very few commercial companies are available to provide these systems. This would cause less desire from designers for EAHEs in UK housing.

- Physical spaces, size and number of pipes, location and the lack of accurate model and guidance to predict EAHEs performance for architects are current major constraints for developing EAHEs.

- This study was only able to quantify the effect of PCM (in Chapter 11) with DesignBuilder, and so the application of EAHE is suggested as an alternative design solution to tackle the risk of overheating but has not been quantified by simulation.

11. NEW UK HOUSE DESIGN PROSPECTIVE, PERFORMANCE EVALUATION AND POTENTIAL IMPROVEMENTS

In previous chapters a simple cell and a simple model were simulated in various conditions. In this chapter, on the basis of current typical UK housing stock, three of the most typical UK dwellings were designed and developed to almost meet the Passivhaus standard. As discussed in previous chapters, shading devices and phase change materials are found to be capable of alleviating overheating risk. These design options are applied in the house models and results are given.

Typical house models designed in this chapter represent a prospective design for future UK housing and are able to demonstrate the likely energy consumption and thermal comfort of future houses. A range of designs solutions has been investigated in the simple cell and the second model with a focus of applying the information learned from initial models to the typical houses. Therefore, in some cases, simulations which might not affect decision-making are not repeated.

11.1 UK housing stock

The UK has an old housing stock with almost 8.4 million homes out of 25 million built before 1945 (4.8 million built before 1919) and a fifth of homes (4.7 million) have been built since 1980 (DCLG, 2008). Semi-detached house, mid-terraced house, detached house and purpose built flat are the most common home types in England. Figure 117 demonstrates that semi-detached is the most common among the typologies.

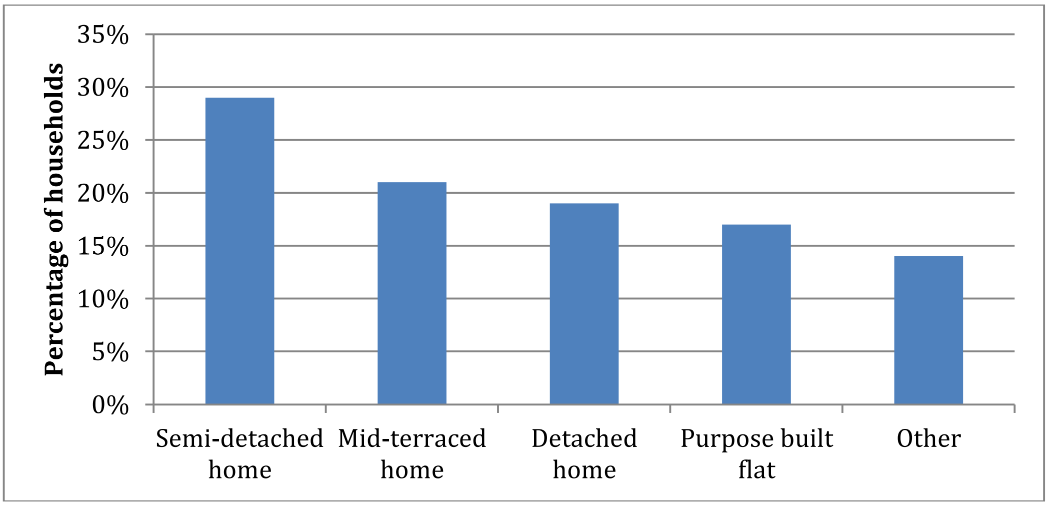


Figure 117 Most common UK housing types, Source: (Gupta & Gregg, 2012)

Furthermore, Figure 118 shows that since 1919, ‘masonry with cavity’ became the most common construction type in English housing with over a 60% share of total housing in

2008. Also, concrete tiles are the most common roof covering in English housing, as shown in Figure 119.

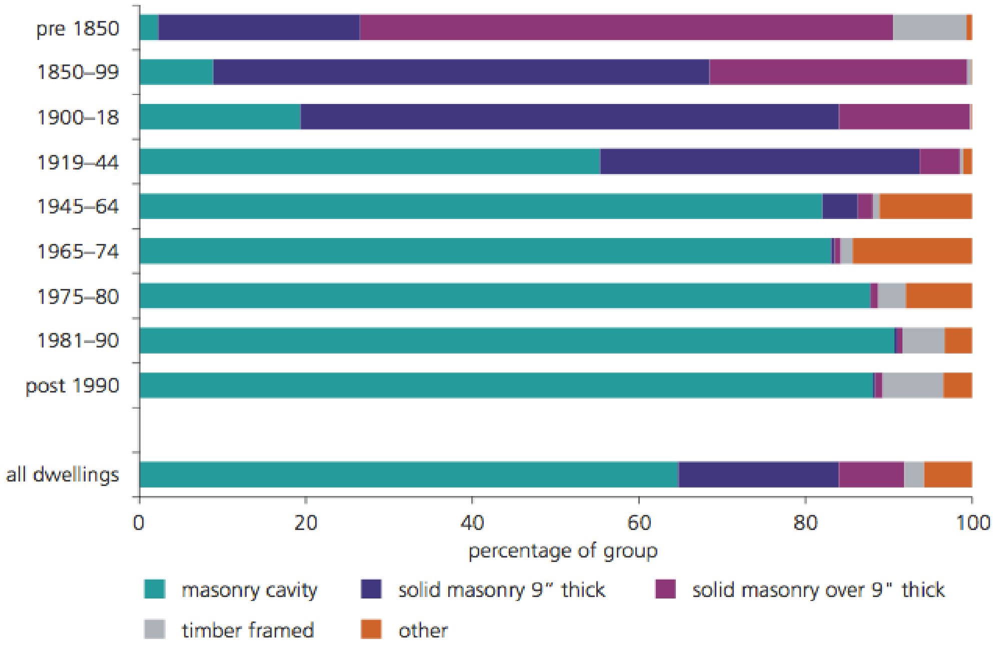


Figure 118 Construction type by dwelling age, Source: (DCLG, 2008)

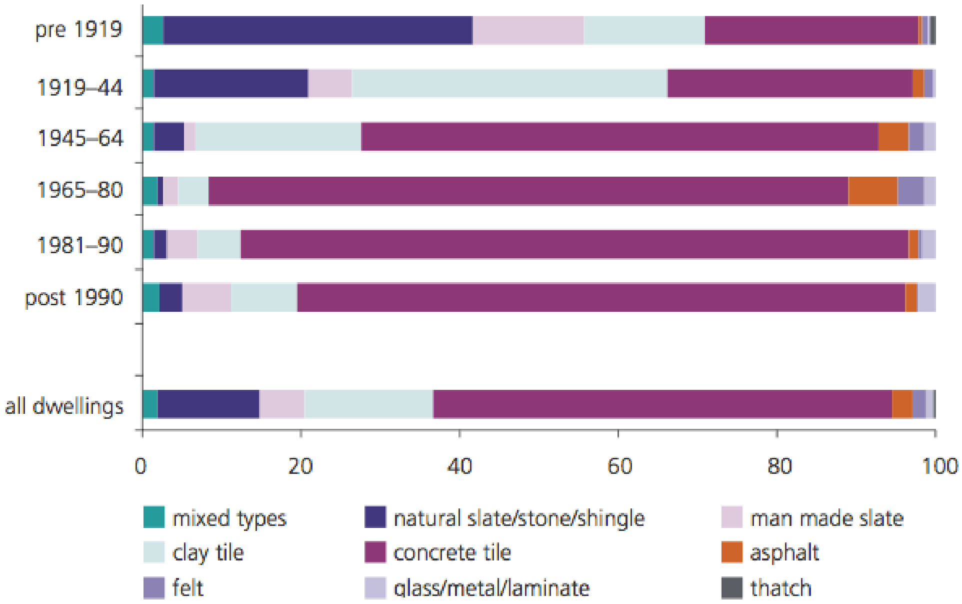


Figure 119 Main English roof type by dwelling age (DCLG, 2008).

It seems that whilst the UK government is committed to develop usage of modern methods of construction (MMC), the construction industry are slow to implement it as MMC has only a 3.6% share in new English buildings. However, according to a study by the Mtech Group with the support of Loughborough University, 64% of house builders believe more MMC utilization is needed in the housing industry, and 58% of those surveyed intend to use more of it in future (Pan, et al., 2005).

Hughes (2000) stated that English houses have become more adaptable and smaller because of population lifestyle change and demographic shifts. However, Figure 120 demonstrates that total usable floor area in a semi-detached house is generally more than 110 m^2, the other house types mostly have between 70 to 89 $m^2$and flats mostly have less than 50 m^2. Hughes also highlighted that more innovate construction methods can be found in social housing rather than in private housing.

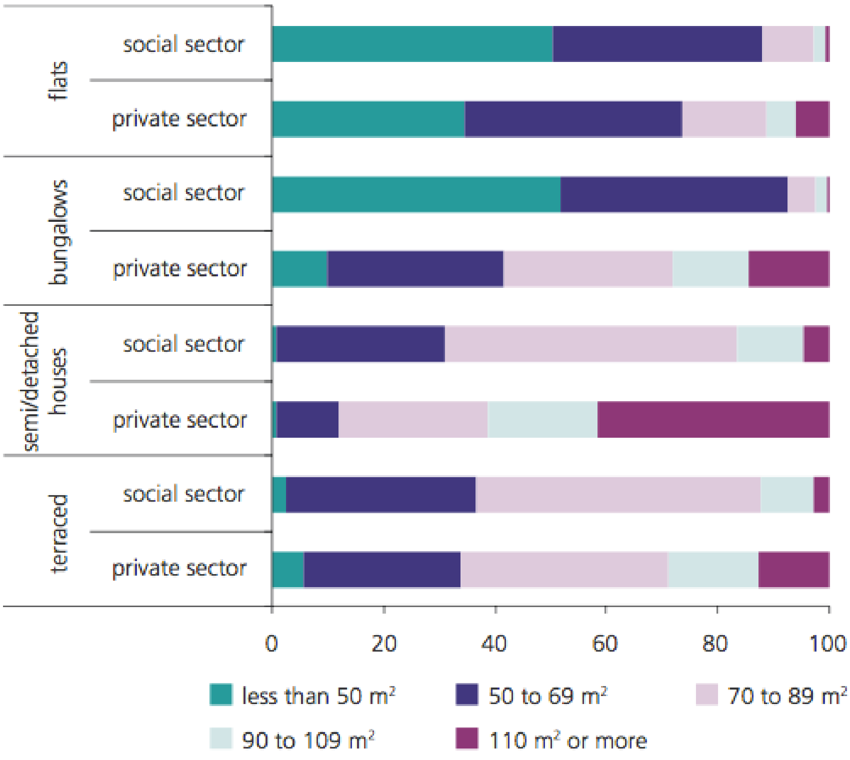


Figure 120 Total usable floor area by dwelling type and tenure

11.2 Prospective design of a semi-detached house

For the purpose of this study a semi-detached house has been designed by the author on the basis of a near-Passivhaus standard for simulation in DB. The model is a two-storey house with three bedrooms. A U-Value of 0.1 W/m^2K is considered for the exterior walls (as shown in Chapter 8), which is examined with the five studied construction systems. Roof and ground floor are also the same as described in Chapter 8. The infiltration rate is set as 0.6 ACH. Natural ventilation is considered in the simulations and windows are triple glazed type with argon filling in a UPVC frame type with a U-

Value of 0.8 W/m^2K. Figures 121 to 124 demonstrate plans, elevations and the 3D model of the house used for simulations.

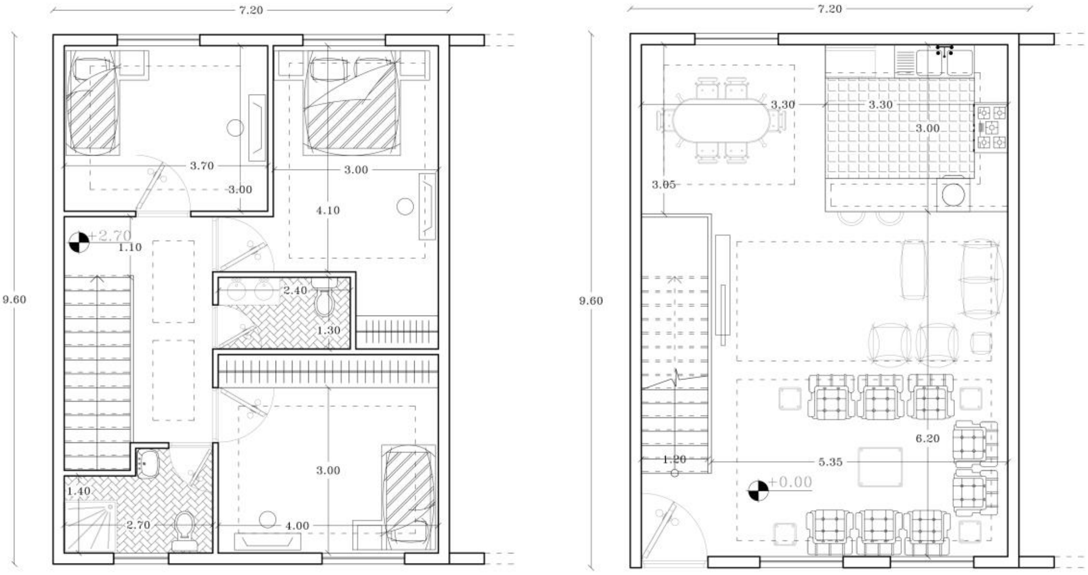


Figure 121 Ground and first floor plans

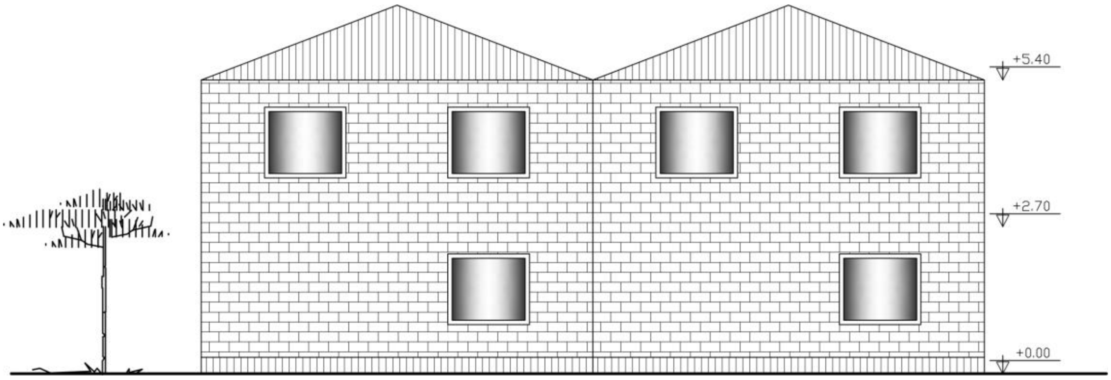


Figure 122 North elevation

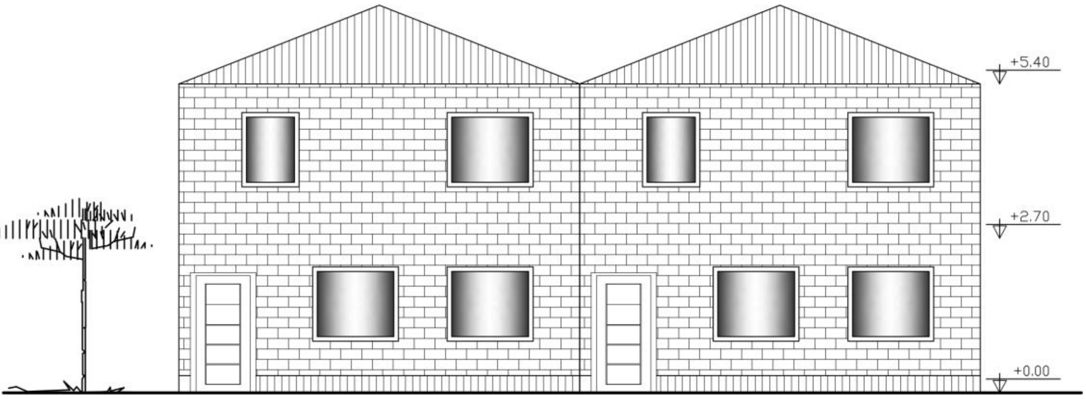


Figure 123 South elevation

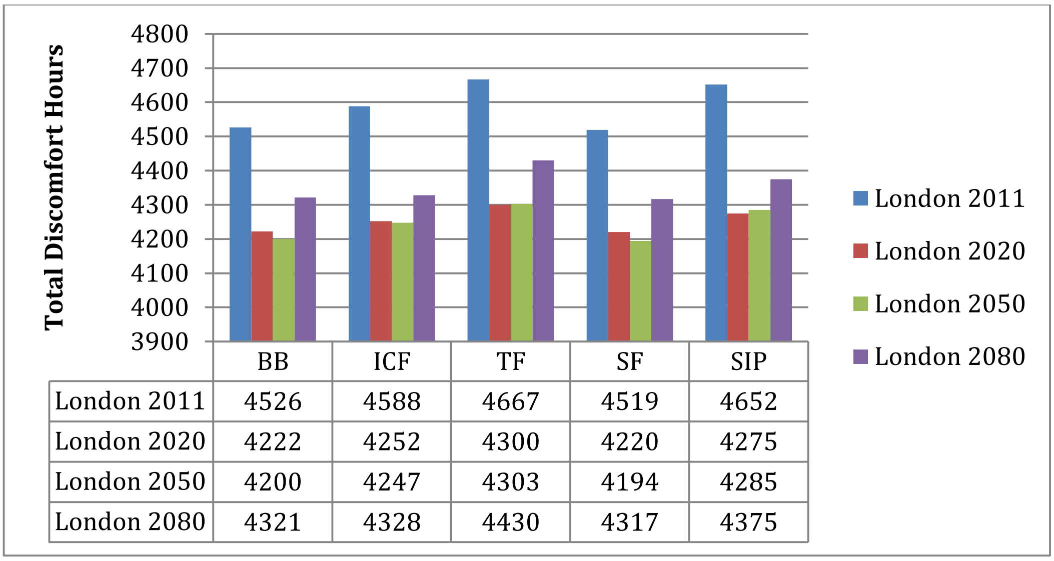
Figure 124 3D model used for simulations (south facing windows)

11.3 Performance results and discussion

11.3.1 Discomfort hours

Figure 125 shows the performance of the studied construction systems on the basis of thermal comfort in a semi-detached house in London with no heating and cooling loads. A minimum of 30 hours and a maximum of 148 hours advantage in overall discomfort hours for BB and SF is observed compared to the TF and SIP. Overall discomfort hours are more in 2011 compared to the other time periods (2020, 2050 and 2080).

Compared to the simple cell and the second model, it can be seen that the differences between construction systems are considerably greater although, qualitatively, similar relative results are achieved. BB with the highest level of thermal mass does not show the biggest advantage but does demonstrate a good level of performance for all times. The performance of SF as a light construction system is the best in all times with lower discomfort hours compared to the other systems. Once again, the result of simulations shows that a high level of thermal mass does not necessarily deliver maximum comfort hours in UK housing.



	BB	ICF	TF	SF	SIP
London 2011	4526	4588	4667	4519	4652
London 2020	4222	4252	4300	4220	4275
London 2050	4200	4247	4303	4194	4285
London 2080	4321	4328	4430	4317	4375

Figure 125 Total discomfort hours, semi-detached house, London

These results demonstrate that some of the claims about the considerable effect of thermal mass in future UK housing are exaggerated. Obviously, occupied buildings can benefit from thermal mass but it has been observed that this effect is limited in sustainable housing design. Besides, it also depends on the parameters chosen by designers.

Figure 126 demonstrates total discomfort hours in Manchester for all times, Similar to London, lower discomfort hours can be seen in future times and the behavior of construction systems seems to be almost the same qualitatively. It has to be mentioned that in this study occupants are assumed to be at home full-time and this, obviously, impacts on simulation results; any changes in occupants' behavior can considerably influence the results.

In the realistic model, simulation results show less discomfort hours in future times compared to the first two models. It was not possible for the used software to split the discomfort hours in overheating and overcooling categories and therefore further studies are required to investigate this when the potential becomes available in the software. However this could possibly be due to the fact that first two models are more exposed to solar gain (building envelope area) and would therefore experience considerably more overheating in future times. [8]

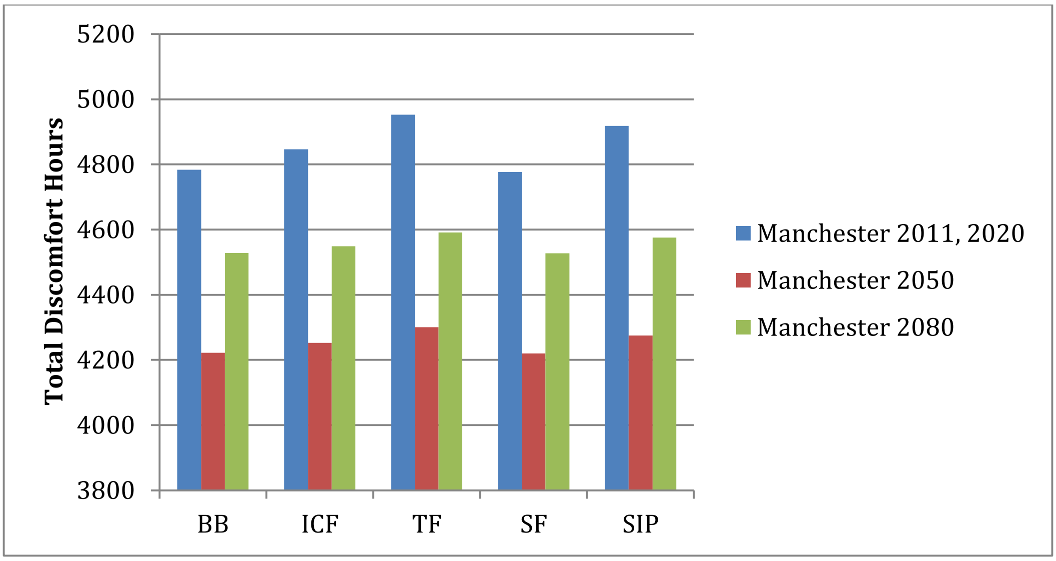


Figure 126 Total discomfort hours, semi detached house, Manchester

11.3.2 Energy consumption

Although the overall discomfort hours can show the behavior of each system, the one with the lowest discomfort hours does not necessarily reflect the lowest energy consumption to provide 100% comfort during the whole year. As mentioned in Chapter 8, the comfort hours considered in this study is on the basis of ASHRAE 55 standard. For example, above 28 °C falls within discomfort hours regardless of any other factors (humidity, etc.). This means that, for example, two construction systems which are delivering 29°C and 30°C inside the model are both considered as uncomfortable but obviously, the system which delivers the lower temperature consume less energy to provide comfort hours.

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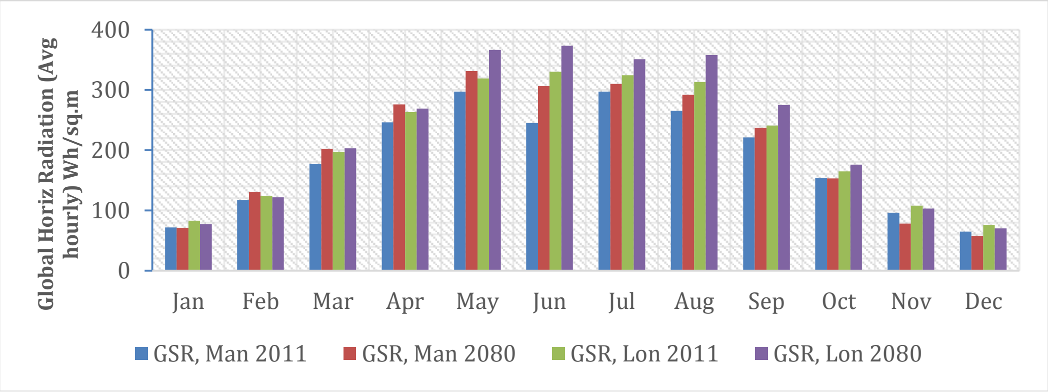
[8] Global solar radiation in Manchester (2011,2080) and London (2011,2080)



In the simple cell model, in almost all cases, the comparison of construction systems on the basis of thermal comfort and energy consumption shows similar results; but in houses, as they are the more sophisticated models, both comfort and energy consumption simulations are more varied - in some cases decision making might be considerably affected.

Figure 127 shows that BB with high thermal mass consumes the lowest energy compared to the other wall constructions in London in most of the times. SIP consumes the most energy and has the lowest performance compared to the others. Figure 127 also demonstrates that as temperatures increase in London, total energy consumption decreases. Figure 128 shows a similar situation in Manchester for all times. Heating loads are projected to decrease by 2080 in both cities, although an increase in cooling loads is inevitable due to the higher temperature in future.

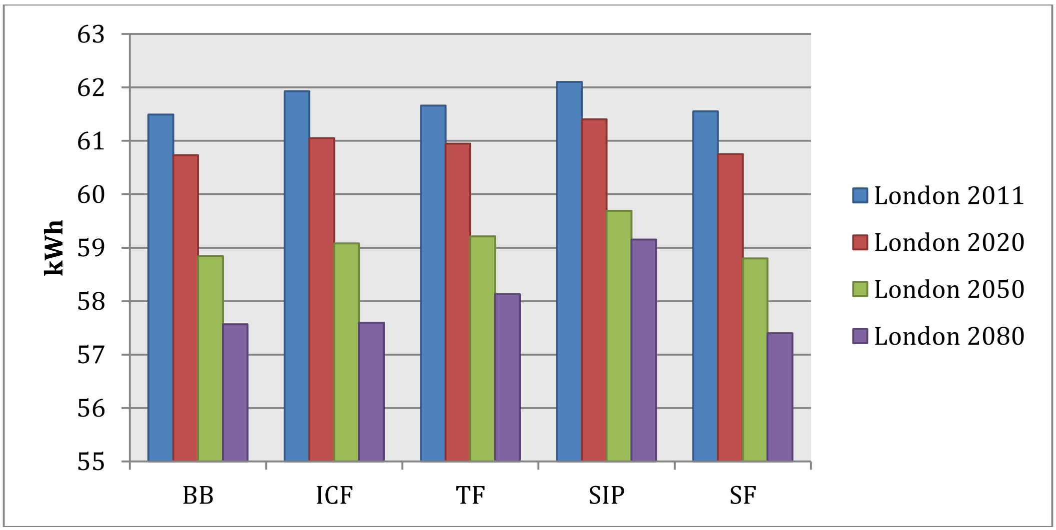


Figure 127 Energy consumption kWh/m^2 in London

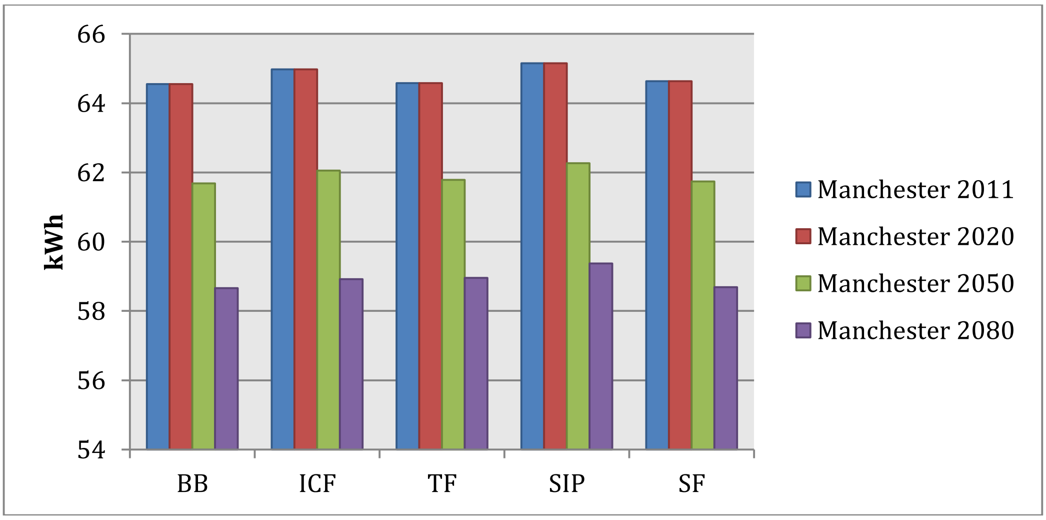


Figure 128 Energy consumption kWh/m^2 in Manchester

11.4 Prospective design of detached house

The detached house is another common type of UK dwelling and has been designed by the author on the basis of a near Passivhaus standards for simulations in DB. The model (Figure 129) is a two-storey house with three bedrooms. A U-Value of 0.1 W/m^{2}K is considered for exterior walls and examined for the five studied construction systems. The infiltration rate was set as 0.6 ACH. Natural ventilation has also been considered in these simulations. Windows were triple glazed with a U-Value of 0.8 W/m^{2}K. Roofs and ground floor were the same as in the semi-detached house.

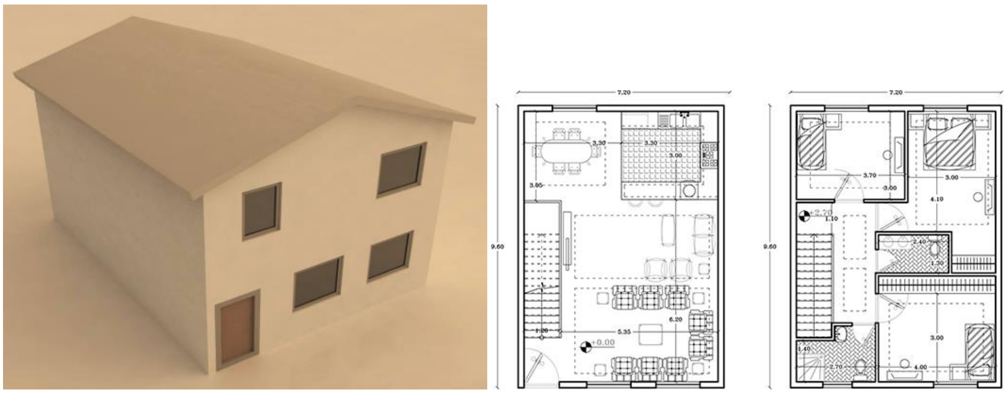


Figure 129 3D model used for simulations (south facing windows)

Figure 130 demonstrates the energy consumption (kWh/m^2) in the detached house when different construction systems were applied in all times in London. Compared to the semi-detached house, a slight increase in energy consumption and almost similar behaviour in construction systems was noted, although the SIP system showed a better performance compared to the other systems in the detached house (see Figure 131). The difference becomes even greater for future weather scenarios. Obviously, the reason for this is because one more side of the house is facing outside weather conditions, which would cause more heat loss during the cold period. This did not appear to cause a considerable advantage in hot period of the year to reduce overall energy consumption compared to the semi-detached house.

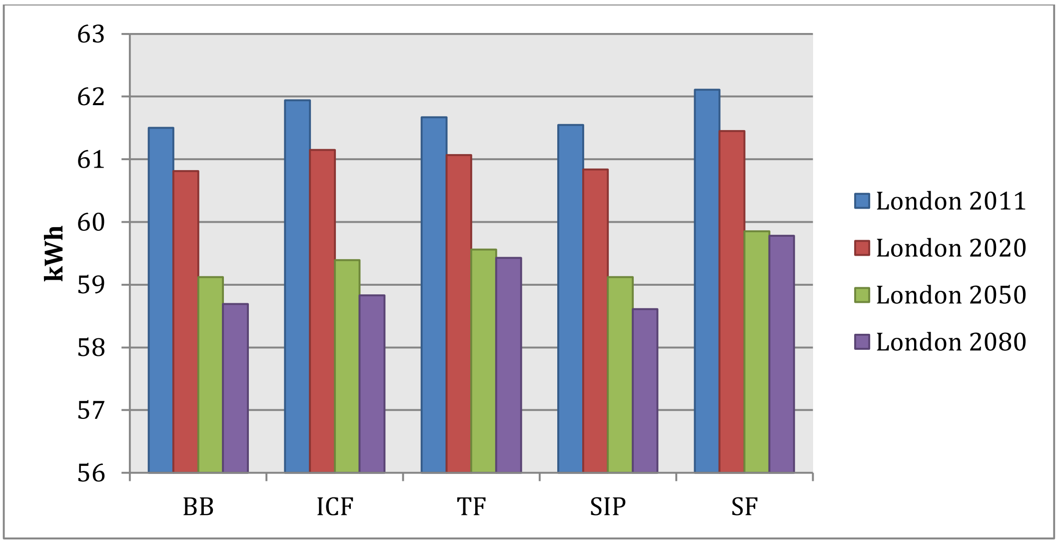


Figure 130 Energy consumption (kWh/m^2) in detached house with different construction system applied in London

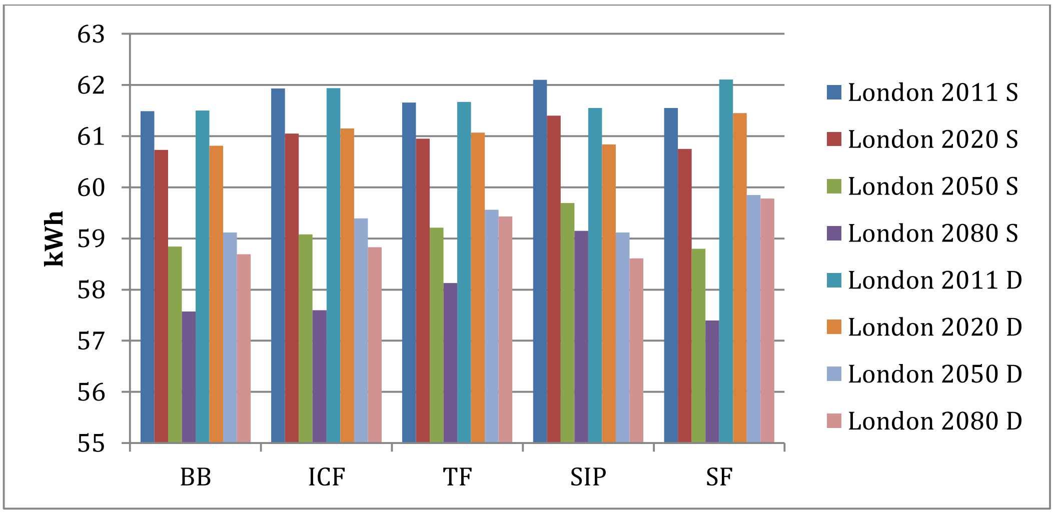


Figure 131 Comparison of energy consumption (kWh/m^2) in detached (D) and semi-detached (S) houses with different construction systems applied, London

Similar simulations for Manchester showed a minor increase in overall energy consumption and no difference in construction system behaviours compared to the detached house. Simulations on the basis of thermal comfort were also carried out and results did not show any difference of note compared to the semi-detached model.

11.5 Prospective design of new UK flats

For the purpose of the study, a four-storey block of flats has been designed by the author on the basis of near Passivhaus standards for simulations in DB, The flat on the second floor was used for the simulations. Each flat has three bedrooms with a similar floor area to the semi-detached house. A U-Value of 0.1 W/m^2K was again used for the exterior walls with the five studied construction systems. The infiltration rate was set as 0.6

ACH. Natural ventilation has also been considered in the simulations and windows are triple glazed type similar to the other models with a U-Value of 0.8 W/m^{2}K. Roofs and ground floor remain the same as for other simulations in this study. Figure 132 to 134 demonstrate plans, elevations and 3D model used for simulations.

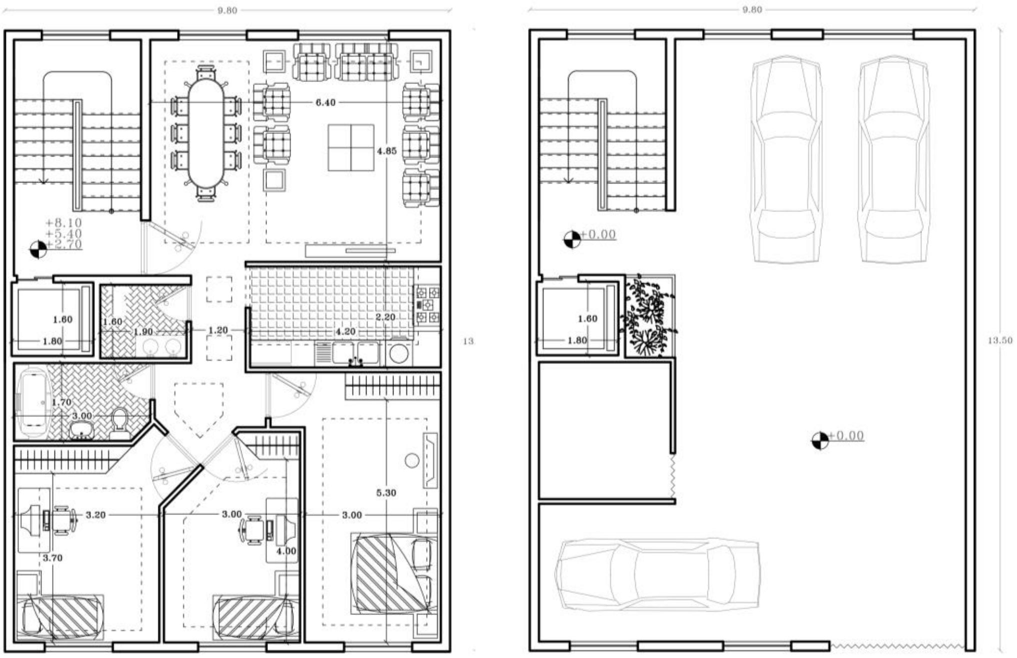


Figure 132 Ground floor & first floor

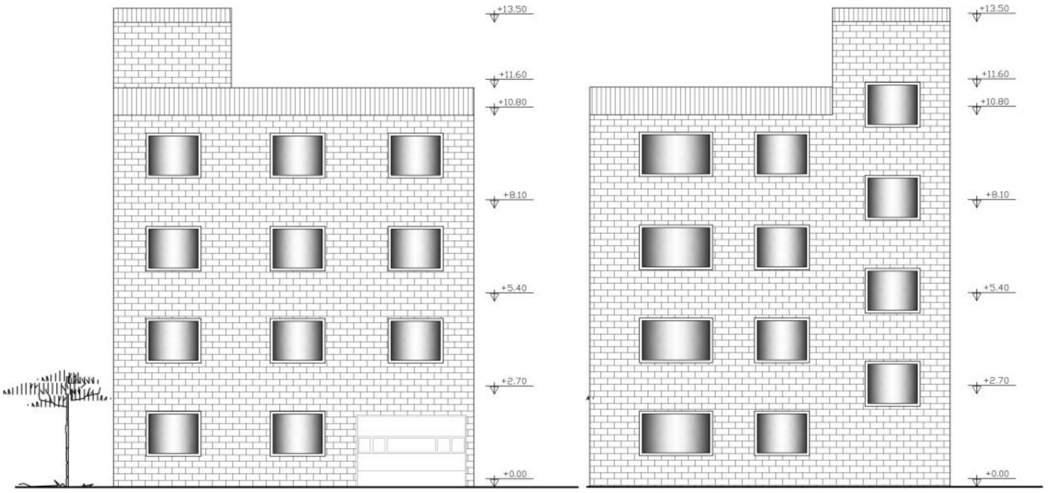


Figure 133 South & north elevation

Figure 134 3D model used for simulations (south facing windows)

11.5.1 Discomfort hours

As with the semi-detached house, a simulation was carried out on the basis of thermal comfort and the results are shown in Figure 135. It seems that in the flat model the behaviour of construction systems were very similar to the house models, with only minor differences. Similar to the semi-detached house, the SF system shows the lowest discomfort hours in the current time but does not remain the same in future weather conditions. BB and SIP show very similar performance from 2020 and with up to a maximum 115 hours advantage compared to ICF, TF and SF. However, similar to the semi-detached results, BB did not deliver the highest comfort hours in all times compared to the others. The performance of SIP were unexpected, with a considerable improvement for future weather condition data.

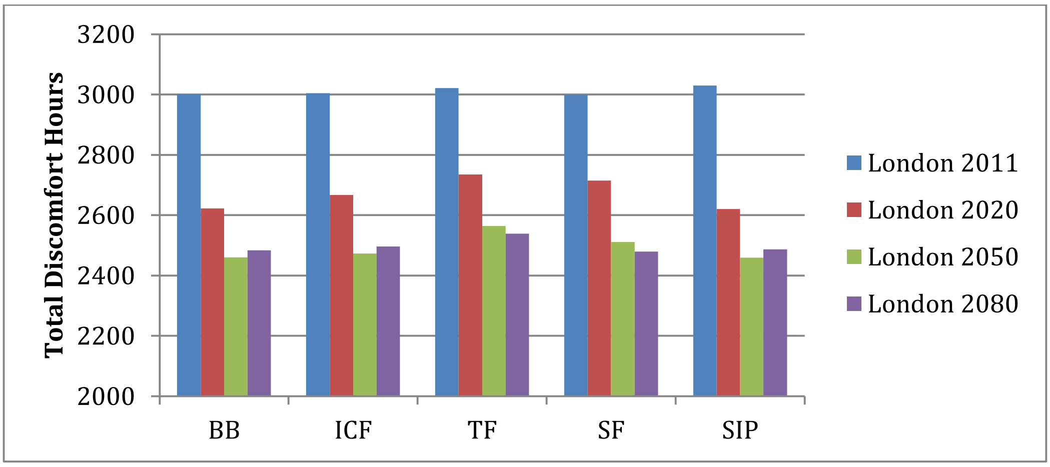


Figure 135 Total discomfort hours per block in London

Figure 136 shows Manchester results for current and future weather scenarios. TF, surprisingly, shows the lowest discomfort hours in current weather conditions and BB, with a high level of thermal mass, shows an advantage over the others in 2050. BB also has the lowest discomfort hours with SF in 2080. Overall, considerably more discomfort hours compared to London can be observed.

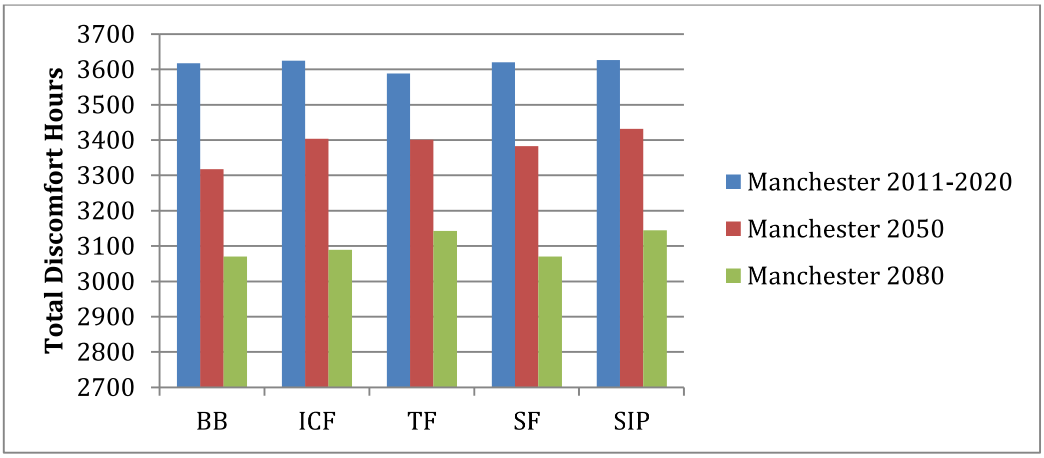


Figure 136 Total discomfort hours per block in Manchester

11.5.2 Energy Consumption

Similar to the semi-detached house, the result of simulations in Figures 137 and 138 show a minor advantage for BB, with the highest thermal mass, and a disadvantage for TF and SIP in most of the times in terms of energy consumption. It seems that the behaviour of construction systems do not change considerably as the temperature increases. A considerable decrease in total energy consumption can be seen by 2080 both in London and Manchester.

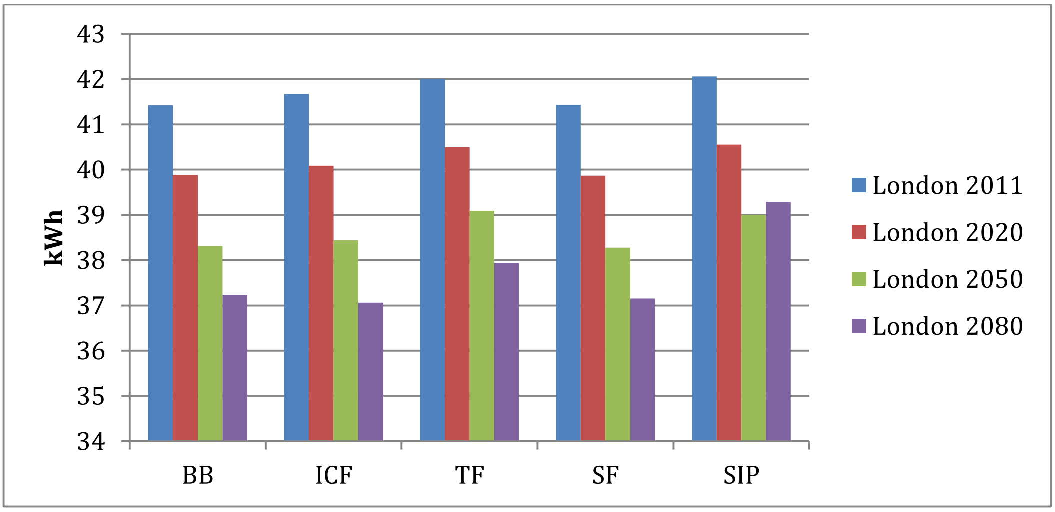


Figure 137 Energy consumption (kWh/m^2) in London for all timelines

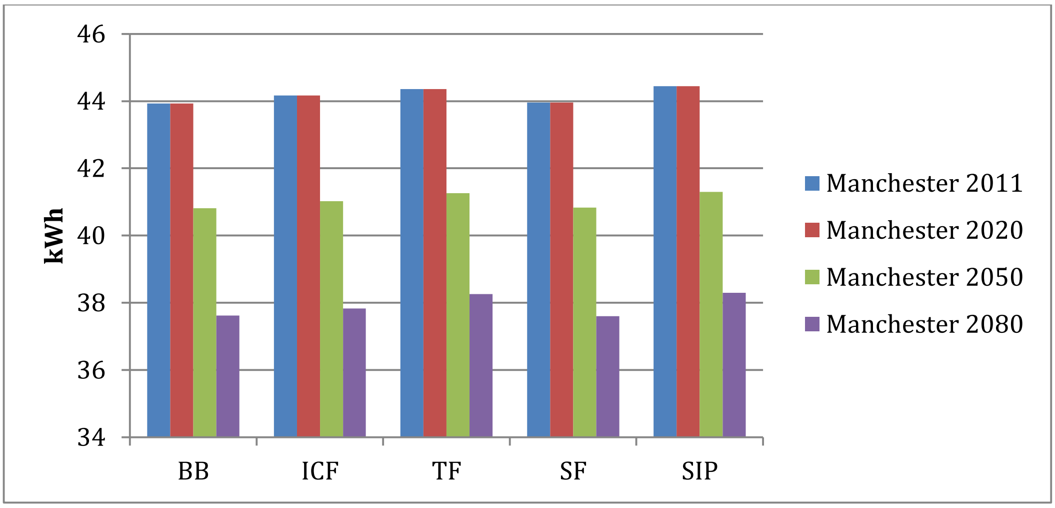


Figure 138 Energy consumption (kWh/m^2) in Manchester for all timelines

Housing typology is an important factor on deciding overall energy consumption. The results of simulations in the flat show considerable reductions in energy consumption compared to the semi-detached house with almost identical usable floor area. Furthermore, the behaviour of each construction system was almost similar to the house models.

The results of the simulations shows that the decision-making process can be affected considerably depending on assessment criteria. The assessment of each construction system on the basis of thermal comfort did not necessarily match with the assessment on the basis of energy consumption in the housing models. As there is a tendency for decision makers to decide on the basis of energy consumption, and also because splitting thermal comfort to overcooling and overheating conditions was not possible for the software used in this study, only energy consumption has been considered for the optimization process.

11.6 Development

As observed from the simple models in Chapter 8 to the more complicated house models in this Chapter, the risk of overcooling is alleviated by increasing future temperatures. On the other hand, the overheating risk is subject to significant increases. Therefore, the major optimization process aims to reduce overheating risk and reduce cooling loads in UK housing. As discussed in previous chapters, shading devices and PCMs are found to be capable of reducing cooling loads. This section shows how effective they could be in both cities and in current and future climates. As detached and semi-detached houses have similar floor plans and have been shown to have very similar energy consumption, only the detached house is selected for simulations in this section. Obviously, the chosen design strategy can have very similar result for the semi-detached house.

11.6.1 Shading device effects for a detached house

Studies in Chapter 9 demonstrated that a 0.5m overhang as a shading device can considerably improve thermal comfort hours in the first simple base model. Therefore, this type of SD was applied to the typical UK house model with SF and BB construction systems in the extreme case (London 2080). Figures 139 and 140 demonstrate the effectiveness of a 0.5m overhang in summer-time in London 2080 as it reduces the cooling loads considerably. However, it causes more energy consumption in the wintertime although, overall, this type of SD causes a reduction in total energy consumption (in SF system, overall energy consumption is 56.98-kWh/m^2 with SD compared to 57.40 kWh/m^2 without SDs in the BB system; overall energy consumption is 57.57 kWh/m^2 without SDs compared to 56.98-kWh/m^2 with SDs - both in London, 2080).

Similar to the first model, the overhang used for the detached house becomes more effective with a high thermal mass construction system (BB). It also shows more disadvantage in cold periods of the year with this system.

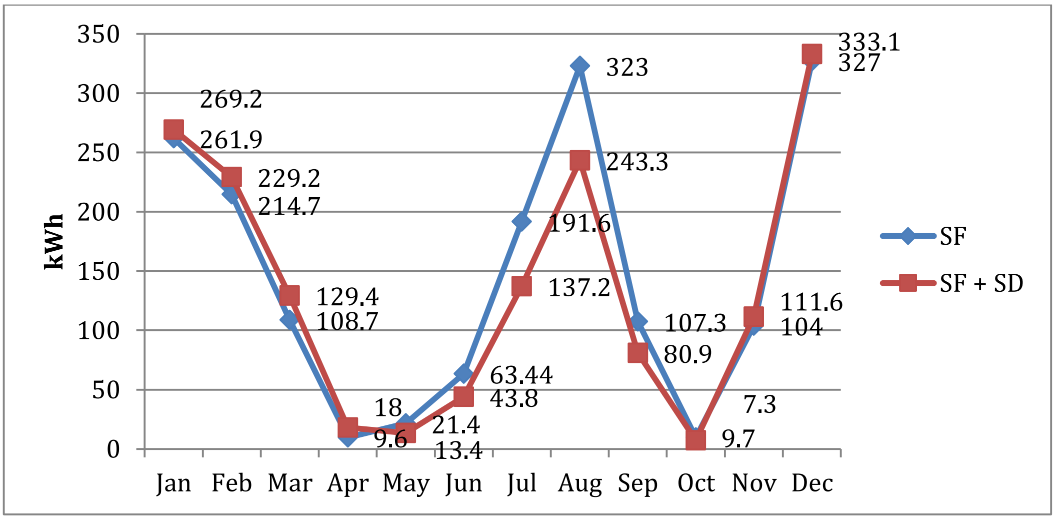


Figure 139 SD effect on energy consumption, SF construction system in detached house, London 2080

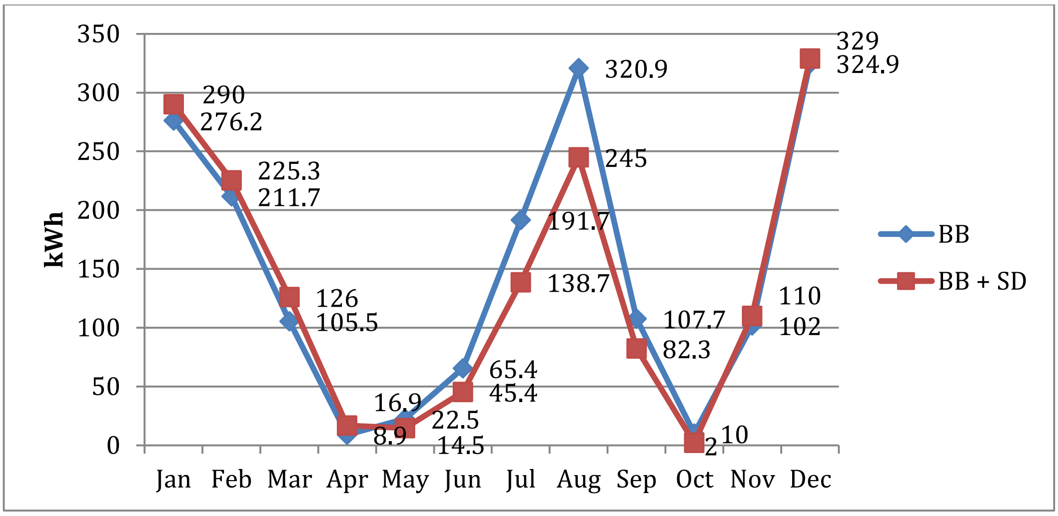


Figure 140 SD effect on energy consumption, BB construction system in detached house, London 2080

11.6.2 Flat with SD in the extreme scenario

As with the detached house, a 0.5m overhang was applied to the flat model and the effect is shown in Figures 141 and 142. It seems that the SD would considerably reduce overheating risk in the hottest case (London 2080). However, the effect of SD with low thermal mass system (SF) is lower than with high thermal mass (BB).

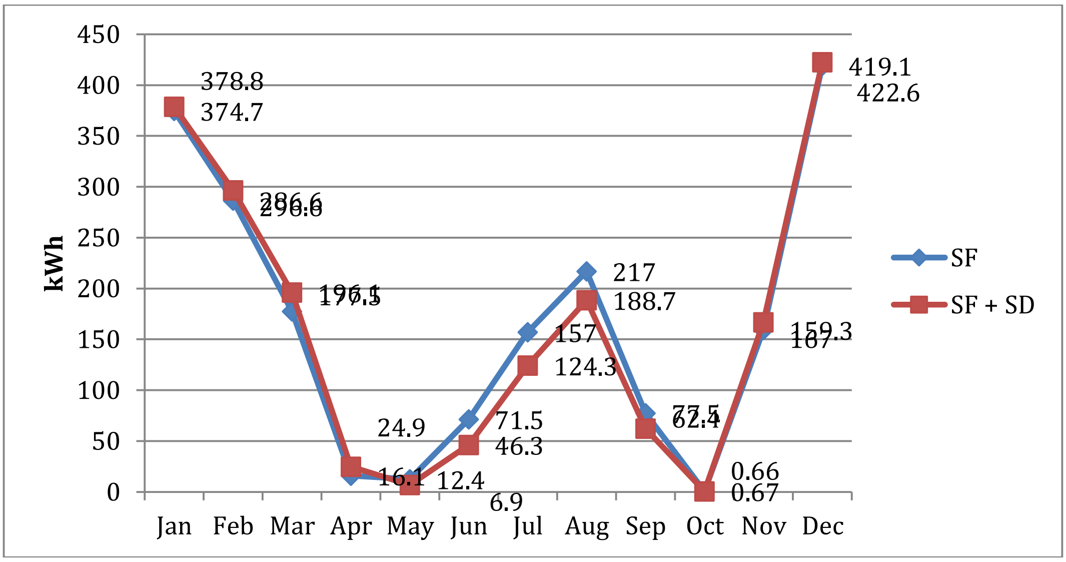


Figure 141 SD effect on energy consumption, SF construction system in flat, London 2080

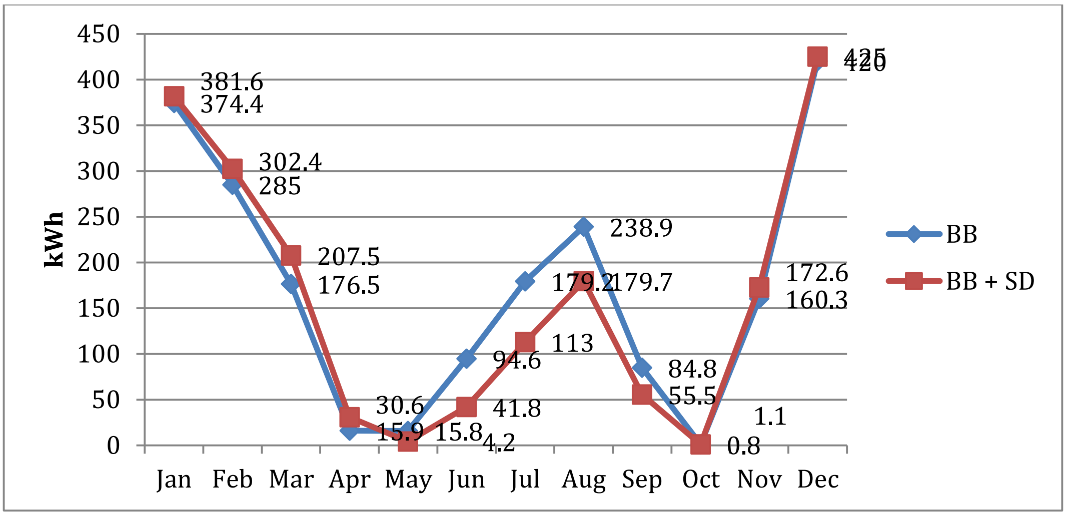


Figure 142 SD effect on energy consumption, BB construction system in flat, London 2080

11.6.3 Modeling use of PCM in construction

The rationale of integrating PCMs in buildings has been discussed in Chapter 10 and a literature review demonstrated its potential applications. However, the mechanism used for optimization in this chapter is inspired by ventilated facades, which essentially provide a ventilation gap for PCM wallboards. Ventilated façades are one of the newer solutions for reducing building energy consumption and offer the possibility of improving the energy efficiency of buildings. Figure 143 demonstrates the concept of a ventilated façade and some of its associated advantages.

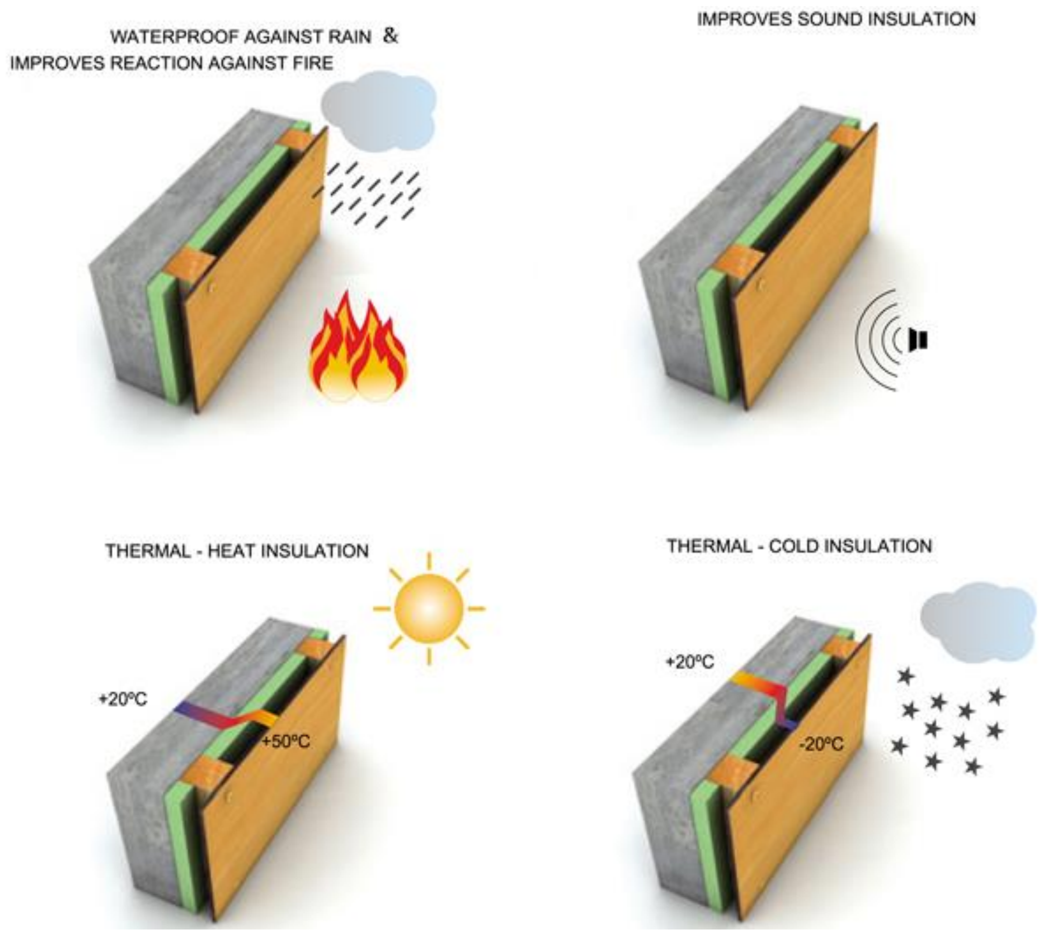


Figure 143 Ventilated façade benefits, Source: http://neweralivingdeco.com

Several authors have studied the thermal performances of ventilated facades (Patania, et al. 2010) (Seferis, et al. 2011). Based on their studies, the following results are acknowledged:

- Thermal insulation becomes more efficient when placed on the inner wall and in contact with the ventilated layer.

- The air gap provided in ventilated façade works as an extra insulation that causes lower heat losses, and the wider the air gap the better the performance.

- The higher the outdoor air temperature, the lower the performance.

Several authors developed the concept of ventilated facades by integrating PCM boards and claimed considerable advantages from using them (Diarce, et al., 2013). This concept has been used for simulations in the detached-house, as shown in Figure 144.

In order to determine the optimum air gap, PCM thickness and melting point, a range of PCMs with $23°C$, $25°C$ and $27°C$ melting points were examined in 12mm, 24mm, 36mm, 48mm and 60 mm thicknesses and with 15mm, 20mm, 25mm, 30mm and 35mm air gaps. Simulations in DB show a 25mm air gap as the optimum thickness (in terms of energy consumption in London for current weather), while the 48 mm thickness for PCM with a $25°C$ melting point seems to be the best [see Tables 17, 18 and 19]. Increasing the PCM content in the wall up to a certain level would increase the level of comfort due to their higher storage capacity (Borreguero, et al. 2011).

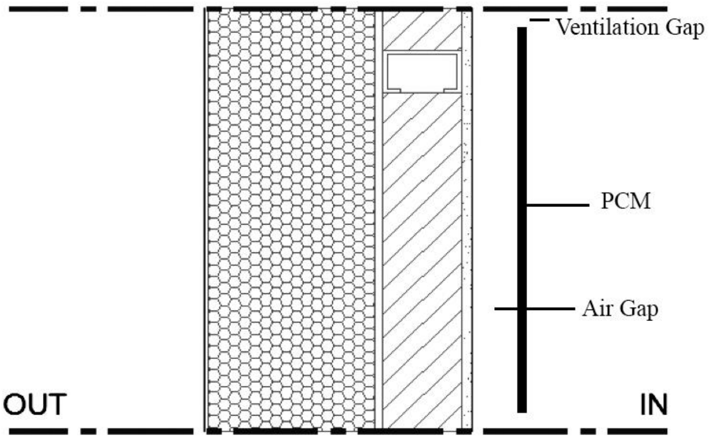


Figure 144 **PCM installation in building envelope**

Table 17 House energy consumption (kWh/m²) for PCM model with 23°C melting point

Air gap	PCM thickness 12mm	PCM thickness 24mm	PCM thickness 36mm	PCM thickness 48mm	PCM thickness 60mm
15mm	60.2	60	59.7	58.9	58.9
20mm	60.2	60	59.7	58.9	58.9
25mm	60.1	59.8	59	59	59.2
30mm	60.1	59.8	59	59	59.2
35mm	60.3	60	59.8	59.8	59.8

Table 18 House energy consumption (kWh/m²) for PCM model with 25°C melting point

Air gap	PCM thickness 12mm	PCM thickness 24mm	PCM thickness 36mm	PCM thickness 48mm	PCM thickness 60mm
15mm	59.2	59	58.7	57.9	57.9
20mm	59.2	59	58.7	57.9	57.9
25mm	59.1	58.9	58	57.2	57.2
30mm	59.1	58.9	58	57.2	57.2
35mm	59.2	59.1	58.5	58.3	58.3

Table 19 House energy consumption (kWh/m²) for PCM model with 27°C melting point

Air gap	PCM thickness 12mm	PCM thickness 24mm	PCM thickness 36mm	PCM thickness 48mm	PCM thickness 60mm
15mm	60.5	60.3	60.1	59.9	59.9
20mm	60.5	60.3	60.1	59.9	59.9
25mm	60.3	60	60	59.8	59.8
30mm	60.3	60	60	59.8	59.8
35mm	60.4	60.2	59.9	59.9	59.9

As shown in Tables 17 to 19, this study examined the novel use of PCM board in construction with the optimum air gap, PCM thickness and melting point. As demonstrated in the Tables, several cases are examined to determine the best efficiency. This novel integration is applied for the house models and the results are provided in the following sections.

11.6.4 PCM in detached house

Figures 145 to 151 show the effect of PCM in detached house in current and future weather in London and Manchester. The effect of PCMs in reducing cooling loads is considerable, but in terms of heating loads the impacts for the models used in this study were limited by the UK weather. Therefore, the potentials of PCM in reducing overheating risk are demonstrated for house models.

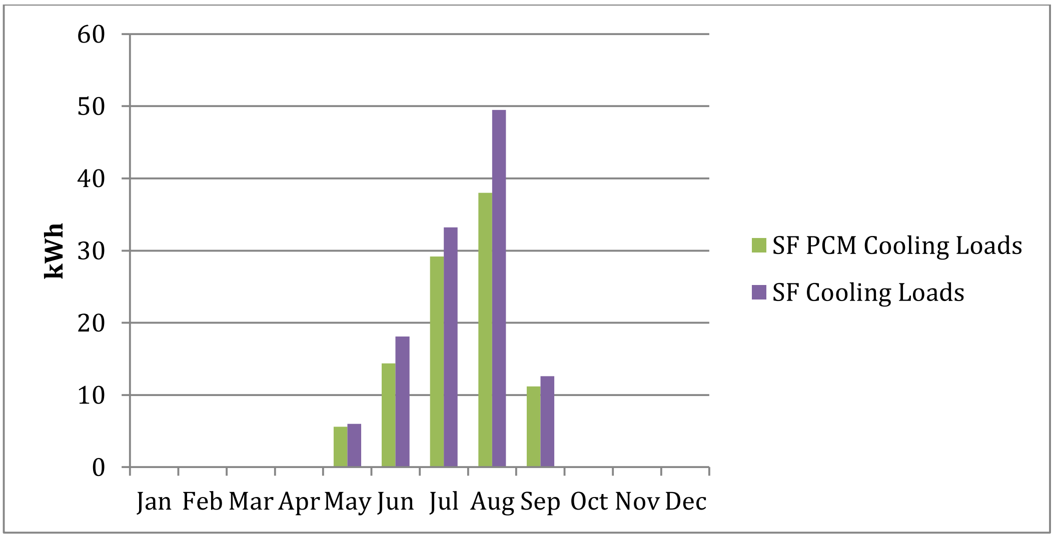


Figure 145 Cooling loads with and without PCM, London 2011

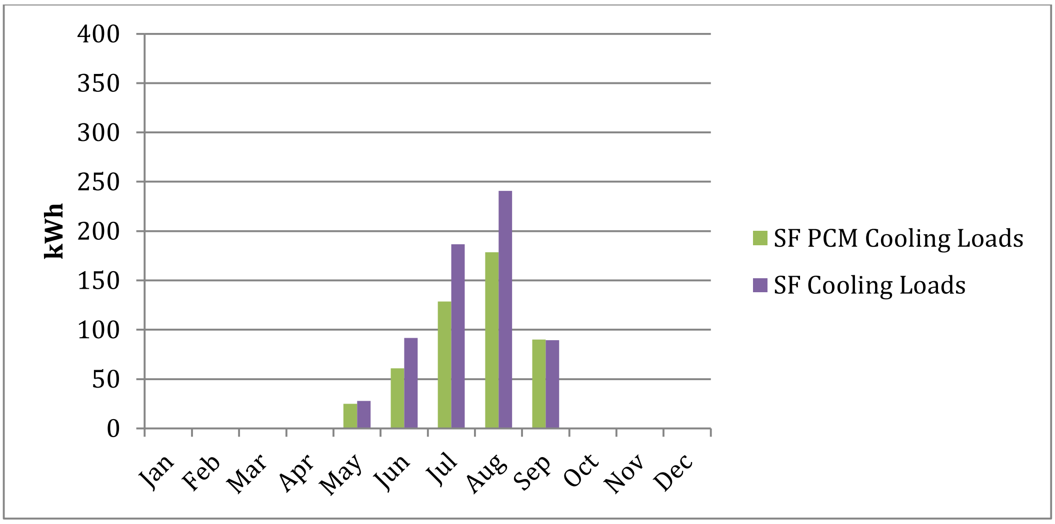


Figure 146 Cooling loads with and without PCM, London 2020

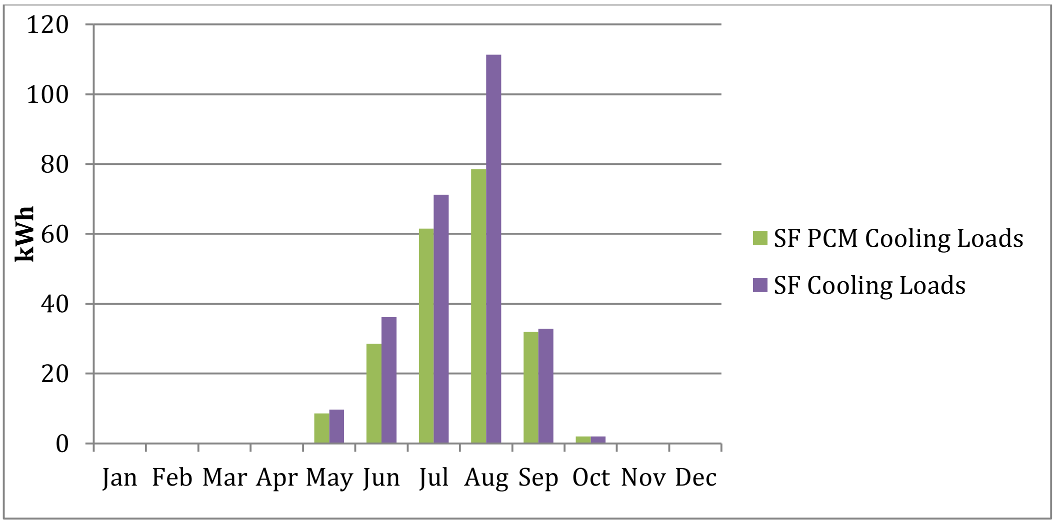


Figure 147 Cooling loads with and without PCM, London 2050

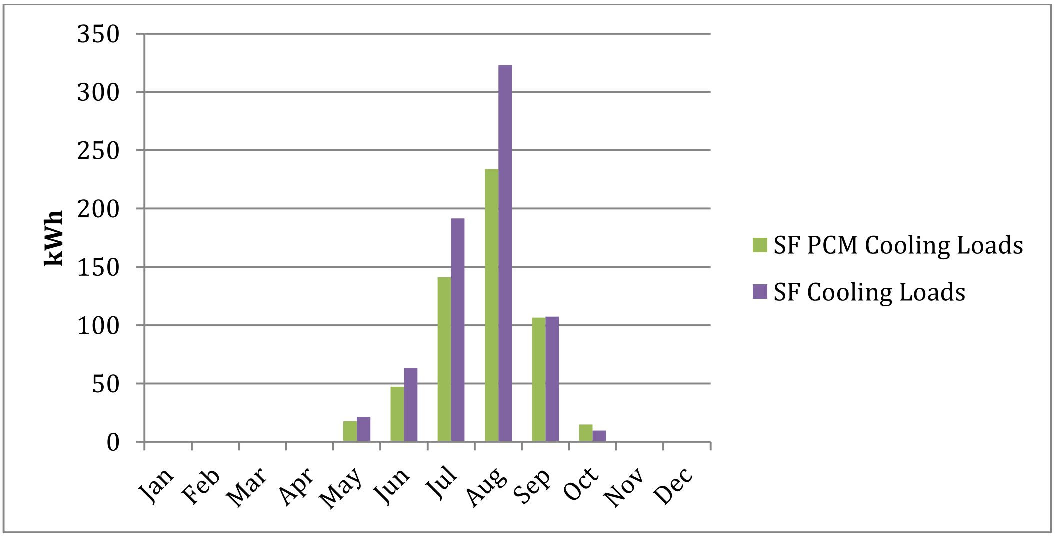


Figure 148 Cooling loads with and without PCM, London 2080

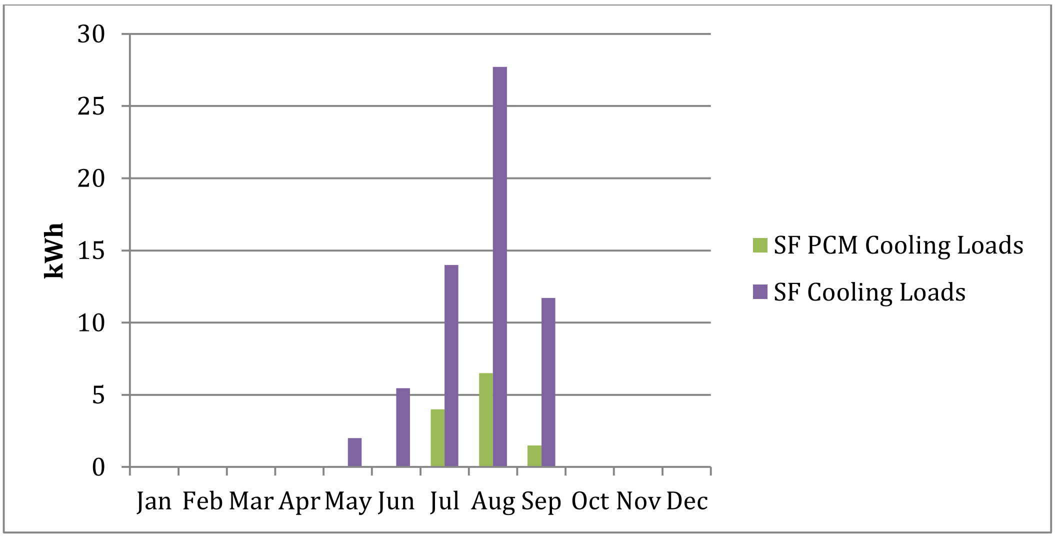


Figure 149 Cooling loads with and without PCM, Manchester 2011

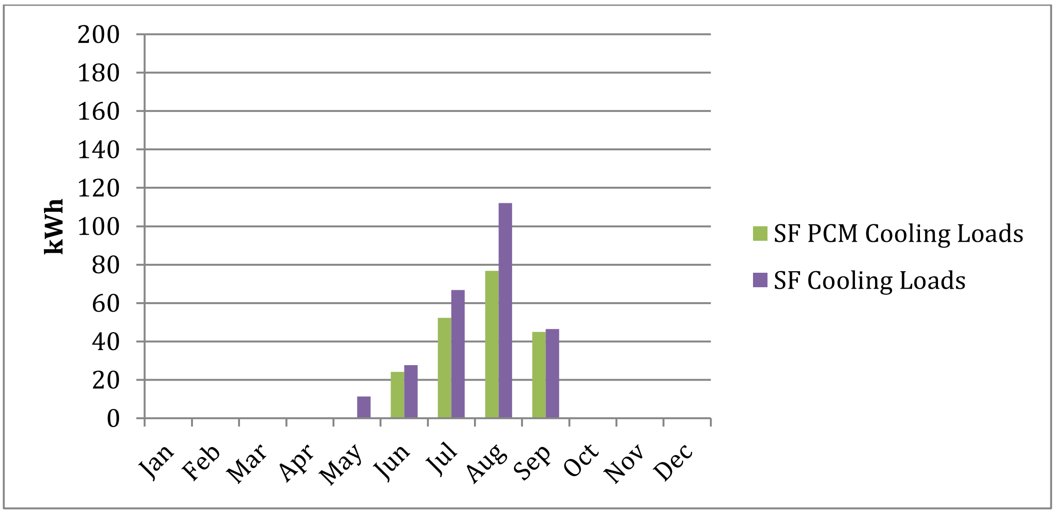


Figure 150 Cooling loads with and without PCM, Manchester 2050

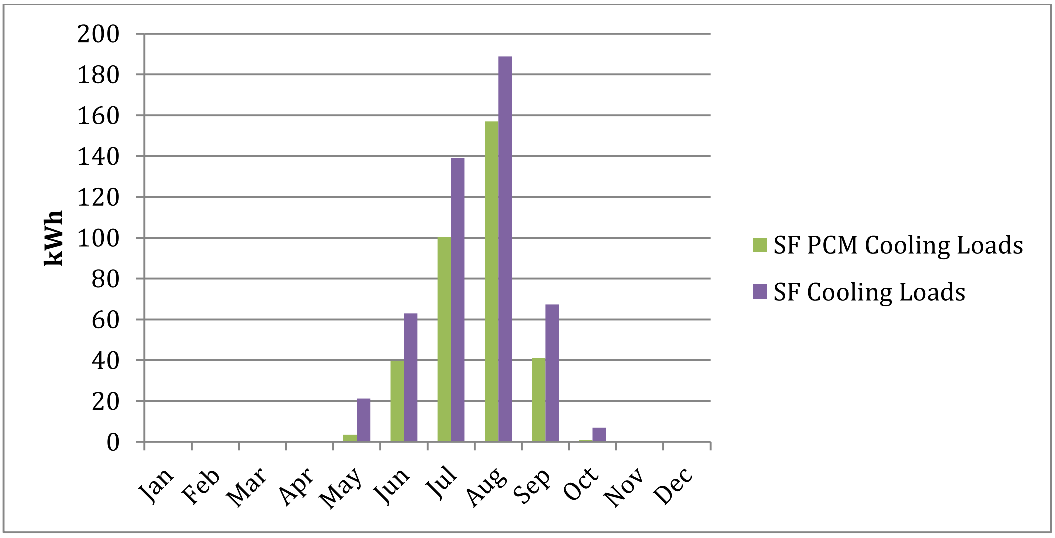


Figure 151 Cooling loads with and without PCM, Manchester 2080

As observed from the above Figures, PCMs can considerably reduce cooling loads in both cities. In extreme cases, like Manchester 2080, the overall energy consumption is 56.18-kWh/m^2 with PCM compared to 58.69 kWh/m^2 without PCM. In London 2080, the overall energy consumption is 57.20 kWh/m^2 with PCM compared to 59.9 kWh/m^2 without PCM.

In order to provide a picture of how PCM would impact inside the model and reduce energy consumption Figure 152 demonstrates average temperatures inside the detached house with PCM applied from the 1st to the 10th of August in London 2080, which is the hottest period of the year. PCM reduces temperature effectively and removes the overheating risk for most of this period.

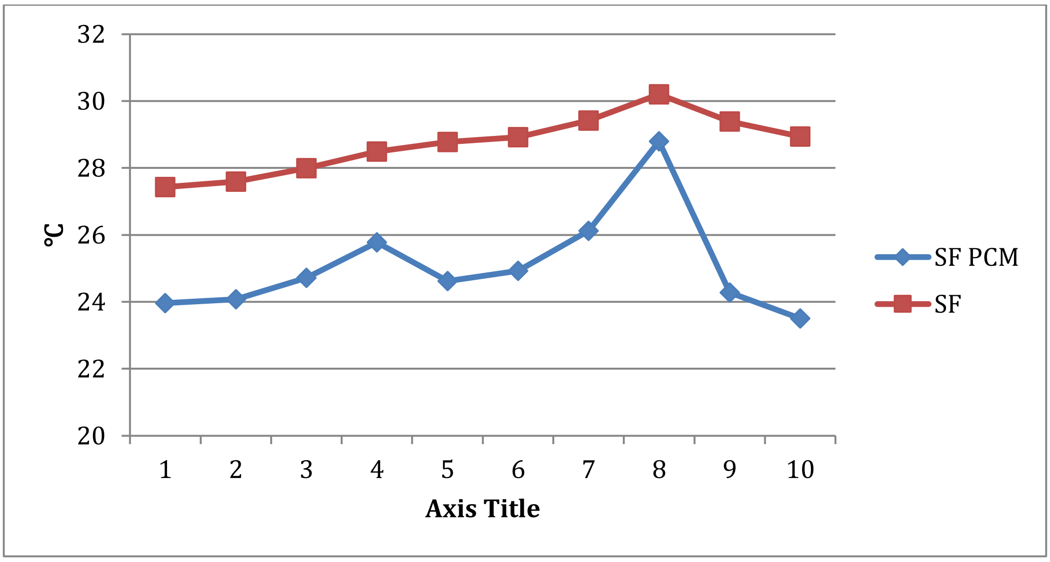


Figure 152 The comparison of average temperatures inside detached house with and without PCM from 1-10 August in London, 2080

11.6.5 PCM in Flat

Figures 153 to 159 show the effect of PCM in the flat model for current and future weather in both London and Manchester. The effect of PCMs in reducing cooling loads is considerable and, as with the detached house, it causes a significant reduction in cooling loads for both cities. The maximum savings would be in August and in some cases PCM almost completely removes the need for cooling loads, mainly in present times.

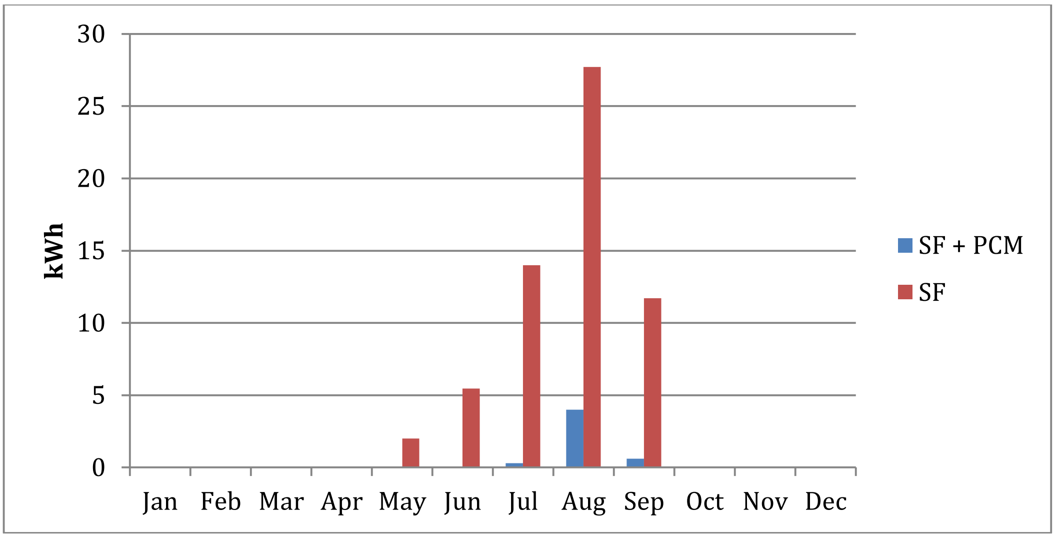


Figure 153 Cooling loads with and without PCM, London, 2011

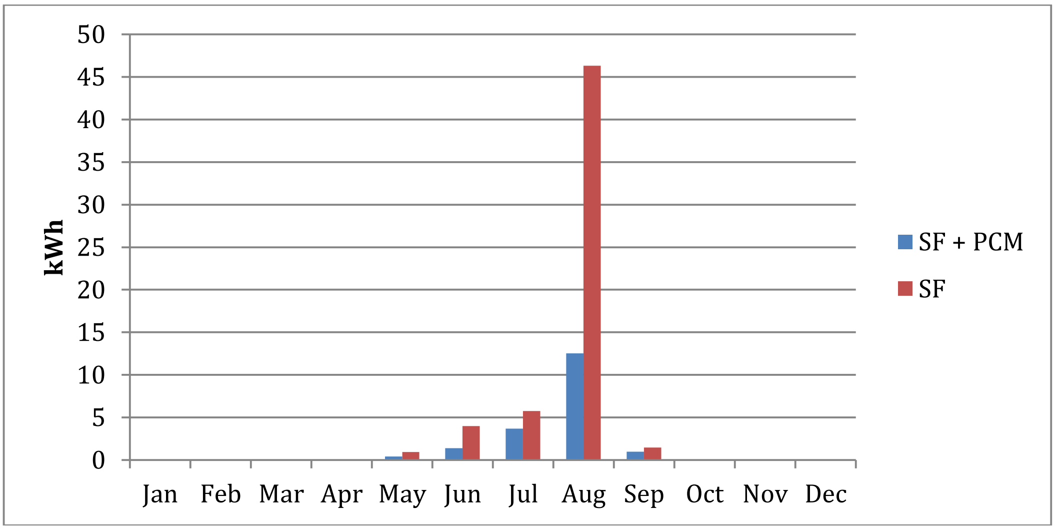


Figure 154 Cooling loads with and without PCM, London, 2020

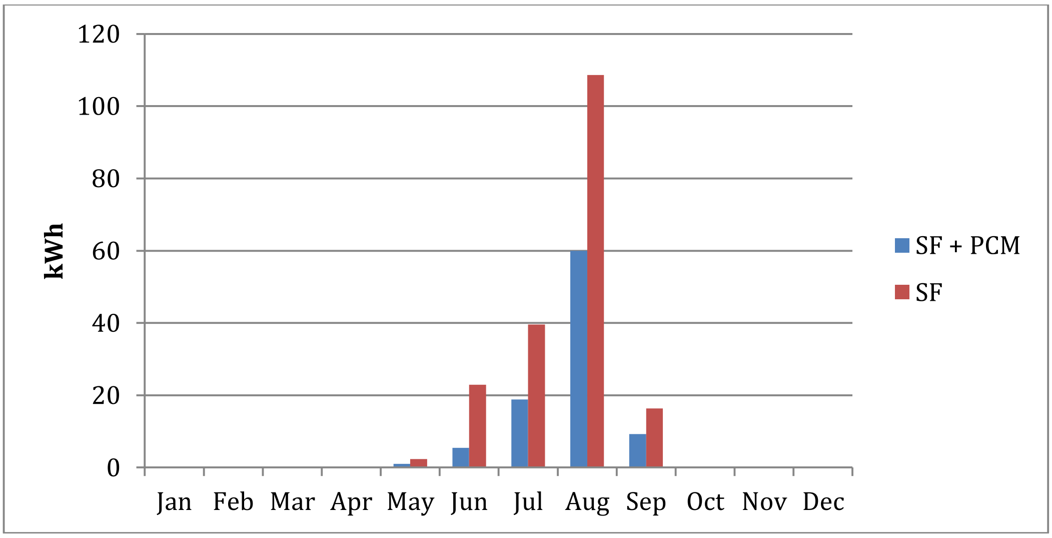


Figure 155 Cooling loads with and without PCM, London, 2050

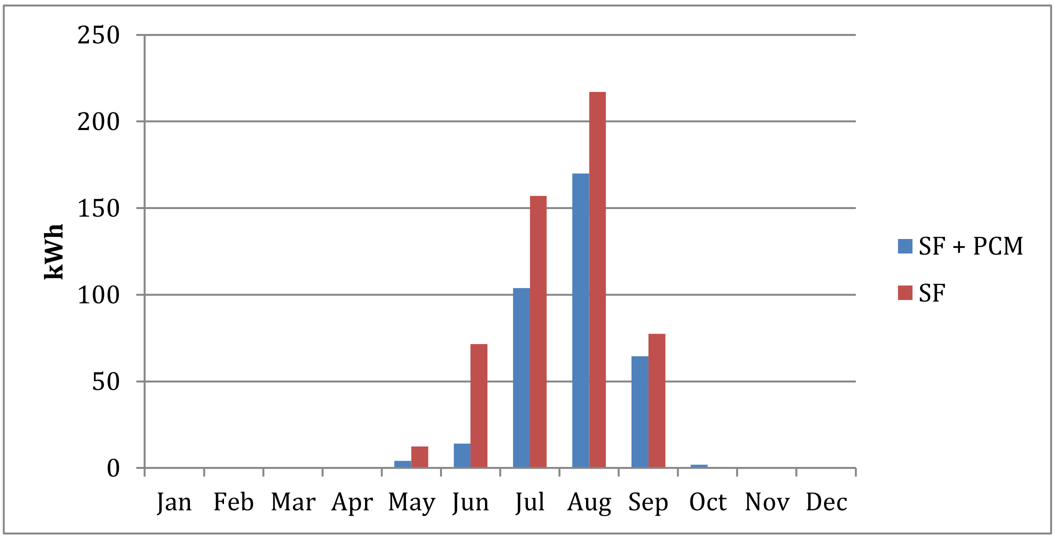


Figure 156 Cooling loads with and without PCM, London, 2080

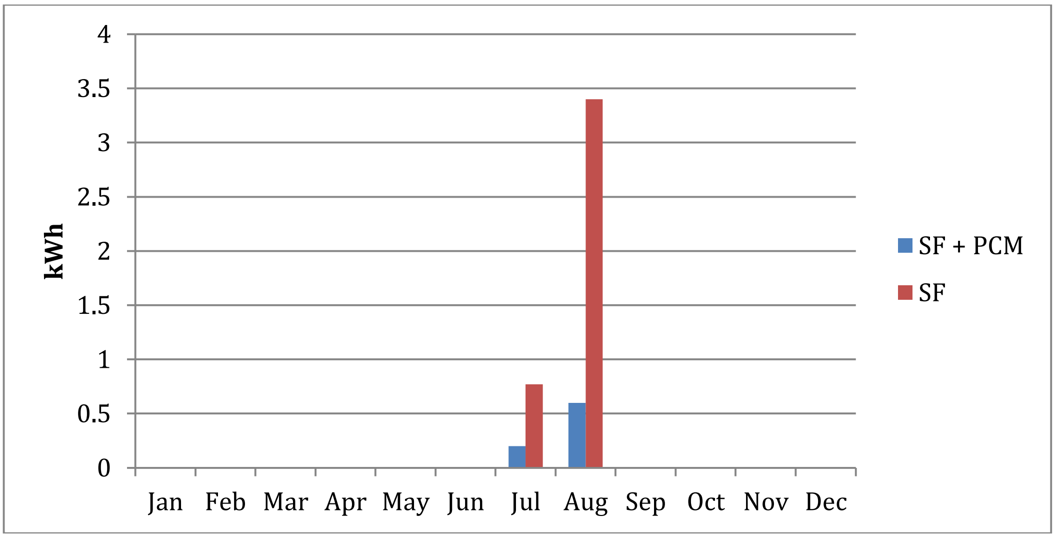


Figure 157 Cooling loads with and without PCM, Manchester, 2011

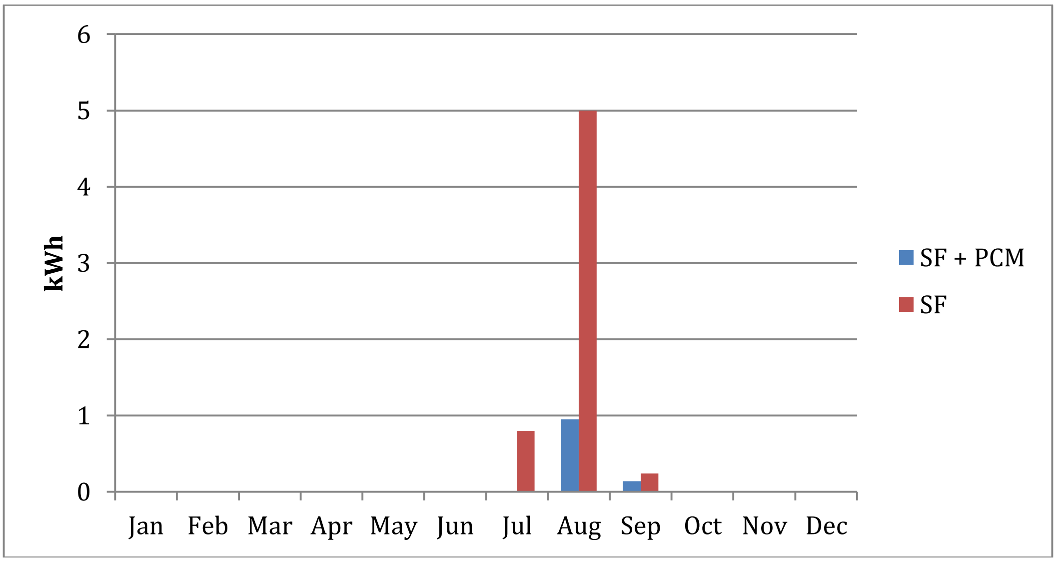


Figure 158 Cooling loads with and without PCM, Manchester, 2050

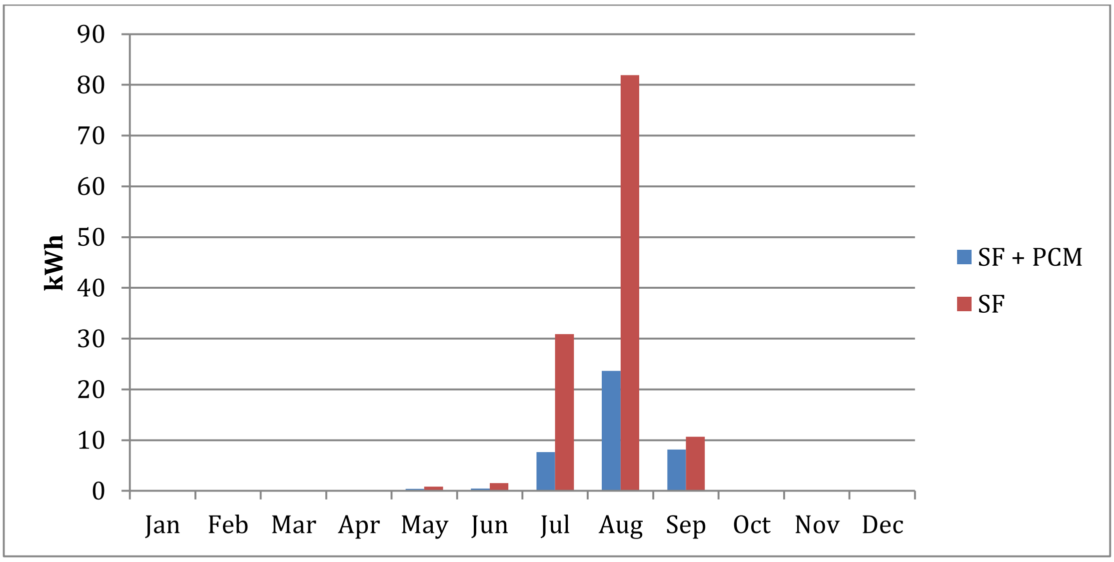


Figure 159 Cooling loads with and without PCM, Manchester, 2080

In order to provide a picture of how PCM would impact inside the flat model and reduce energy consumption, Figure 160 demonstrates average temperatures inside the flat with PCM applied from 1-10 of August in London 2080, which is the hottest period of the year. PCM effectively reduces temperatures and removes the overheating risk in most of this period.

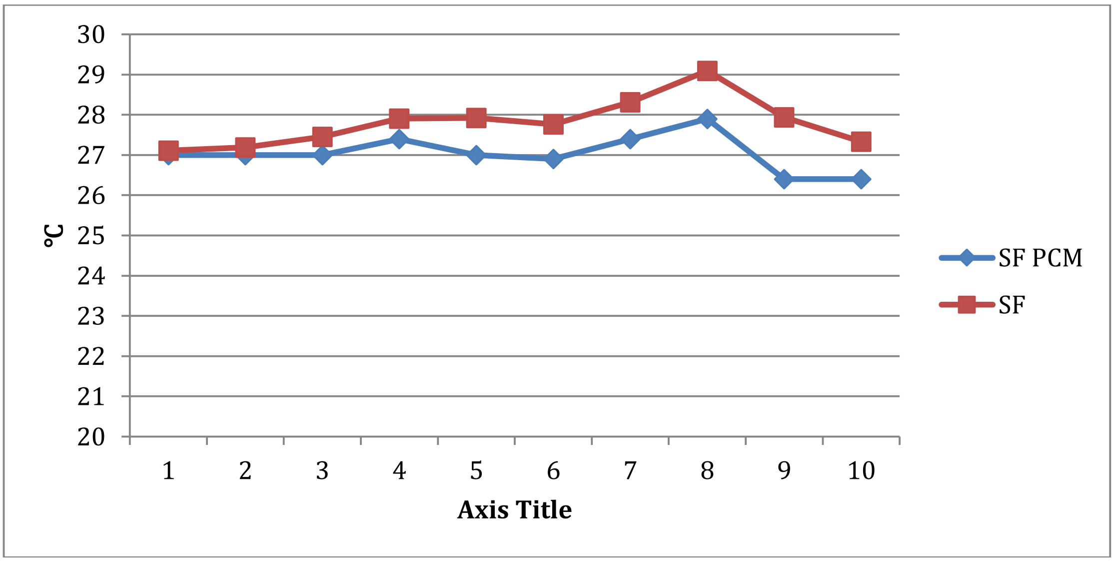


Figure 160 Comparison of average temperature inside flat with and without PCM from 1-10 August in London 2080

The comparison of average temperatures inside the models shows that PCMs would cause more temperature reduction in the detached house than in the flat. However, PCMs caused inside temperatures to remain just below 28°C for most of the time which is highly likely to be in thermal comfort range. This would effectively reduce overheating risk and energy consumption.

11.6.6 SD + PCM

The combination of SD and PCM can result in the lowest energy consumption in the summer months in both the flat and the detached house. In the worst-case scenario, the combination of a 0.5m overhang SD and PCM can reduce energy demand by up to 151.6 kWh in the detached house in the hottest month (August), as shown in Figure 161. It is also more effective compared to SD and PCM alone in June, July and September.

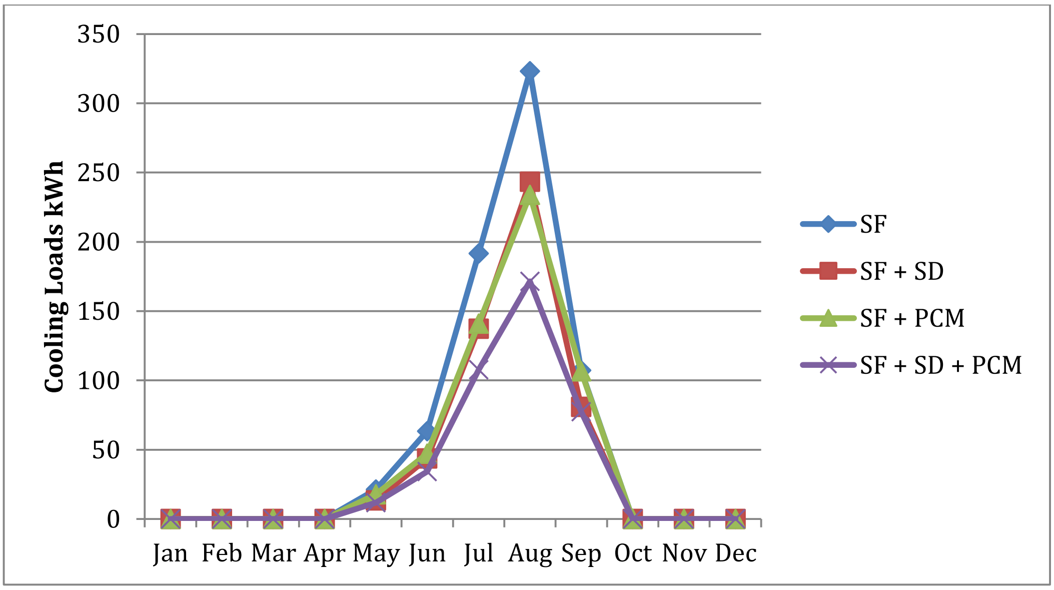


Figure 161 Comparison of SD, PCM and SD + PCM effect in detached house

Although Figure 161 demonstrates the potential of the suggested design solutions to reduce cooling loads in order to address the aim of this study, but it has to be mentioned that the usage of SDs could also increase required heating loads in winter time as discussed in Chapter 9 (Figure 114). Furthermore, the comparison of the studied SDs in Chapter 9 also showed that 0.5 overhang could cause minimum discomfort hours compared to the other SDs in future winter times.

In the flat, the combination of SD and PCM can cause a cooling load reduction of up to 97.7 kWh in the hottest month and, as in the detached house, it is also more effective compared to PCM and SD alone in the other months, as shown in Figure 162.

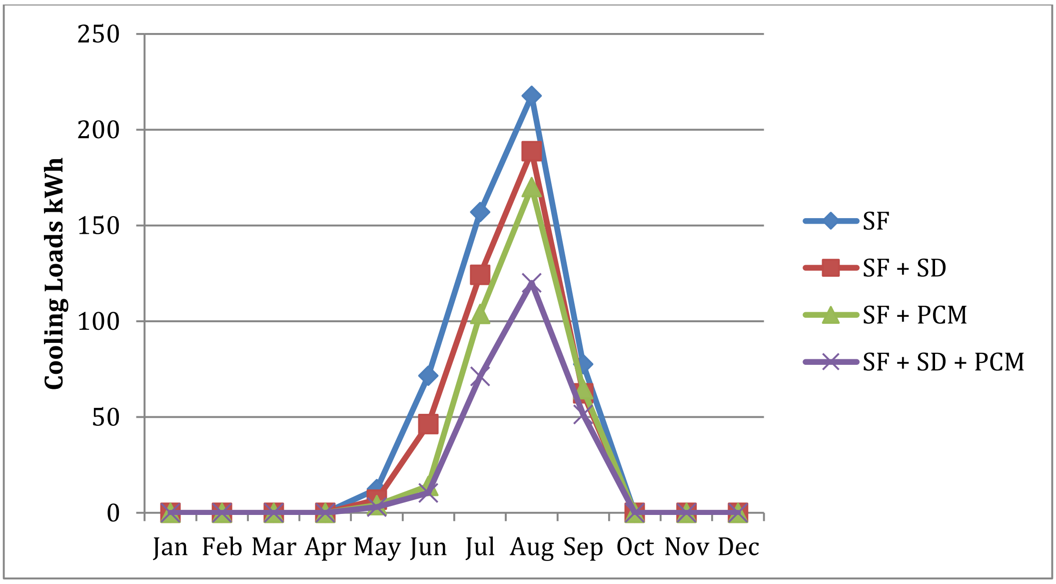


Figure 162 Comparison of SD, PCM and SD + PCM effect in the flat for SF construction

In general, the need for energy reduction in new buildings has become critically important due to climate change. To address this problem, new buildings must be designed to control indoor temperatures in order to reduce energy consumption. PCM and SD are both found to be good elements in alleviating the overheating risk problem when applied as a building material. They can improve the thermal performances of building fabrics and moderate the indoor temperature in hot periods of the year.

This study focused on the effect of PCMs as one of the available thermal energy storage technology and SDs as a traditional option to alleviate overheating risks in UK housing. This chapter presents their effect on energy consumption, with the main focus being on the climate change effect in London and Manchester. A mechanism in integrating PCMs with ventilated air gap into the building envelope has been proposed. The system can be used in new buildings and refurbishing processes.

The air gap provided has the advantage of providing air circulation for PCM boards in addition to acting as an extra insulation for the building. The effect of PCMs in London and Manchester weather becomes greater as the temperature increases to 2080 levels. Most cooling loads savings would be in the month of August and from 2020 onwards.

11.7 Summary

- The semi-detached house is the most common UK housing typology, with normally over 110 m^2 floor area and a masonry cavity wall as the construction system. Flats and detached houses are also among the most common UK housing typologies.
- Three prospective new UK houses have been designed and their possible energy consumptions simulated. Results show that in most cases high thermal mass construction systems deliver only minor advantages compared to others in terms of energy consumption.
- A comparison of construction systems on the basis of thermal comfort and energy consumption did not necessarily show similar results as they did in the simple cell and the second model.
- Although high thermal mass construction system demonstrates some advantages, their effect in UK housing has been exaggerated. ICF with medium thermal mass performance does not have any advantage over the systems..
- The flat model consumed considerably lower energy compared to the detached and semi detached house, but the examined construction systems showed almost similar behaviours in all models.
- The effect of SDs with high thermal mass construction system is higher in both the detached house and the flat. The 70.7 kW cooling load reduction is the maximum potential of SDs in the extreme case (London 2080) and could be lower in other cases.
- Providing an air gap optimises the effect of PCM. Simulations in DB showed a 25mm air gap as an optimum thickness while the 48 mm thickness for PCM with $25°C$ melting point seems to be optimum.
- PCMs can reduce operative temperature by over 5℃ in detached houses and by up to 2℃ in flats in extreme cases (August, London 2080) and can eliminate cooling loads in the months of May and June in all times in Manchester for the flat model. They are capable of reducing cooling loads in all cases, however their exact effects could differ in each month in each case.

12. CONCLUSION, LIMITATIONS AND FURTHER WORK

The UK government has set targets to reduce energy consumption in current buildings and building zero carbon homes from 2016 was, until recently, a target. Modern Method of Construction (MMC) have been promoted in order to provide better quality homes in a shorter time. In order to achieve these goals significant changes are required in the design of new houses.

Applying sustainable design standards is currently in sharp expansion due to the great necessity of reducing energy consumption and carbon emissions and improving thermal comfort. Despite the fact that super insulated airtight buildings do have advantages recent works have implied potential overheating risks on the basis of current sustainable standards requirements, and because of the likely future temperature increases in UK. The Secretary of State for Communities and Local Government in 2010 stated “The UK requires better homes, built to high standards both in terms of design and environmental impact, new homes need to be part of the solution to climate change; not part of the problem”.

The aim of this study has been to define a method to assess the impact of current sustainable standards on new building thermal performance in current and future climates, and to examine how available construction technologies can be used to alleviate the overheating risk. There has been a special focus on design decisions for building construction systems in the early stages of the design process. It has been underlined by this study that sustainable standards should not be the aim - they should be the starting point of a new process to deal with the future problems.

Recent studies have suggested that well-insulated buildings may suffer from overheating risk in future climates. The study is inspired by the fact that it is easier and less expensive to alter design decisions in the initial sustainable design stages rather than later on in the process, and that alterations made in initial stages have a greater impact on the building performance compared to the alterations made later. It is therefore essential to develop methods that emphasize design decisions in the initial stages, and that those methods are adaptable. This study addresses these concerns by creating simple and realistic models.

By computer simulations, this works has shown how current sustainable standards would impact the behaviour of MMC and traditional systems and their performance has been quantified and overheating risk has been highlighted. Additionally, the study highlights the failure of current sustainable standards to deliver optimum energy consumption and thermal comfort in future.

The study introduces the principles and most effective influential factors of passive design strategies, which established the scene for the development of the study. The study also provides an insight into future energy policies to emphasize the necessity of opting for new approaches at the present time and that the amount of uncertainty is considerably high in predicting energy suppliers and costs. Therefore, utilizing robust solutions to alleviate the problems is of great necessity.

Further studies in this thesis contain a detailed study on heat transfer in buildings and influential factors on heat storage as well as investigating common materials in order to provide an insight to performing simulations in initial models and the prospective design of a new UK homes. This work provides a framework for decision-makers to choose adequate solutions from traditional options to new technologies. The study opens the door for further works on upcoming technologies and methods to tackle overheating risk.

Five different wall construction systems with different capacities of thermal mass but similar U-Values were simulated for five different building models, from a simple cell to a prospective design for a detached house, semi detached house and purpose-built flat. The decrement factor, admittance and time constant did not necessarily reflect the simulations results and were not found to be comprehensive values to quantify thermal mass. Moreover, the effect of thermal mass is found to be exaggerated in the literature.

The study assessed the behaviour of construction systems on the basis of thermal comfort and energy consumption in each month for the four timelines of 2011, 2020, 2050 and 2080. Minor differences were observed in initial models but the differences became more significant in housing models. The simulations have indicated an overheating risk and demonstrated future trends in London, where climate change effects are extreme, and in Manchester, where the effects are less dramatic. The risk of overheating is likely to increase in both cities.

The study not only showed the potential of small quantities of PCMs to improve comfort and reduce energy consumption by at least 20%, but also demonstrated a new mechanism for better efficiency. Most of the recent works in integrating PCMs were accomplished in laboratories and the data were difficult to find. However, a new version of DesignBuilder provided the opportunity for this study to highlight their potential. Louvers and overhang capabilities to improve thermal comfort with the construction systems have been investigated in simple cell and typical house models and their potentials quantified. In most cases the effect of a 0.5m overhang seemed to work best in reducing discomfort hours. In extreme case the reuction was around 173 hours difference in terms of overall discomfort hours (TF with 0.5m overhang compared to 0.5m louvers in London 2020).

It has also been suggested to decision makers by this thesis to consider the effect of EAHEs in order to use the soil's temperature to control outside air before delivering into the house. Although the author was unable to perform dynamic simulations to quantify their potential effect due to limitation in available software, a literature review emphasized their potential. Furthermore, the use of nano technology in insulations and their ability to reduce insulation thickness to achieve the U-Value of 0.1 W/m^2K has been suggested.

It should be kept in mind that buildings, which are constructed today, should be able to perform for decades. Therefore, the future weather should be considered in the early design stages. As observed, the integration of smart materials shows promising results for the future as the weather become warmer. Therefore, in order to avoid expensive energy costs, these materials should be considered at present.

In general, this study investigates how future thinking on the building performance can be integrated into the selection of building components, materials and new technologies. Five models were simulated in the UK that represented current sustainable design regulations. It is shown that sustainable design accommodates current needs but design strategies have to be more flexible to deal with climate change and accommodate future changes. Furthermore, a new generation of decision-support tools that are capable to integrate modern techniques with sustainability assessment methods should also be developed.

12.1 Contribution to the Knowledge

The study made a review on the most practical issues on the performance of sustainable homes and assessed their performance on the basis of thermal comfort and energy consumption with the main focus on the building envelope for current and future climate. The research demonstrated the critical issues for decision-making and quantified the effect of the most practical construction systems with different performance levels from both traditional constructions and MMC.

The research planned a step by step method to evaluate the performance of sustainable buildings by designing five models and demonstrates the effect of climate change on their performance with the examined construction systems.

The research has also quantified the effect of SDs and PCMs by computer modeling to improve energy consumption in the models. The study investigates modern techniques and proposed new mechanism of integrating PCMs with a ventilation gap to alleviate the risk of climate change overheating.

12.2 Limitations and further research

One of the limitations of this work was the unfeasibility of validating the simulations within the project time and funding scales. However, the study compared the simulations to the existing practical data as far as possible to prove the accuracy of the result. Moreover, the most recent DB version at the time of this study provided ASHRAE 2004 for thermal comfort calculations although minor differences exist with 2010 standard. It was not possible for this study to simulate the effect of EAHE as one of the suggestions for improving comfort in UK housing. The study simplified the building models to five representatives and the plan shapes are limited to rectangular forms only and up to four storeys maximum. Further research might include:

- In this study, only single-criteria of sustainability standards have been investigated. A multi-criteria assessment will enable the decision-maker to examine the tradeoff between different performance parameters in decision-making.

- The present simulations do not include reliability analysis, which will support the building optimization assessment to include the likelihood of failure in alleviating the risks.

- Only high emission climate change scenarios were considered in the simulations of this study in Manchester and London, Further studies might include cities in the north of UK with minimum climate change effect as well as different climate change scenarios.

- Typical low-rise houses were assessed in this study; further studies might include the other housing typologies as well as high-rise buildings.

- This study mostly focused on the passive design options in current and future climate; further studies may include integrating active strategies with other building modeling software that are able to simulate those, such as IES.

- Further studies may also consider the effect of EAHE by means of computer simulations (when available) in the UK housing.

- Actual climate observations show the precise choice later than is needed. Therefore, it is reasonable to modify design frameworks to take sets of uncertainties into account. In essence, a classification of “no-regret strategies” and “flexible strategies” in decisions is recommended for further studies.

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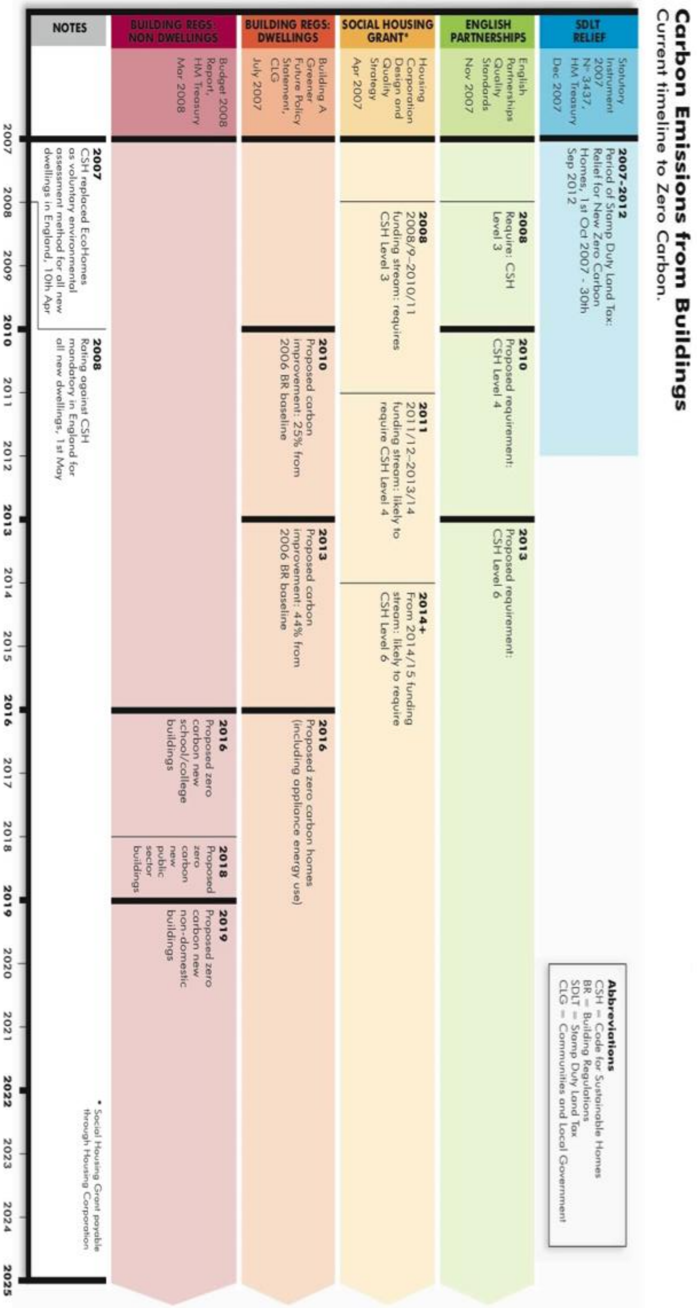
Appendix 1


Carbon Emissions from Buildings
Current timeline to Zero Carbon.
SDLT RELIEF
Statutory Instrument 2007 Nº 3437, HM Treasury Dec 2007
2007-2012 Period of Stamp Duty Land Tax: Relief for New Zero Carbon Homes, 1st Oct 2007 - 30th Sep 2012
Abbreviations
CSH = Code for Sustainable Homes
BR = Building Regulations
SDLT = Stamp Duty Land Tax
CLG = Communities and Local Government
ENGLISH PARTNERSHIPS
English Partnerships Quality Standards Nov 2007
2008 Require: CSH Level 3
2010 Proposed requirement: CSH Level 4
2013 Proposed requirement: CSH Level 6
SOCIAL HOUSING GRANT*
Housing Corporation Design and Quality Strategy Apr 2007
2008 2008/9–2010/11 funding stream: requires CSH Level 3
2011 2011/12–2013/14 funding stream: likely to require CSH Level 4
2014+ From 2014/15 funding stream: likely to require CSH Level 6
BUILDING REGS: DWELLINGS
Building A Greener Future Policy Statement, CLG July 2007
2010 Proposed carbon improvement: 25% from 2006 BR baseline
2013 Proposed carbon improvement: 44% from 2006 BR baseline
2016 Proposed zero carbon homes (including appliance energy use)
BUILDING REGS: NON DWELLINGS
Budget 2008 Report, HM Treasury Mar 2008
2016 Proposed zero carbon new school/college buildings
2018 Proposed zero carbon new public sector buildings
2019 Proposed zero carbon new non-domestic buildings
NOTES
2007 CSH replaced EcoHomes as voluntary environmental assessment method for all new dwellings in England, 10th Apr
2008 Rating against CSH mandatory in England for all new dwellings, 1st May
* Social Housing Grant payable through Housing Corporation
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Appendix 2

VIP insulations are considerably more expensive compared to the traditional insulations (Fricke, et al., 2008). But it can be argued that, in return, they would cause more space saving which could considerably reduce the payback costs. According to a study by Alam, Singh and Limbachiya (2011) VIPs payback period are even less than EPS insulation when the 0.24 w/m^2k U-value is to be achieved. Figure 11 shows the comparison of payback periods when 0.4 w/m^2k , 0.31 w/m^2k, 0.27 w/m^2k and 0.24 w/m^2k U-Value are applied.

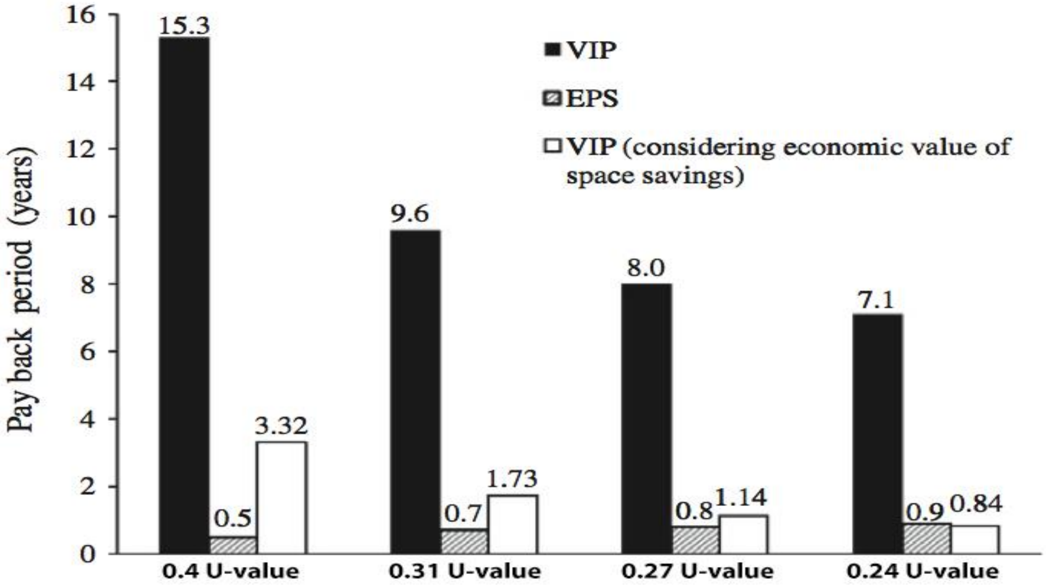


Figure 163 Payback period comparisons of VIP and EPS in different insulation scenarios, Source (Alam, et al., 2011)

Appendix 3 - Publications

RISK AND UNCERTAINTY IN SUSTAINABLE BUILDING PERFORMANCE

Seyed Masoud Sajjadian, John Lewis and Stephen Sharples

School of Architecture, University of Liverpool, Liverpool, UK

ABSTRACT

Decision-making in the design of sustainable building envelopes will mostly consider the trade-off between initial cost and energy savings. However, this leads to an insufficiently holistic approach to the assessment of the sustainable performance of the building envelope. Moreover, the decisions that designers face are subject to uncertainties and risks with regards to design variations. This research examines a range of concepts and definitions of risk, uncertainty and sustainability in the context of climate, building construction and overheating. These concepts are then combined to objectify a range of risks and uncertainties affecting the decision. A simple computer model was used to analyze different building cladding constructions in terms of an overheating risk inside a building. The paper concludes by considering how the cladding materials may be chosen to optimize a model that will aid decision-making in design. The research suggests that none of the cladding systems would completely eliminate the risk of overheating for a range of climate change scenarios.

KEYWORDS

Risk, Uncertainty, Climate Change, Overheating, Environment

INTRODUCTION

For researchers in science and engineering the terms uncertainty and risk are explored and reviewed within a large number of academic articles and reports. Essentially, no general definitions are observed for these terms, although many constraints and context-dependent definitions exist. Almost every definition is problem-specific, implying that every time a decision problem is stated particular definitions for risk and uncertainty are presented for the decision problem. A consensus within these definitions, however, is that risk and uncertainty are frequently related. Every definition considered consists of three comprehensive areas - Economics and Finance, Operations

Research, and Engineering (based on the affiliation of the author to the specific field). The challenge can be extended into a design problem by introducing design parameters in construction and demonstrating how climate change models uncertainty and quantifies risk in the availability of feasible options for the decision-maker.

BACKGROUND

Increasingly, there is recognition that potential changes in UK climate are likely to have impacts on the built environment. Perhaps the most significant of these changes concerns the influence of higher temperatures on thermal performance. Bill Dunster Architects and Arup R&D (2005) demonstrated the significance of mitigating climate change effects by designing homes with passive features to offset the expected increases in air temperatures. This research also identified that thermally lightweight homes would result in levels of discomfort by creating considerably higher room air temperatures. The study stated that masonry houses with inherent thermal mass can save more energy over their lifetime compared to a lightweight timber frame house.

The risk of overheating in highly insulated houses happens not only in the summer but also in other seasons. The risk of overheating exists as long as there is solar penetration into the building (Athienitis and Santamouris 2002). Orme et al. presented research work which illustrated that in a lightweight well-insulated house, external temperatures of 29°C may result in internal temperatures of more than 39°C (Orme, Palmer and Irving 2003).

Trying to calculate how a range of design variables will perform over time is fraught with uncertainty. Obviously, heating and cooling loads are influenced by the thermal properties of the building envelope, which are likely to be sensitive to future conditions. Therefore, the efficiency of decisions made due to the thermal characteristics of the built environment need to be considered in the light of climate change scenarios.

SUSTAINABILITY AND HIGH PERFORMANCE

Currently, in lean construction thinking, sustainability and high performance seem to be gaining significant momentum. The ASHRAE Standard 189.1 defines the high performance green building as a “building designed, constructed and capable of being operated in a manner that increases environmental performance and economic value over time”. Consequently, the challenges observed from this definition are i) that it casts the problem as being one of definition; ii) in fact, it is more a question of prediction of which features will meet the criteria and of achieving consensus on which of those features would be deemed appropriate for inclusion; and iii) it does not account for the range of interrelated time and space scales. One of the essential challenges in the long term is uncertainty, and sustainability by any definition refers to the long term. The question arises of how to describe and manage sustainability under uncertainty. In this interaction the following must be answered:

- What are the factors that need to be sustained?
- At what level and for how long, should the factors last?
- What degree of uncertainty is acceptable?

Sustainability is about thoughtful choices, without spending more on non-essential options but with confidence of earning more return on investment. In a general sense, it is about dealing with nature – not ignoring it. Additionally, it is not about constructions that appear to be environmentally-responsible but which eventually sacrifice occupant comfort. It becomes clear therefore that “Sustainability in Buildings” is a multi-criteria subject, which includes interlinked parameters of economics, environmental issues, and social parameters (Vesilind, et al. 2006). Therefore, this paper tries to explore the interaction of each feature by using a set of criteria to optimize the thermal performance of a variety of construction types in dealing with uncertainty and risks.

CLIMATE CHANGE

Adaptation of buildings to climate change is becoming increasingly necessary. Adaptation, a responsive adjustment to decrease or remove risk, will be critically important since, in even the most optimistic projection of climate-change scenarios, temperatures will increase considerably around the world. It is very unlikely that the mean summer temperature increase will be less than 1.5°C by the year 2080 (IPCC 2010). Figures 1 and 2 illustrate a range of increasing temperatures in the UK in summer and winter with different probabilities. The ‘worst-case scenario’ is thought to be essential when considering change for construction types. The construction adapted for the extreme case should be the most robust design - a design that is durable in both the current climatic condition and in response to the maximum envisaged change in future climate.

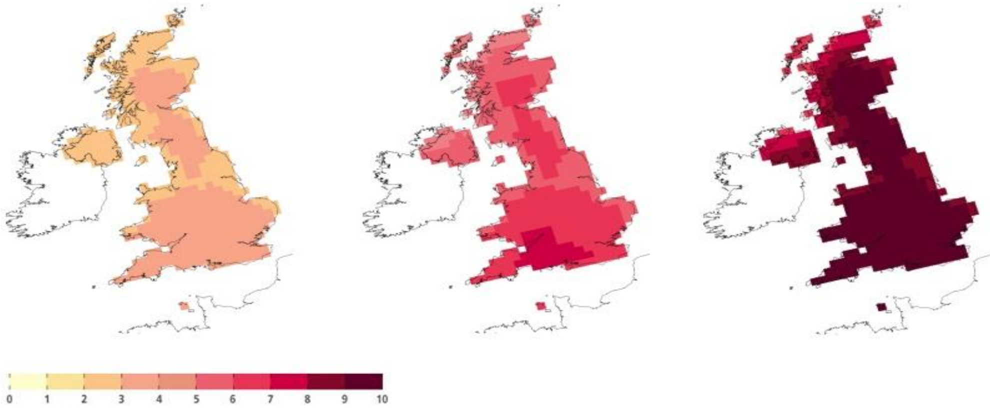


Figure 1: Summer mean temperature in 2020, 2050, 2080; 90% probability level, very unlikely to be less than the degrees shown on maps [Source:http://ukclimateprojections.defra.gov.uk/content/view/1293/499/]

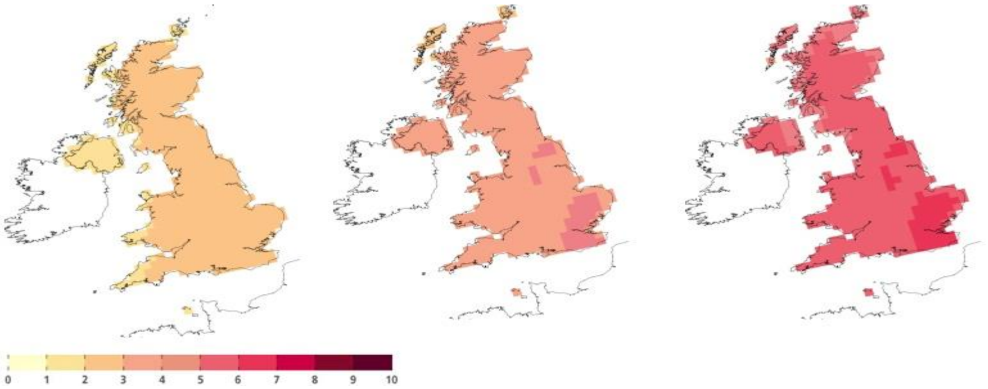


Figure 2: Winter mean temperature in 2020, 2050, 2080; 90% probability level, very unlikely to be less than degrees shown on maps [Source: http://ukclimateprojections.defra.gov.uk/content/view/1284/499/]

As can be seen from Figure 1, around an 8°C increase in the summer is 90% likely to happen in most of the UK. Obviously, the rate of increase would be less in winter but is still quite considerable. Revealing the potential impacts of climate change scenarios in dealing with construction types demonstrates the need for an optimization in the decision-making process to optimize both the thermal comfort of occupants and future energy consumption regardless of active design impacts. These are essential determinants when attempting to establish the vulnerability of occupants during a heat-wave, and the potential change in energy usage and CO_2 emissions are a consequence of changing climatic conditions. In essence, this approach causes effective and practical adaptation strategies for decreasing the potential for overheating in the homes. Currently, it has been observed that a large number of dwellings in the UK have no mechanical cooling systems. Therefore, an increase in summer temperatures has considerable potential to increase occupant vulnerability to overheating as well as the potential to considerably raise energy consumption (Collins et al 2010).

THERMAL COMFORT

ASHRAE defines thermal comfort as “that condition of mind which expresses satisfaction with the thermal environment”. This symbolizes the complexity and uncertainty of the issue of thermal comfort and likewise overheating or discomfort levels (ASHRAE 2010). Figure 3 demonstrates the potential comfort adaption to a climate change.

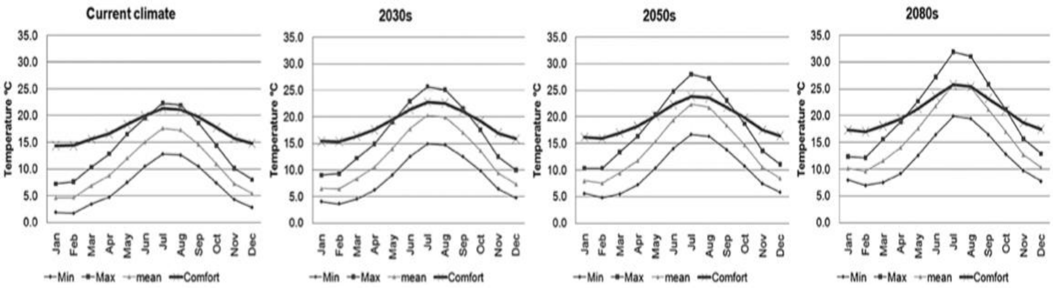


Figure 3: Potential comfort adaption to a change in climate [Source: Gupta and Gregg 2012]

METHODOLOGY

For quantification purposes and simplification of decision-making, a building model using the Ecotect thermal software was used. The indoor air temperature at which overheating occurred was taken to be when the average interior home air temperature was 26°C or greater. This condition was used to simplify the image of overheating hours in the home. What is most important here is the relative change in ‘over-heating’ hours between projections when different construction types are tested. Basically, in an optimization process concerned with risk and uncertainty, decisions are made on certain quantitative measures to determine the best course of action possible for a decision complexity. As such, three main elements are required to be considered before reaching a decision (Al-Homoud 1994):

- Selection options from which a selection is created (variables)
- Precise and quantitative information of the system variables’ interface (constraints)
- Particular measure of system efficiency (objective function)

In this study the variables are a range of five typical cladding systems. Constraints are likely to be wall-thickness, environmental and economic performance. The objective function is established as the decrement factor (the ability to decrease the amplitude of temperature from outside to the inside), time constant (the time takes the maximum outside temperature makes its way to a maximum inside temperature), admittance (building fabric response to a swing in temperature) and U-value (overall heat transfer coefficient). The research considered five construction techniques, all of which are appropriate for use in house walls. This number was considered satisfactory to make useful comparisons but not to be excessive to consider in detail. The selection criteria were:

- Recent use for housing in the UK so the availability of detailed information is met
- Method appropriate for the UK housing use
- The potential of achieving Part L of UK thermal building regulations (U-value set to 0.12 W/m^{2}K)

The typical cladding systems examined were:

- Brick and block wall (BB)

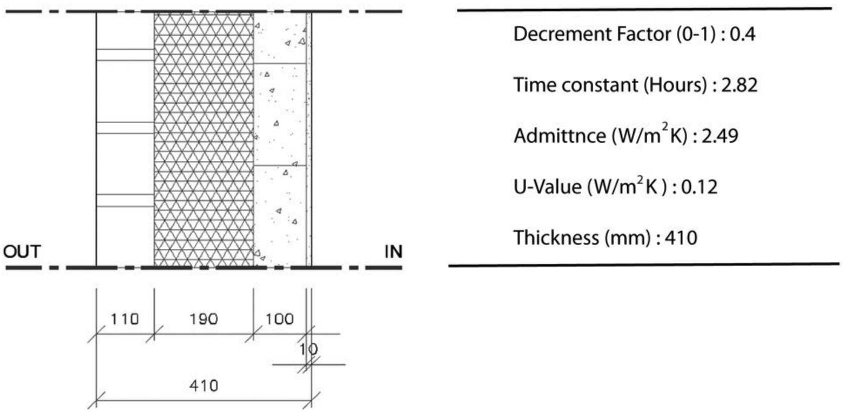


Figure 4: From Out to in: 110mm Brick Outer Leaf, 190mm Phenolic Insulation, 100mm Aerated Concrete Block, 10mm Lightweight Plaster

- Timber frame wall (TF)

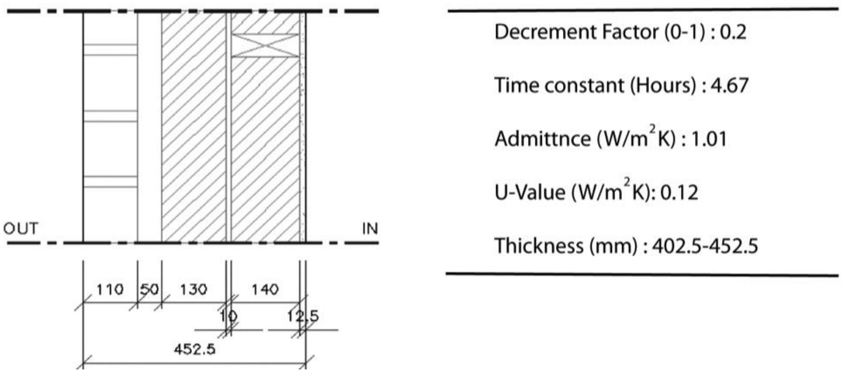
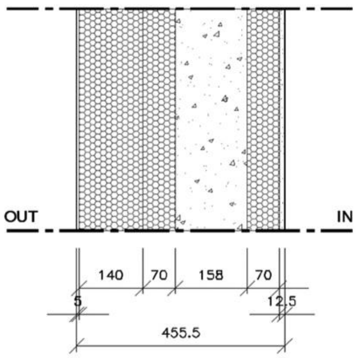


Figure 5: From Out to in: 110mm Brick Outer Leaf, 50mm Air Gap, 130mm Rockwool, 10 mm Plywood, 140mm Rockwool, 12.5mm Plasterboard

- Insulating concrete formwork (ICF)



Decrement Factor (0-1) : 0.03

Time constant (Hours) : 116.5

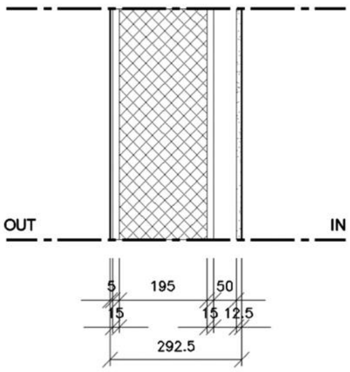
Admittnce (W/m^{2}K): 0.66

U-Value (W/m^{2}K) : 0.12

Thickness (mm): 455.5

Figure 6: From out to in: 5mm Rendering, 140mm Extruded Polystyrene (EPS), 70mm Extruded Polystyrene (EPS), 158mm Heavyweight concrete, 70mm Extruded Polystyrene (EPS), 12.5mm Plasterboard

- Structural insulated panel (SIPs)



Decrement Factor (0-1) : 0.81

Time constant (Hours) : 2.4

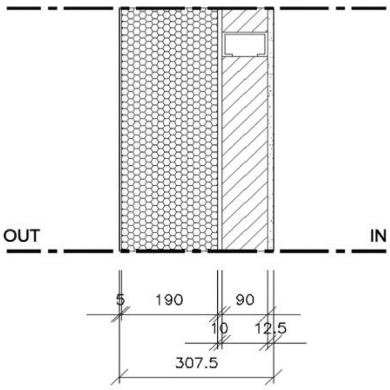
Admittnce (W/m^{2}K) : 2.28

U-Value (W/m^{2}K) : 0.12

Thickness(mm) : 242.5-292.5

Figure 7: From out to in: 5mm Rendering, 15mm Softwood board, 195mm Extruded Polyurethane (PUR), 15mm Softwood board, 50mm Air Gap, 12.5mm Plasterboard

- Steel frame wall (SF)



Decrement Factor (0-1) : 0.36

Time constant (Hours) : 4.9

Admittnce (W/m^{2}K) : 1.01

U-Value (W/m^{2}K) : 0.12

Thickness (mm) : 307.5

Figure 8: From out to in: 5mm Rendering, 190mm Extruded Polystyrene (EPS), 10mm Plywood, 90mm Rockwool, 12.5mm Plasterboard

The environmental modeling software Ecotect was used to analyze the thermal performance of the building model shown in Figure 9. The weather data used were based on Manchester, UK climate data from the year 2011 with no heating period (1st of May to the 30th of September), and without any internal gains. The infiltration was assumed as 0.05 air change per hour (ACH) and no ventilation was considered. A U value of 0.1 W/m^{2}K for the roof and floor and 0.8 W/m^{2}K for triple glazed windows were assumed.

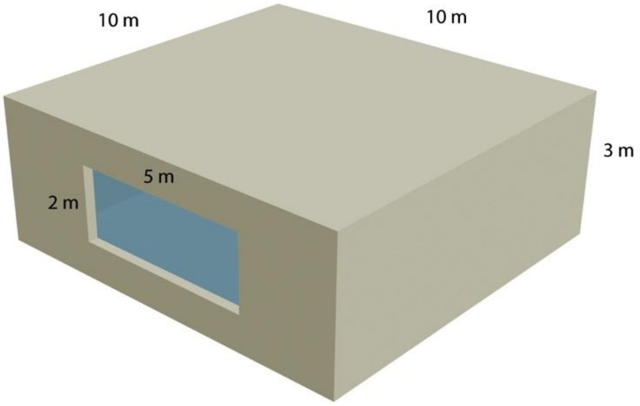


Figure 9: Model building examined in Ecotect

DISCUSSION AND RESULTS

Figure 10 compares the thermal properties of the examined wall system systems. As can be seen, a higher wall thickness means a lower admittance and decrement factor in most cases. It seems that ICF has the lowest decrement factor and admittance rate with the highest thickness. It could be observed that SF, with considerably less thickness, shows an acceptable level of performance.

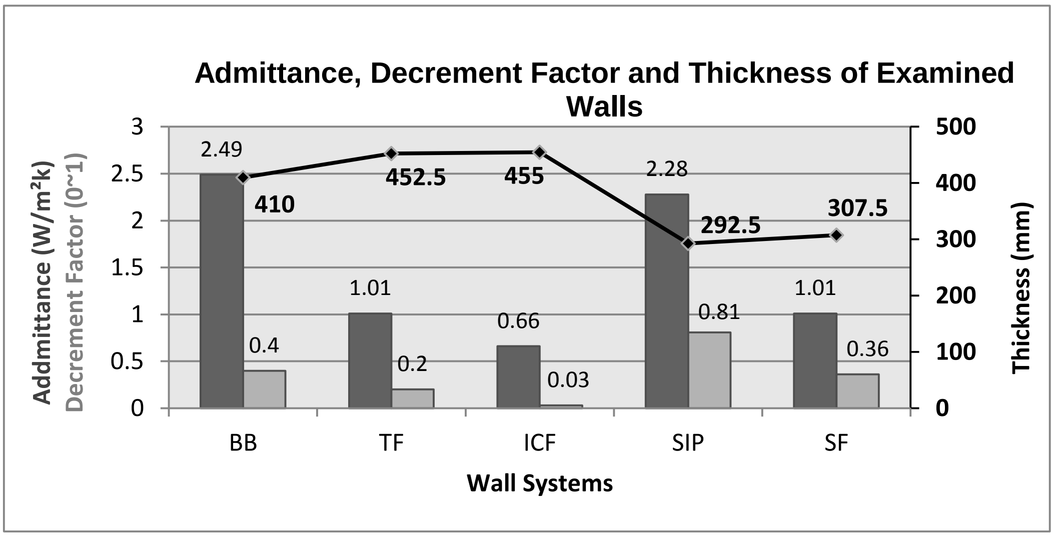


Figure 10: Admittance, Decrement Factor and Thickness of the Examined Walls

With regard to overheating, Figure 11 illustrates that TF had the worst performance among the construction systems. The SF performance was not much better. As was expected, ICF seems to have the best performance, with the lowest percentage of overheating, although the maximum thickness does not seem to be ideal.

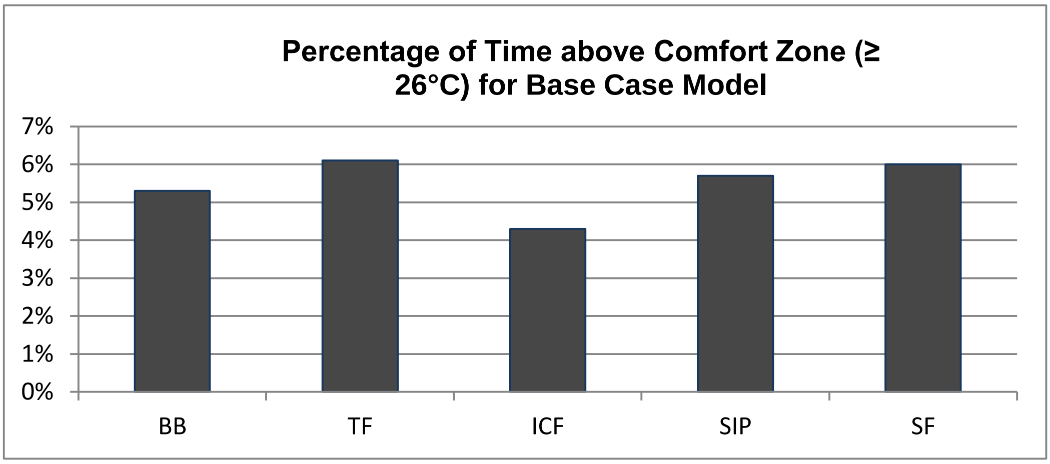


Figure 11: Percentage of time above comfort zone (≥26°C) for base case model – current Manchester weather data

CONCLUSION

In this paper, the proposed approach models uncertainty in current climate and quantifies overheating risk. The wall construction options tested in this study have only a small difference in their performance in dealing with this risk. However, further works in his area should consider future climate change scenarios in assessing risk. This leads to a decision problem offering the decision maker an opportunity to arrive at a decision influenced by their knowledge. Clearly, one ‘‘correct’’ decision is not given to decision-makers but rather a small collection of choices to reduce or eliminate the negative impacts on comfort and energy consumption. It has been assumed that dealing with the uncertainty and risk proposed in this paper will make the decision-making more dynamic and environment- specific.

Unfortunately, the climate observations show that the right choice comes after it is needed. Climate models cannot deliver what is the present-day decision-makers necessary framework; the only answer is to modify design frameworks to enable them to take a range of uncertainties into account. Regarding this, a classification of “no-regret strategies” and “flexible strategies” in decisions is proposed for consideration. ‘No-regret’’ decisions represent the ability to deal with climate uncertainty. These strategies produce paybacks even if climate change does not happen. Improving building insulation is the most appropriate example of this strategy in construction systems, since this energy saving can frequently pay back the additional cost in the short term. Secondly, it seems wise to add external passive design strategies such as shadings and louvers, which are reversible, over permanent choices. Clearly, the aim is to minimize as far as possible the cost of being wrong about prospective climate change. Eventually, the research found that none of the construction types optimization common strategies could entirely remove the risk of overheating in the homes for current weather conditions in Manchester.

FURTHER RESEARCH

A major risk for sustainable design is the uncertainty in future climate. Preferably, climate models would be able to produce more accurate climate statistics; clearly, this is the evidence that researchers in engineering and science need to optimize future investments. Basically, two major issues remain that make a precise model difficult for future scenarios. Initially, there is a scale misfit between what decision-makers need and what climate models can deliver. Secondly, the epistemic uncertainty of climate change is important. However, the initial issue can be alleviated by downscaling techniques such as using regional models with limited domains. But the second issue seems to be more difficult to overcome, at least in the short-term future; clearly, there is a real risk of misperception between old data and model output.

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Interpretation and Determination of Thermal Comfort for Future Climate Resilience

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Abstract

Thermal comfort is a complicated subject and is thus hard to quantify generally and specifically and the existing quantification methods are unlikely to be reliable for naturally ventilated houses. The challenge for designers is to produce a comfortable built environment that is sustainable in terms of minimizing energy consumption. This study uses the UK Climate Change Projections to assess the current thermal comfort models and identify their effectiveness in dealing with conditions predicted for the years 2020, 2050 and 2080. A typical wall system is tested under conditions predicted for London, UK. This process focuses on reducing energy consumption and improving indoor air quality on the basis of thermal neutrality models. Among the passive options tested, the research found that high-density insulation in addition to shading devices could be effective design solutions to minimize the extreme effects of climate change, although none could completely provide a full year comfort zone, particularly by the 2080's.

Keywords

Thermal Comfort, Indoor air quality, sustainability

Introduction

The five traditional methods of human perception give neutral pieces of information. Thermal sense is not recognized within those and mainly the difference is that this sense is never neutral; it is actually imitating what the body is experiencing. This sense can tell adapting time of the body to heat loss or gain but cannot read the temperature. Hensen (1991) defined thermal comfort, as "a state in which there are no driving impulses to correct the environment by the behavior''. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) also defined it as ''the condition of the mind in which satisfaction is expressed with the thermal environment'' (ASHRAE, 2004).

Satisfaction is associated with thermal sensation of "neutral" or slightly warm or cool.

To clarify the matter, the search for acceptability explain the goal of pursuing thermal comfort for buildings' occupants more clearly. On a similar vein, ASHRAE (1992) mentioned that "thermal environmental conditions for human occupancy, is to specify the combinations of indoor space environment and personal factors that will produce thermal environmental conditions acceptable to 80% or more of the occupants within a space''.

Background

A number of studies focused on the impact of climate change on the built environment utilizing sophisticated simulation tools to make hour-by-hour computation of the heating/cooling loads. Building energy simulation is a satisfactory technique to estimate temperature by dynamic interactions between the outside climate, the building envelope and the internal heating and cooling system. This technique has also been used by a number of researchers to evaluate climate change effect on energy use in buildings. De Wilde et al (2010) considered the uncertainties in the impact of climate change prediction on the thermal performance of buildings. For a terraced house, the uncertainty is enormous, at 60% or more. Similarly, Collins et al. (2010) assessed the impact of climate change on the future energy consumption in the UK housing stock at four weather data locations: Cardiff, Edinburgh, London and Manchester.

Approximately 2.3 million houses in England are now anticipated to be in fuel poverty, and it seems with growing energy cost, more households will be subject to fuel poverty (Moore, 2005). A household in fuel poverty is assumed to be one with a fuel bill more than 10% of income to maintain satisfactory thermal comfort. Basically, fuel poverty is a result of high-energy cost, low income and energy inefficient dwellings. With consequent increased health risk and poor quality of life from continued exposure to cold and hot temperatures (Wilkinson, Landon, Armstrong, Stevenson, & McKee, 2001).

Methodology

This paper assesses a range of thermal comfort definitions and assessment tools and highlights the effectiveness of each method. A simple model is utilized for quantification purposes and uses the Design Builder simulation tool and future climate scenarios for 2020, 2050 and 2080 in order to evaluate indoor temperature with regard to thermal comfort definitions. Insulation and shading devices have been chosen to decrease the risk of overheating and overcooling.

Thermal comfort

The clarification of an acceptable thermal comfort for occupants is important to the success of a building, not only because of the air quality, but also because it will decide a building's energy consumption and consequently has impacts on its sustainability. Therefore, specific thermal comfort standards are essential to assist building designers to provide an indoor climate which will be found thermally comfortable by occupants.

Thermal comfort is closely associated with the thermal balance of the body. This balance is influenced by two major categories of variables (CIBSE, 2006):

1) Environmental parameters including:

- Mean Radiant Temperature (MRT)
- Air Temperature (AT)
- Relative air velocity (Vel)
- Relative Humidity (RH)

2) Personal parameters including:

- Activity level (Act)
- Clothing level (Clo)

Thermal comfort approaches

Currently, two sorts of approaches for the definition of thermal comfort exist: the rational or heat-balance approach and the adaptive approach. The heat-balance approach uses data from climate chamber studies, best illustrated by the Fanger's model while the adaptive approach is base on the field studies of occupants in building.

Heat balance approach

The most well known method, in this category is "Predicted Mean Vote" (PMV) and "Predicted Percentage of Dissatisfied" (PPD) model proposed by Fanger which combines the impacts of theories of heat balance with the physiology of thermoregulation factors into an specific value on a thermal sensation scale which has been accepted widely (Fanger P. , 1972). Figure 1 below shows the relationship between PMV and PPD in the Fanger model.

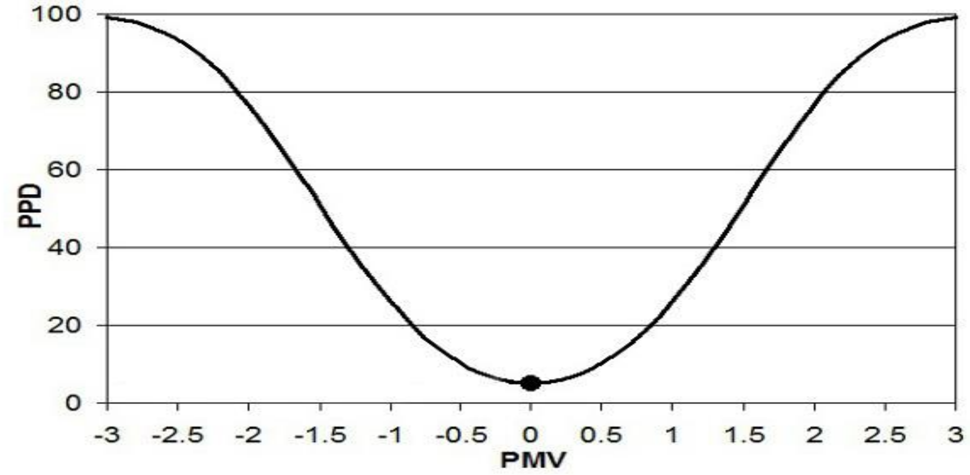


Figure1: Relationship between PMV and PPD, Source: http://www.intechopen.com/books/air-quality/a-review-of-general-and-local-thermal-comfort-models-for-controlling-indoor-ambiences-

According to Fanger's theory, our body employs physiological processes such as sweating and shivering to keep a balance between the heat gains and losses. However, Fanger highlighted that ''man's thermo-regulatory system is quite effective and will therefore create heat balance within wide limits of the environmental variables, even if comfort does not exist'' (Fanger P. , Thermal comfort, analysis and application in environmental engineerig , 1970). The Fanger's model on thermal comfort was a ground-breaking contribution to the evaluation of indoor thermal environments as well as to the theory of thermal comfort. It is generally accepted and used for the assessment of thermal comfort (ibid).

Adaptive approach

Fanger's model has come to be regarded as applicable across wide range of building types, populations and climate zones (Parsons, Thermal comfort standard: Past, Present and future, and open discussion that follows, 1994). But this approach has been challenged by many researchers arguing that his model ignores significant cultural, social, climatic and contextual dimensions of comfort, leading to an exaggeration of the demand for air conditioning (De Dear & Brager, 1998). Therefore, as it can be seen in the Figure 2, although the Fanger's model shows reasonable accuracy in most air-conditioned buildings, failed considerably in the naturally ventilated buildings,

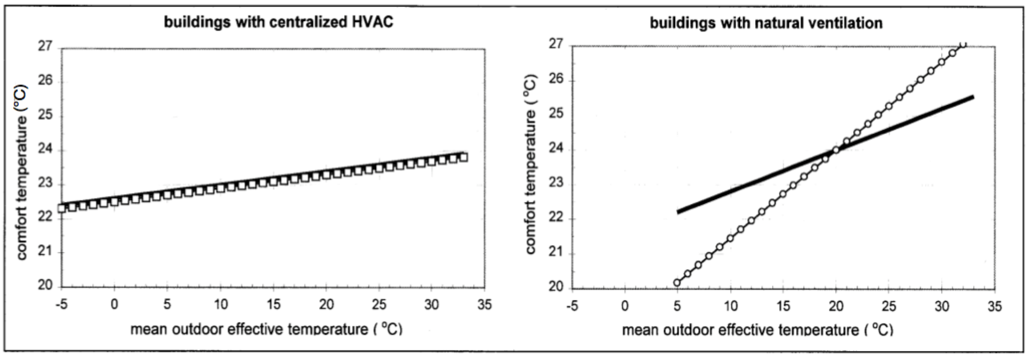


Figure 2: mean outdoor effective temperature in centralized HVAC and natural ventilation, Source: (De Dear & Brager, 1998)

Significant failures in results for naturally ventilated buildings and rising dissatisfaction with static comfort temperatures has driven interest in a variable indoor temperature standards. Basically, in these buildings, a variable indoor temperature standard, based on the adaptive model of thermal comfort, would have more particular relevance rather than static models. An adaptive standard links thermal comfort to the climatic context of the building and considers past thermal experiences as well as occupants' current thermal expectations. Past thermal history and contextual factors are assumed to modify thermal preferences and expectations (De Dear & Brager, 1998).

In essence, the adaptation term could be assumed broadly as the gradual reduction of the organism's response to frequent environmental stimulation. Within this comprehensive definition, it is feasible to distinctly classify three categories of thermal adaptation including behavioral, physiological and psychological adjustment. Behavioral adjustment could be further classified into technological (such as turning on/off cooling or heating systems), personal responses (such as removing or wearing clothes) and cultural responses (such as having a siesta). In fact, unconsciously or consciously these modifications are totally specific responses for thermal comfort. Physiological adjustment includes any changes in the physiological responses that might result from thermal environmental factors exposure, and would cause a gradual adaption by such exposure. Physiological adaptation can be classified into genetic adaptation and acclimatization. Psychological adjustment refers to a reaction to and perception of physical information related to expectations and past experiences (Clark & Edholm, 1985).

In adaptive models, in fact, it is the interaction between occupants and the building or any other environment that determines comfort temperature. Clearly, climate is the major contextual variable. Climate is a main effect on the psychological, physiological and behavioral adjustment of people and thus, on the design of the buildings. Although, climate may not change the fundamental mechanisms of the human interaction with the thermal environment, a number of detailed ways exist in which people are subject to stimuli, and these play an increasing role in peoples' reaction to the indoor climate.

Building as the second major contextual factor in determining comfort plays a part through its services. Time is the third contextual parameter. This indicates that the comfort temperature is repeatedly fluctuating. The magnitude of these fluctuations and their rate at which they occur is a significant concern (Nicol and Humphreys 2002)

Climate change and uncertainty quantification

Nicol and Roaf (1996) suggested the Eq. (1) model for occupants of naturally ventilated buildings. Other adaptive models have also been suggested such as Humphreys models for neutral temperature, as given by Eq (2) and (3) (Humphreys MA, 1976). Auliciems and de Dear established relations for calculating group neutralities on the basis of mean indoor and outdoor temperatures, as shown in Eqs. (4), (5) and (6), which were recommended by ASHRAE in Eq. (8) (ASHRAE, 2004).

$T_{n,o} = 17 + 0.38T_o$ (1)

$T_{n,1} = 2{:}6 + 0.831T_i$ (2)

$T_{n,o} = 11{:}9 + 0.534T_o$ (3)

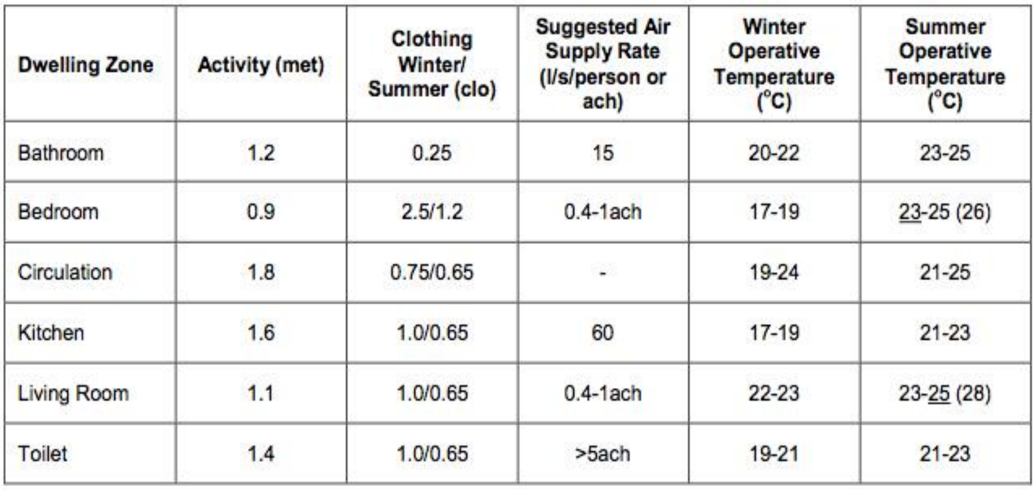
$T_{n,i} = 5.41 + 0.731T_i$ (4)

$T_{n,o} = 17.6 + 0.31T_o$ (5)

$T_{n,i,o} = 9.22 + 0{:}48T_i + 0.14T_o$ (6)

$T_c = 17.8 + 0.31T_o$ (7)

In equation above, T_c is the comfort temperature, T_o is the outdoor air temperature, T_i is the mean indoor air temperature, $T_{n,i}$ is the neutral temperature on the basis of mean indoor air temperature, and $T_{n,o}$ is the neutral temperature on the basis of the mean outdoor air temperature. CIBSE (2006) recommended comfort temperature based on common environmental and physiological factors shown in Table 1.



Dwelling Zone	Activity (met)	Clothing Winter/ Summer (clo)	Suggested Air Supply Rate (l/s/person or ach)	Winter Operative Temperature (°C)	Summer Operative Temperature (°C)
Bathroom	1.2	0.25	15	20-22	23-25
Bedroom	0.9	2.5/1.2	0.4-1ach	17-19	23-25 (26)
Circulation	1.8	0.75/0.65	-	19-24	21-25
Kitchen	1.6	1.0/0.65	60	17-19	21-23
Living Room	1.1	1.0/0.65	0.4-1ach	22-23	23-25 (28)
Toilet	1.4	1.0/0.65	>5ach	19-21	21-23

Table 1: Recommended comfort temperature range for dwelling based on common environmental and physiological factors, source: (Taranto Rodrigues, 2009)

It can be understood from the Table above than a temperature range of 18-26 is highly likely to be within comfort area. Moreover, ASHRAE 55-2004, clarified thermal comfort as a subjective response and is defined as the 'state of mind that expresses satisfaction with existing environment' (Brager & de Dear, 1998). It can be observed by this definition that a specific value cannot be assigned to thermal comfort. "State of mind" generally depends on occupants' perception and expectation. However, ASHRAE-55 is based on the static heat balance and is based on of four environmental variables, i.e. temperature, mean radiant temperature, relative humidity and air velocity as well as activity and clothing level of the occupants. This includes PMV/PPD calculation methods and the concept of adaption (Figure 3). Therefore, this paper uses this standard for quantification purposes and simplification of decision-making.

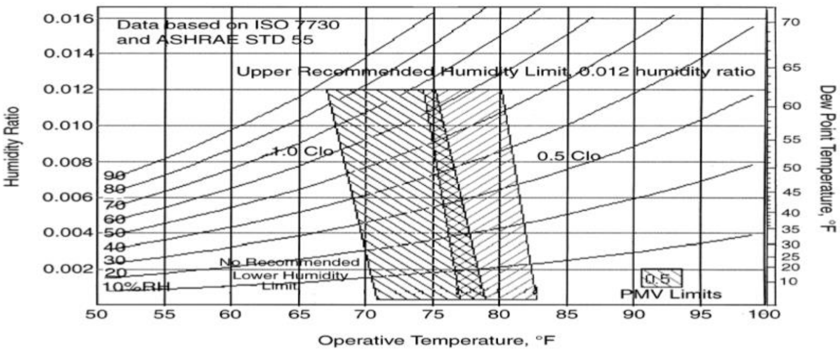


Figure 3: ASHRAE comfort zone, source: (Brager & de Dear, 1998)

A simple model with High, Low and shading device tested in Design builder with 2011,2020,2050 and 2080 climate data to observe total discomfort hours in each category as shown in Figure 4.

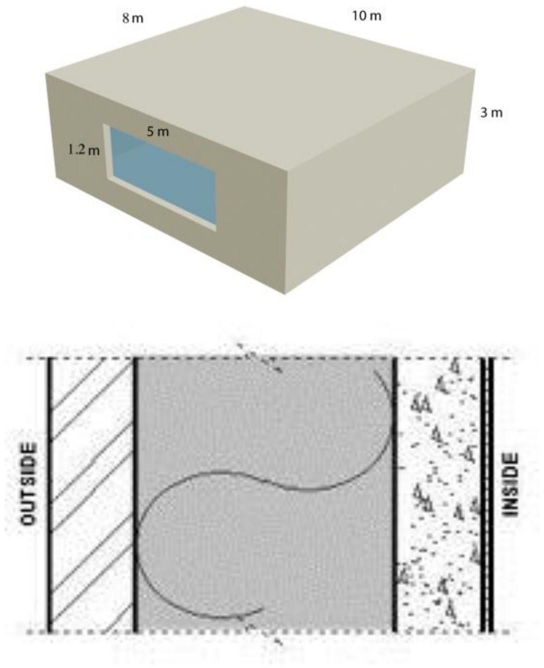
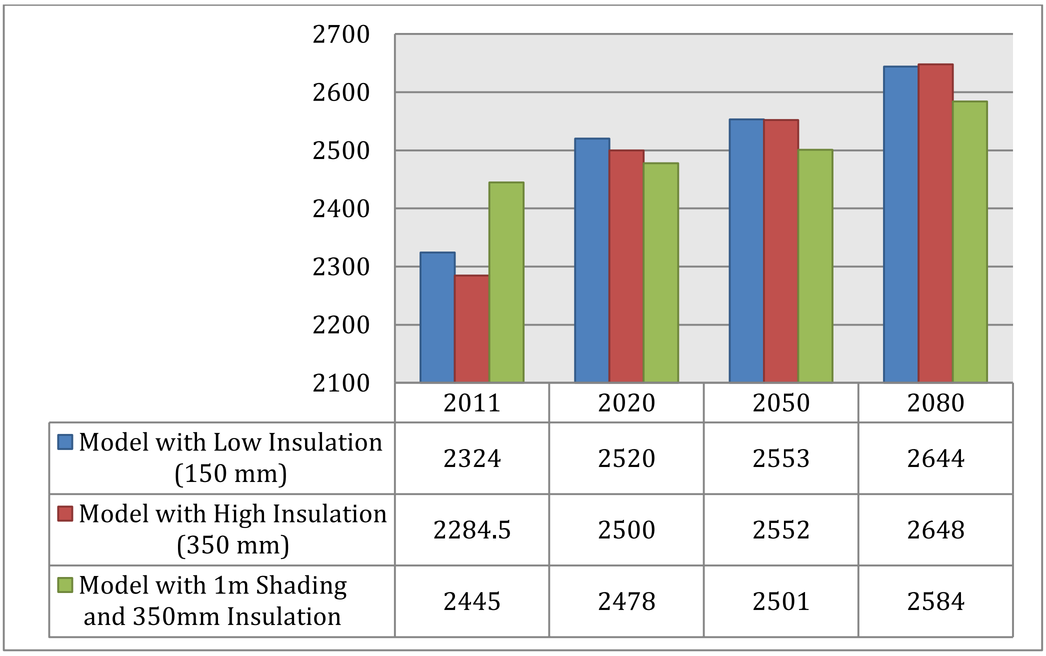


Figure 4: model under calculation, Brick and block Construction System



	2011	2020	2050	2080
🟦 Model with Low Insulation (150 mm)	2324	2520	2553	2644
🟥 Model with High Insulation (350 mm)	2284.5	2500	2552	2648
🟩 Model with 1m Shading and 350mm Insulation	2445	2478	2501	2584

Figure 5: Total discomfort hours in London

It can be noticed from graph and Figure above that increasing temperature will cause more discomfort hours and neither high insulation nor shading device can reduce total discomfort hours, Although 1m shading device effectively performs better than high insulation after 2020. Not that much differences between high and low insulation observed from 2020. Increasing the thickness of insulation would cause higher u-value and increasing total discomfort hours might be more overheating than overcooling in 2080.

Conclusion

The current standards, which mainly describe human thermal comfort conditions, appear to be an essential factor in the building sustainability determination. From the range of criticisms and uncertainties involved, however, a definite value cannot be employed to thermal comfort. State of mind is generally determined by expectation and perception of the occupants. Therefore, different persons may perceive the similar thermal environment differently or different persons may perceive the similar thermal comfort level at different thermal environments. In essence, the question is, how can thermal comfort standards play a role in facilitating the appropriate use of energy-efficient, climate-responsive building design strategies? Clearly, more integrative view of the indoor environment is needed. Most analyses look at one result at a time, and try to evaluate the ideal environmental conditions for thermal comfort optimization, energy consumption or indoor air quality (comfort).

In order to clarify the objectives for thermal comfort environment, it is better to define whether slightly warmer or cooler situation could still be considered in the range of acceptability in the existing standards. The answer may depend on context whether the priority is to optimize comfort or energy reduction. However, passive design strategies in tested model shows that discomfort hours could be reduced significantly by using shading device and high insulation, but depends highly on the period of occupation assumed.

Further research and development work

It is generally believed that our climate is changing and the thermal and energy performance of buildings will be affected. Architects and building engineers can no longer assume a constant static condition for their designs, and need to consider the values of design variables for future years. Also, a reduction in heating energy use and an increase in cooling requirement would result in a shift towards more demand for electrical power. The issue of carbon footprint of fuel mix and the role of renewable energy need to be addressed.

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Quantifying the Effect of Shading Devices to Improve Comfort in Current and Future UK Housing through Integrated Simulations with High and Low Thermal Mass Construction Systems

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ABSTRACT

Numerous architectural features exist that have impacts on buildings indoor climate and energy consumption, such as window size, thermal insulation and glazing material. In addition to these features, shading device (SD) effects can also have a major influence on building thermal performance. The aim of this research was to evaluate the thermal performance of buildings with the effect of SDs when high and low thermal mass is applied to the building. The role of SDs becomes more important in dealing with potential indoor overheating due to climate change effects. Building energy simulations were conducted for the effect of louvers and overhangs in high and low thermal mass construction system for two UK cities, Manchester and London, for present and future climates (2020, 2050 and 2080). It was found that SDs are more effective when applied to high thermal mass systems in both London and Manchester than low thermal mass system in both locations.

Key Words: Shading Devices, Thermal Mass, Climate Change and Thermal Comfort

1. INTRODUCTION

The thermal mass (a material’s ability to absorb, store and release heat [1]) of a building envelope can cause a delay in heat gain penetrating through walls [2]. SD is one of the passive design options that can cut part of the solar heat gain and consequently reduce the average heat flow and affect thermal mass performance. Simple and low cost SDs retrofitted to existing building façade improves future performance as climate changes.

On the other hand, building energy consumption is highly affected by SDs and glazed areas. External view and day lighting are important and desirable factors which create a tendency for building engineers to opt for more heavily glazed facades. However, the risk of overheating and overcooling then needs to be considered [3,4]. The most effective way to reduce cooling loads is to block solar load before it reaches the glass by external louvers and overhangs [5]. Fully shaded glazed areas can cause an up to 80 % solar heat reduction and improve indoor air quality by reducing overheating hours [6].

The latest climate change scenarios for the UK suggest considerable temperature increases by 2080 [7]. Figure 1 illustrates likely temperature increase in UK up to 2080 in high emission scenario. Therefore, more energy is needed for cooling loads and there is a necessity for long term thinking and considering passive design options like SDs for adaptability into the design process. Lisq [8] emphasized “the possible impacts of climate change on the building stock being built over the next few decades must be addressed today”.

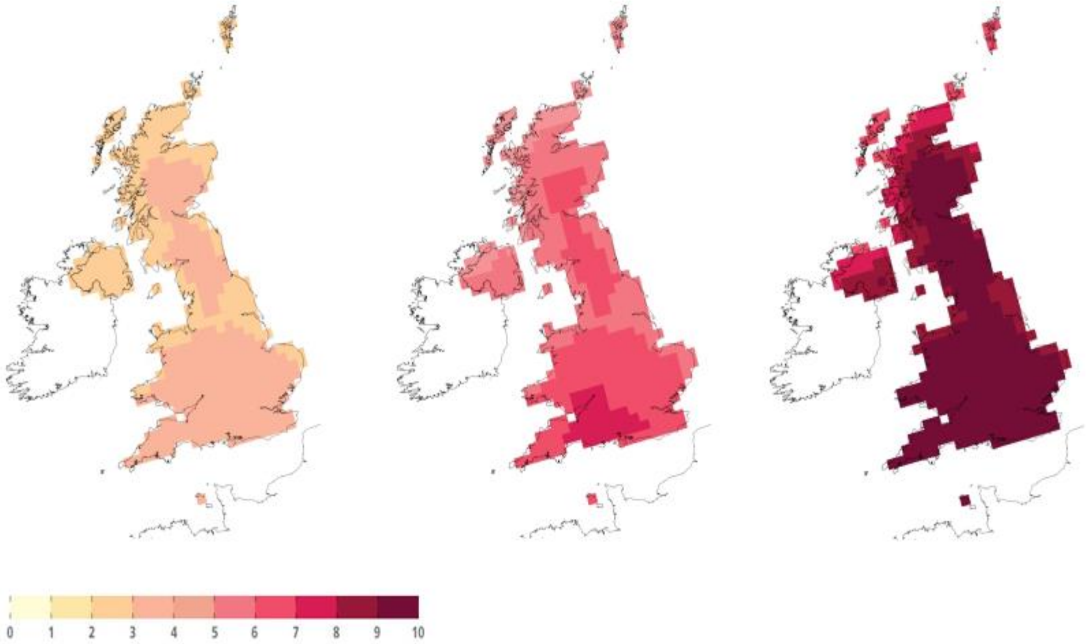


Figure1: Summer mean temperature in 2020, 2050, 2080; 90% probability level, very unlikely to be less than the degrees shown on maps [7].

2. METHODOLOGY

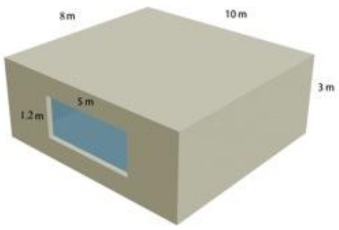
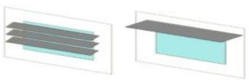
Two commonly used construction systems in UK have been selected and upgraded to achieve a U-value of 0.1 W/m^{2}K with high and low thermal mass performance. Design Builder software was used for running dynamic thermal simulations in a simple and south oriented building model as shown in Table 1. In order to quantify the effect of climate change, future weather data for three timelines of 2020, 2050 and 2080 in Manchester and London has been created by CCWeather Gen file in a process known as morphing [9].

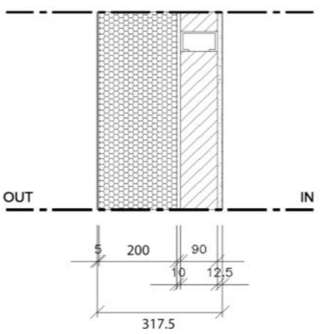
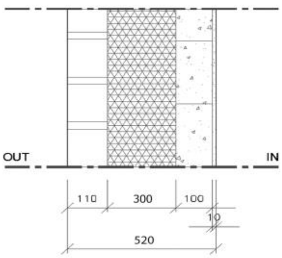
CCWeather Gen transforms UK's Chartered Institution of Building Service Engineers (CIBSE) TRY (Test Reference Year) files into future EPW files with projections from UK Climate Impacts Program (UKCIP). The process of creating future weather data on the basis of available climate change scenarios is called Morphing procedure. This EPW file is then applied to DesignBuilder to simulate the effect of 0.5m louvers and 0.5m, 1m overhangs as shown in Table 1. The infiltration was assumed as 0.25AC/H (air change per hour) and no ventilation was considered. A U-Value of 0.1 W/m^{2}K for the roof and floor and 0.8 W/m^{2}K for a triple glazed window were assumed.

2.1 THERMAL MASS

Thermal mass utilization in buildings is an effective way of reducing building heating and cooling loads, which is applicable in locations that have considerable daily temperature fluctuations. Thermal mass creates a reduction in temperature fluctuations and absorbs excessive energy both from solar and internal heat gains. Numerous studies have demonstrated that energy demands in buildings with massive walls could be lower than those in similar buildings with lightweight wall construction system in some locations [10]. Integrating thermal mass effect with another passive design options, such as double skin facades, achieved a better internal environmental performance compared with individual thermal mass effect [11][12][13]. This study aims to moderate the effects of solar gain and compare these effects in high and low thermal mass constructions as a mechanism for dealing with climate change effect in the UK (see Table1).

Table 1: Model used for simulation, construction system and their thermal characteristics

 Model used for simulations  Louvers and Overhang	**Decrement factor**	**Time constant (Hours**	**Admittance (W/m^{2}K)**	**U-Value (W/m^{2}K)**	**Thickness (mm)**

 Steel frame (SF) - Low thermal mass	**0.81**	**2.4**	**5.3**	**0.1**	**397.5**
 Brick and Block (BB) – High thermal mass	**0.23**	**5**	**1.16**	**0.1**	**520**

*Decrement factor: the ability to decrease the amplitude of temperature from outside to the inside

* Time constant: the time takes the maximum outside temperature makes its way to a maximum inside temperature

*Admittance: building fabric response to a swing in temperature

*U-value: overall heat transfer coefficient

2.2. Thermal comfort and discomfort

ASHRAE 55-2004 defines thermal comfort as the ‘state of mind that expresses satisfaction with existing environment’ [14]. This definition clarifies that a precise value cannot be assigned to thermal comfort, as it is highly dependent on residents’ perceptions and expectations. ASHRAE-55 is based on four environmental variables (dry bulb temperature, mean radiant temperature, relative humidity and air velocity) as well as activity and clothing level of the occupants.

For quantification purposes this paper considered this Standard as a measure to evaluate the thermal behaviors. Figure 2 demonstrates the range of likely comfort hours in this Standard. Therefore, any other situation would be considered as discomfort hours. For example, less than about 19°C and over than about 30 °C are considered as discomfort regardless of any situation of humidity level or clothing level.

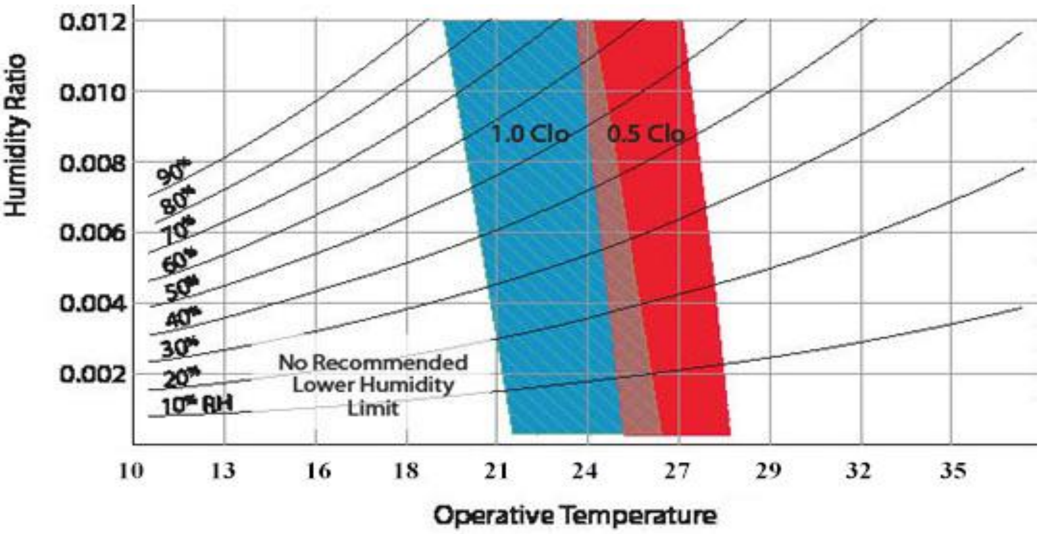


Figure 2: ASHRAE summer and winter comfort zones [14]

3. SOLAR GAIN AND SHADINGS MECHANISM

The Earth constantly receives solar radiation. However, the amount of solar radiation reaching the Earth's surface depends on cloud cover and absorption in the atmosphere [15]. Fixed SDs, as shown in Figure 3, can block solar radiation and reduce thermal loads during the summer [16][17].

Accurate estimates of future solar radiation levels are of fundamental importance but considerable uncertainty is involved due to technical limitations [1][18]. However, by morphing procedure as explained above the prediction shows a considerable shift in solar radiation particularly in London, which would cause more efficiency in SDs.

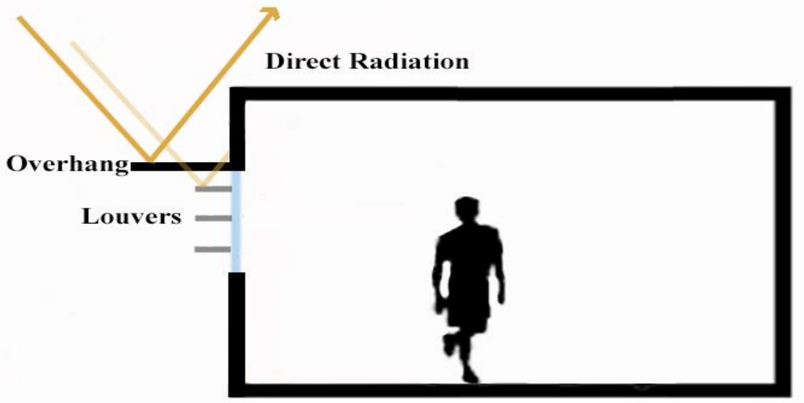


Figure 3: SDs (Overhang and louvers) mechanism in blocking solar radiation

4. Results and Discussion

It is assumed that SDs can reduce overheating and consequently improve thermal comfort inside the simple model. The results for the simulation with a 0.5 and 1m horizontal overhang and louvers are given in Figure 4.

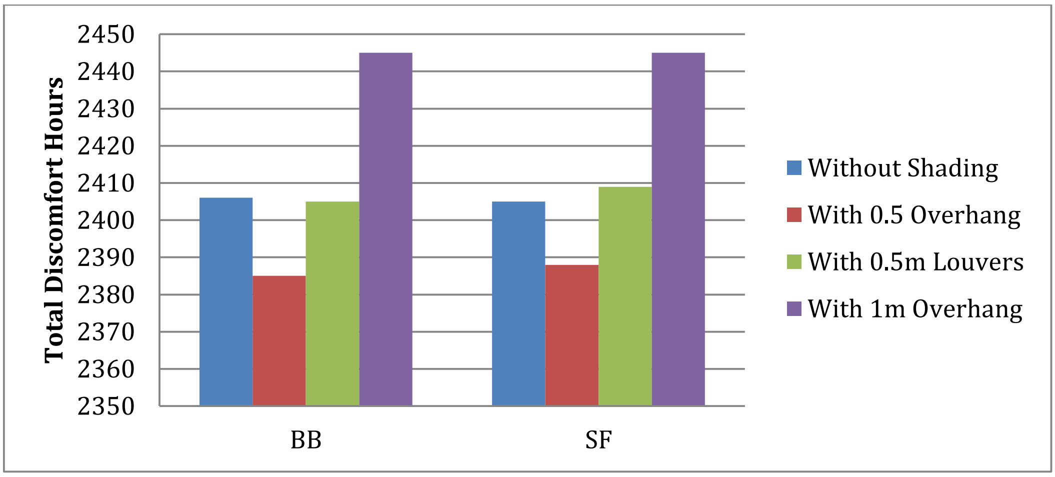


Figure 4 Total discomfort hours in base case model with and without SDs, Manchester 2011

Figure 4 demonstrates that the 0.5 m overhang is a more effective strategy in comparison with louvers and 1m overhangs in Manchester 2011. However, 0.5m overhang and louvers cause less discomfort hours in brick and block system with high thermal mass performance compared with low thermal mass performance steel frame although the differences are not considerable. Figure 5 to 7 demonstrate these effects in future.

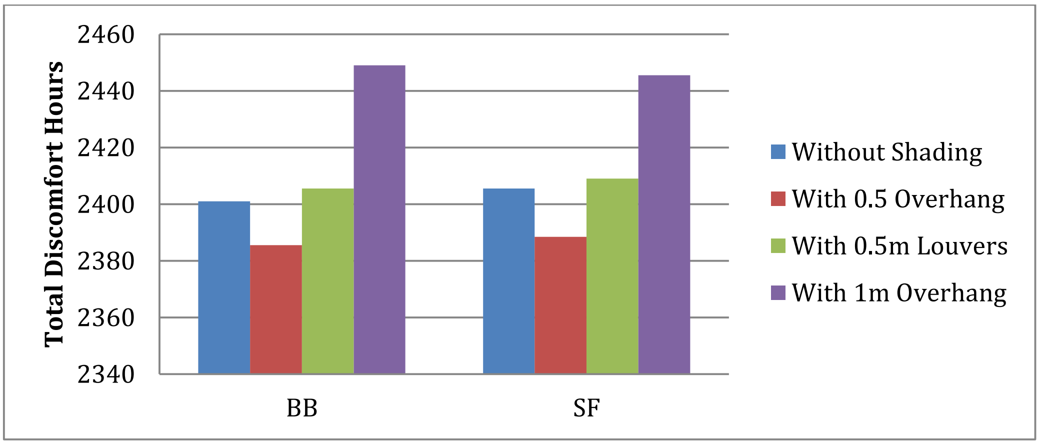


Figure 5 Total discomfort hours in base case model with and without SDs, Manchester 2020

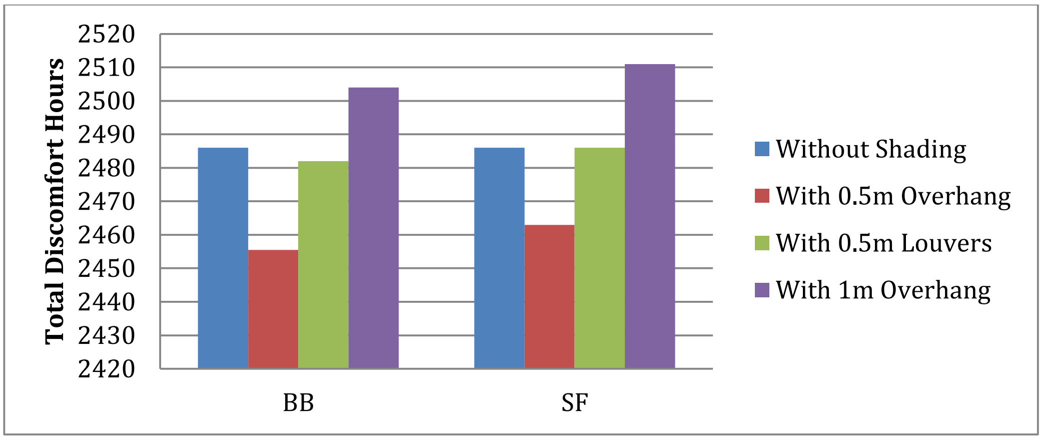


Figure 6 Total discomfort hours in base case model with and without SDs, Manchester 2050

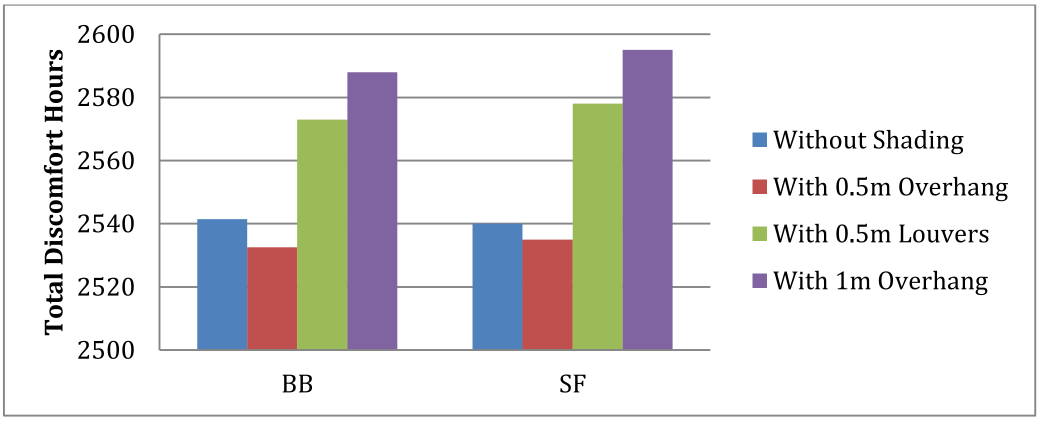


Figure 7 Total discomfort hours in base case model with and without SDs, Manchester 2080

In 2020, 2050 and 2080 the 0.5m-overhang performs better than the others and all SDs are more effective when applied to the BB construction system. Obviously, SDs cause less absorption of solar gain and consequently affect thermal mass performance. Any success in thermal mass performance in building is mainly due to the effect of absorbing excessive solar gains [19]. Therefore, SDs can have considerable effect on their performance. Figure 8 to 11 demonstrate SDs effects in London.

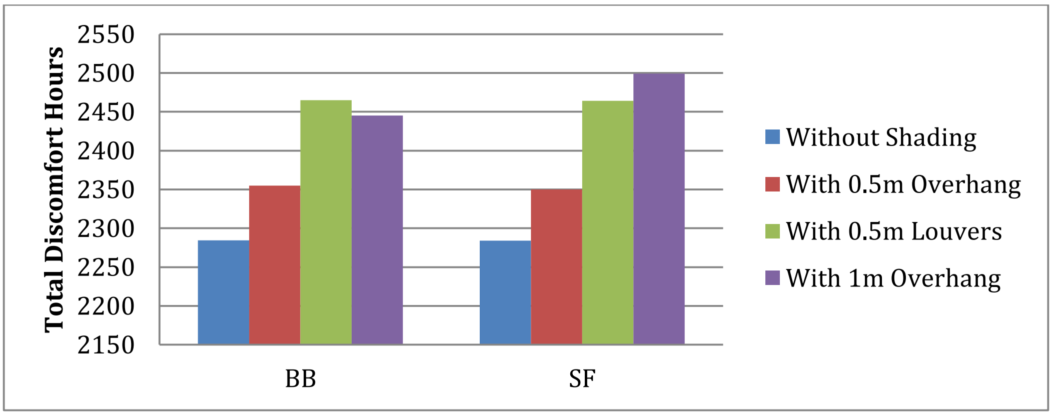


Figure 8 Total discomfort hours in base case model with and without SDs, London 2011

Unexpectedly, neither of the SDs causes less total discomfort hours in London, 2011. This is probably due to the increase in total overcooling hours. Less solar gains can cause a considerable increase in overcooling hours, which probably replace the summer overheating discomfort hours in total. Both high and low thermal mass systems show almost similar performance except for the 1m-overhang case. However, Figures 9, 10 and 11 show that differences become more considerable for future climate scenarios.

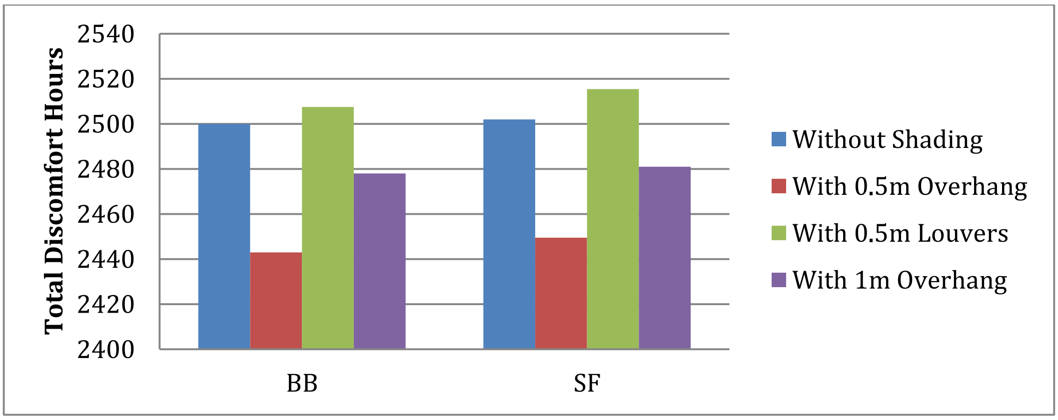


Figure 9 Total discomfort hours in base case model with and without SDs, London 2020

Comparing Figure 9 with Figure 8 shows that as the temperature gradually increases in London, by 2020, 0.5m and 1m-overhang shadings cause less total discomfort hours. Better performance of the 1m-overhang shading in comparison with 0.5 louvers came as a surprise in simulations. As in Manchester, BB construction system with high thermal mass has less discomfort hours compared with SF. Figure 8 illustrates that any types of SD will improve thermal comfort inside the model compared with the case without any SDs.

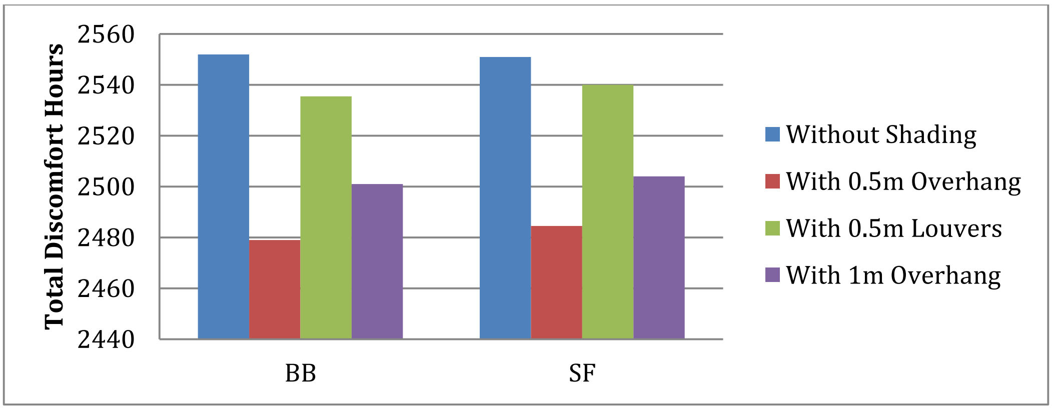


Figure 10 Total discomfort hours in base case model with and without SDs, London 2050

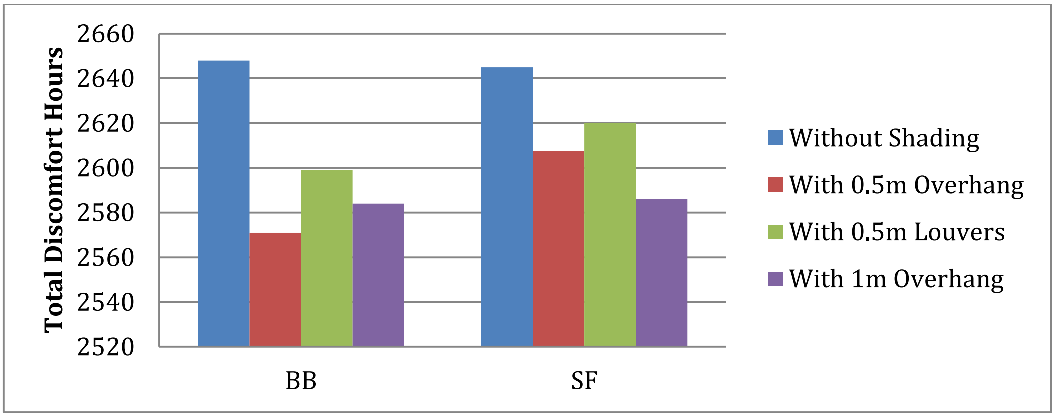


Figure 11 Total discomfort hours in base case model with and without SDs, London 2080

Figures 10 and 11 show that from 2050 afterwards in London, all SDs reduce discomfort hours considerably and an overhang of 0.5m seems to be the most effective shading type. Generally, it can be observed that SDs as a kind of “flexible strategy” could reduce the risk of discomfort hours effectively. Differences between BB and SF become more considerable for 2050 and 2080 timelines in London and SDs perform better when applied to the BB system.

5. CONCLUSION

In order to mitigate the overheating risk of climate change and to improve thermal comfort in current and future UK housing, a new concept of integrating solar shading types of 0.5 and 1m with high and low thermal mass construction system has been investigated. Therefore, this paper provides a methodology for future adaption by addressing future climate possibilities. Generally, thermal simulations were carried out to show comparable results of the SDs effect on high and low thermal mass systems with respect to thermal comfort.

In London, the significance of a 0.5 overhang and louvers are higher than Manchester in terms of total discomfort hours. Also, the effects of SD with high thermal mass construction are higher than low thermal mass both in London and Manchester. Consequently, larger energy load reductions can be expected when a high thermal mass system is integrated with SDs in London.

Furthermore, the study considers total discomfort hours but further investigation in London 2080 clarified that in each month considerable differences exist and design decision maker should notice when temporary SDs are applied, perhaps further investigation in each month should be accomplished.

FURTHER STUDIES

Different angles of SDs might change their efficiency and cause more or less comfort hours in buildings. Further studies might focus on enhancing solar shading angles to deal with future climate scenarios and propos an ideal model.

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The Potential of Phase Change Materials to Reduce Domestic Cooling Energy Loads for Current and Future UK Climates

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Abstract

Phase change materials (PCM) are known as an effective technology to store larger amounts of thermal energy per unit mass than conventional thermal mass building materials such as concrete and stone. They add thermal stability to lightweight constructions without adding physical mass. This paper presents a method to assess the effect of PCMs on thermal comfort and energy consumption in UK dwellings in summer months. A methodology is presented to assess the impact of climate change temperature increases in the UK by considering current, 2020, 2050 and 2080 weather scenarios using the dynamic thermal simulation software DesignBuilder, which employs EnergyPlus as its calculation engine. The study used simulations of a high performance detached house model with a near Passivhaus standard in London, where the impact of climate change effect is predicted to be significant. It was shown that appropriate levels of PCM, with a suitable incorporation mechanism in to the building construction, has significant advantages for residential buildings in terms of reducing total discomfort hours and cooling energy loads.

Keywords: PCM, Climate Change, Thermal Comfort, Cooling Loads

1. Introduction

The long-term increase in the price of fossil fuels, their reducing availability and the need to decrease carbon emissions, show the need for new, more rational and energy efficient technologies. Up-to-date climate change scenarios for the UK imply considerable temperature rises by 2080 [1]. Figure 1 shows likely average temperature increases in the UK up to 2080 for a high emission scenario in summer months. As a result of the potentially much hotter summers, more energy will be required to cool UK houses to comfort conditions. Lisq [2] has stressed that '*the possible impacts of climate change on the building stock being built over the next few decades must be addressed today*'. Consequently, there is an obligation on designers to consider alternative approaches that will, using low carbon technologies and passive strategies, reduce future overheating and energy usage in dwellings. One such approach is the use of smart materials like phase change materials (PCM) in to the design process.

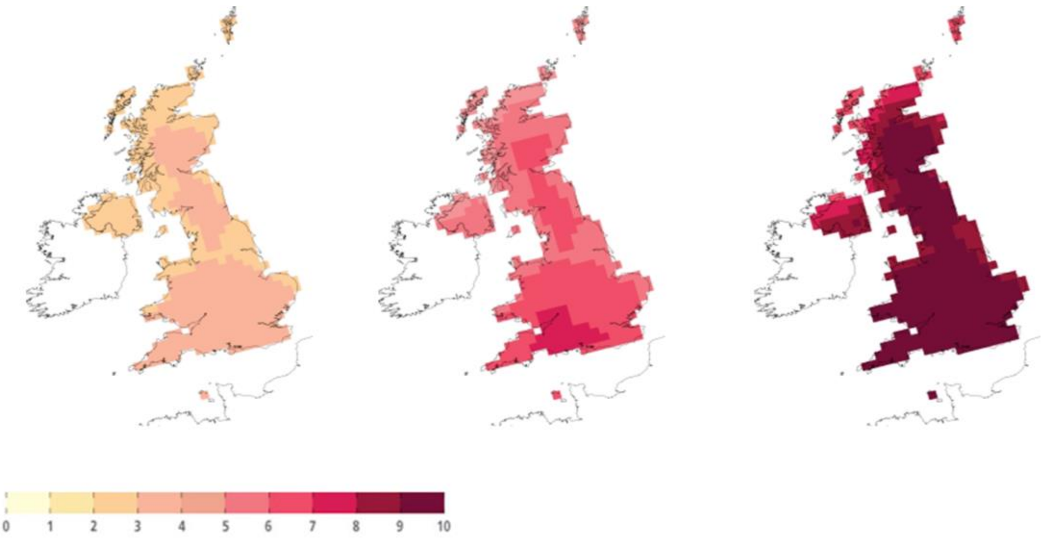


Figure1: Summer mean temperature increases from 2020, 2050, 2080; 90% probability level, very unlikely to be greater than the increases shown on the maps [3]

Generally, the concept of utilizing PCMs is to increase thermal mass without adding weight to the building system. PCMs are materials that undergo a phase change process by reorganizing their microstructure, causing the release or storage of heat. Practically usable PCMs must undergo this phase change at temperatures normally encountered in buildings. The latent heat energy absorbed the PCM on melting (and released on re-solidification) is much greater per unit mass of material than the specific heat energy absorbed (or released) by the material undergoing temperature changes of the size normally encountered in buildings. This means that a form of programmable inertia can be reached by controlling the melting temperature and quantity PCM used in the building's structure.

The aim of this study is to quantify the PCM effect on cooling loads and thermal comfort in a UK detached house. The study introduces a mechanism to apply and assess PCM in buildings which results in higher energy savings and increased comfort hours compared to the traditional methods of construction. The method demonstrates its capability not only in current weather but also for future climate scenarios.

1.1 PCM applicability in buildings

PCM have considerable thermal energy storage densities and are able to absorb or release large quantities of energy by undergoing a phase change. [4]. However, the way PCM are applied in a building envelope is important in terms of their actual temporal and thermal performance which should, ideally, match the demand. For example, design decision makers should regulate how much heat needs to be absorbed by PCM, when is the peak time in the day (in terms of the heat flows) and whether the discharge time of the material is short enough to be effective before the next cycle begins. For better efficiency of PCM, an appropriate ventilation strategy is also necessary before integrating PCM into the building envelope. This might become a serious issue in well-insulated buildings.

Carter [4] compared two PCM with melting points of 21°C and 27 °C and investigated how much PCM was required. His study showed that the high phase change temperature could lead to overheating and that the PCM with the lower melting point one required large surface areas. He discovered that in locations with low solar radiation levels and mild winters (like the UK) the PCM that work effectively are those which have their change of phase temperature above the indoor thermal comfort average temperature.

Principi et al. [5] compared three box-like structures with: a) PCM; b) a ventilated air gap and c) PCM + ventilated air gap. They concluded those two boxes with PCM consumed up to 50% less energy. Furthermore, Shilei et al [6] installed PCM boards in a room and found that PCM were effective in reducing indoor temperature fluctuations in summer and winter. Voelker et al [7] performed similar studies in Germany and concluded that PCM with temperature ranges between 25°C and 28°C could reduce indoor peak temperature by up to 4°C. They also discovered that in the absence of proper ventilation, PCM will lose its heat storage capacity after a few consecutive hot days.

Feustel and Stetiu [8] also found PCM were effective in decreasing indoor air temperatures for Californian climates, and emphasized that when outside temperatures were greater than 18°C then utilizing mechanical ventilation was necessary for optimal performance. However, Neeper [9] suggested wallboards with a medium performance of 400kJ/m^2 latent heat capacity can perform almost similarly to exposed masonry on internal surfaces.

Furthermore, Farid et al. [10] and Sharma et al. [11] suggested the following desirable features for PCM use in buildings::

6- Thermal properties

- To assist discharging and charging of heat, a high thermal conductivity (over $\sim 0.5\ W/m$℃) of PCM is required
- To minimize the essential physical size, high latent heat per unit volume is required (latent heat capacity is the quantity of heat energy needed for a state change of a unit mass of a substance, J/Kg [12]).
- To match a building's operative temperature, an adequate PCM phase-transition temperature is required

7- Physical properties

  - High density to make containers smaller
  - Small volume change during the phase transformation

8- Chemical properties

  - Long-term durability for sTable capability over repeated cycles
  - Non toxic to minimize health and safety risks
  - Completely reversible melting and freezing cycle

9- Kinetic properties

  - Adequate crystallization rate when freezing to allow the system to meet heat recovery demand
  - Adequate nucleation rate to prevent super cooling

10- Economics

    - Cost effectiveness and abundance

The PCM used for simulations in this study had the characteristics shown in Table 1. Melting point and thickness was decided by means of dynamic simulations as described in the Methodology section. Therefore, the chosen PCM met most of the required properties mentioned above and the results of this paper can be considered applicable for use in the UK and similar moderate climates.

Table 1, Thermal characteristic of PCM used for dynamic simulations

Density	900 $kg/m3$
Latent heat storage capacity	110 kJ/kg
Specific heat storage capacity	1.2 $kJ/kg°C$
Total heat storage	110 kJ/kg
Thermal conductivity liquid phase	0.52 W/m°C)

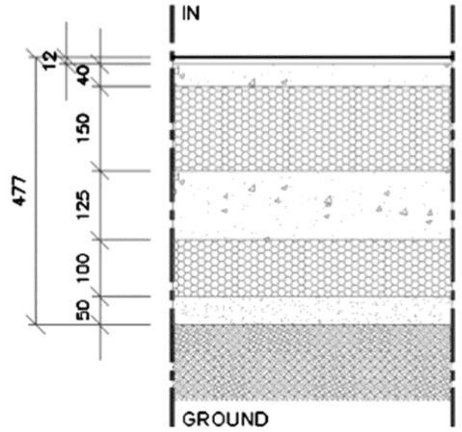
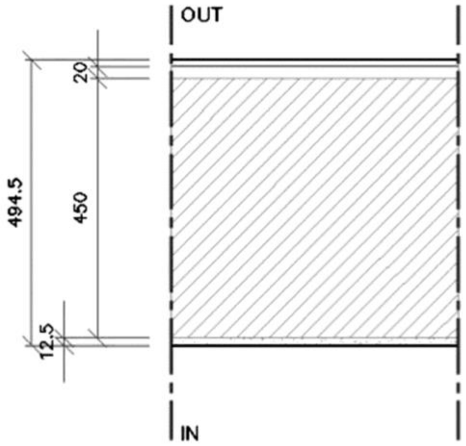
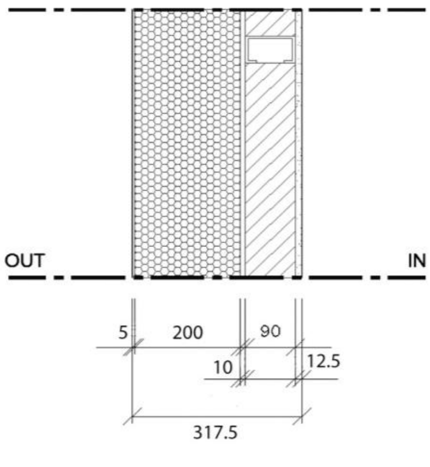
1.3 PCM classifications

Generally, PCMs are divided into eutectic, organic and inorganic types. Organic ones are mainly paraffin and fatty acids, which have high latent heat and low conductivity. Inorganic ones are mainly metallic and salt hydrates, which have a higher latent heat compared with organic ones as well as high thermal conductivity and lower costs. Eutectics are mainly consisting of two or more components and can be organic-inorganic combinations. [13][14].

2. Methodology

A detached house was designed and modelled in DesignBuilder (DB) on the basis of the German Passivhaus standards. Passivhaus is one of the world's fastest growing building energy performance standards and was developed in Germany in the 1990s [15]. No mechanical ventilation is used in the simulations and the model is a two storey house with three bedrooms. A U-Value of 0.1 W/m^2K was applied to exterior walls, the roof and the ground floor (Table 2). The infiltration rate was set 0.6 air change per hour (ACH). Natural ventilation has also been considered in the simulations. The modelled windows were triple glazed with argon filling in a UPVC frame type with a U-Value of 0.8 W/m^2K. Figure 2 demonstrates the plans and Figure 3 shows the 3D model used for the simulations.

Table 2: Ground floor, roof and exterior walls in the model

	Ground Floor From top to bottom; 12mm pine wood floor, 40mm concrete screed, 150mm extruded polystyrene (EPS), 125mm concrete slab, 100mm extruded polystyrene (EPS), 50mm sand, crushed brick
	Roof From top to bottom; clay roof tile, roofing felt, 20mm air cavity, 450mm Rockwool, 12.5mm plasterboard
	Steel frame for exterior walls From out to in: 5mm rendering, 200mm extruded polystyrene (EPS), 10mm plywood, 90mm Rockwool, 12.5mm plasterboard

For future climate scenarios that were used for simulations in this study, the weather files were available from the UK Climate Impact Programme (UKCIP), which provides monthly values of climate data for the UK until 2080 [16]. The University of

Southampton in the UK has developed an Excel file named ‘CCWeather Gen’ to create future weather files for simulation in DB from UKCIP predictions. [17]. For appropriate climate change scenarios related to overheating risk the ‘extreme’ scenario for three climate periods was used. Extreme climate change is characterized by the high emissions scenario at 90% probability (where change is highly unlikely to be more than a given value).

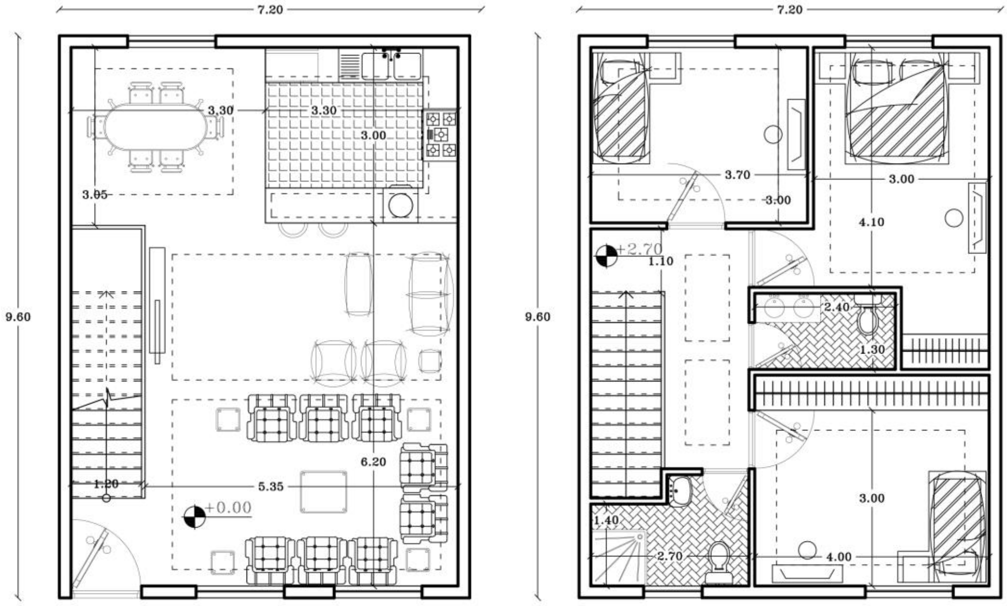


Figure 2 Ground floor and first floor

Figure 3: 3D model (south-facing windows)

Figure 4 shows how the PCMs are installed in the wall construction system. The concept of providing an air gap is similar to ventilated facades and provides the advantage of extra insulation and airflow [18][19][20], which maximize the operation of the PCM.

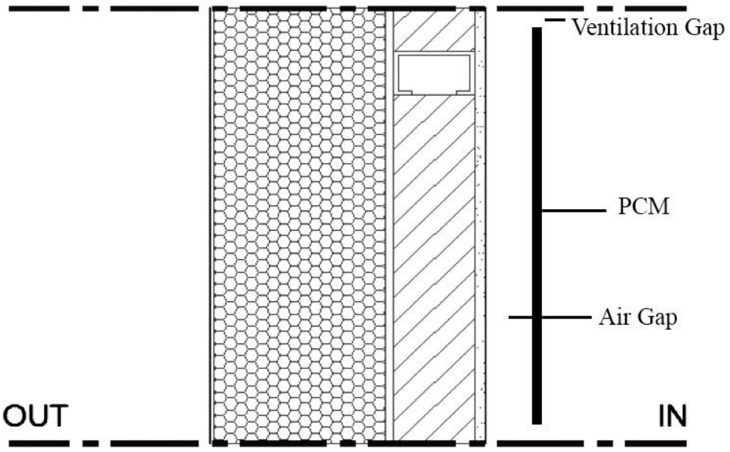


Figure 4: PCM installation in building envelope

In order to determine the optimum air gap, PCM thickness and melting point temperature, a range of PCMs with 23, 25 and 27°C melting points were examined for PCM thicknesses of 12, 24, 36, 48 and 60 mm and with 15, 20, 25, 30 and 35 mm wide air gaps. Simulations in DB showed that a 25mm air gap was the optimum width in terms of annual energy consumption per square metre (kWh/m^2) in London for current weather) while the 48 mm thickness for PCM with 25°C melting point seems to be an optimum (see Tables 3, 4 and 5). Therefore, in the future climate scenario analyses, below, a 25mm air gap with a 48 mm thickness of 25°C melting point PCM was used.

Table 3 House annual energy consumption (kWh/m^2) for PCM model with 23°C melting point

	PCM thickness 12mm	PCM thickness 24mm	PCM thickness 36mm	PCM thickness 48mm	PCM thickness 60mm
Air gap 15mm	60.2	60	59.7	58.9	58.9
20mm	60.2	60	59.7	58.9	58.9
25mm	60.1	59.8	59	59	59.2
30mm	60.1	59.8	59	59	59.2
35mm	60.3	60	59.8	59.8	59.8

Table 4 House annual energy consumption (kWh/m^2) for PCM model with 25°C melting point

	PCM thickness 12mm	PCM thickness 24mm	PCM thickness 36mm	PCM thickness 48mm	PCM thickness 60mm
Air gap 15mm	59.2	59	58.7	57.9	57.9
20mm	59.2	59	58.7	57.9	57.9
25mm	59.1	58.9	58	57.2	57.2
30mm	59.1	58.9	58	57.2	57.2
35mm	59.2	59.1	58.5	58.3	58.3

Table 5 House annual energy consumption (kWh/m^2) for PCM model with 27°C melting point

	PCM thickness 12mm	PCM thickness 24mm	PCM thickness 36mm	PCM thickness 48mm	PCM thickness 60mm
Air gap 15mm	60.5	60.3	60.1	59.9	59.9
20mm	60.5	60.3	60.1	59.9	59.9
25mm	60.3	60	60	59.8	59.8
30mm	60.3	60	60	59.8	59.8
35mm	60.4	60.2	59.9	59.9	59.9

3. Thermal comfort and discomfort

The ASHRAE-55 Standard describes thermal comfort as the ‘state of mind that expresses satisfaction with existing environment [21]. This definition emphasizes that an accurate absolute value cannot be given to thermal comfort. Furthermore, it is highly reliant on a person’s perceptions and expectations. ASHRAE-55 works on the basis of four environmental variables (dry bulb temperature, mean radiant temperature, relative humidity and air velocity) as well as the activity and clothing level of a person. In order to quantify the effect of PCM, this paper considered the ASHRAE-55 Standard as a measure for evaluation. Figure 5 shows the range of likely comfort conditions from this Standard. For instance, less than 19°C and over than about 28 °C are classified as discomfort, regardless of any other factors that might have an impact such as humidity or clothing level.

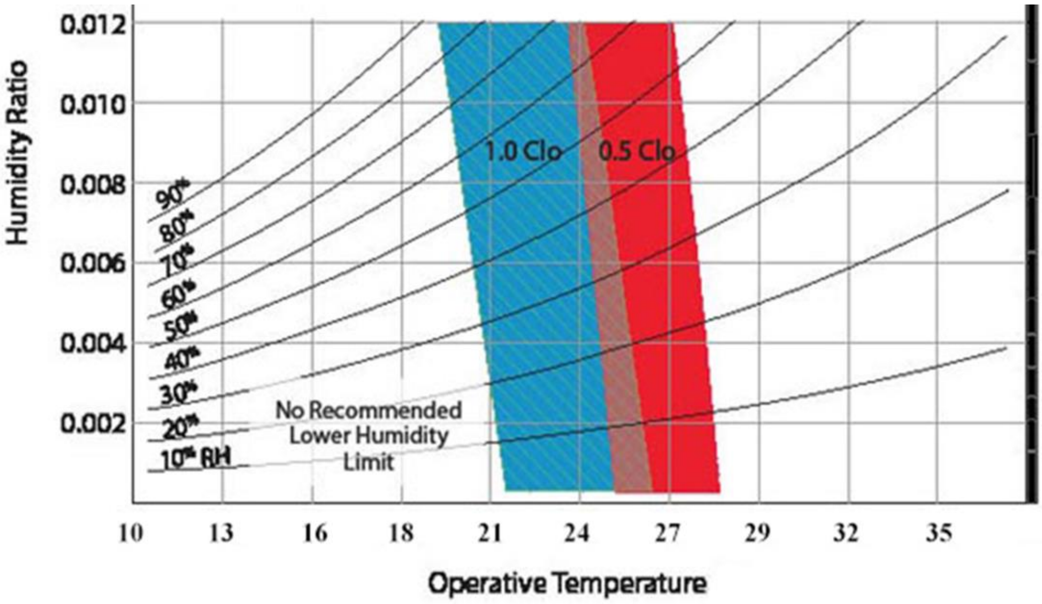


Figure 5: ASHRAE Comfort zone [21]

4. Results and Discussion

4.1 Model without PCM

A detached house in London under current and future climate scenarios was simulated to quantify overheating risk and energy consumption. Simulation results given in Figure 6 show predicted discomfort hours for summer months for the detached house before PCMs were installed. Figure 6 also demonstrates that, despite overall discomfort in current conditions being small, discomfort hours are going to be highly affected by climate change in the future. There is relatively little increase in June but future discomfort hours for July and August show a sharp increase from 2020 onwards compared to 2011.

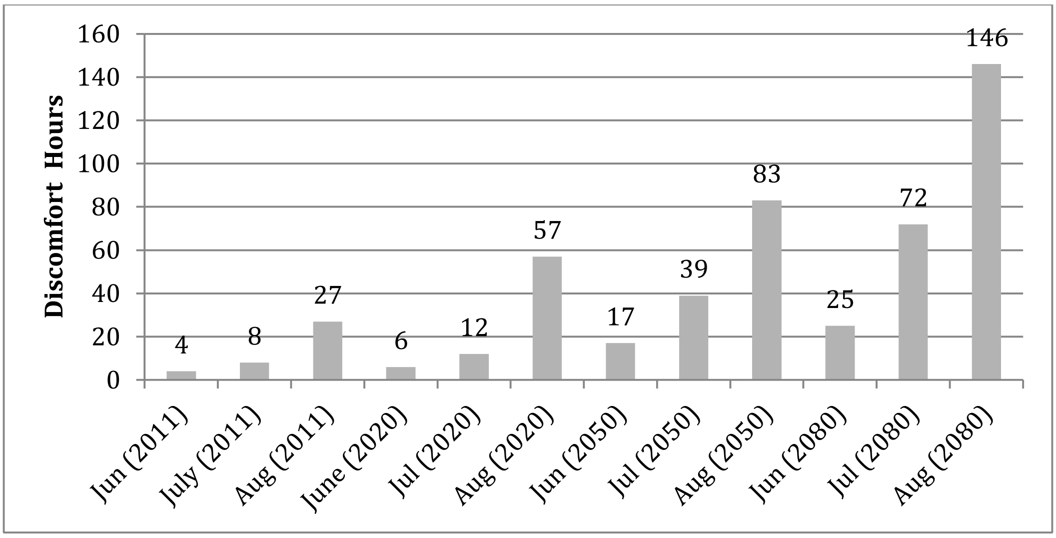


Fig 6 Discomfort hours in summer months in model without PCMs

Changes in discomfort hours in London are obviously due to the increase in external air temperature in future summer months. It can be concluded from the results that in the summer period the operative temperature (the average of internal dry bulb air and mean radiant temperatures) may exceed 28 °C (around the upper limit of the comfort range as shown in Figure 5). Without the application of adaptive strategies, such as PCM panels, it is highly likely thermal discomfort would become an increasing problem in dwellings.

The simulated detached house was very well insulated and very air tight, with a minimum infiltration rate of 0.6 ACH. These factors might also have some effect on the number of discomfort hours and an increase operative temperature. Besides, natural ventilation is also considered during the daytime to maximize the thermal comfort hours.

Figure 7 demonstrates the cooling loads required to remove discomfort hours in the detached house in the summertime before PCMs were installed. An energy efficient fan coil unit was used to cool the house and, as might be expected, more energy was required in July and August to remove overheating compared to June. There is a sharp increase in cooling loads from 2050 onwards. The overall cooling load in 2020 is estimated as 131 kWh, which is 1.7 times greater than in 2011; in 2080 the load is 716 kWh - over fourteen times more than the 2011 cooling load. Clearly, these results indicate that current sustainable design standards and regulations may result in high levels of discomfort in future. In addition, future energy prices are highly likely to increase due to fossil fuel reserve limitations and uncertain market share for renewables due to their intermittency problems [22]. Therefore, the necessity for new design approaches, such as smart materials, in new dwellings should be addressed.

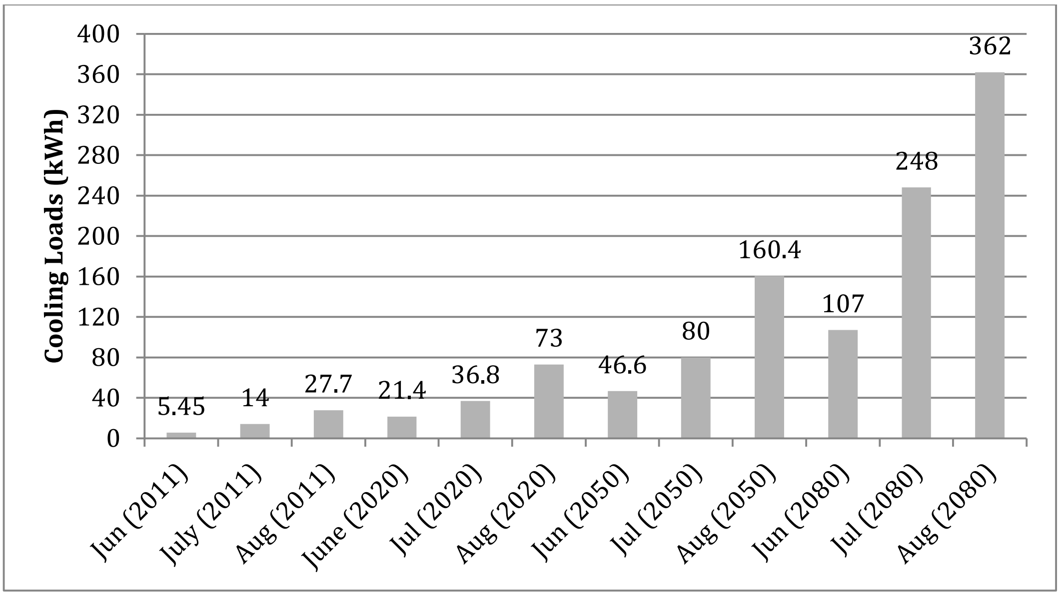


Figure 7 Cooling loads required to remove discomfort hours in summertime in 2011, 2020, 2050 and 2080 in London for house with no PCM installed.

4.2 House Model with PCM

PCM wallboards were installed in exterior walls and partitions inside the house, using the optimum configuration determined above, and simulations carried out without any consideration of furniture effects. Figure 8 demonstrates simulation predictions after installation of the PCM wallboard. As can be observed, there is negligible impact on discomfort hours for 2011 when the PCM is applied.

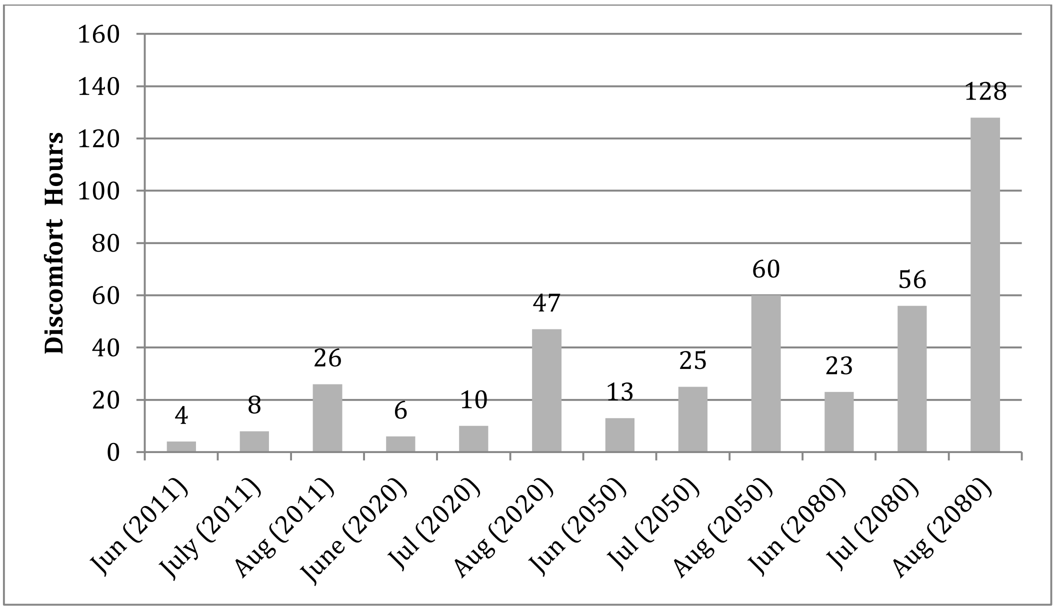


Figure 8 Discomfort hours in summer months in model with PCMs

The PCM used in the wallboards has a melting point of 25°C. However, PCM wallboards have specific capacity and as the indoor temperature exceeds a certain level then PCM wallboards are not able to remove the overheating risk completely. Besides, when the temperature constantly remains above the PCM melting point, it would affect the PCMs' performance [7]. Figure 9 shows not only the considerable effect of PCMs in reducing operative temperature but also confirms that on very hot days, like the 8th of August in 2080, they might not be able to remove completely the overheating risk.

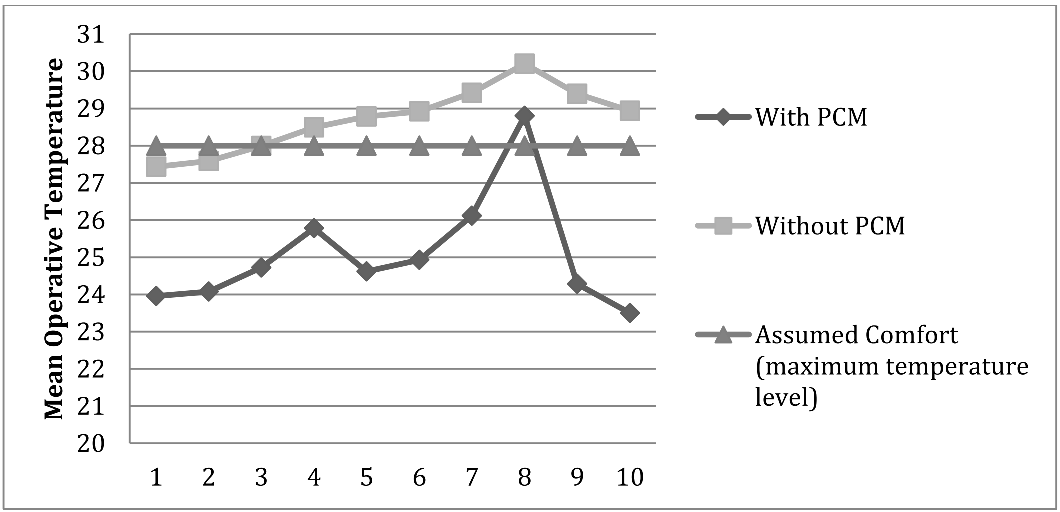


Figure 9: Operative temperature in London 2080 from 1-10th of August

Figure 10 shows the cooling loads in kWh required to remove discomfort hours in the model with PCM wallboards in summertime. A similar cooling system was used for cooling in the house model without PCM and again, as was expected, more energy is required in July and August to remove discomfort hours compared to June. There is a slight increase in cooling loads from 2020 and a significant increase in August 2080.

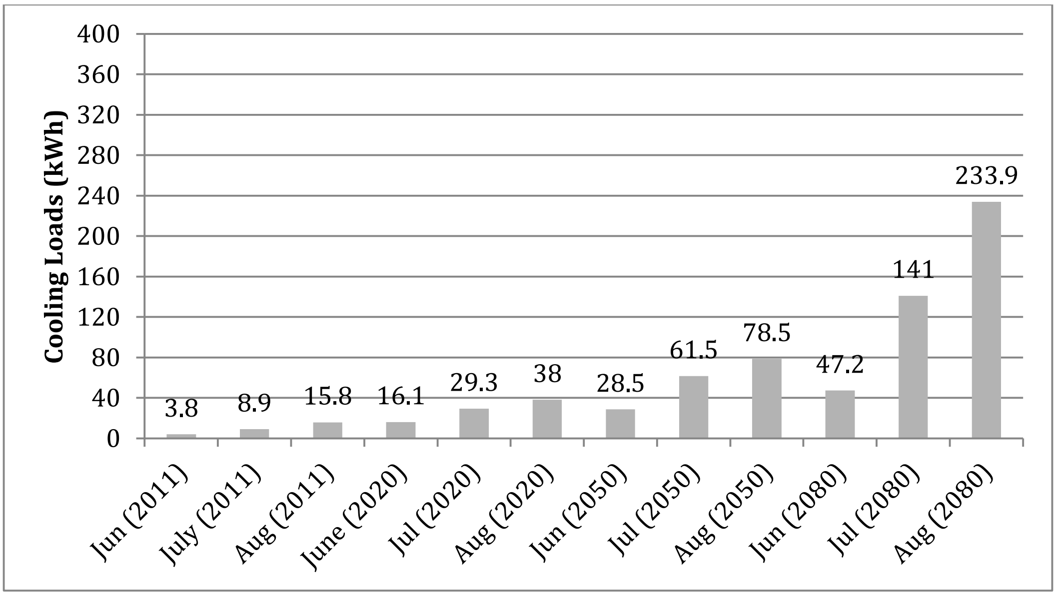


Figure 10 Cooling loads required in a model with PCM in summertime for all timelines

Figure 11 shows the cooling loads reduction when PCM is applied to the house model and the percentage decrease in load.

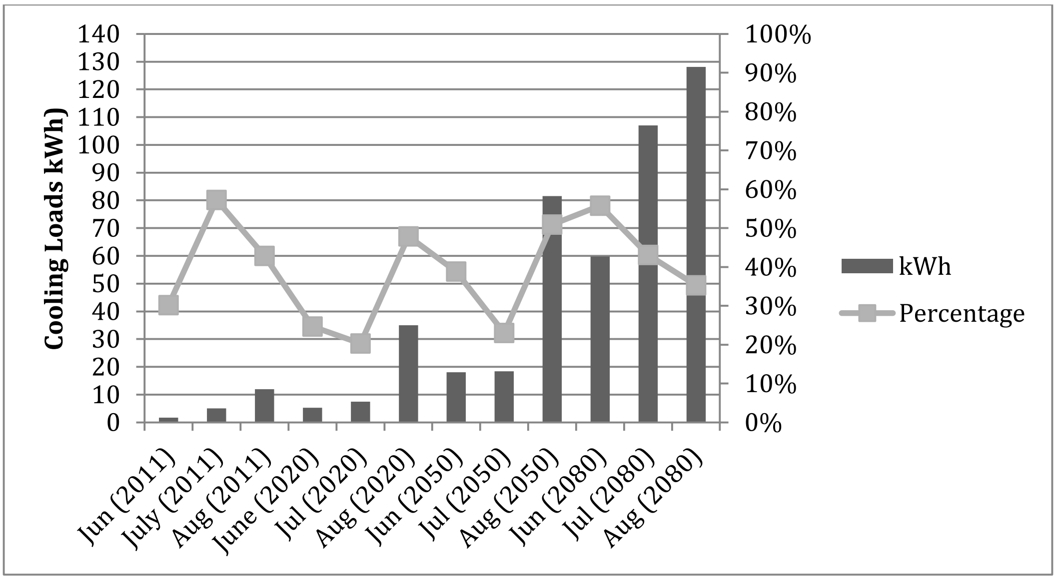


Figure 11 Cooling loads reductions in kWh and percentage decrease with PCM installed

PCM technology is relatively new to the construction industry. Future prices of PCM products, their long term durability and energy cost fluctuations all make calculating payback times for PCM highly uncertain. Furthermore, it was not an objective of this research to perform a present-value, whole-life cost analysis of the use of PCMs. However, a simple analysis can be performed, assuming an electricity price of 15 pence per kWh [23] and an initial cost of installing 76.2 m^2 PCM wallboards as $\pounds 1143$ [24], then the payback period would not be favorable in the near future (considering only cooling loads savings). However, the efficiency of PCMs in reducing energy consumption and improving comfort hours could create market growth in the coming years, which potentially would lead to cheaper installation cost and more favourable payback times in the future.

5. Conclusion

In a changing outdoor climate, new buildings must be designed to control indoor temperatures as passively as possible in order to reduce energy consumption. PCM is found to be a good passive design option to alleviate overheating risk problems when applied as a building material. PCMs can improve the thermal performances of building fabrics and moderate the indoor temperature in hot periods of the year.

This study focused on the effect of PCMs as one of the available thermal energy storage technologies in UK housing, and presents the effect of PCM on thermal comfort and energy consumption in summer months, with the main focus being on climate change effects in London. A mechanism for integrating PCMs with ventilated air gaps in the building envelope has been proposed. The system can be used in both new buildings and refurbishment schemes.

The air gap provided has the advantage of providing air circulation for PCM boards as well as an extra insulation layer for the building. The effect of PCMs for current London weather is very limited but becomes more effective as temperature increase to 2080 levels. Most cooling load savings would occur in the month of August and from 2050 onwards. Cooling load savings could be up to 128.1 kWh in August 2080.

Further research is suggested to focus on examining different house types, such as terraced and semi detached dwellings, together with apartments, as these are common UK housing types. Further work might also consider the durability and long-term thermal behavior of PCM wallboards as well as increasing geographical range of research.

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International Conference on Sustainable Design, Engineering and Construction

Heating and Cooling Loads in High Performance Construction Systems- Will Climate Change Alter Design Decisions?

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Abstract

Climate change and its consequences are of great concern. Buildings can be affected by climate change in different ways, such as changes in energy needs and thermal comfort. However, the challenge is to quantify and assess the uncertainties involved in future climate data as well as the relevant adoption strategies. The aim of this paper is to demonstrate potential energy consumption changes in high performance building construction systems in a changing climate. In this paper, current and future weather data of three time slices of 2020, 2050 and 2080 were used to simulate the performance of a simple building in Manchester and London using DesignBuilder software which employs Energy Plus as its calculation engine. Five of the most commonly used and high performance construction systems were examined in terms of energy consumption in this model and results are given. In general, this paper provides a useful methodology for simplification in design decision-making for current and future UK housing. It is observed that future climate scenarios do not have major effects in qualitative comparisons of construction systems.

Peer-review under responsibility of organizing committee of the International Conference on Sustainable Design, Engineering and Construction 2015.

Keywords: Climate Change; Energy Consumption; Construcion Systems; UK

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1. Introduction

Among the developed countries, UK has the oldest housing stock [1] and this is a real constraint on the energy saving development. The age and condition of the property is linked to its energy consumption. Preston [2] found new build to be a better solution

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compared with retrofitting to deal with fuel poverty and carbon targets. Hamza and Dudek [3] highlighted that in the UK new build adds only around 1% to the housing stock and Boardman et al [4] emphasized that the rate of demolition should increase considerably to achieve the target of energy efficient dwellings.

Currently, approximately 50% of carbon emissions are from buildings in the UK [5]. Therefore, there is a necessity to consider the implementation of energy efficient strategies in construction. Domestic energy consumption alone is responsible for more than 30% of all primary energy demand and almost 60% of this consumption is used for space heating in the UK [5].

According to the Brundtland Commission's definition [6] of sustainability, sustainable buildings should meet current needs without compromising the future uses requirements. Buildings capable of responding to future changes are not going to be obsolete; therefore, key decisions regarding energy performance of buildings should be 'future-proofed' from the early design stages against long-term environmental changes.

The latest climate change scenarios for UK predict considerable temperature increase by 2080 as shown in Figure 1 [7]. Therefore, more energy will be needed for cooling and there is a necessity for forward thinking in terms of energy consumption for generating more appropriate solutions in the design process.

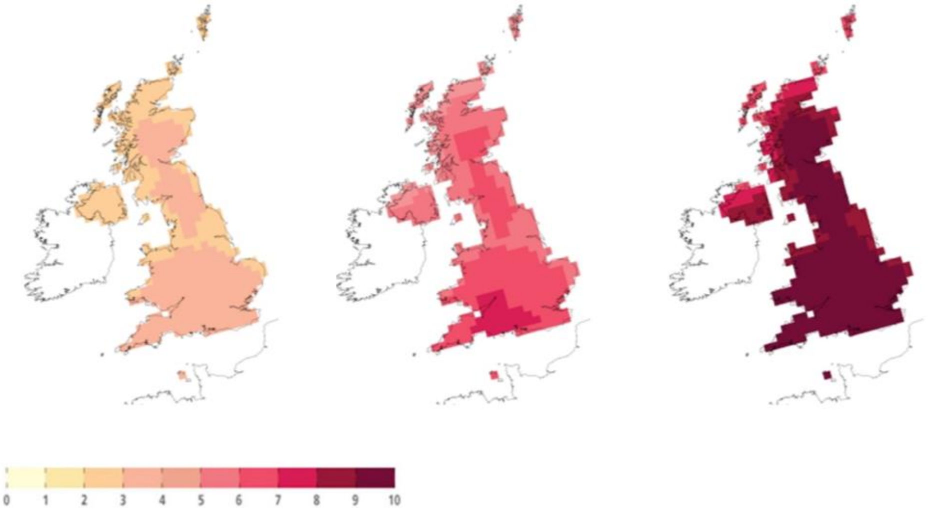


Fig. 1. Summer mean temperature in 2020, 2050, 2080; 90% probability level, very unlikely to be less than the degrees shown on maps (Kalogirou, et al., 2002).

The objective of this paper is to provide an insight into the possible consequences of climate change in UK and, in particular, whether the consequences might cause a change in design decision-making process. Obviously, temperature increases as demonstrated in Figure 1 will affect buildings in terms of energy consumption but the focus in this paper is on whether this influence can cause change in the design decisions between commonly used, high-performance, construction systems.

Bill Dunster Architects and Arup R&D [8] revealed the importance of alleviating climate change consequences by passive design features to offset the predictable temperature rises. The study also recognized that thermally lightweight homes could cause levels of discomfort due to higher room temperatures. The research work emphasized that masonry houses with high inherent thermal mass can result in less energy consumption over their lifetime compared to, for example, a lightweight timber frame house. In a similar vein, Orme et al [9] presented a study, which identified that in a lightweight, well-insulated house; outdoor temperatures of 29°C may cause overheating and result in internal temperatures of more than 39°C.

2. Methodology

Five of the most commonly used wall construction systems in the UK have been selected, as shown from Figure 2 to 6, and upgraded to all achieve a U-Value of 0.1W/m^2K. Design Builder (DB) software was used for running dynamic thermal simulations in a model as shown in Figure 7. In order to quantify the effect of climate change, future weather data for three time slices of 2020, 2050 and 2080 in Manchester and London has been created by CCWeather Gen file in a process known as morphing [10]

CCWeather Gen is an Excel file which transforms the UK's Chartered Institution of Building Service Engineers (CIBSE) TRY (Test Reference Year) files into future EPW files with projections from UK Climate Impacts Program (UKCIP). This EPW file is then applied to DB for simulations. The infiltration was assumed as 0.6 AC/H (air change per hour) and natural ventilation was used (very few homes in the UK are currently designed with mechanical ventilation of cooling systems).

2.1. Brick and block wall (BB)

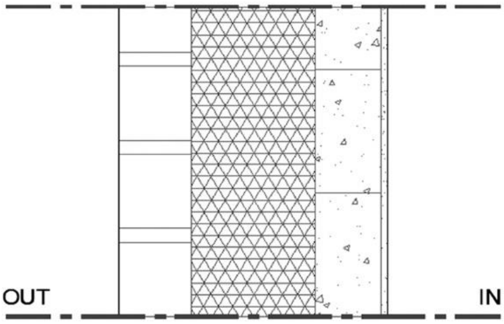


Fig. 2. Brick and block. From Out to in: 110mm Brick Outer Leaf, 300mm Phenolic Insulation, 100mm Aerated Concrete Block, 10mm Lightweight Plaster. (Decrement factor (0-1): 0.23, Time constant: 7.7 hours, Admittance: 5.4 w/mm^2K, U-Value: 0.1 w/mm^2K, Thickness: 520mm)

2.2. Timber frame wall (TF)

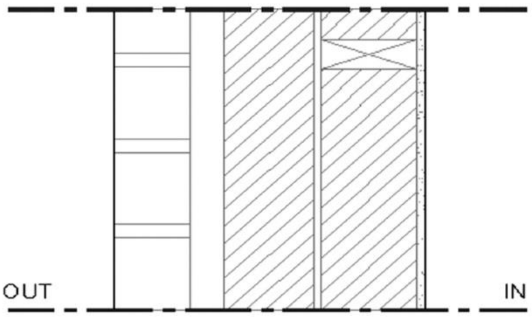


Fig. 3. Timber frame. From Out to in: 110mm Brick Outer Leaf, 50mm Air Gap, 140mm Rockwool, 10 mm Plywood, 200mm Rockwool, 12.5mm Plasterboard. (Decrement factor (0-1): 0.01, Time constant: 3 hours, Admittance: 1.54 w/mm^2K, U-Value: 0.1 w/mm^2K, Thickness: 522.5 mm)

2.3. Insulating concrete formwork (ICF)

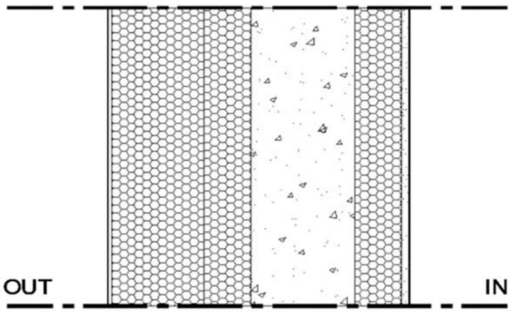


Fig. 4. Insulated concrete Formwork. From out to in: 5mm Rendering, 120mm Extruded Polystyrene (EPS), 100mm Extruded Polystyrene (EPS), 160mm Heavyweight concrete, 100mm Extruded Polystyrene (EPS), 12.5mm Plasterboard. (Decrement factor (0-1): 0.47, Time constant: 5 hours, Admittance: 2.96 w/mm^2K, U-Value: 0.1 w/mm^2K, Thickness: 497.5mm)

2.4. Structural insulated panel (SIPs)

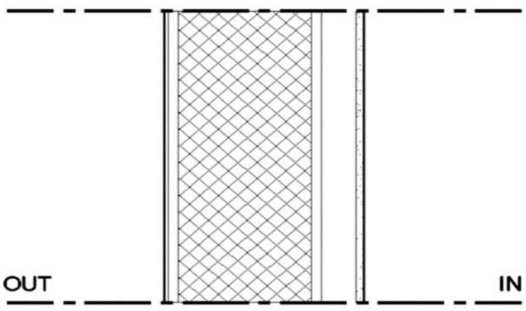


Fig. 5. Structural insulated panel. From out to in: 5mm Rendering, 15mm Softwood board, 200mm Extruded Polyurethane (PUR), 15mm Softwood board, 50mm Air Gap, 12.5mm

Plasterboard. (Decrement factor (0-1): 0.81, Time constant: 2.4 hours, Admittance: 1.16 w/mm^2K, U-Value: 0.1 w/mm^2K, Thickness: 397.5 mm)

2.5. Steel frame wall (SF)

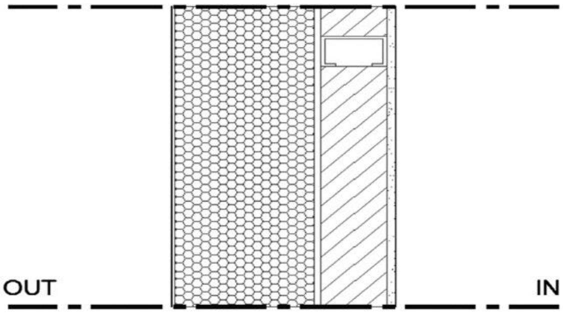
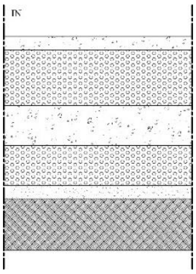
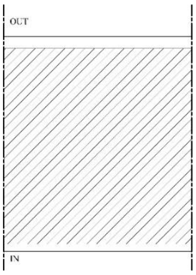


Fig. 6. Steel frame. From out to in: 5mm Rendering, 200mm Extruded Polystyrene (EPS), 10mm Plywood, 90mm Rockwool, 12.5mm Plasterboard. (Decrement factor (0-1): 0.36, Time constant: 4.9 hours, Admittance: 1.39 w/mm^2K, U-Value: 0.1 w/mm^2K, Thickness: 317.5 mm)

Table 1 shows the roof and floor type used for simulations with 0.1 W/m^2K U-Value and triple-glazed, gas-filled windows with 0.8 W/m2K U-Value were used.

Table 1. Ground floor and roof

Detail	Info.
Ground floor 	From top to bottom; 12mm Pine Wood floor, 40mm Concrete Screed, 150mm Extruded Polystyrene (EPS), 125mm Concrete Slab, 100mm Extruded Polystyrene (EPS), 50mm Sand, Crushed Brick
Roof 	From top to bottom; Clay Roof tile, Roofing Felt, 20mm Air Cavity, 450mm Rockwool, 12.5mm Plasterboard

As it can be observed from Figure 7, the model is a single bedroom house with $65m^2$. This study considers the amount of energy to keep the internal conditions within the comfort zone (see section 3, below).

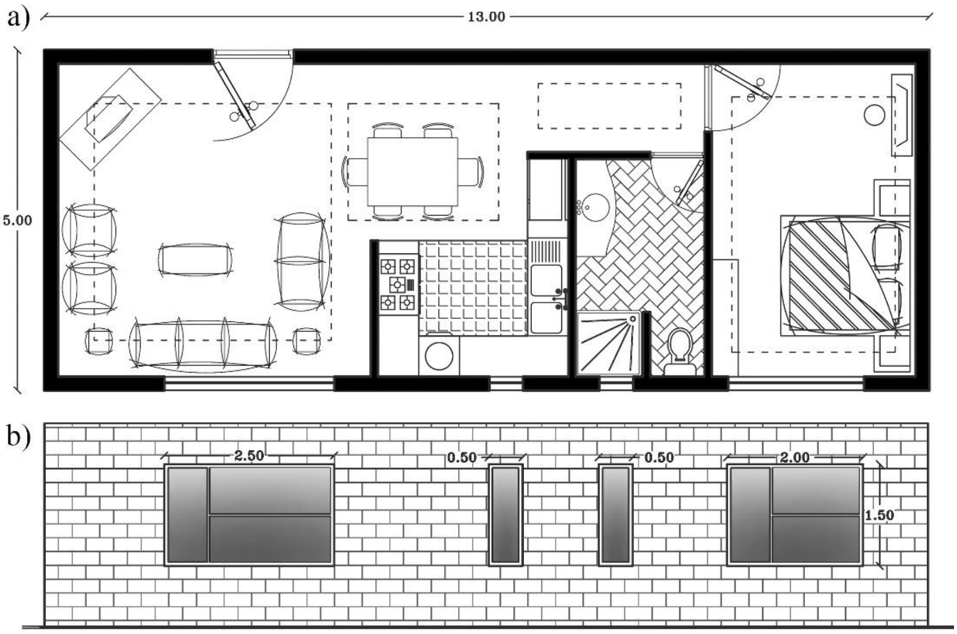


Fig. 7. Model used for simulations; a) Plan; b) South elevation

3. Thermal Comfort

Thermal comfort is an important factor in determining energy consumption in residential buildings. But thermal comfort is a complicated subject that includes the ecological conditions, the human perception and their behaviors. Therefore, it is quite difficult to quantify generally. However, ASHRAE 55-2004 defines thermal comfort as the ‘state of mind that expresses satisfaction with existing environment’ and considers four environmental variables (temperature, mean radiant temperature, relative humidity and air velocity) as well as activity and clothing level of the occupants (see Figure 8) [11].

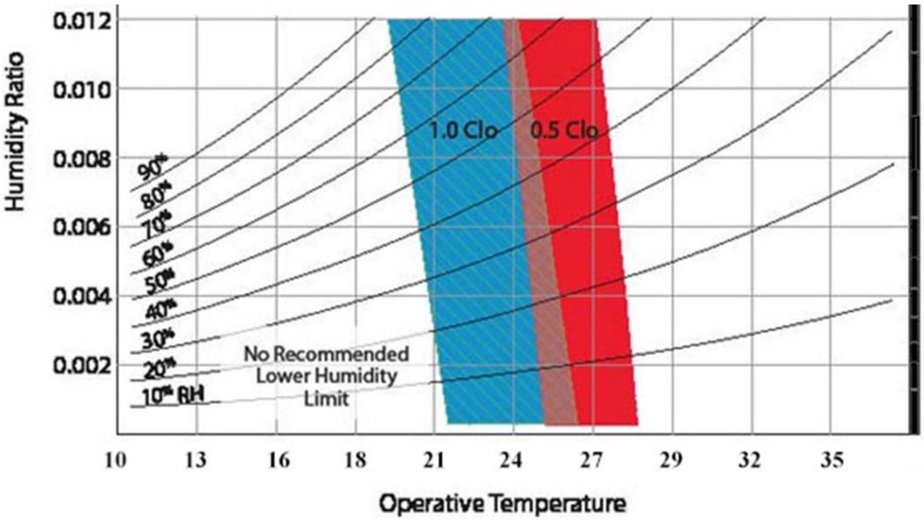


Fig. 8. ASHRAE comfort zone

The shaded zones in Figure 8 show the range of likely comfort condition according to the 2004 standard. Therefore, any other location outside these zones is considered as “discomfort”. For instance, less than 18°C and over than about 29 °C are classified as discomfort, regardless of any other factors that might have an impact, like humidity or clothing level.

Recent updates from ASHRAE 55 for 2010 and 2013 have also been reviewed. These more recent versions are more sophisticated (for example including metabolic rates of the human body). However, the most recent version of DB software did not incorporate these changes and the 2004 standard was used to determine energy consumption for all simulations. The authors’ believe, from their initial analysis, that this omission will not significantly alter results in terms of energy usage in this case.

4. Results and Discussion

Selected wall systems are known to have different thermal mass behaviors even though they have similar U-Value and different thicknesses of construction. Thermal mass utilization can be an effective way of reducing building energy loads, and this approach is even more applicable in locations with high daily temperature variations [7]. The incorporation of thermal mass in the building decreases temperature fluctuations and absorbs energy excesses from solar and internal heat gains [12]. A number of studies have confirmed that in some locations, heating and cooling energy loads in buildings with high thermal mass could be lower than those in similar buildings constructed using lightweight structures with low thermal mass [13] [14] [15].

Figure 9 demonstrates the differences between the wall systems. The Admittance factor (building fabric response to a swing in temperature [16]) is assumed as the measure of thermal mass performance. Therefore, a range of high, medium and low performance systems have been considered. Another factor, which is considered in the Figure 9 comparison, is decrement factor, which demonstrates the construction's ability to decrease the amplitude of temperature from outside to inside [17].

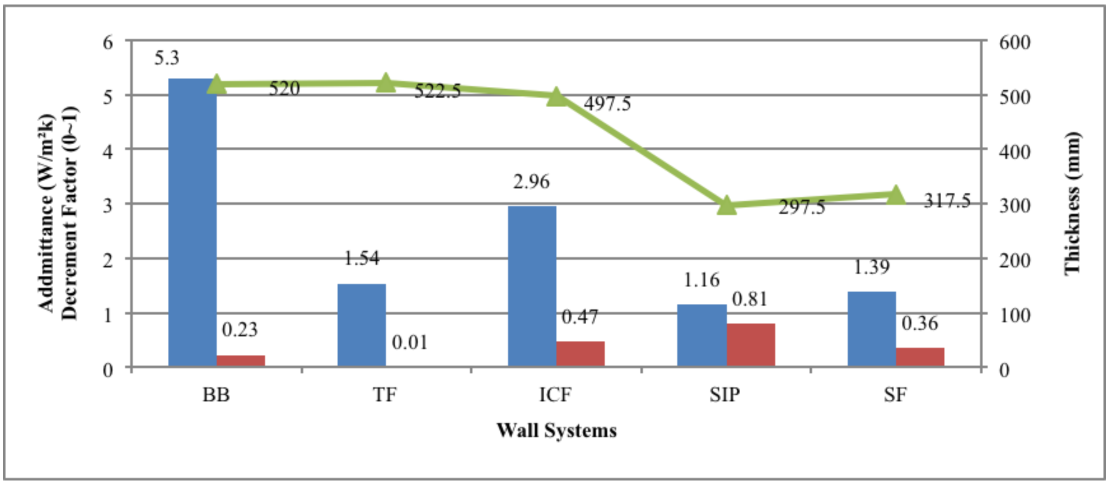


Fig. 9. Admittance, decrement factor and thickness of examined wall

Figure 10 and 11 demonstrate the overall energy consumption predicted by the model, for all time-slices, in Manchester and London respectively. As it can be seen, timber frame (TF) construction results in the most energy consumption and using structural insulated panels (SIP) generally results in the lowest consumption. It appears that high or low admittance factor does not necessarily correlate with lower or higher energy consumption. Thus, it does not seem that applying high thermal mass in UK construction systems necessarily reduces energy consumption. This is supported by the fact that "BB" (brick/block construction) with the highest thermal mass does not show any advantages compared to "SF" (steel frame), which has the lowest admittance factor.

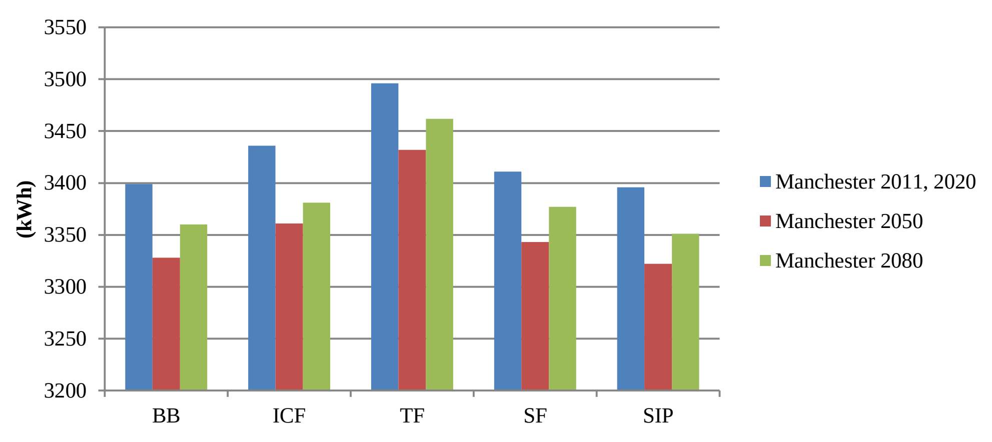


Fig. 10. Overall energy consumption in second model, Manchester

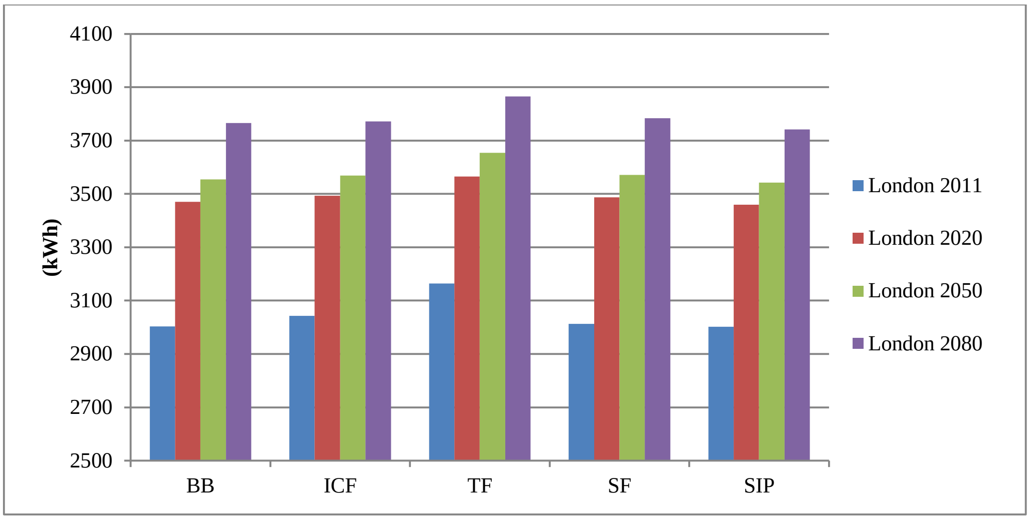


Fig. 11. Overall energy consumption in second model, London

Apparently, climate change causes a considerable rise in energy consumption in London, but would cause lower energy consumption in Manchester, compared to the present time. Obviously, as the weather becomes warmer it would reduce heating loads in both cities, but would increase cooling loads considerably. Predictably, as shown in Figure 1, the effect of climate change is more extreme in London, and the necessary higher cooling loads are the main reason for higher energy consumption in the future in that city.

Importantly for the aims of this study, the relative performance of the different systems does not show significant change with time and thus, climate change. This suggests that similar thermal behavior can be observed from all construction systems for all time-slices. Furthermore, qualitative comparison of the examined construction systems shows almost similar behavior in both cities although the difference between systems is less, in relative terms, in London than in Manchester.

5. Result Validation

As observed, DB has been used for the simulations in this study, which is highly validated building simulation software among researchers. Diarce, et al. [18] studied ventilated active façade with PCM by DB and compared the result with practical experimetns and observed good agreement with experimental data from DB results although moderate differences observed. Also, Baharvand, M, et al. [19] examined air velocity and temperature disturbution and mentioned DB results are reliable and acceptable although some errors exist. Furthermore, a study by the University of Northumbria compared the analysis of Computational Fluid Dynamics by DB with a specialist commercial CFD modelling package- Phoenics and highlighted that the results from DB are in a reasonable difference with Phoenix [20].

6. Conclusion

The study examined the effect of a changing climate on the behavior of some commonly used construction systems. The study was in the two UK cities of Manchester and London, for five different types of construction systems, in a simple single-storey building model. The study considered energy consumption at four times: 2011, 2020, 2050 and 2080.

The simulation results quantify the behaviors of construction systems on the basis of energy consumption. Timber frame construction had the worst performance in terms of energy consumption and structural insulated panel systems generally performed the best. It appeared that low or high thermal mass systems do not result in considerable advantage or disadvantage. These results are comparable to Dodoo, Leif and Sathre [21] who found a concrete-frame building has slightly lower energy demand compared to a wood-frame one in a cold climate of Sweden. Noren et al. [22] also found similar result by emphasizing on limited capability of high thermal mass in cold climates.

Moreover, the principal conclusion of this study is that the simulations suggest that climate change, of itself, would not affect the decision of which construction system to choose, in the early design stages. Although heating loads are going to decrease and cooling loads are going to increase as the weather become warmer, the construction systems’ behaviors and relative performance remain almost the same under changing conditions.

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